MORAINES IN THE CHILEAN LAKE DISTRICT: FORM, PROCESS AND CHRONOLOGY.

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Submitted for the degree of
Doctor of Philosophy
at
The University of Edinburgh

July 1995

ABSTRACT

The aim of this thesis is to determine the extent and timing of fluctuations of two adjacent former outlet glaciers in the Lake District of southern Chile. This is in order to investigate the relative importance of climatic and topographic controls on glacier response. The Lake District is important because it is an area where moraine sequences have been used to establish a 'type' glacial chronology for southern South America. The chronology has been compared with northern hemisphere records to investigate mechanisms of global climate change. The moraines around Lago Puyehue and Lago Rupanco can be divided into two types on the basis of their form, location and constituent materials: rampart moraines are broad, amalgamated moraine complexes whilst ridge moraines are narrow, single ridges usually located around lake shores. Both types have lateral moraines with low up-glacier longitudinal gradients. The moraines are made up of stratified fluvioglacial sediments overthrust on their proximal flanks by clay-rich tills composed of reworked fluvioglacial and glaciolacustrine sediments. A single model explains the location, morphology, sediments and structures of the two types of moraines. Once a lake has formed, it allows the deposition of fine-grained lacustrine sediments which in turn affects the dynamics of the glacier during any subsequent advance and retreat. Glaciers advancing over deformable sediment in the lakes adopt low gradients with low basal shear stresses. The glaciers reach the end of the lakes and form moraines at the lakeshore where there is a transition to more permeable, coarser and less easily deformed sediment. The glaciers are stable there for a wide range of mass balance conditions, and are thus partly decoupled from climate.

A relative chronology reveals a number of similarities and differences between the behaviour of the Puyehue and Rupanco glaciers. Both glaciers had the same broad pattern of advance and retreat but Rupanco lagged Puyehue in its response to climate change. The shorter response time of Puyehue also means for a given climatic deterioration it was more likely to reach the downglacier end of the lake. The empirical evidence of differential response has been used as a test of a glaciological model developed in parallel with this research and helps to explain the geomorphological record. The differences in response reflect the more uniform, steeper longitudinal bed slope of the Puyehue glacier basin, and the influence of contrasting lake bathymetry on calving dynamics. Radiocarbon dating has confirmed that the moraines belong to the last glaciation and that the timing of advances demonstrates a similar pattern to neighbouring glaciers such as Llanquihue. All the glacier basins show advances at c. 21 ka and c. 14.5 ka but the precise timing from basin to basin may have differed by as much as 1500 years.

There are a number of implications to be drawn from the moraine-forming model and the chronologies of the Puyehue and Rupanco glaciers. In areas where temperate glaciers advance into lakes they are likely to be partly decoupled from climate and their behaviour influenced by the presence of the lake and lake sediments. Field evidence of these advances is closely superimposed and detailed morphostratigraphic and lithostratigraphic criteria are needed in conjunction with radiocarbon dating to distinguish different advances. Topography also plays an important role in determining glacier response. These are additional factors to be considered when establishing glacial chronologies from such moraine sequences. The contrast in timing of some advances has important implications for regional and interhemispheric correlation of Lake District glacier chronologies to other climate proxy records.

I certify that the work recorded in this thesis is my own, except where specifically acknowledged. It has been composed by me and has not been submitted previously for any other degree.

Acknowledgements

Primarily, my thanks go to my supervisor, David Sugden, for providing unstinting encouragement and enthusiasm during my tenure as 'one of DES's students'. I enjoyed our meetings and am grateful for the guidance I received. Thanks also to my second supervisor, Chalmers Clapperton, who has been supportive throughout my studentship and helped introduce me to the Quaternary of South America. The work was carried-out whilst I was in receipt of a NERC studentship (GT4/91/GS/38), and my thanks go to the Higher Education Section for enabling me to attend the Santiago workshop in November 1993.

Martin Sharp and a second, anonymous, reviewer provided constructive comments on a paper which helped clarify my thinking on some of the ideas on moraine formation contained in this thesis.

My fieldwork in Chile benefited enormously from the expertise and company of Bob McCulloch and Alun Hubbard. 'Don Bob' and Al both helped make my time in Chile into a never-to-be-forgotten experience. I was also aided in the field by David Sugden, Debbie Greene, Charles Warren, Caroline Wickham-Jones and Wendy Broadgate. The people of Chile always made me welcome and I am grateful for the opportunity to have visited their country and stayed in their homes. In particular, the Hernandez sisters made quite an impression on a fresh-faced *gringo,* and Claudia Uníon from Salfa-Sur Rent-a-car in Osorno helped more than she realises to ensure that transport in the Lake District was never a problem. Juan Pinto was a valued companion during my otherwise solo sojourns at Puyehue. Drs Arturo Hauser, Wladimir Steffen, Hugo Moreno and the staff at CONAF helped smooth scientific problems.

In the Department of Geography in Edinburgh I am grateful for the support I received and the discussions with colleagues. In particular, Bob McCulloch and Debbie Greene have been a great help, whilst my knowledge of glaciology has benefited from sharing an office with Nick Spedding. My thanks also go to Malcolm Murray and Anthony Newton for patiently answering my innumerable computing queries. Alun Hubbard, Andy Kerr, Andy Dugmore, Jane Boygle, Maria-Teresa Ramiréz, Hermione Cockburn, Mike Cressey, Anna Ferrant, Dave Robinson, Sheila Paul, Alastair Borthwick, Pete Nienow, Charles Warren, Andy Macintosh, and Dan Jones have all provided support and made the Department a pleasure to work in. I am also grateful to Gus Wares and the Secretaries, Sue Maclachlan, Anna, Lena and Shona for fielding my queries and requests with efficiency and constant humour. Pete Hill and Stuart Kearns in the Department of Geology coached me in the use of the Microprobe, whilst Chris Minty and Malcolm Murray dealt with my laboratory queries closer to home. Ray Harris, Martin Byrne and Nicola Exley in Drummond Street Reprographics, and Steve Dowers in the computing suite have been an invaluable source of technical help in the production of papers and this thesis and my thanks go to them.

Flatmates past and present have made my time in Edinburgh extremely enjoyable. In particular, thanks to Richard Corrigan who has helped keep everything in perspective and made No. 14 a superb place to live. Thanks also to Sally Brown for inviting me to Greece, and to Lindsey Robb and Dave Edwards who were valuable sources of support during a difficult period.

I am grateful to my parents for the opportunities they have given me and their constant support during this PhD. I appreciate immensely their continued interest in what I do.

Finally, my greatest thanks are reserved for Anya. Her continued support in all spheres of my life, and particularly the unswerving encouragement she gave me during the production of this thesis have made an enormous contribution to its completion, and my enjoyment of it.

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Abbreviations

BP
All radiocarbon dates are reported as uncalibrated radiocarbon years before present (taken as AD 1950). This is abbreviated to BP. The dates have not been calibrated because most lie in the range from 10,000 to 30,000 BP and there is not yet a widely accepted calibration curve for this interval.

ka
To facilitate easy-to-read discussion of the most important radiocarbon dates, the abbreviation 'ka' is used to indicate 'thousands of years before present'. This is only used after the full date has been given previously.

Notes on pronunciation

Many of the place names in the field area date from the indigenous Mapuche tribe who had extensively settled the area prior to the Spanish Conquest. A guide to the most important, non-intuitive names is given below. The syllable '-hue' occurs at the end of many words, and means 'place of'. It is pronounced *'whay'* or *'way'*.

Llanquihue	*yan-kee-way*
Puyehue	*poo-yay-way*
Rupanco	*roo-pan-ko*
Pilmaiquen	*pill-my-ken*
Chiloé	*chill-oh-way*
Rahue	*ra-way*

Chapter 1: Aims, Background and Approach

1.1. Aim

This research aims to investigate the relative importance of local and climatic factors on the fluctuations of two former outlets of the Patagonian ice sheet in the Lake District of Chile during the last glaciation. More specifically, the research aims to:

(i) determine the extent of glacier advances around the basins presently occupied by Lago Puyehue and Lago Rupanco.
(ii) determine the geomorphological and sedimentological nature of the glacier advances
(iii) establish the relative chronology of glacier fluctuations in the two basins.
(iv) establish the absolute chronology of fluctuations and their wider significance.
(v) investigate the role of regional climate and local topographic factors in explaining the glacier behaviour.

This project is part of a wider effort to establish an accurate glacial chronology which reflects past climate change in the Lake District. Chronologies such as this from the Southern Hemisphere are required in order to compare with Northern Hemisphere records when attempting to explain the mechanisms of global climate change.

1.2. Background to the research: the scientific rationale

The rationale for this research lies in the relatively recent change in focus of investigations into past climate change. Formerly, most explanations concentrated on the link between palaeoclimate and cyclical variations in the Earth's orbit (Hays *et al*, 1976). A shift of attention to more internally-forced mechanisms came with a number of key discoveries in the North Atlantic region, particularly in the ice core and marine sediment records. This has led to the recognition of the need for detailed proxy records of climate from the Southern Hemisphere.

Evidence has recently emerged from Greenland ice core studies that abrupt changes in climate were relatively common during the last glacial epoch (Dansgaard *et al*, 1993; Taylor *et al*, 1993; Grootes *et al*, 1993) (Fig 1.1). Oxygen isotopes in the ice cores show that cooling cycles ('Bond' cycles (Broecker, 1994)) with asymmetrical saw-tooth shapes terminating in an abrupt shift to warmer conditions occurred throughout the last glacial (Bond and Lotti, 1995; Bond *et al*, 1993). Each Bond cycle lasted 7 to 10 thousand years but was made up of a series of smaller Dansgaard-Oeschger cycles, averaging a few thousand years in duration.

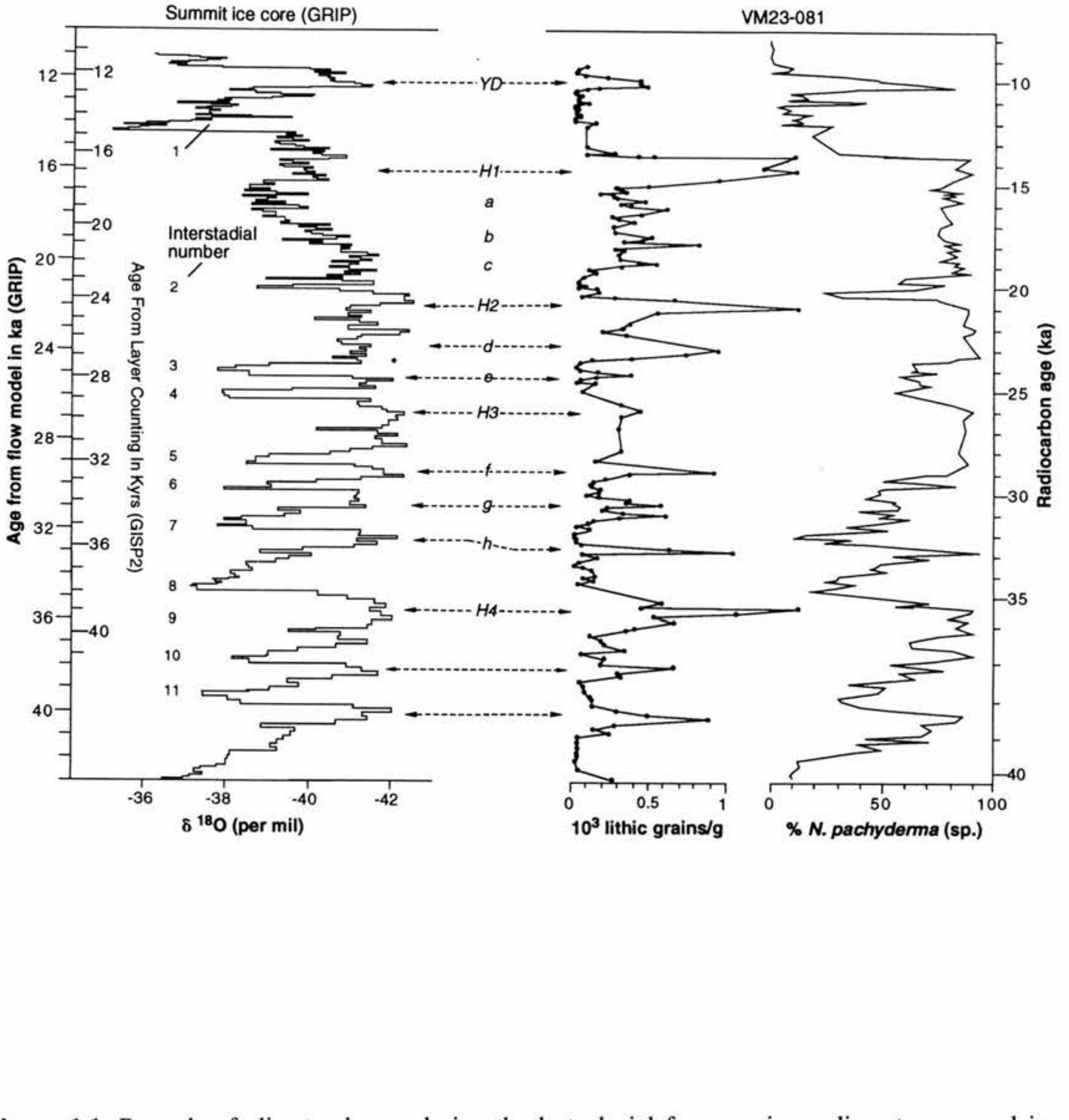


Figure 1.1. Records of climate change during the last glacial from marine sediment cores and ice cores. The concentration of lithic clasts larger than 150 microns provides a proxy record of the amount of ice-rafting occurring in the North Atlantic. Peaks in this record are thought to reflect large pulses of icebergs being discharged from the eastern margin of the Laurentide Ice Sheet. $\delta^{18}O$ values from the ice core provide a proxy of air temperatures over Greenland for the same interval. Note that there is a good correlation between the pattern of the two records, particularly the match of peak cold intervals in Greenland and major pulses of ice-rafting (from Bond and Lotti, 1995).

There is a striking correlation between the ice core data and records from marine sediment cores of changing conditions in the North Atlantic Ocean. The sediment cores show that just prior to the abrupt warming at the end of each Bond cycle there was sea-surface cooling, reduced surface salinities, and deposition of layers rich in lithic clasts, thought to be ice-rafted debris (Fig. 1.1) (Broecker, 1994; Bond *et al*, 1992; Bond *et al*, 1993; Heinrich, 1988). These cold intervals have been termed Heinrich events and are thought to record an increase in the discharge of icebergs into the North Atlantic. The lithological characteristics and distribution of the ice-rafted debris, largely detrital carbonate, points towards eastern Canada as the dominant source (Bond and Lotti, 1995; Bond *et al*, 1992).

Whilst it is widely accepted that massive pulses of icebergs from the eastern margin of the Laurentide Ice Sheet are the most likely cause of Heinrich events, opinions differ as to whether the Laurentide changes were internally or externally driven, and whether the effects were transmitted beyond the North Atlantic region. Initially, the evidence for the fluctuations in the marine sediment and ice core records appeared to be largely restricted to the North Atlantic region and so most attempts to explain them invoked regional mechanisms, with little influence outside the area. One possibility is that the iceberg armadas were purely a result of internally-forced changes in the Laurentide Ice Sheet (Alley, 1990; Macayeal, 1992; Clark, 1994). The idea of internal forcing came from the recognition that the ice sheet may have oscillated due to variations in basal regime in the Hudson Strait area. For example, the theory proposed by Macayeal (1992) suggests that periodic ice stream surges were set up by the freezing and thawing of soft basal sediments. The resultant pulse of meltwater and icebergs cooled the water of the North Atlantic and dramatically changed the thermohaline circulation and hence regional climate. At present a major shallow current of relatively high salinity flows northwards into the North Atlantic region, supplying a great deal of heat and moderating the climate significantly. The water eventually cools sufficiently that it sinks to form North Atlantic Deep Water, giving up large amounts of heat in the process. The maintenance of this continuous circulation forms the so-called 'salt conveyor' (Broecker and Denton, 1989). During periods of increased melting and calving of the Laurentide Ice Sheet the pulse of freshwater entering the North Atlantic is thought to have decreased the average density of surface waters to such an extent that the formation of the North Atlantic Deep Water was switched 'off'. Thus, the North Atlantic would have experienced a net cooling. An implication of this argument is that the events recorded in the Greenland ice cores are an effect of the internal dynamics of the Laurentide Ice Sheet.

A second alternative is that the Heinrich events were driven by an external trigger, probably in the atmosphere (Denton, *pers. comm.*). The case for some form of atmospheric forcing has been strengthened by the recent discovery that Heinrich-like events were also associated with the Fennoscandian Ice Sheet and fluctuated in phase with the Laurentide Ice Sheet (Fronval *et al*, 1995).

Another intriguing development is the discovery that ice-rafting events recurred at intervals of 2000-3000 years, much more frequently than the Heinrich events (Bond and Lotti, 1995). The millenial-scale events were apparently in phase with the Dansgaard-Oeschger events recorded in the Greenland ice cores. In addition, the Younger Dryas cooling event between c.10,800 and 9900 BP (Broecker, 1992), regarded by many as a special case of a Heinrich event, may have had a global signature (Denton and Hendy, 1994; Clapperton, 1993a). If Heinrich events or the Younger Dryas, or both, did have a global signature then this puts quite a different perspective on attempts to explain climate change mechanisms exclusively by changes in the North Atlantic region. The idea of external forcing suffers from the fact that the lengths of cycles are too short for Milankovitch orbital variations to be responsible and the orbital variations would provide opposing forcing in northern and southern hemispheres. Neither models nor theory yet provide a mechanism where the atmosphere on its own can jump from one quasi-stable mode of operation to another (Broecker, 1994).

A third alternative group of theories suggests that although climate variations were initiated in the North Atlantic region, possibly by internal factors, the changes were rapidly transmitted world-wide. The thermohaline circulation of the North Atlantic is thought by many to have been the primary agent for translating changes in the Laurentide Ice Sheet into changes affecting other areas. This supposes that the cooling effect of shutting down the thermohaline conveyor was transmitted beyond the North Atlantic region by changes in global ocean circulation. Other alternative mechanisms which have been suggested for conveying the climatic shifts globally include cooling caused by a 'dust screen' created by increased cyclogenesis in low latitudes (Clapperton, 1993a), or changes in tropical production of water vapour, a powerful greenhouse gas (Broecker, 1994).

Attempts to assess these theories point to the importance of climate proxy records from both hemispheres. Did abrupt millennial-scale climate perturbations occur far outside the North Atlantic region and were they simultaneous with, or did they lag, the North Atlantic changes? Marine cores are an effective means of recording changes in ocean temperatures and circulation and such records now exist for most oceanic areas, but in order to establish former conditions on land and obtain higher resolution records it is necessary to turn to the continents. Terrestrial records tend to yield a higher resolution record of former climate change because, in general, sedimentation rates are higher than in the oceans. Additionally, several proxies are available which can be tested against each other. Continental records tend to be discontinuous but this can be overcome by using different proxies. In addition, it is not always necessary to obtain a continuous record. For example, in the case of global correlation of cold events, glacial records can be used successfully since they record the coldest intervals; the glacier positions are not known during warmer intervals but this need not matter. A particularly sensitive indicator of climate change is the geologic record of glacial advance and retreat in temperate montane regions. Three locations exist for obtaining a glacial proxy of climate change in the Southern Hemisphere, namely Antarctica, New Zealand and the southern Andes. Although fluctuations occurred in Antarctica there is poor dating control because of the paucity of organic material. Glaciers in New Zealand provide a relatively good proxy of climate change but do not encompass a very large latitudinal range. Also, many glaciers on the west side of the Southern Alps of New Zealand terminated in the ocean (Suggate, 1989) whilst those to the east terminated on a relatively arid, sparsely vegetated plain; this means that organic material is less abundant and a high resolution chronology is potentially problematic.

One of the best places in the southern Andes to investigate the record of glacial fluctuations is the Lake District of southern Chile, between latitude 39°S and 41°30′S (Fig. 1.2). During the last glaciation outlet glaciers from the Patagonian Ice Sheet discharged west onto the broad plain of the Central Valley of Chile, leaving a sequence of moraines around the western end of a series of piedmont lakes. The glaciers advanced into a forested and boggy landscape (Clapperton, 1993b) and so there is good potential for radiocarbon dating of the moraine sequence. Although outlets on the east side of the ice sheet also fluctuated to produce multiple moraines the aridity of this region means that few organic deposits exist for dating. Further north, glaciers terminated in the high valleys of the Andes where much of the evidence has since been eroded, whilst to the south they terminated on the continental shelf, leaving little terrestrial evidence.

The Lake District lies just north of the present-day Polar Front (Fig. 1.2) and is within the influence of the Southern Hemisphere westerlies. Glaciers here receive high precipitation and thus respond rapidly to climate change (Lowell *et al*, *in press*; Hulton *et al*, 1994, Kerr and Sugden, 1994). Volcanic activity throughout the Quaternary has also left several tephra layers and lahars, providing the basis for a tephrochronology which is a potentially useful stratigraphic tool in establishing the timing of glacial fluctuations. The area also has a number of sites which have provided palynological records of past climate change and so there is a largely independent climate proxy against which the glacial evidence can be compared. Mismatches between the two records highlights the possible leads and lags in the climate system, which are crucial to an understanding of climate change. Discordant records can also indicate times of anomalous behaviour or insensitivity of one of the records. Thus the Lake District of southern Chile is one of the best Southern Hemisphere locations in which to establish a glacial chronology which may be compared to Northern Hemisphere records. This is the main rationale behind this study.

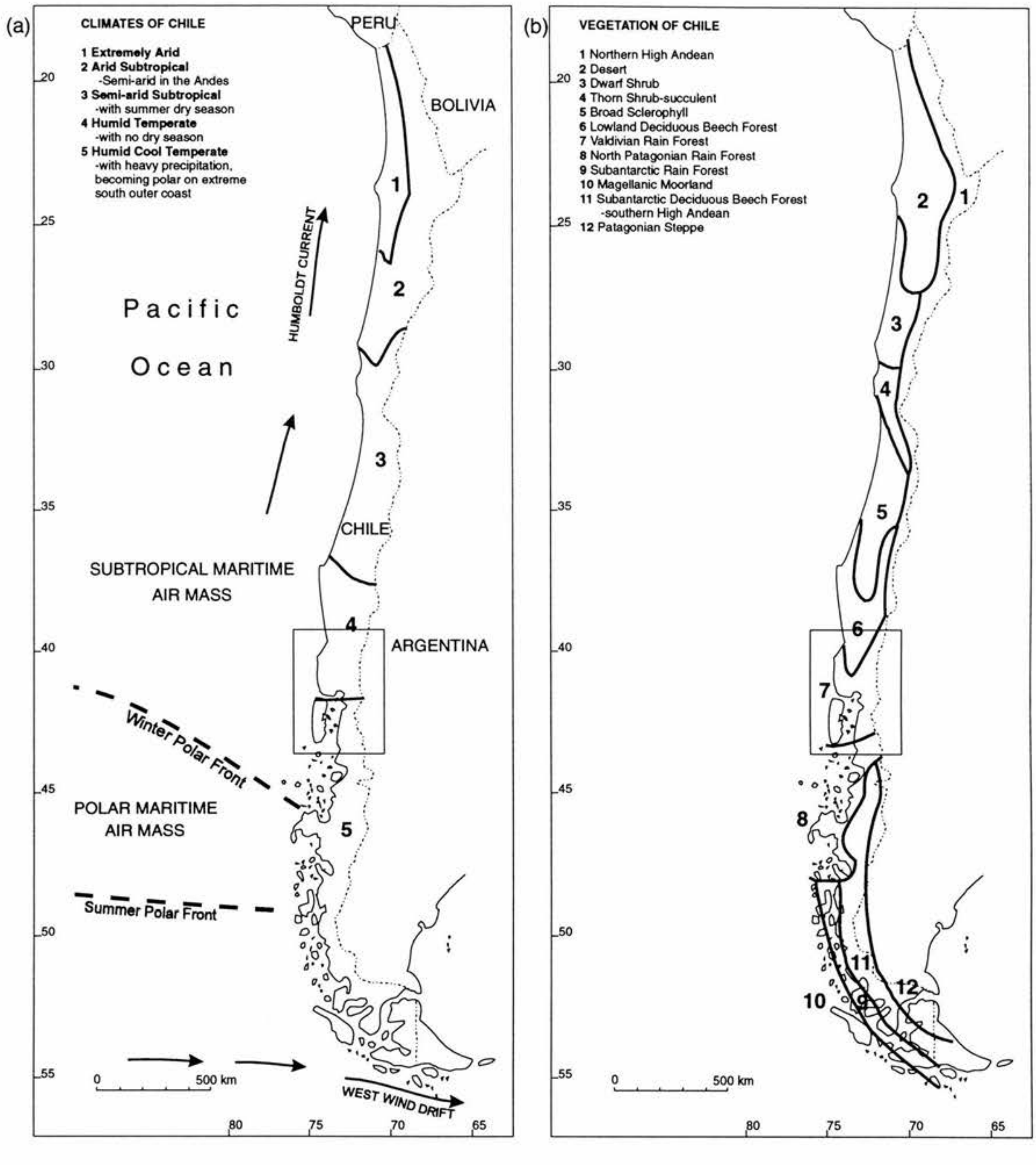
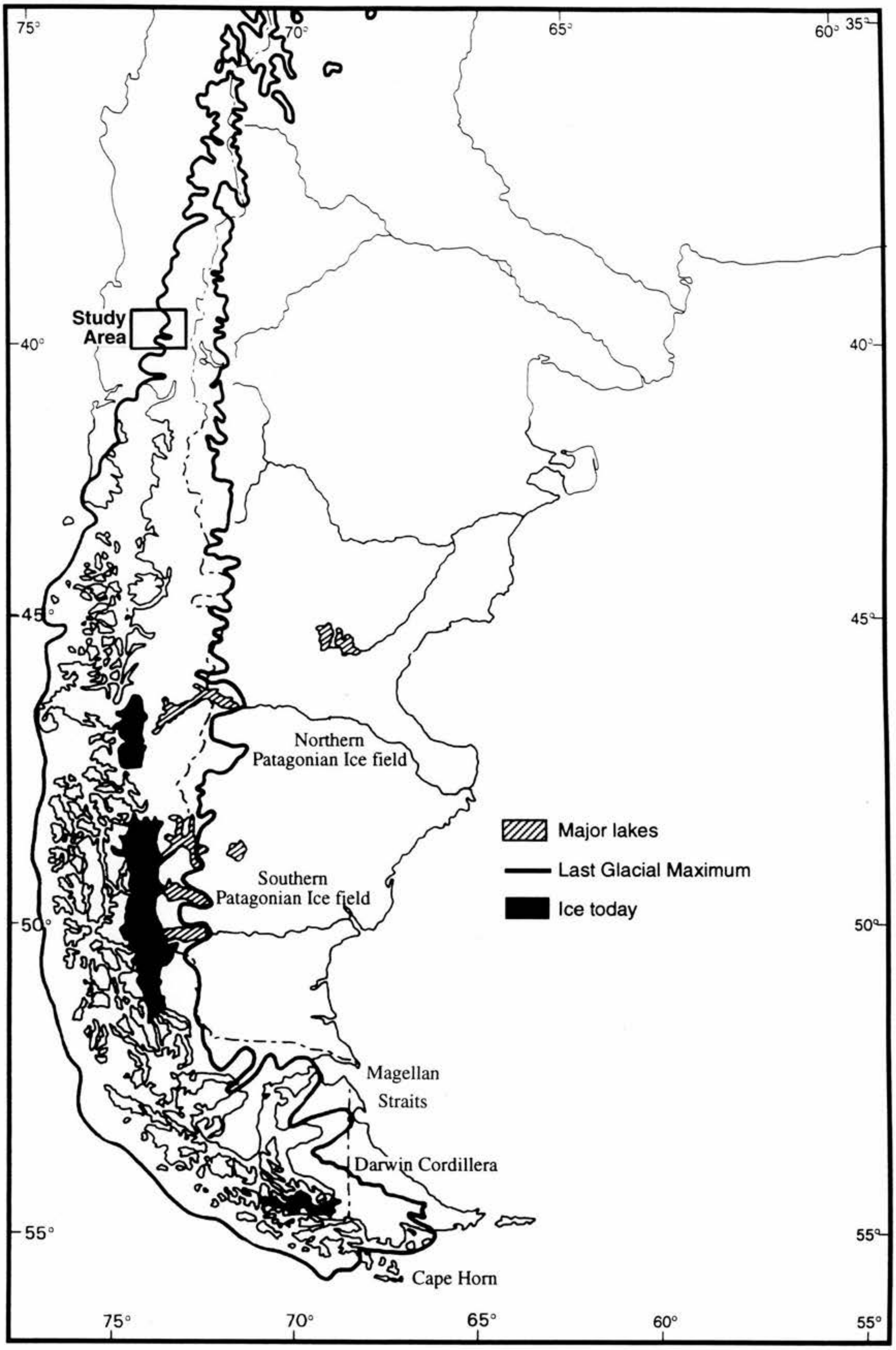


Figure 1.2. Climate, vegetation and glaciers of Chile.
(a) Climate zones of Chile. The country shows a striking latitudinal zonation of climate ranging from extremely arid in the north to sub-polar in the south. The atmospheric polar front lies south of the humid temperate Chilean Lake District and migrates north each winter (Data from Almeyda and Saez, 1958).
(b) Vegetation zones of Chile. The vegetation is distributed in latitudinal bands but in the extreme south the strong west-east precipitation gradient is the dominant control on vegetation distributions. Subantarctic Beech Forest and Magellanic Moorland were the dominant vegetation assemblages in the Lake District during the last glacial but are now restricted largely to the archipelagic region of southern Chile (Data from Heusser, 1974).



(c) Glaciation of Chile. The Northern and Southern Patagonian icefields are the largest ice masses in the southern Hemsiphere, outside Antarctica. The maximum limit of the Patagonian ice sheet during the last glaciation extended into the fjords of the archipelago and onto the continental shelf in the south of Chile, whilst further north the outlets terminated on land. In the northern parts of Chile, glaciers terminated in the high valleys of the Andes (Last glaciation limits from Hollin and Schilling (1981), with modifications reflecting recent work in the Magellan Strait from Porter *et al* (1992), and in the Lake District from unpublished data and Porter (1981)).

1.3. Characteristics of the study area

The Chilean Lake District can be divided into three north-south physiographic zones: the Andean Cordillera, the Central Valley, and the Cordillera de la Costa (or Coastal Range) (Fig. 1.3). The Andes of the Lake District are significantly lower than in north and central Chile; few peaks east of the lakes exceed 2000m whereas summits rise up to more than 6000m further north. The mountains are volcanic in origin and consist of Tertiary and Quaternary andesitic lavas and pyroclastics along with an extensive series of Miocene granitoid plutons (Le-Bert and Dresner, 1964; Munizaga *et al*, 1988). The major volcanoes of the area, all lying on or west of the Andean crest, are (from north to south) Villarica (2840m), Puyehue (2200m), Casablanca (1990m), Puntiagudo (2493m), Osorno (2660m), Tronador (3554m) and Calbuco (2015m). Many of the volcanoes have been active through the Quaternary and into historic times. For example, eruptions have been recorded in 1835 for Volcan Osorno (Darwin, 1845) and in 1961 for Volcans Calbuco (Klohn, 1963), Puyehue and Osorno. A number of peaks support small glaciers today. Prominent among these are Volcan Villarica, Volcan Osorno and Volcan Puntiagudo which have ice descending their flanks to an altitude of c. 1800m. The summit craters of Volcan Puyehue and Volcan Casablanca are both filled with permanent snow.

The Central Valley of Chile is a longitudinal depression which has undergone tectonic subsidence during much of the Pliocene-Quaternary (Paskoff, 1977). The valley is at less than 250m altitude and descends southwards such that south of Puerto Montt it forms the Gulf of Ancud. Geophysical measurements show the infill of volcanic, glacial and fluvial sediment thickens southwards to a recorded maximum of 4000m at Puerto Montt. Río Bueno, Río Pilmaiquen and Río Rahue, draining Lagos Ranco, Puyehue and Rupanco respectively, flow west across the valley. Lago Llanquihue is drained by the Río Maullin which flows southwest.

The Coastal Range comprises low, rounded hills rising to less than 1000m, except north of Osorno where elevations reach 1500m. The range is largely made up of Palaeozoic metamorphic rocks and is tectonically active. There is no evidence for former glaciation of any part of the Coastal Range. Isla Grande de Chiloé forms the southern extension of the Coastal Range south of Puerto Montt. It has been affected by former glaciation derived from the Andes.

The glacially-eroded lake basins of Lagos Llanquihue, Rupanco, Puyehue and Ranco occupy the transition from the Andean cordillera to the Central Valley. Lagos Puyehue and Rupanco are elongate and have surface areas of 153km² and 224km², respectively. They are at similar altitudes to each other; Puyehue is 182m a.s.l. and Rupanco is 118m a.s.l. Lagos Ranco and Llanquihue are lobate with areas of 408km² at 70m a.s.l., and 851km² at 51m a.s.l., respectively. The differences between smaller,

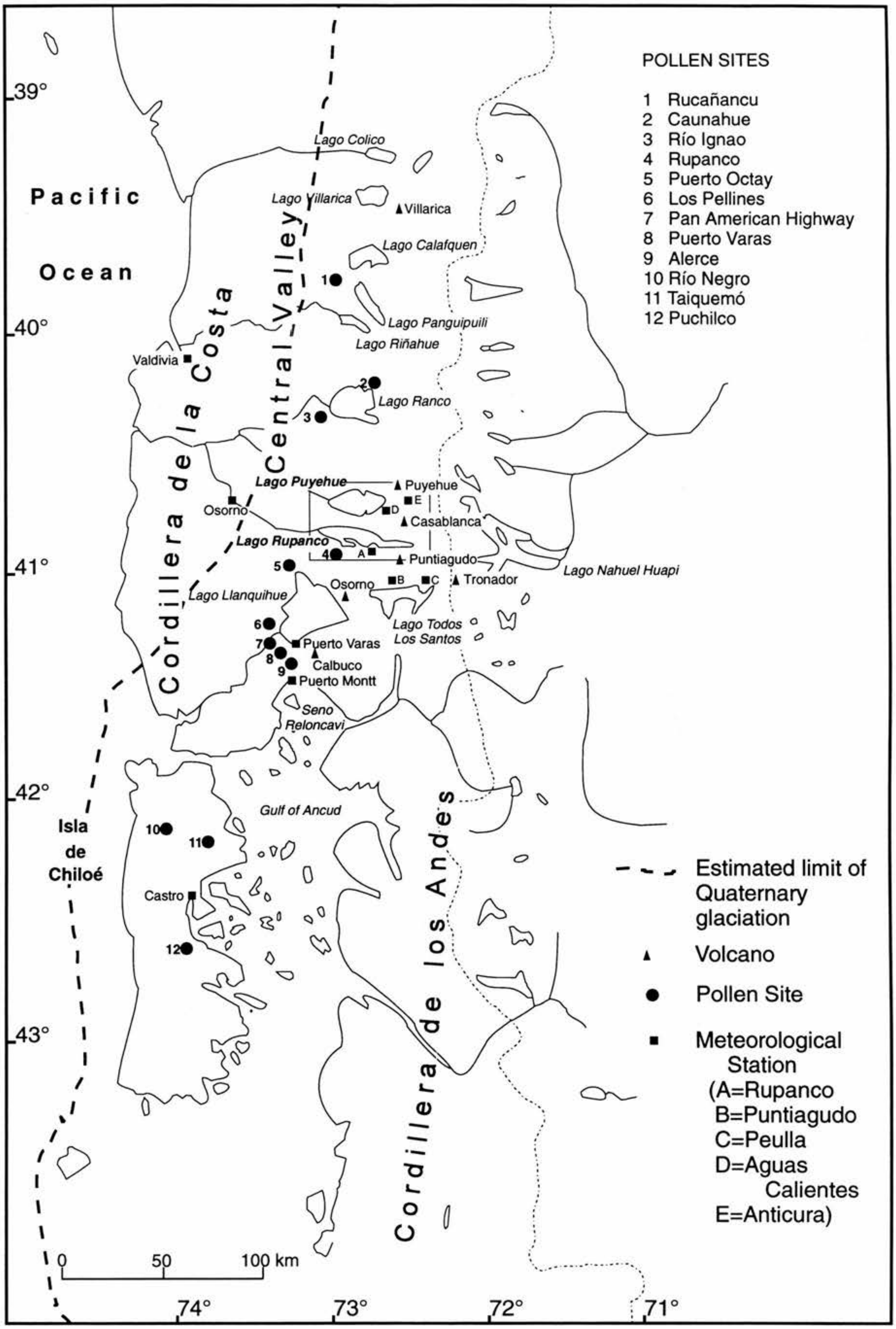


Figure 1.3. Location Map of The Chilean Lake District. Study area is boxed. A series of lakes have been glacially-eroded on each side of the Andes by the former outlets of the Patagonian Ice Sheet. During the last glaciation, each of the lakes plus Seno Reloncavi and the Gulf of Ancud (east of Castro) were occupied by outlet glaciers. Isla de Chiloe is an extension of the Cordillera de la Costa south of the point where the Central Valley extends below sea level to form the Gulf of Ancud. The major volcanoes lie on a north-south line west of the main Andean crest, which is marked by the international border. Pollen sites, glaciation limit and meteorological stations are also shown.

elongate lakes and larger, lobate lakes are important when interpreting the glacial geologic record around each lake since catchment morphology can affect glacier response.

The present-day humid temperate climate of the Lake District results from it being situated close to the latitudinal band of the prevailing westerly winds. During winter, cyclonic storms pass over the Lake District and penetrate as far north as 30°S. The storms derive from the polar front, the boundary between the (cold) subantarctic and (warm) subtropical air masses. During summer the polar front shifts poleward and so storms become far less frequent; precipitation during spring and summer is commonly half that received during autumn and winter (Table 1.1). North of 38°S there is little or no rainfall during summer months. The foothills of the Andes (e.g. Peulla) have substantially higher rainfall totals than in the Central Valley (e.g. Osorno) while further east, near the crest of the mountains, precipitation declines until it reaches a minimum on the Argentinian side of the Andes. This is because precipitation close to the western foot of the Andes is enhanced by the orographic effect of the mountains. The result is a steep precipitation gradient of up to 30mm/km from west to east. Consequently, rainfall variations of the order of metres/year occur over distances of tens of kilometres. For example, to the east of Lago Puyehue, there are two sites, 10 kilometres apart, where annual rainfall totals differ by one metre per year.

Station	Location	Elevation (m)	Mean January temperature (°C)	Mean July temperature (°C)	Precipitation (Autumn+Winter) (mm)	Precipitation (Summer+Spring) (mm)
Osorno	40°35'S, 73°09'W	24	17.6	8.3	898	381
Puerto Varas	41°20'S, 72°57'W	51	15.7	9.0	1173	633
Puerto Montt	41°28'S, 72°56'W	5	15.3	7.6	1225	735
Rupanco	40°50'S, 72°25'W	141	-	-	1239	608
Puntiagudo	41°05'S, 72°17'W	190	15.0	6.4	1925	1090
Peulla	41°05'S, 72°02'W	190	-	-	2190	1140
Aguas Calientes	40°43'S, 72°18'W	500	13.7	4.3	2332	1388
Anticura	40°41'S, 72°10'W	400	14.7	5.2	1770	979

Table 1.1: Climatological data from the southern Lake District. Data from Almeyda and Saez (1958) and Corporacion Nacional Forestal (CONAF) (*pers. comm.*).

Temperatures are generally characteristic of a warm temperate climate with a mean January (summer) temperature of 15-16°C. Winter temperatures around Lago Llanquihue drop to an average of c.8.5°C in July. From limited data Heusser (1974) extrapolated temperatures along a west-east altitudinal transect from Osorno (alt. 80m, mean Jan. temp. 17.6°C) to the summit of Antillanca (alt. 1990m, estimated mean Jan. temp. c.10°C). However it should be stressed that no meteorological data exists above 500m in this region.

Present-day glacier equilibrium lines (snowlines) in the southern Andes reflect the decline in precipitation from the peak totals in the foothills to lower values at the Andean crest. Consequently, the equilibrium lines are characterised by a steep east-west gradient. The gradient is common to maritime glaciated regions, reflecting a reduction in precipitation inland. The Equilibrium Line Altitude (ELA) at the latitude of the Lake District, as measured using the Accumulation Area Ratio (AAR) method (Andrews, 1975), is at 1800m at the crest of the Andes and decreases to 1600m on the volcanoes directly around the lakes (Hulton *et al*, 1994). The ELA also descends markedly to the south, a reflection of the increasing influence of the southern westerlies. At 54°S the ELA lies as low as 800m on the coast and 1000m at the Andean crest. Porter (1981) used the median altitude of glaciers on the flanks of volcanoes around Lago Llanquihue as an estimate of the modern snowline. Using this method the snowline rises from 1900±125m close to the lake to c.2100±125m on the Andean crest. The two methods do not provide a close match but encompass a reasonable range of ELA values. The variability is due to the paucity of mass balance data and the fact that many of the ELA measurements derive from 1:250000 scale maps of small local glaciers which show relatively large differences between closely adjacent peaks. In some cases the maps have been compiled from maps produced from air photographs taken at different times of the year which would introduce errors into the ELA calculations. For example some winter snowfields have been classified as glaciers on some maps (Hulton *et al*, 1994).

1.4. Previous work on the glacial history of the southern Lake District

The glacial deposits of the Chilean Lake District have a long history of investigation. Early studies were characterised by extensive geomorphological mapping of moraine belts and attempts to distinguish glaciations on the basis of moraine morphology, landform relationships and clast weathering characteristics. Most of the studies agreed that there are three or four glaciations recorded between the Andes and the Coastal Range (Table 1.2). The moraine belt marking the most extensive of the glaciations lies up to 60km west of the lakes. Moraine stratigraphy was established in different geographic areas and from different sedimentary sections. This resulted in differences in stratigraphic terminology and difficulties in correlating from one moraine belt to possible equivalents elsewhere in the region. However, the moraines around the western shores of the lakes were almost exclusively attributed to the maximum of the last glaciation with the notable exception of Brüggen (1950) who interpreted them as retreat stages from a more extensive glaciation. Caldenius' (1932) study of

	Brüggen (1950)	Weischet (1958)	Weischet (1964)	Olivares (1967)	Lauer (1968)	Laugenie (1971)	Mercer (1976)	Heusser and Flint (1977)	Porter (1981)	Laugenie (1984)
Area studied	W side of Central Valley, Cordillera de la Costa, Lago Llanquihue	Central Valley and W of Lago Puyehue	Central Valley and W of Lago Puyehue	West of Lago Llanquihue	Lago Ranco, Central Valley	Northern part of Lake District	Lago Llanquihue, Central Valley	Isla Grande de Chiloé	Lago Llanquihue, Central Valley	Lagos Llanquihue and Rupanco
Last glaciation	Rahue + retreat stages around west shore of Llanquihue	'Seestirn' (lakeshore) moraine	El Salto	Moraine equivalent to Würm (European Alps)	3 moraine loops around Lago Ranco	Morainic loops around lakes	Llanquihue	Llanquihue	Llanquihue	Neollanquihue Mesollanquihue Eollanquihue
Penultimate glaciation	Contaco	Rahue	Río Negro II Río Negro I	2 moraines, correlated to Riss (European Alps)	San Pablo	Hualapulli Huidif	Casma Colegual	Intermediate	Santa María	
Pre-penultimate glaciation II		Contaco	Rahue		East flank of Coastal Range	San José Nochaco	Río Frío	Fuerte San Antonio	Río Llico	
Pre-penultimate glaciation II			Contaco						Caracol	

Table 1.2. Stratigraphic terms for the moraine belts of the Chilean Lake District. Correlations are fairly good for the last glaciation but discordance in the number of moraine belts recognised means that correlation of earlier events remains speculative.

Patagonian glaciation included four mapped moraine limits for the Lake District but he did not describe the moraines. The moraines were attributed to the European Finiglacial, Gotiglacial, Daniglacial and Initiglacial events - an early example of attempts at inter-hemispheric correlation. Weischet (1964) recognised three moraine loops within the El Salto moraines at Lago Puyehue and two loops within those at Lago Rupanco but did not map them in detail. Lauer (1968) described 3 moraines at the west end of Lago Ranco but did not attempt to date them. Heusser (1974) introduced the term 'Llanquihue Glaciation' to describe the last glaciation and this was followed by Mercer (1976) who used 'Llanquihue drift' to describe the moraines around the lakes.

The first dates on the Llanquihue moraines were obtained by Mercer (Table 1.3) who was the first to show the full potential of the southern Lake District for establishing a well-constrained glacial chronology for southern South America (Mercer, 1972; 1976; Mercer and Laugenie, 1973; Stuiver *et al*, 1975). Radiocarbon dates on the Llanquihue drift showed there were at least three, probably four advances reaching the western shore of Lago Llanquihue during the last glaciation. They also demonstrated for the first time that the moraine belts further west were beyond the range of radiocarbon dating and so probably belonged to earlier glaciations. The antiquity of the moraines has been supported by K-Ar dates and magnetostratigraphy of lava flows interbedded with glacial deposits east of the Andes in Patagonia which show that the probable equivalents of the pre-Llanquihue glaciation moraines accumulated over millions of years (Mercer, 1976; Mörner and Sylwan, 1989). On the basis of dated organic horizons interbedded with tills and outwash Mercer recognised advances west of Lago Llanquihue at pre-50,000 BP and pre-39,900 BP, followed by a long interstadial. The last glacial maximum on the south side of Lago Rupanco and to the western shore Lago Llanquihue occurred shortly after 19,450 BP, the date being obtained on wood from a bog overridden by the advance. Dates on sections along the western shore of Lago Llanquihue were interpreted as showing that a subsequent advance reached the western shores of Lago Llanquihue at 13,000 BP following the *Varas* interstade (Mercer, 1972) when glaciers shrank considerably.

Porter (1981) was the first to distinguish pre-Llanquihue drift sheets on the basis of quantitative measurements of depth of weathering, thickness of weathering rinds on volcanic clasts, intensity of limonisation, extent of MnO_2 deposition on clasts and in matrix and detailed descriptions of moraine morphology. Subdivision of the Llanquihue drift on the basis of lithologic or relative weathering criteria was not possible but landform mapping and sedimentological criteria were used to separate the drift into three units of stadial status: Llanquihue I, Llanquihue II, and Llanquihue III. Radiocarbon dates on reworked organic clasts and organic beds interstratified with tills and outwash showed that these occurred before 30,000 BP, between 19,000 and 20,000 BP, and shortly after 13,000 (Table 1.3). Both the number and timing of advances was in broad agreement with Mercer but Porter's chronology was based on more dates so it provided firmer constraints on the latter two advances. He

Radiocarbon years BP	**Mercer (1976)**	**Porter (1981)**
		9410+/-400
		Tephra post-dating deglaciation
-------10,000------	11,000 Glacier Tempano within present borders	10,520+/-300
	12,200+/-400 Lago Ranco ice-free	12,165+/-900 Basal seds, post-glacial bog
	12,460+/-190 Seno Otway deglaciated	***LLANQUIHUE III †***
	Culmination of advance.	13,900+/-120 Stump below LIII(?) drift
	13,300+/-550 Closure of eastern outlet	14,200+/-135 Peat and plant fragments
	of Lago Llanquihue	15,220+/-160 below lacustrine seds
	Varas interstade	15,400+/-400 signalling onset of LIII
	17,370+/- 670 Basal peat, Pto. Octay spillway	15,715+/-440 Peat in LIII terrace *
	Advance to western lakeshores	18,170+/-650 Basal peat in spillway cut
	19,450+/-350 Overidden peat, Laguna Bonita	18,900+/-370 into LII outwash
--------20,000------		***LLANQUIHUE II***
	20,100+/-500 Overidden bog at Frutillar Alto	20,100+/-500 Overidden bog (Mercer)
	Glaciers	
	Retreat	
	Unknown	
		29,600+/-350 Gyttja under LI or LII gravel
---------30,000-----	*Distance*	30,400+/-1150 Clast in probable LII drift
		30,700+/-1300 Peat clasts in possible
	32,000+/-700 Wood beneath outer end moraine	31,700+/-1000 LI till
	(probably contaminated)	32,800+/-1600 Peat clast in LII outwash
		37,400+/-500 Gyttja under LI or LII gravel
		LLANQUIHUE I ?
	39,900 Log under outer moraine (contaminated?)	
--------40,000------	>40,000 Outermost moraine	
	Advance to	42,400+/-500 Seds under outwash of LI or LII age
	Outermost	>45,600 Wood in stratified (?LI) drift
	Moraine	47,600+3400/-2400 Stump under Llanquihue drift
---------50,000-----	*?Interstadial*	
	Undated	
	(?Early	57,800+2300/-3200 Wood overlying Sta Maria till
		(?contaminated)
	Llanquihue)	
		Deposition of Santa
---------60,000-----	***Advance***	***Maria drift***

Table 1.3: Glacial Chronologies, established mainly for the Llanquihue outlet glacier, according to Mercer (1976) and Porter (1981).

†= possibly preceded by an advance at 15,000 B.P. with retreat between 14,500 and 15,000 B.P.

*=several other dates have been obtained for material from this LIII terrace (16,270±360, 15,050±100, 14,280±230, 14,485±120, 14,250±400, 13,965±235, 13,750±295, 13,300±550, 13,200±320, 13,145±235)

also argued that another advance occurred at c. 15,000 BP, closely preceding Llanquihue III. The evidence for this was based on radiocarbon dates of peat layers buried by laminated lake sediments thought to represent a rising level of Lago Llanquihue as the glacier advanced across its normal drainage outlet. Differences between dates from a number of localities at different altitudes around the lake were interpreted as showing that the glacier advanced once close to 15,000 BP, then retreated between 14,500 and 15,000 BP before advancing to the lakeshore terrace which forms the Llanquihue III limit at c.13,000 BP However, if the dates are plotted with two standard deviations (i.e. 98% probability that the actual date lies within the range) then the buried peats could simply record a continuously rising lake level from 15,700 until the culmination of the Llanquihue III advance. Without further evidence the 15,000 BP advance remains speculative.

Laugenie (1984) carried-out detailed geomorphological mapping west of Lagos Rupanco and Llanquihue and focused on the outwash units rather than the moraines themselves. He did not provide any more radiocarbon dates. The Llanquihue glaciation was divided into 3 periods, an Eollanquihue advance at >40,000 BP, the Mesollanquihue interstadial and the Neollanquihue advance at c. 20,000 BP but these were only constrained by existing dates and no correlation to Llanquihue I, II, III was attempted.

The most recent work on the timing of Llanquihue glacial advances is that of Lowell *et al* (*in press*), a project directed by George Denton and carried-out in parallel with this study. The project had the specific aim of developing a well-constrained radiocarbon chronology for the southern Lake District comparable to those in New Zealand and parts of the Northern Hemisphere so that inter-hemispheric correlation of climate change could be attempted. Both studies have revealed a more complex glacial history than previously recognised. The radiocarbon chronology for Lago Llanquihue is probably now the best-dated glacial record for any part of South America and is likely to become the benchmark against which other records may be compared. At least six glacier advances during the last glaciation have been recognised from evidence west of Lago Llanquihue and on Isla Grande de Chiloé (Lowell *et al, in press*). More than 100 radiocarbon dates on 3 glacier lobes (Llanquihue, Seno Reloncavi and Castro) have established that maxima were achieved at 14,500-14,700; 21,000; 23,100; 26,900; 29,200 BP; and at least once before 35,000 BP (Fig. 1.4). The timing of most of the advances is well-constrained by multiple dates from a number of sites for each lobe. Most of the advances of the Llanquihue lobe were to a position close to the western edge of the lake and so the dates have been derived from sections in a stacked series of moraine loops forming a single complex. A large number of dates on the youngest Llanquihue advance have been obtained from the lakeshore terrace which forms the western shore of Lago Llanquihue. The fluctuations of the Seno Reloncavi lobe have been dated from stacked outwash units near Puerto Montt. Further south, several dates have been obtained

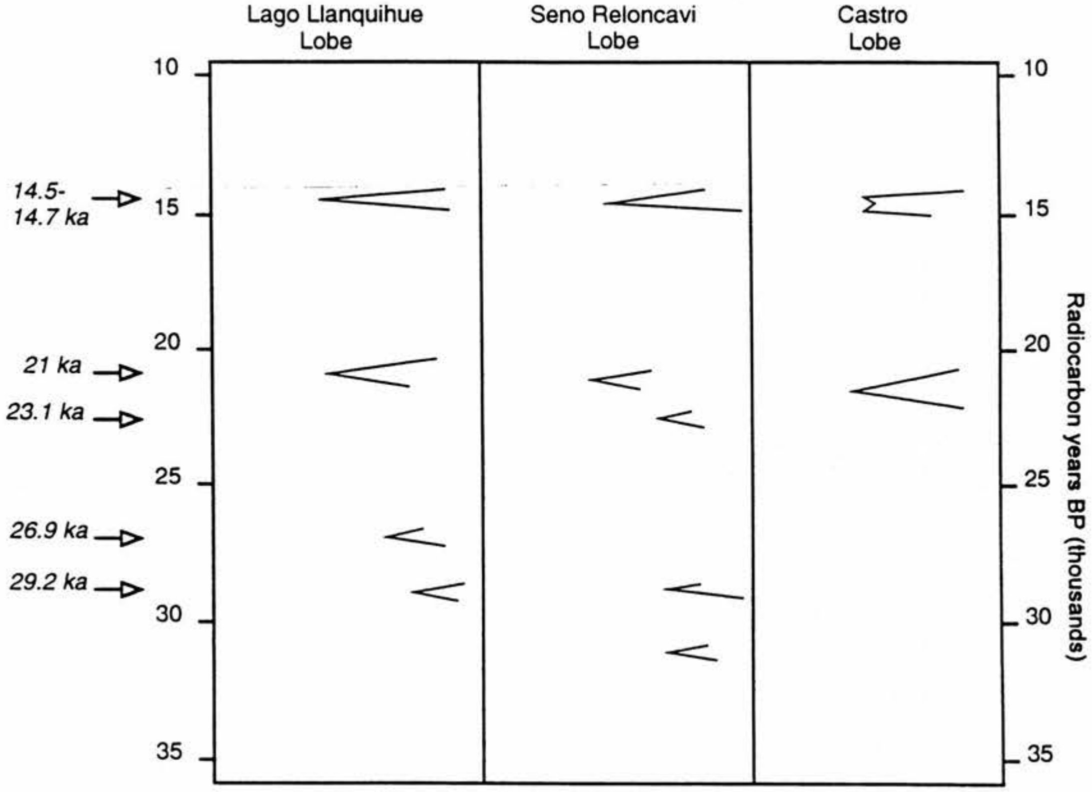


Figure 1.4. Time-distance diagram for the Llanquihue, Seno Reloncavi and Castro lobes. Culminations of advances are recognised at 14.5-14.7, 21, 23.1, 26.9, 29.2 ka, and at least once before 35 ka. Modified from Lowell *et al* (*in press*).

from wood overridden by the Castro lobe as well as from organic silt layers interbedded with tills and outwash.

New dates on the lakeshore terrace of Lago Llanquihue which place the youngest advance at 14,500-14,700 BP are significantly earlier than postulated by Mercer and Porter, but the timing appears to be confirmed by several dates on an equivalent advance over Grande Isla de Chiloé to the south. The next youngest advance, culminating close to 21,000 BP is also apparently older than previous work suggested; attempts to revisit Mercer's original sites and replicate the results yielded significantly older dates. The advance is bracketed in places by reworked organic clasts and basal organic matter in abandoned meltwater spillways. Dates from various sites show that the advance reached its maximum position between 20,600 BP and 22,000 BP. The next oldest advance, at 23,100 BP, is not well constrained. The evidence for it rests on a single date from a site near Puerto Montt. At this site a sequence of fluvioglacial units are each separated by peat or gyttja beds. A date on the upper surface of the peat directly below the topmost fluvioglacial unit yields a date of 23,120 +130/-125 BP (A-7626). Although this peat is apparently not eroded it may still only represent a maximum for the 21,000 BP advance so the advance at 23,120 must remain speculative. The advances at 26,900, 29,200 and pre-35,000 BP are all constrained by multiple dates on organic silt interbedded with till and outwash units. The dates on the 26,900 BP advance are thought to be particularly reliable since they derive from apparently undisturbed fossil grass and leaf litter on the top of one of the silt layers, directly below till. Scattered sites west of Lago Llanquihue and on Chiloé afford dates older than 35,000 BP and the deposits have been assigned a Llanquihue glaciation age from their weathering characteristics and lack of evidence for interglacial conditions in pollen profiles above them. Although at least one advance occurred prior to this time, the precise number has not yet been established.

It is widely agreed that deglaciation from the lake basins and Gulf of Ancud would have been relatively rapid as the glaciers withdrew and calved into progressively deeper water. Rapid recession may have been enhanced by isostatic depression of the lake basins if deglaciation occurred before substantial isostatic recovery took place. Ice recession was underway on Chiloé by 14,350 BP (Lowell *et al, in press*), Lago Ranco was free of ice by 12,200 BP (Mercer, 1976) and glaciers formerly reaching the Gulf of Ancud had receded to within 10km of their current termini by 12,310 BP (Lowell *et al, in press*). Further south, dates of 11,000 BP from peat situated close to present termini show that glaciers were within their present borders and have not advanced beyond the peat sites since that date (Mercer, 1976). The timing of ice recession in Lago Llanquihue is not known but is thought to have begun shortly after 14,500 BP (Lowell *et al, in press*).

In summary, the Llanquihue glacial chronology constrains well the time of four advances, at 14,500-14,700; 21,000, 26,900 and 29,200 BP. A fifth postulated advance at 23,120 BP is based on one date.

The earliest advance(s) before 35,000 BP is not well dated. The chronology is better-constrained than any others and provides an excellent basis for considering past fluctuations in the climate of the region.

1.5. The biological record of the last glaciation

'Most biogeographers try to check their conclusions against the background of geological facts to the best of their ability. It seems to me that geologists, in their turn should spend some time on attempts to understand and evaluate the biological way of thinking which, actually is not very complicated' (Lindroth, 1972). The biological record of past climate change during the Llanquihue Glaciation in the Chilean Lakes Region provides a useful proxy which is largely independent of the glacial geologic record and so the two can be tested against each other. This section reviews the biological evidence for environmental change from palynology, Coleoptera and megafuana.

1.5.1. Palynology

Using a uniformitarian approach to the relationship of pollen assemblages to climatic conditions, several workers have attempted to infer the climate changes occurring in mid-latitudes of Chile during the last glacial cycle. Chief amongst these is Heusser whose work (1974; 1976; 1981; 1991) has become a benchmark for studies in the region. His initial work defined the vegetation zones in north-south and east-west transects of Chile and related the zones to climatic parameters, particularly mean January (summer) temperature and annual precipitation (Heusser, 1974). This established a framework for palaeoclimatic studies by allowing former pollen assemblages to be interpreted in climatic terms. Heusser and Streeter (1980) extended this work and developed regression equations to provide values for temperature and precipitation. However, his quantitative multi-variate approach (Heusser and Streeter, 1980; Heusser *et al.*, 1981) has drawn criticism. The method supposes that plant distributions are in equilibrium with climate, an assumption that has been questioned by recent studies (Ashworth and Hoganson, 1984). Most workers have avoided this method and instead used a largely qualitative approach comparing past pollen assemblages to those associated with present climate (e.g. Markgraf, 1989a).

The earliest parts of the Llanquihue glaciation have not yet received palynological study, largely due to the dating problem. The oldest pollen data come from a non-glacial deposit from Río Ignao, southwest of Lago Ranco, which is dated at >56,000+2000/-1700 BP (Stuiver *et al.*, 1975). The pollen indicate that grassland in a dry, cold climate was superseded by a slightly warmer, wetter episode with mean January temperatures at least 3-4°C colder than at present (Heusser, 1976). A reversion to cold, dry conditions followed (Fig. 1.5). Since temperatures never reached a comparable level to those of

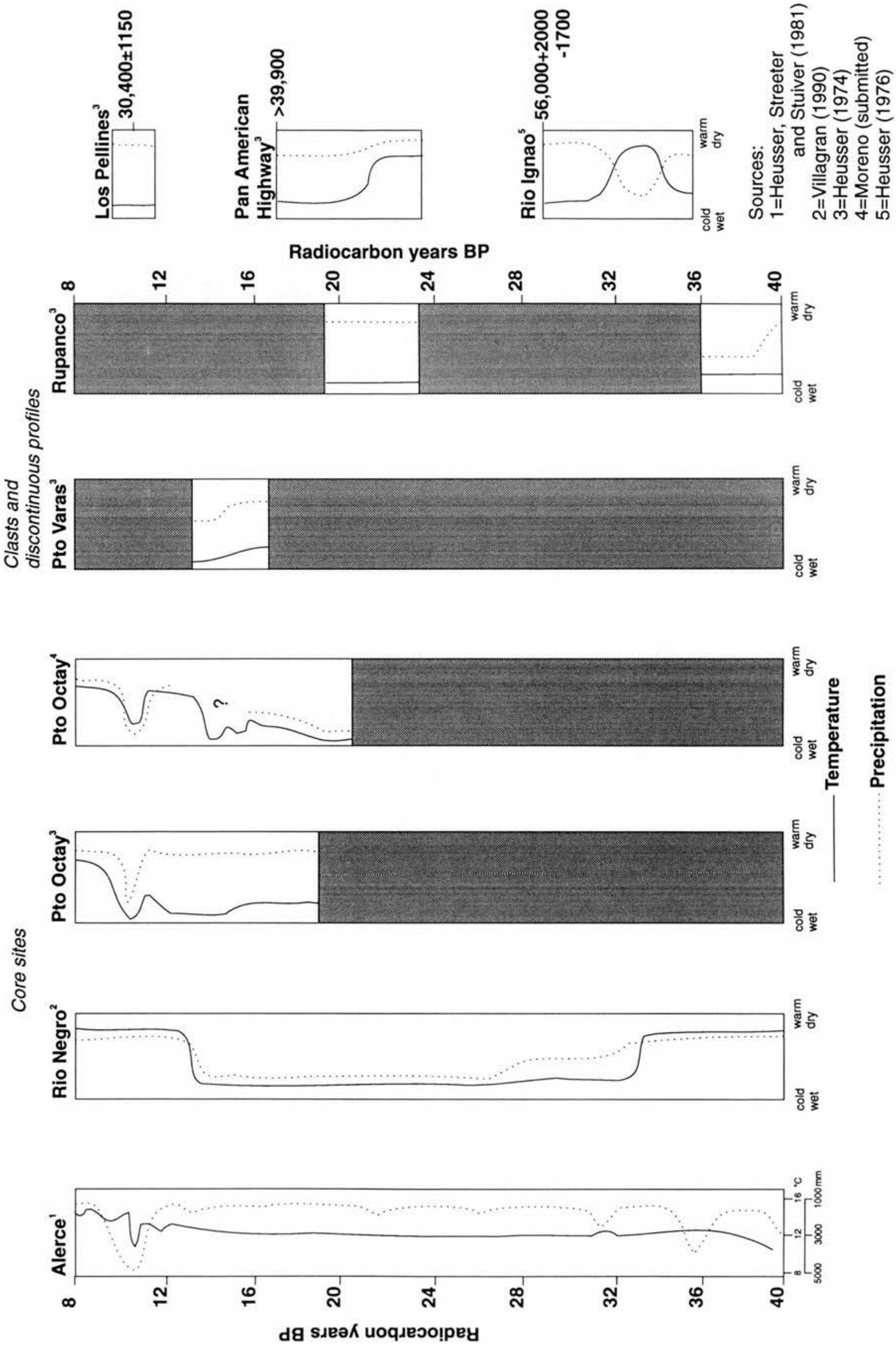


Figure 1.5. Summary of Lake District palynological records for the last glaciation. All sites are marked on Figure 1.3. The Alerce core has been interpreted quantitatively to give values of temperature and precipitation (see text for discussion) whereas other records have been interpreted more qualitatively. Only a few sites yield records spanning a substantial range of the latter part of the last glaciation.

today, this warm interval is assigned interstadial rather than interglacial status. Between >40,000 and 36,000 BP tundra or parkland vegetation gave way to subalpine or high montane southern beech (*Nothofagus*) forest with temperate semi-humid conditions. Mean January temperatures were between 11 and 13°C. The interval 36,000-24,000 BP is recorded in few Lake District cores but allochthonous gyttja clasts of this age point towards a cold, subantarctic parkland environment. The parkland was composed of patches of beech forest in open grassland. A small increase in precipitation may have occurred between 31 ka and 26.6 ka (Heusser *et al*, 1981). There was a small increase in the grass elements and commensurate decrease in beech between 25-22.5 ka and subsequent rise to former levels by c. 17.5 ka (see Fig. 2 of Lowell *et al*, *in press*). The opening of the beech forest suggests a minor cooling, but not sufficient to introduce new vegetation assemblages. There is disagreement as to whether the cold subantarctic parkland was wet (Moreno, 1993; *submitted*) or dry (Heusser, 1974). Mean January temperatures at the glacial maximum were c. 9-11°C, or between 5°C and 7°C colder than present (Heusser, 1974; Moreno, *submitted*). Subsequent to the maximum, beech forest advanced as the climate warmed and humidity increased but open vegetation was still dominant. A reversion to glacial conditions after 15,000 BP is shown by low *Nothofagus* pollen abundances. Deglaciation and the transition to present-day humid temperate conditions apparently commenced with a rapid warming after 14,000 BP shown by the rapid influx of North Patagonian rainforest vegetation (Moreno, 1993; Lowell *et al, in press*). This is in close agreement with the glacial geologic record. However, some of the pollen records show that the warming was interrupted by a further, short-lived cooling between 11,000 and 10,000 BP (Moreno, 1993; Heusser, 1993). Certain of the results derived from Heusser's regression equations seem unrealistic, such as a c.10°C cooling interpreted between 11,300 and 10,800 BP (Heusser *et al*, 1981). Although this is noted as 'unrealistically high' no method of correction is suggested. The regression equations used also imply that present climate is 4°C colder and with 1000 mm less rainfall than actually recorded at meteorological stations. The interval 43,000 to 14,100 BP shows that although temperatures were apparently 5°C lower than present the variation was minimal. The amount of variation in temperature was within the standard error limits of the regression equations, whilst precipitation only varied within error limits in the interval 26,600 to 14,120 BP. The lack of variation in the temperature and precipitation results is puzzling given the geologic record. For these reasons it is assumed in this study that the record of Moreno (1993) and Lowell *et al* (*in press*) is probably a more realistic reflection of Lake District climate for the interval from c.21 ka to the end of the glaciation.

The pollen record on Isla Grande de Chiloé shows a number of differences to the Lake District. Primarily, the dominant vegetation type during the last glacial was Magellanic moorland. Sites on Chiloé record an expansion of Magellanic moorland from 24 ka up to 18 ka, suggesting the island was cool and wet at this time (Villagran, 1990; Markgraf, 1989a). Despite the difference in vegetation types the climatic interpretation agrees with Moreno's cold, wet interpretation in the Lake District but contrasts with Heusser's suggestion of cool, dry conditions. Moreno (*submitted*) and Lowell *et al* (*in press*) suggested that the contrast between the Chilotan Magellanic moorland and the subantarctic parkland to the north may have been a reflection of substrates rather than a climatic difference. At present Magellanic moorland develops on poorly-drained areas, often over rocky substrates. They argued that during the last glacial, subantarctic parkland developed on the well-drained outwash of the Central Valley and around the lakes. Magellanic moorland made up the lowland vegetation in boggy areas on moraine belts or where former meltwater spillways cut deeply into outwash plains, leaving poorly drained depressions. The conditions for development of the Magellanic moorland assemblage were particularly extensive on Chiloé. On Chiloé the Magellanic moorland was succeeded at 12,500 BP by the influx of the present-day forest assemblages (Villagran, 1990).

1.5.2. Faunal studies

A few studies have examined the glacial deposits of the Lake District for fossil fauna. Coleoptera have proved the most useful in palaeoclimatic reconstructions but only the interval 18,000 to 10,000 BP has been covered. Fossil megafauna are found scattered in deposits from the last glacial maximum (19,000-14,000 BP) up to 9,000 BP when they became extinct, but the remains add little to our knowledge of the last glaciation.

Disarticulated beetle remains from a number of sites show that after 18,000 BP an assemblage of beetles characteristic of moorland habitat colonised the Lake District (Ashworth and Hoganson, 1991). Low species diversity supports the notion of a cool, wetter climate until 14,000 BP, when arboreal species started to replace species of open habitat. The interval 14 ka to 12.5 ka BP saw a temperature rise of 4-5°C until, at 12,500 BP, only rainforest assemblages existed (Ashworth and Hoganson, 1984; 1991; Hoganson and Ashworth, 1991; Ashworth and Hoganson, 1993). The change from glacial to post-glacial Coleopteran assemblages was rapid, occurring in the space of c.1500 years, suggesting that there was a rapid, single-step climate transition at the end of the glacial period (Hoganson and Ashworth, 1991). Conditions were then similar to now, and remained fairly constant up to the present day.

In a combined study of fossil animals and plants Heusser (1991) concluded that there was a northward migration of biota during the Late Pleistocene glaciation. Mastodon (*Cuvieronius*) remains from 20 sites in Chile range in age from 18,700 to 9,100 BP. The animals roamed over expanses of open grassland with occasional tracts of southern beech (*Nothofagus*). The mastodon populations were unable to withstand the change to more forested terrain after the glacial period. Trapped by the Andes to the east, desert to the north and the fjord country to the south they became extinct in mid-latitudes of Chile before 9,000 BP. There is some evidence this extinction was speeded by the arrival of hunters (Heusser, 1991).

Faunal evidence points to a cool, wet climate in the Lake District during the glacial. At 14,000 BP there was a rapid transition to conditions similar to today. The faunal evidence does not record the climatic event at 14.5 ka recorded by the glacial and palynological proxies, nor any of the other climate variations recorded by pollen in the interval 18 ka to 14 ka. The contrast between the faunal records and the palynological and glacial geologic records suggests that the faunal evidence only provides a low resolution record. Heusser (1993) argued that the disharmony may be due to the more rapid migration of beetles but this is puzzling since this should result in a more sensitive record. Alternatively, the contrast may be a reflection of poorly known empirical relations between beetle populations and climate (Ashworth and Hoganson, 1984) or the derivation of these relations from present populations which may contain foreign species unrepresentative of present climate.

1.6. The Late Glacial Controversy

The question of whether there was a marked late-glacial cold interval in Chile has long been the subject of vigorous debate between palynologists, glacial geologists and palaeoentomologists. Heusser (1974) places the end of the Llanquihue glaciation at about 10,000 BP, when mean January temperature rose from c. 10°C to c. 20°C. The termination followed a two-step deglaciation including a cold and wet phase from about 11,000 to 9,800 BP when mean January temperatures were as low as 9°C. In contrast to this, Mercer (1976) and Ashworth and Hoganson (1993) detected no evidence for a cold interval from glacial geologic or beetle records during the late-glacial and so suggested the termination of the last glaciation in southern South America was a single-step event beginning at 14,000 BP. The pollen-inferred event proposed by Heusser is approximately coeval with the Younger Dryas Stade of Europe. In terms of intra- and inter-hemispheric correlations The Younger Dryas is an important event and as such it is crucial that its presence or absence in the Lake District is resolved. Recent reviews have examined the evidence in South America (e.g. Clapperton, 1993a) and elsewhere in the Southern Hemisphere for this event. This section focuses on the evidence from the Lake District.

Quantitative palynological analysis of a core from Alerce (41°25'S) in the Lake District revealed an interval from 11,300 to c.9,400 BP when mean January temperatures were as much as 6-7°C colder than present (full-glacial=c.5-6°C colder). In this interval precipitation reached 5000mm which was substantially greater than present-day totals of 2000-3000mm (Heusser and Streeter, 1980). Although Heusser and Streeter admit that their actual figures of temperature and precipitation may be uncertain they insist the trends are correct. A similar cooling was interpreted for this interval from cores at Rucañancu in the northern Lake District and Puchilco on Chiloé. A core from Puerto Octay was cited as additional evidence but a subsequent date of 1190±135 BP on the 'presumed Younger Dryas stratigraphic level' of Heusser has thrown this correlation into doubt (Hoganson and Ashworth, 1991). Recent work on another core from the Puerto Octay site has shown that there was an opening of the North Patagonian rainforest. This also suggests that there probably was a cooling in the interval 11.1-10.2 ka (Moreno, *submitted*). However, at other sites, such as Caunahue, the palynological evidence for a climatic reversal has been challenged; changes in pollen are instead interpreted as due to edaphic (soil-forming) processes or local, non-climatic changes in conditions such as water levels (Markgraf, 1989a).

Beetle remains provide no evidence of any climatic change after 12,500 BP, thereby arguing against a late-glacial cooling event (Ashworth and Hoganson, 1984; 1991; Hoganson and Ashworth, 1991). However, the beetle record also does not show up other, well-proven events. These include the Hypsithermal and Neoglacial episodes that exist in other proxies in the region. This is puzzling since Coleoptera normally provide a sensitive index of climate variation; beetles often show more rapid migration rates in response to climate change than plants (Bradley, 1985).

In the Lake District no moraines or other glacial deposits younger than c. 12000 BP have been found. Their apparent absence may be due to rapid retreat of the glaciers at the end of the glaciation such that they were small or even absent in the interval 10,000-11,000 BP (Clapperton, 1993a). The cooling would not have been sufficiently prolonged to cause the glaciers to grow large enough to advance into the lake basins. Therefore, if there is glacial evidence of a Younger Dryas equivalent event it is likely to be located far up the Andean valleys. These valleys are remote and cloaked in temperate rainforest so have not been studied by glacial geologists. From glacial geologic evidence Mercer (1976) showed that glaciers discharging from the present-day Patagonian icefields retreated rapidly after 14,000 BP to be within their present limits by 11,000 BP. There was no readvance until the Neoglacial maxima at 4600-4200 BP, 2700-2000 BP and 350 BP. This has been cited as evidence against a Younger Dryas equivalent event. However, the dated material was sampled from sites in front of calving glaciers and it has been argued that the glaciers may not have responded to a short-lived cooling if they were situated in unfavourable topographic positions (Clapperton, 1993a).

In summary the biological evidence for the presence or absence of a late-glacial cooling event in mid-latitudes of Chile is still equivocal; essentially resting on a few pollen sites in the Lake District. The lack of any change in nearby pollen profiles remains a strong objection but it has been suggested that biotic assemblages may be relatively insensitive to small temperature changes (1.5-2°C), particularly away from ecotonal boundaries, so this may explain the discrepancies between many of the cores (Clapperton, 1993a). The cooling of 6-7°C interpreted at the Alerce site suggests that this explanation may not be sufficient since this magnitude of change should be recorded by many biotic assemblages.

However, the Alerce record remains untested and no other palynological sites record anything like this magnitude of change. There may be direct glacial geological evidence of a cooling event but at present it remains inaccessible. The glacial evidence against this cooling is largely based on calving glaciers located south of the Lake District which may have been decoupled from climate. The existing beetle data do not appear to have the necessary resolution to record such an event. The case for a Younger Dryas equivalent event in the Lake District is not yet persuasive but it cannot be dismissed.

1.7. Climate Change during the last glaciation

If the chronology proposed by Lowell *et al* (*in press*) reflects climate then it has important implications for our understanding of climate change. The close correlation on a timescale of 100-1000s of years between the glacial advances in the southern Andes and cold intervals in the North Atlantic implies that the climate fluctuations had a global signature (Fig. 1.6). It is therefore important to examine the mechanisms of regional climatic changes proposed to explain the glacial and palynological records in the Lake District, and how these might be linked to changes elsewhere.

Two approaches have been adopted to describe the changes in climate affecting the Lake District during the last glaciation. The first approach is based on glacial geological evidence and uses the glacier ELA as an indicator of the severity of climatic conditions. From reconstructions of former AARs, Porter (1981) suggested that the ELA was up to 1000m lower during the last glacial maximum. The second approach compares the position of modern ecotones to those recorded in the palynological record and thus estimates changes in temperature and humidity. A link between the two approaches comes from modelling which attempts to simulate ELAs using temperature and precipitation changes derived from the pollen record (Kerr and Sugden, 1994). Both the palynological evidence and the modelling studies suggest that the key to interpreting the climate of the Lake District is the polar front; debate centres on whether this moved northward or southward during the last glaciation. However, it should be noted that there are significant disparities in the descriptions of the present positions of the polar front and westerlies (Table 1.4) Consequently, authors are actually discussing significantly different scenarios. This confusion may be preventing a resolution of the controversy.

AUTHOR	POLAR FRONT	WESTERLIES	N BOUNDARY OF SUMMER-DRY ZONE
Villagran (1990)	50°S(winter)- 55°S(summer)	38-56°S	30°S
Heusser (1974)	46°S(winter)- 49°S(summer)	42-56°S	31°S
Markgraf (1989b)	40°S(winter)- 45°S(summer)	South of 35°S	-

Table 1.4. Present-day positions of polar front and westerly circulation, as given by various authors.

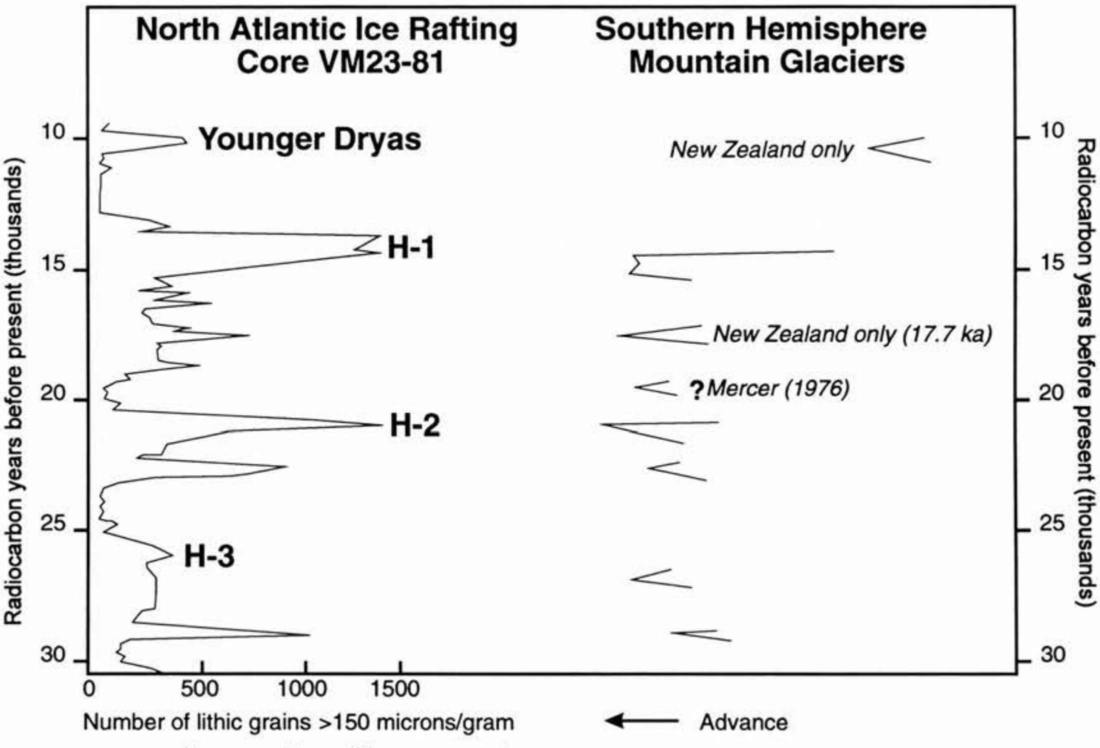


Figure 1.6. Correlation of Southern Hemisphere mountain glacier advances to the North Atlantic ice-rafting record. The glacier record has been compiled from New Zealand records and an average of the Llanquihue, Seno Reloncavi and Castro glaciers in the Chilean Lake District. Modified from Lowell *et al* (*in press*).

In advocating a northward shift of the polar front of c.5° Heusser (1974) cites the palynological evidence for a colder, drier climate in the Lake District and a wetter climate than present to the north. This would have been brought about by a reduced influence of the subtropical maritime air mass in high latitudes coupled with an intensification of the westerlies, leading to greater penetration of colder, polar Pacific air equatorward. A simultaneous increase in discharge of cold, upwelled water by the Peru (Humboldt) current (CLIMAP Project members, 1981) would decrease evaporation and hence cause a drier climate in the Lake District. Other supporting evidence for an equatorward shift of westerly circulation comes from the sub-tropical Andes where palaeoenvironmental evidence suggests a migration of up to 5° north occurred (Caviedes and Paskoff, 1975; Hastenrath, 1971). In the Northern Hemisphere the oceanic and atmospheric polar fronts moved towards the equator during the Late-Glacial cooling (Ruddiman and MacIntyre, 1981). Marine evidence shows the oceanic Antarctic Polar Front was 5-7° nearer the equator at 18,000 BP, as was the Subtropical Convergence (Heusser 1984; 1989). However, much of this data is based on the South Atlantic and Indian Oceans. There was little change in the position of the oceanic Polar Front in the Drake Strait during the last glaciation, probably due to topographic 'pinning' (Kennett, 1978). The South Atlantic and Indian Ocean Polar Front positions should not be directly extrapolated to the Pacific since the fronts are thought to have had uneven geographic extents in the Southern Hemisphere. Indeed, Heusser (1984) attempts to explain some of the intra-hemispheric differences in Pleistocene climate by their irregular nature. Most authors agree with Heusser that the polar front moved north but suggest that the increased influence of the westerlies would cause a wetter rather than a drier climate.

In contrast to Heusser's northward shift of vegetation zones, Markgraf (1989a; 1989b) insists the palynological data show that montane vegetation merely shifted downhill, remaining at the same latitude. She argued that seasonally dry conditions existed during glacial times, except on Chiloé where Magellanic moorland indicates that cool, wet conditions predominated (Villagran, 1987; 1988; 1990; Markgraf, 1989a). Markgraf concludes this evidence of seasonal aridity is incompatible with a northward migration of westerlies. She argues that if Chiloé came under increased influence of subantarctic air it should record increased aridity, not the wet conditions she describes. Instead, Markgraf (1989a; 1989b) interprets a poleward shift of the polar front and intensification of the westerlies at the latitude of Chiloé. The polar front change would have been accompanied by a southerly shift of the sub-tropical circulation and consequent increased precipitation (Pittock, 1980). This would account for the wetter conditions at 34°S implied by pollen data and for snowline depression data (Hastenrath, 1971). She cites the good agreement of her results with several independent palaeoclimate models. However, much of Markgraf's data suggesting drier conditions during the glaciation derives from the east side of the Andes which is more arid than the Chilean side and different weather systems predominate (Miller, 1976; Prohaska, 1976). The contrast almost certainly existed during glacial times. In addition, her postulated position of the polar front is further north than given by other authors. Therefore, some of the sites where she might expect increased precipitation if the polar front moved north may actually be located too far north to record any influence. Additionally, the differences in substrate, and hence drainage, between Chiloé and the lakes to the north may have influenced the distribution of vegetation (Moreno, *submitted*; Lowell *et al*, *in press*). Such substrate effects are discounted by Markgraf.

Results from attempts to model the entire latitudinal range of the Patagonian ice sheet during the last glaciation suggest that neither Heusser's nor Markgraf's scenarios are sufficient to simulate the necessary ELA depression in the Lake District (Kerr and Sugden, 1994). The model agrees with Heusser and Moreno that a northward migration of the westerlies is necessary but that this also needs to be accompanied by a general cooling. In addition the model suggests that northward movement of the polar front would have led to commensurate migration of precipitation belts and so the Lake District was wetter than present during the glacial. Thus, modelling is a powerful tool in not only showing what polar front changes were likely to have occurred to fulfil the necessary glaciological conditions but it also points towards Moreno's (1993) interpretation of cold and wet conditions as being the most appropriate palynological interpretation.

In summary, the field evidence and modelling studies are in favour of a northward movement of the polar front. Much of the opposing evidence can be attributed to local effects such as differences in the substrate, or extrapolation from east of the Andes where different circulation patterns prevail.

1.8. Questions arising from previous research

The work carried out in the Lake District raises a number of important questions, particularly in relation to the glacial geologic record. These questions, listed below, have provided the main impetus for the specific research aims of this thesis.

- Is the Llanquihue glacial chronology an accurate reflection of glacial climate? Can we exclude the influence of local factors? If so, the chronology has considerable implications for mechanisms of global climate change. To discover this it is essential to assess the influence of climatic and local influences on glaciers in the region.

- Few studies have specifically described the glacial landforms and sediments. Could a detailed investigation of the geomorphology and sedimentology provide insights on the chronology and closely-spaced distribution of the moraines around the western shores of the lakes?

- Did all the Lake District outlet glaciers respond simultaneously? This seems unlikely given that the different glaciers were calving into lakes and had different sizes, shapes and long profiles. The most likely mechanism of climate change was migration of precipitation belts, which would not have occurred instantaneously, or allowed a similar response in different zones. What was the magnitude of the lags, if any, between the different glaciers and are they significant in the context of the glacier chronology?

- The former Llanquihue lobe left no evidence for a Younger Dryas equivalent advance during the late-glacial interval. Was early, rapid deglaciation with no late-glacial advance(s) a common feature of all glaciers in the Lake District? If so, then what are the reasons for the mismatch between the pollen and glacial records?

1.9. Approach and Methods

This research attempts to answer these questions using a field-based approach examining the glacial landforms and sediments. The key is to establish the relative timing of the fluctuations of more than one glacier in the Llanquihue area. This can be achieved by examining landform relations in areas where former glaciers have interacted. Individual moraines around Lago Llanquihue cannot be traced confidently for any great distance (G. Denton, *pers. comm.*) and their lateral equivalents to north and south are not clear. This study focuses on the two lakes directly north, Lago Rupanco and Lago Puyehue. The lakes are elongate with relatively well-defined moraine loops around their western shores. There is a zone between the lakes where landforms from the two former glaciers intersect; this is important for deciphering relative effects on the glaciers. The field area allows both the number of glacial advances that occurred in the two basins and their relative timing to be established by studying the geomorphology and sedimentology of the glacial deposits around the lakes.

Another way to disentangle local and climatic factors is to look at the processes operating during the glacial fluctuations. This can be achieved by studying the morphology and sediments of the glacial landforms. By developing a glacial stratigraphy based largely on morphostratigraphic and lithostratigraphic criteria the behaviour of two closely adjacent glaciers which must have experienced the same climate can be investigated. Comparison with the behaviour of the Llanquihue glacier can then be achieved through radiocarbon dating. Any differential response of the two glaciers to each other and to the Llanquihue lobe will have a bearing on the climatic significance of the fluctuations.

1.9.1. Geomorphological mapping

Aerial photographs at 1:50000 scale from the Instituto Geografico Militar (IGM) de Chile were viewed stereoscopically in order to map the geomorphology onto acetate overlays, with specific emphasis on glacial landforms. The overlays were then compiled to form a geomorphological map of the area around Lagos Puyehue and Rupanco. Component overlay maps were not corrected for scale changes towards the edges of the photographs but there was substantial overlap between adjacent overlays so there were minimal differences in the location of specific features at photograph edges. The map was checked in the field to confirm the recognition of landform types and to investigate their relations in detail. Key landform profiles were surveyed with an Abney Level and 50m tape measure.

1.9.2. Sedimentological analysis

Sedimentary sections in the Puyehue-Rupanco area are confined to relatively few road cuttings and quarries used to extract surfacing material. Riverside and lakeshore sections are obscured by dense vegetation. This contrasts with Lago Llanquihue where extensive development for tourism has yielded numerous sections in the morainic belt.

A combination of graphic logs, detailed descriptions and further field and laboratory analysis was used to characterise each unit and elucidate the sedimentological and tectonic history. Exposed sections were logged using the scheme in Table 1.5. Polaroid photos with overlays were used to sketch sections in the field.

Diamict, D		Gravel, G	
Dm	matrix supported	Gms	massive, matrix-supported
Dc	clast supported	Gm	massive or crudely bedded
D-m	massive	Gt	trough cross-bedded
D-s	stratified	Gp	planar cross-bedded
D-g	graded		
Genetic interpretation, ( )		Fine grained (mud), F	
D--(r)	resedimented	Fl	laminated
D--(c)	current reworked	Fm	massive
D--(s)	sheared	F-d	with dropstones
Sands, S		C	plant macrofossils
Sr	rippled		
St	trough cross-bedded		
Sp	planar cross-bedded		
Sl	low-angle cross-beds (<10°)		
Sh	horizontal lamination		
Sm	massive		
Sg	graded		
Sd	soft sediment deformation		

Table 1.5. Lithofacies codes for sediments. Slightly modified from scheme of Eyles *et al* (1983) and Miall (1977).

Individual units were sampled for clast size distributions; clast shape analyses; fabric analysis to determine former ice directions; structural analysis of folds and faults to establish major stress directions; and weathering rind thicknesses of clasts as a crude measure of relative age. Clast size distributions down to 2mm were measured in the field with sieves. The proportions of smaller particles were measured in the laboratory using sieves and a Micromeritics Sedigraph 5000ET. Nomenclature followed the scale of Wentworth (1922). Clast shapes were established by field measurement of a, b and c axes of populations of clasts. Structural and fabric measurements were made with a Silva compass-clinometer. Further analysis was carried-out on Polar Stereographic projections, and statistical operations on three-dimensional data were calculated using the *Stereoplot* program on the Apple Macintosh. From this data the depositional environment of each unit has been interpreted and these have been drawn together to provide a sedimentation and deformation history at each site.

1.9.3. Pumice correlation

A common method for correlating glacier advances in time is to use geochemically-linked tephras (eg Dugmore, 1989). In an area with frequent volcanic eruptions the interbedding of tephra layers and glacigenic sediments allows glacial events to be correlated over a wide area and, if the eruption dates are known, minimum and maximum dates for the glacial event can be established.

The volcanoes of the study area have erupted frequently during the Quaternary (Paskoff, 1977) and there have been a number of significant historic eruptions up to the present day (Casertano, 1963). Unfortunately, interbedded tephra layers and glacial sediments are sparse, probably because the glacial units tend to be thick and so few sections expose more than one glacial event. Interglacial or interstadial soils are rare. However, many of the tills and virtually all the fluvioglacial units contain pumice. The pumice is usually white, yellow or orange but there is no systematic variation in colour between different units, suggesting the colour is a weathering feature rather than primary colour. By analysing the pumice in each unit it should be possible to link advances in the two basins on geochemical grounds. A reference section of dated tephras is not yet available so the technique could only provide a floating chronology but it is potentially a useful additional tool for identifying markedly asynchronous glacier behaviour.

Pumice fragments up to 8mm diameter were sampled from till and outwash units. The fragments were then crushed, ground and polished, mounted on microprobe slides and carbon-coated. Analysis was carried-out on a Microscan MkV Electron Microprobe at the Department of Geology, University of Edinburgh. A 20kV potential and 15nA beam current were used throughout and Garnet (andradite composition) standards were analysed every 10 samples in order to maintain sample comparability. Other analytical details were as for Dugmore *et al* (1992).

Pumice derived from the 1961 eruption of Volcan Puyehue is common close to the ground surface on the flanks of the volcano. It is also found on the beaches around Lago Puyehue. The material was used as a preliminary test and showed that recent pumice deposits provide good analyses with well-defined geochemistry. However, the pumice from older units did not analyse well, most of the samples having been weathered to clays. Those samples which contained glass suitable for analysis showed that pumice from different parts of the outwash associated with the Puyehue V moraine were of similar composition despite their different colours, confirming the colour is a weathering feature. Good analyses from older deposits proved too problematic and for this reason the tephrochronological approach was abandoned for this study area. However, the method may be applicable to areas with younger glaciation or less pervasive weathering of pumice.

1.9.4. Radiocarbon dating

Organic material was sampled for radiocarbon dating in order that the results from the Puyehue-Rupanco area can be compared to other glacial chronologies and proxy records. At the outset of the work it seemed reasonable to assume that sufficient organic material suitable for dating could be obtained to constrain the timing of most of the glacial stages. Previous work has shown that sites around Lago Llanquihue are rich in organic material (Mercer, 1976; Porter, 1981; Lowell *et al*, *in press*; Denton, *pers. comm.*) suggesting that the Puyehue and Rupanco area might be similar. However, there were a number of problems, particularly concerning the amount and type of material available, and so the timing of many of the glacial stages is not closely bracketed.

One of the most obvious differences between this project and the study headed by George Denton is the number of radiocarbon dates. The 102 dates of the Llanquihue chronology are described as 'selected dates' so this provides a minimum estimate for the total number of dates. This is in contrast to the 19 dates in this study of the Puyehue and Rupanco lobes. Apart from the obvious reason that George Denton is unsurpassed at discovering samples, there are several possible other reasons for the contrast in amount of dateable material.

- **Level of economic development**. Most samples used in both projects were derived from open quarry sections. The chance of finding appropriate sites is directly related to the number of existing quarries. The Llanquihue area is extensively developed for agriculture and for tourism which has resulted in a large number of roads and hence quarries for surfacing material. The Puyehue and Rupanco areas are less developed in terms of population centres and tourism and so there are commensurably fewer roads and quarries. A contrast in the number of open section sites yielding samples for radiocarbon dating also exists between Puyehue and Rupanco. Puyehue has more roads and yielded 6 sites where a total of nine radiocarbon samples were extracted from open sections whereas Rupanco had only two open section sites, yielding two dates.

- **Boundaries of former vegetation zones.** The present-day northern boundary of North Patagonian Rainforest lies approximately three degrees south of the Lake District. During glaciation, the transition between this and Tundra-Grassland to the north would have shifted northwards in sympathy with the migrating polar front. Sites with abundant wood are common in Chiloé and southern Llanquihue but are rare in Puyehue and Rupanco. Thus, it is possible that the vegetation boundary lay close to the southern edge of the Puyehue-Rupanco and so advances in the Llanquihue basin advanced into forest whereas to the north advances were into grassland with commensurably less potential for preservation of a large amount of material well-suited to radiocarbon dating.

- **Lobate versus elongate margins.** Both the Rupanco and Puyehue glaciers were long and narrow in plan. The Llanquihue lobe had a far more lobate form because of the lack of constraining valley walls. Thus, during each advance the Puyehue and Rupanco lobes advanced with very similar lateral limits whereas the Llanquihue lobe had the potential to advance with a different margin each time. Such behaviour means that each advance of the Llanquihue lobe may have been more likely to rework previously undisturbed organic material as the glacier took up different marginal configurations. The Puyehue and Rupanco lobes scoured the same parts of the valley walls each time they advanced and so only the first advance after any prolonged interstadial would have a high chance of incorporating significant organic material.

- **Length of former glacier margin.** The Llanquihue lobe had a much longer margin than the Puyehue and Rupanco glaciers and so there was an overall greater chance of incorporating organic material.

- **Dates from lacustrine material.** Many of the Llanquihue dates, particularly those bracketing the 14,000 BP advance, are derived from peat layers deposited during periods of fluctuating higher lake levels of Llanquihue, for which there is no clear equivalent in Puyehue and Rupanco. This sort of material is more likely to be suitable for radiocarbon dating than the dominantly inorganic sediment deposited directly from glacier ice.

Samples were taken from exposed sections and from cores. The most common material collected was gyttja (carbonaceous mud, often lacustrine) but peat, wood, charcoal and other plant fragments were also sampled. In the field all samples were cleaned, foil wrapped to prevent mould or algal growth, and then bagged and labelled. After extraction samples were kept as cool as possible and refrigerated on return to Edinburgh. The outer surfaces of all samples were cleaned before submission to the East Kilbride (NERC) or University of Arizona radiocarbon laboratories for dating. Coring was used to provide samples to date geomorphological features where they were not otherwise dateable and to provide intermediate checks on other dates. Most cores were used to obtain basal material from abandoned meltwater channels but minimum dates for outwash plains and kettle holes also derived from coring. Cores were obtained using a 5cm diameter Russian corer and a 2.5cm diameter Gouge corer. The Russian corer proved difficult to use in the compact, relatively dry soils and peats that are typical of the field area. It also had the added disadvantage of being unable to sample the basal 10cm of any core because of the solid nose cone. This is a serious handicap with dates of geomorphological significance since it is necessary to know that the dated material overlies sediments derived from the glacial event and to obtain material as close as possible to the upper interface of this sediment As a result the gouge corer became the mainstay of the coring work. It penetrated the sediment easily and samples with closely-spaced layering showed that it did not disrupt the stratigraphy and the sediment was not deformed at the margins of the core. Repeat cores taken 50cm apart at most of the sites demonstrated that it consistently yielded reproducible results. In addition, those sites which were sampled with the Russian corer and gouge corer showed the same stratigraphy in both types of core. The main objection to the gouge is that contamination can smear up the tube. To minimise this problem the gouge was thoroughly cleaned between samples and the outside portion of each sample was removed initially in the field and further cleaned in the laboratory.

Chapter 2: Geomorphology

2.1. Introduction

Geomorphology is useful in interpreting two aspects of the glacial history of the field area. First, it yields information on the processes operating during moraine formation and provides a spatial framework for the sedimentological studies. Secondly, the intersecting relations of glacial landforms can be used to help establish a relative chronology. Therefore accurate mapping and recognition of glacial landforms is important. This chapter describes the topography and bathymetry around Lagos Puyehue and Rupanco and the smaller-scale glacial landforms which have been superimposed on the landscape. Moraines and their relationships with each other are the main focus. Six types of landform are described: terminal moraines (divided into ridge and rampart moraines), lateral moraines, meltwater channels, outwash plains, non-aligned moraines, and shorelines. The sediments making up the landforms are described in the two following chapters.

Much of this chapter is based on the geomorphological map shown in Figure 2.1 (see pocket in back cover). The map shows the location of the landforms around the two lakes with particular emphasis on the glacial geomorphology. An inset shows the topography and demonstrates the contrast in relief between east and west. The field area lies at the western foot of the Andes Mountains. Here, the steep-sided volcanoes of the Cordillera meet the flat Central Valley (Valle Longitudinal) of Chile. Consequently the area has high relief in the east and low relief in the west (Fig. 2.2.). A second inset shows the areas of the map which have been mapped and field-checked in detail. Some areas, particularly the islands in the lakes, have been mapped from aerial photos but have not been closely examined in the field.

To the west of the lakes a plain dips at a shallow angle (<1°) towards the Pacific. Steep-sided river valleys, many incised more than 100m, are the only features to interrupt the flat Central Valley between the moraines of the study area and the city of Osorno. The two lakes, Rupanco and Puyehue, lie between broad spurs which descend westwards from the west flank of the Cordillera. To the north-east of Lago Puyehue the ground rises steeply to the summit crater of Volcan Puyehue (2236m) and its western spur, the Cordon Caulle. Similarly, to the south-east of Lago Rupanco the ground rises to the eroded plug of Volcan Puntiagudo (2493m). The spur between the lakes rises steeply to Volcan Casablanca (1990m) and the main summits of the Cordillera beyond. A broad col (the 'Pichilifaquen col') interrupts this spur approximately half-way along the shores of the lakes. Laguna Pichilifaquen is situated on the west side of this col and the lowest point of the col is only 25m above the present level of Lago Puyehue. To the west of the col, between the western portions of the lakes, an area of higher ground stands 60 metres above Lago Puyehue (182m) and 120 metres above Lago Rupanco (alt.

Figure 2.2. Topography of study area:
(**a**) Looking east up Lago Rupanco. The steep cliffs around the east end of the lake and the foothills of the Andean Cordillera are visible on the north side of the lake. Relief is up to 2000 metres. The foreground is directly underlain by bedrock and colluvium. No glacial drift is exposed.
(**b**) Looking west up Lago Rupanco. The low angle slopes on north shore of the lake are at progressively lower altitudes to the west such that the relief at the west end of the lake is only tens of metres. The raised feature at left centre is the bedrock form of Peninsula del Islote.

118m). The higher area is probably underlain by bedrock, forming part of the inter-lake spur, but is largely mantled with glacial deposits. The eastern portions of the lakes have high relief with both the lakes themselves and their feeder valleys flanked by steep bedrock walls. This is seen most clearly at the east end of Lago Rupanco and along the trough of the Río Golgol. In places, the cliffs rise near-vertically for one hundred metres or more.

The smaller-scale glacigenic landforms lie in a broad north-south trending belt, encompassing not only the immediate surrounds of Lagos Puyehue and Rupanco but also the area up to 15 kilometres west and a few kilometres east of the lakes. This zone contains numerous erosional and depositional landforms, distributed in a clear pattern around the lakes. The eastern end of the lakes is underlain directly by bedrock. This has been areally scoured to form an area of bedrock knolls up to 100m high, separated by broad troughs up to 300m wide. In places the knolls have a roche moutoneé form; they are rounded and relatively smooth on their upstream (eastern) side and steep on their downstream (western) side. The zone of areally scoured bedrock is now densely vegetated so the meso- and micro-scale forms of the bedrock are not exposed. In the main valleys leading into the lakes, linear scouring has formed the steep cliffs which enclose the eastern end of both lakes.

The lakes themselves were eroded by repeated glaciation during the Quaternary (Clapperton, 1993b; Mercer, 1976). The bathymetry of the lakes reflects the broad differences between the low relief of the west and the high relief of the east (Fig. 2.3). Lago Puyehue is divided into two basins by a submarine ridge which extends to the south and northwest of Isla Fresia. The narrow inter-basin ridge rises up to 60 metres above the level of the bottom of the basins on each side. The basin to the west is flat-bottomed, up to 100 metres deep and has relatively gentle sides, particularly at the western end. The eastern basin, although flat-bottomed and of similar depth to the western basin, has near-vertical northern and southern margins where it is rimmed by bedrock cliffs. Lago Rupanco is divided into two main basins: one at its eastern extremity which is steep-sided and reaches a depth of 260m, and a much larger basin to the west occupying almost two-thirds of the lake. The latter basin is steep-sided at its eastern end but has gentler marginal slopes to the west, with depths of up to 270 metres and a flatter bottom than the eastern basin.

The rest of this chapter details the morphology of the landforms and is the basis of a glacial chronology and an analysis of the processes operative during glaciation of the area. The main landforms of interest are moraines, both terminal and lateral; meltwater channels; outwash plains; bedrock forms; shorelines and non-aligned moraines.

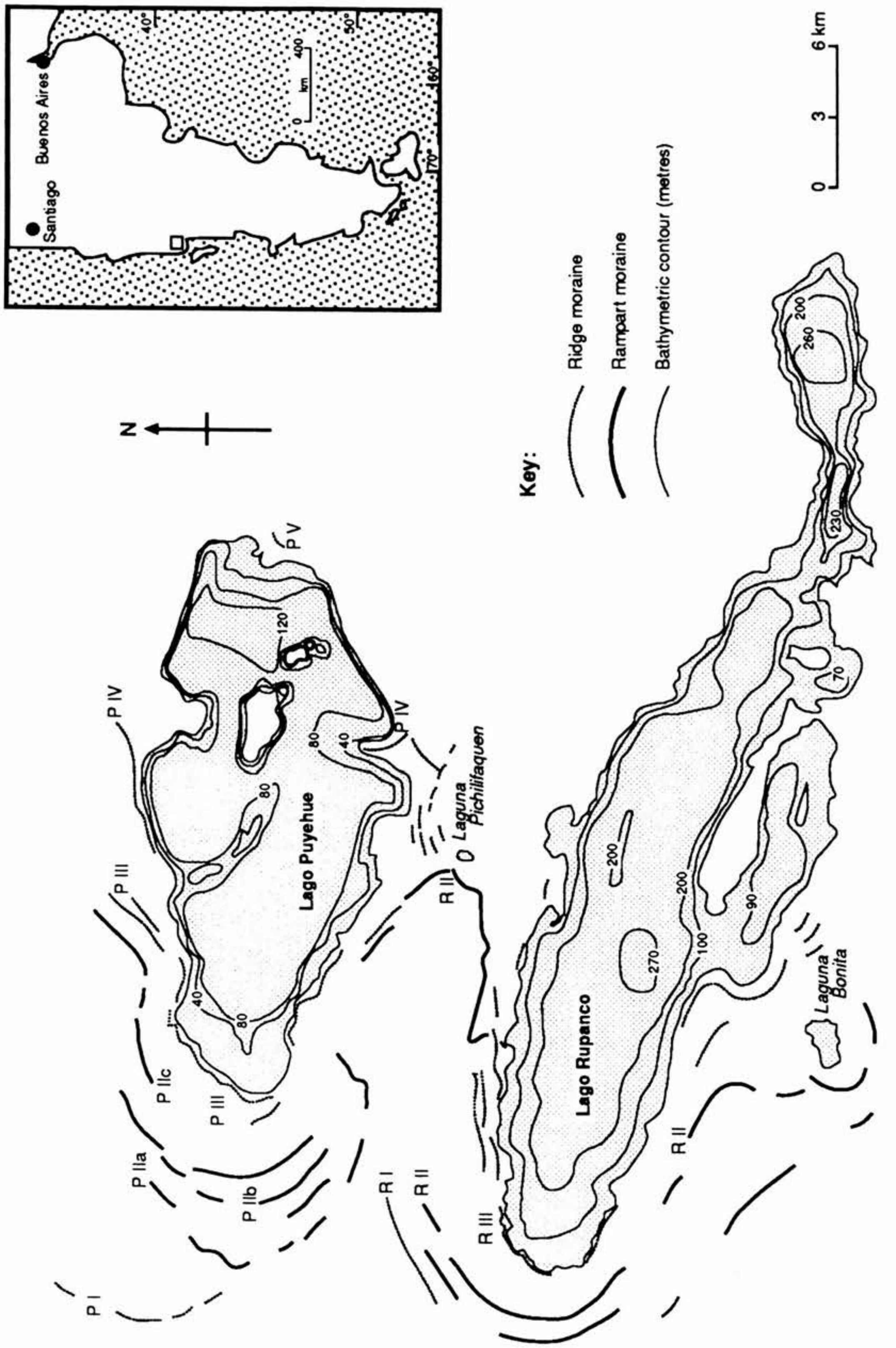


Figure 2.3. Summary of concentric moraine sequences around Lago Puyehue and Rupanco. Rampart and ridge moraines are differentiated on the basis of location, morphology and dimensions. Bathymetry from Campos *et al* (1989; 1992) shows a submarine ridge connecting the north and south segments of the Puyehue IV moraine.

2.2. Terminal Moraines.

Moraines were recognised on the basis of five main criteria.

- Linear, upstanding, ridge-like form.
- Boulders, often striated, along the crest of the ridge.
- Relatively constant dimensions along the length of the ridges.
- Orientation and location consistent with logical margins of glaciers flowing westwards from the Andes along the outlet valleys.
- The ridges are unbranched. Exceptions occur where the features recognised as moraines on the basis of the other criteria run into one another.

Ice-contact slopes were also identified on many of the moraines. Ice-contact slopes are slopes against which the glacier margin was in direct contact, and which have remained substantially unmodified since. These were recognised as proximal moraine slopes which are uniform along their length, with minimal downslope gullying by channels, or oversteepening due to channels flowing along their base. Commonly, channels originate at the top of the slope and flow away from the slope in a down-glacier direction. Another common characteristic of the ice-contact slopes is their form parallel to the moraine axis. In particular they have broad, subdued spurs and embayments with a wavelength of approximately 200 metres on the proximal slope of the moraine. Kettle holes are commonly associated with the moraine crests and form enclosed basins, between three and five metres deep, often circular, and with steep sides.

Terminal moraines form a concentric, arcuate pattern around the west end of each of the lakes, reflecting the fluctuations of the Puyehue and Rupanco glaciers respectively (Fig. 2.1). The two arcs intersect roughly half-way between the two lakes. The area of intersection, where both glacier lobes influenced the geomorphology, is important in allowing reconstructions of the relative glacial chronologies of the Puyehue and Rupanco glaciers. The number, spatial distribution, form and constituent sediments of the end moraines, along with their relations to each other and other landforms can also be used to elucidate the processes operating during the glacial events.

The moraines around both lakes have been numbered according to their position from the outermost (Puyehue I and Rupanco I) to the innermost (Puyehue V and Rupanco III). Each of these moraines are separated by flat outwash plains. Where separate ridges or ice-contact slopes occur but with no flat outwash plain between them, the moraines have been sub-divided. For example, Puyehue IIA, Puyehue IIB, and Puyehue IIC are all separate ice-contact slopes but are closely amalgamated with no intervening outwash. This numbering system is based purely on moraine position and does not imply any close association in time of particular moraines.

A number of terminal moraines do not fit the general arcuate pattern. These are either located at intermediate positions along the shores of the lake (Puyehue IV) or to the east of the lakes (Puyehue V), and represent less extensive positions of the glaciers. Such moraines provide important information on the pattern and relative timing of deglaciation in this area. In addition, the terminal arcs of the Puyehue I and Rupanco I moraines are slightly offset to the north from the concentric pattern of the Puyehue II, Puyehue III, Rupanco II and Rupanco III moraine arcs.

The morphologies of the moraines around Lago Puyehue are shown in Table 2.1 and those around Lago Rupanco in Table 2.2. The moraines can be divided into two main types on the basis of their form, dimensions and position. Rampart moraines are broad amalgamated moraine complexes whilst ridge moraines are narrow, single ridges usually located around the present-day lakeshores. The moraine sequence around the two lakes is similar but not identical.

2.2.1. Rampart Moraines

The main examples of rampart moraines are the Puyehue II and Rupanco II moraine complexes. The moraines are between 2km and 5km across and form arcuate loops located 1-3 kilometres from the western shores of the lakes. The trend of the Rupanco II moraine follows a relatively smooth arc west of the lake whilst the arc of the Puyehue II moraine shows an asymmetric, lobate bulge to the southwest of Entre Lagos (Fig. 2.3).

The two moraine complexes are made up of a number of closely-spaced, arcuate ice-contact slopes. The slopes mark the proximal sides of a series of amalgamated moraines. Proximal slope angles are typically 6-9° and the slopes are from 30 to 90m high (Fig. 2.4). The area between each of the ice-contact slopes forms a gently undulating topography with meltwater channels and kettle holes which tend to occur on, or near, the crests of the moraines. Well-defined kettle holes occur on the top of Puyehue II and close to the distal side of the Rupanco II moraine. Distal slope angles are low (<5°); the rampart moraine topography of broad ridges, low mounds and hollows grades westwards into gently dipping outwash plains. The Rupanco II moraine rises higher above the outwash on its proximal side than does the Puyehue II moraine. This, along with the lower altitude of Lago Rupanco and the steep northern shore of the lake gives the impression of a deeper basin.

a

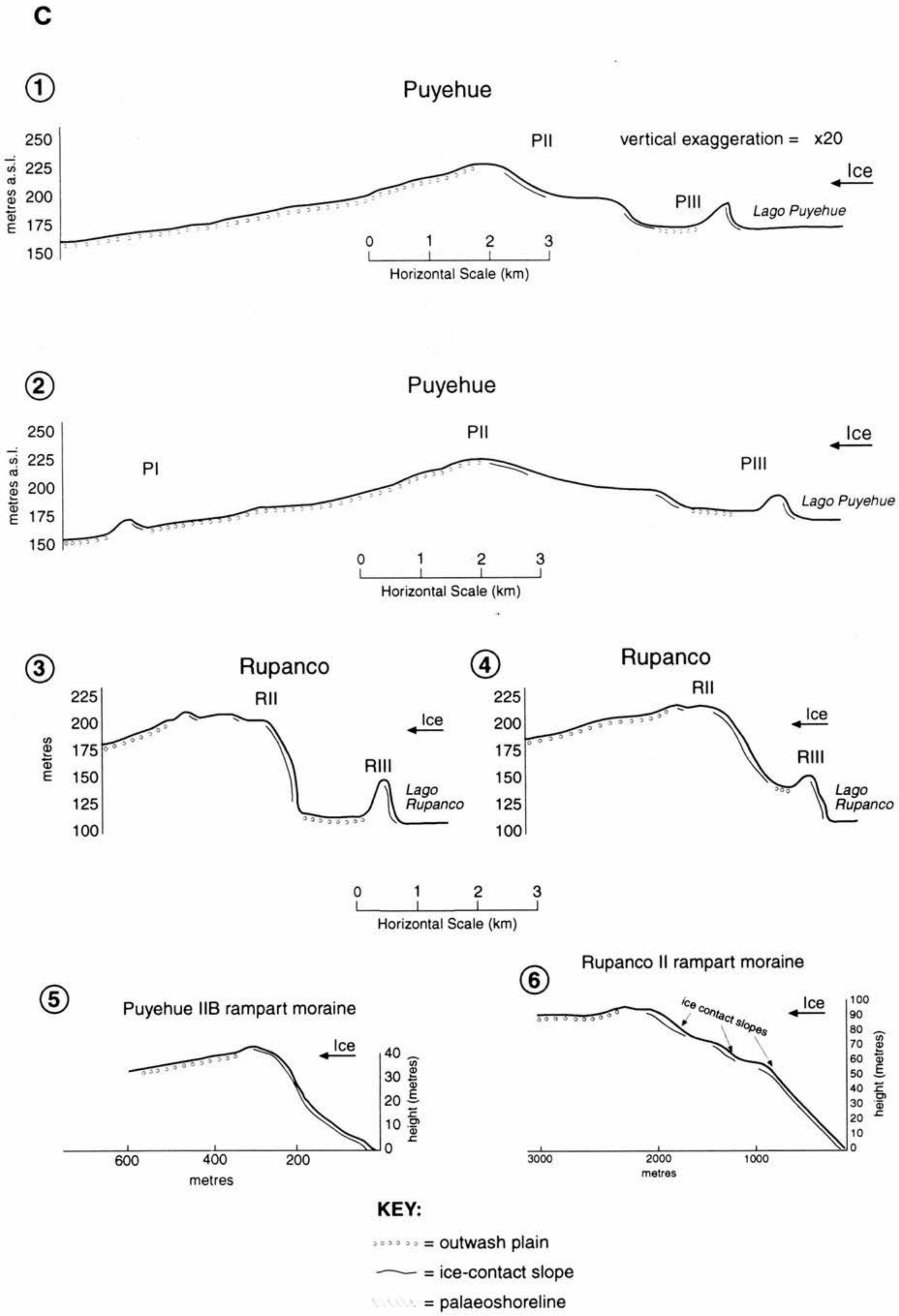
b

Figure 2.4. Rampart moraines.

(a) Looking east along proximal slope of Rupanco II rampart moraine below Bellavista, north shore of Lago Rupanco. Slope is c. 50m high and rectilinear. Clasts within the till underlying the slope are imbricated parallel to the slope.

(b) Puyehue IIC rampart moraine. Crest is 35m above the Puyehue III outwash plain in the foreground.

(c) Levelled profiles of rampart moraines around Lago Puyehue and Lago Rupanco.


C
①
Puyehue
250
225
200
175
150
metres a.s.l.
PII
vertical exaggeration = x20
Ice
PIII
Lago Puyehue
0 1 2 3
Horizontal Scale (km)
②
Puyehue
250
225
200
175
150
metres a.s.l.
PI
PII
PIII
Ice
Lago Puyehue
0 1 2 3
Horizontal Scale (km)
③
Rupanco
225
200
175
150
125
100
metres
RII
Ice
RIII
Lago Rupanco
④
Rupanco
225
200
175
150
125
100
RII
Ice
RIII
Lago Rupanco
0 1 2 3
Horizontal Scale (km)
⑤
Puyehue IIB rampart moraine
Ice
40
30
20
10
0
height (metres)
600
400
200
metres
⑥
Rupanco II rampart moraine
ice contact slopes
Ice
100
90
80
70
60
50
40
30
20
10
0
height (metres)
3000
2000
1000
metres
KEY:
= outwash plain
= ice-contact slope
= palaeoshoreline

MORAINE	MORPHOLOGY	DIMENSIONS	MORAINE TYPE
Puyehue I	Sharp-crested, discontinuous ridge	>8m high. Proximal slope=8-10˚, distal slope=4°	ridge
Puyehue II			
Puyehue IIA	Outermost ice contact slope. Discontinuous arc breached by meltwater channels. Broad crest, gentle distal slope has been modified by outwash and grades into Puyehue II outwash plain and through gaps in Puyehue I	30m high. Proximal slope=9-14°, distal slope=3-5°.	rampart
Puyehue IIB	Well-defined ice-contact slope with meltwater channels and kettle holes along crest.	40m high, continuous arc of >5km. Proximal slope=11-17°, distal slope=1-3°.	rampart
Puyehue IIC	Continuous ice-contact slope	c.30m high. Proximal slope=8-11°, distal slope=3-5°.	rampart
Puyehue III	Sharp-crested, continuous, meltwater channels breach crest. Horizontal around west end of lake, lateral moraines have longitudinal gradients <0.5°.	25-30m high. Proximal slope=10-14°, distal slope=2-5°.	ridge
Puyehue IV:			
North	Sharp-crested, narrow, linear, continuous for 5km+. Meltwater channels breach crest	Proximal slope=13-25°, height=50m Distal slope=12-22°, Height=22m	ridge
South	Two short, arcuate ridges: outer is discontinuous, outwash from inner ridge extends through gaps in outer.	Proximal slope=6-11°, height=32m. Distal slope=5-8°, height=9m.	ridge
Puyehue V	Two ridges on edge of raised, flat-topped terrace	<10m high	

Table 2.1: Summary of the characteristics of moraines around Lago Puyehue.

The Puyehue II moraine consists of three ice-contact slopes; these are amalgamated and so show no flat outwash areas between them. The three-fold division is seen most clearly around the southwest margin of the lake where the moraines have been labelled Puyehue IIA, Puyehue IIB and Puyehue IIC from west (outermost) to east (innermost). The individual moraines can be mapped as a number of segments. The segments can be correlated over distances of a few hundred metres where they are separated by other landforms such as channels. Segments of Puyehue IIA and Puyehue IIB can be traced for up to three kilometres each whilst Puyehue IIC segments are more than ten kilometres long. Similarly, the Rupanco II moraine is not continuous but made up of a small number of discontinuous crests. However, the relations between the moraine segments is more complex and they cannot be correlated confidently so the number of constituent ice-contact slopes is more difficult to establish. In places, segments of two ice-contact slopes are closely superimposed. The Rupanco II rampart moraine is narrower than the Puyehue II moraine and so the width and number of crests imply it is unlikely to be made up of more than two ice-contact slopes.

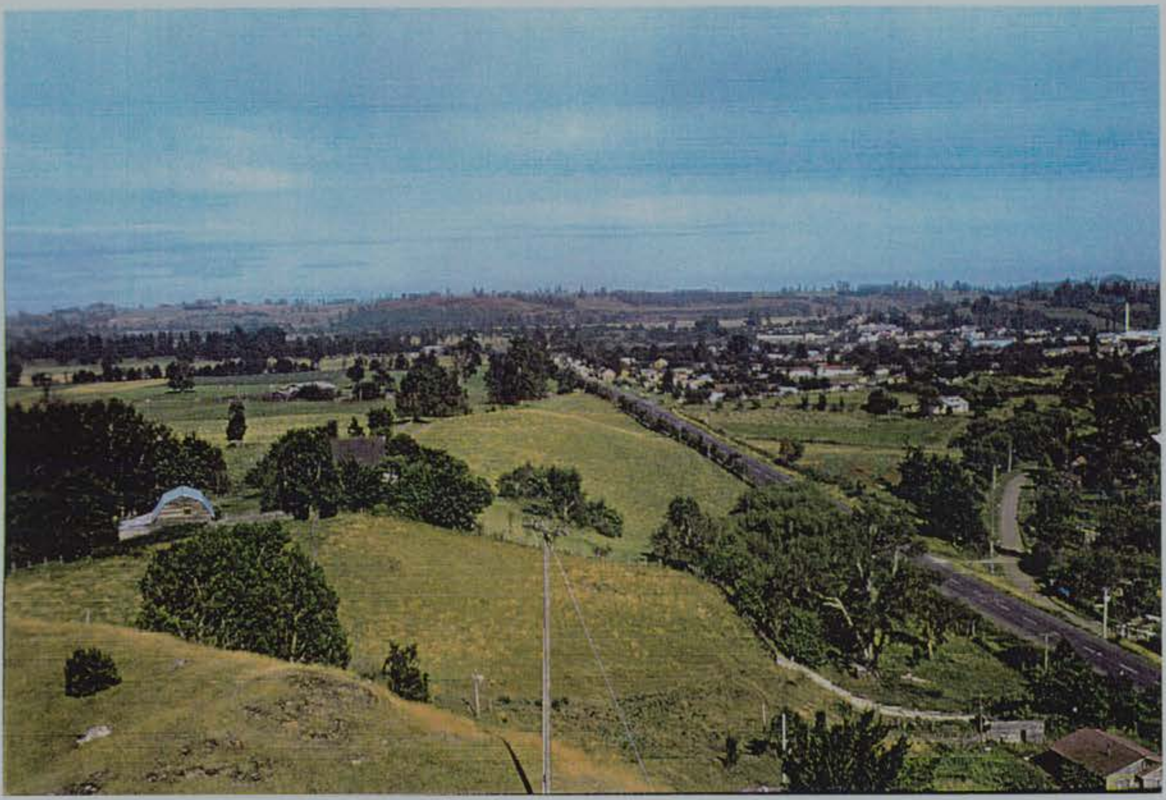
MORAINE	FORM	DIMENSIONS	MORAINE TYPE
Rupanco I	Subdued, discontinuous ridge fragments surrounded by Rupanco II outwash plain. Crests relatively broad.	c.10m above surrounding outwash. Ridge up to 200m across	ridge
Rupanco II	Largest Rupanco moraine. Made up of more than one ice-contact slope. These encircle western half of lake. Breached by one major perched channel (Mayelhue) at 200m asl. Slope is stepped. Very broad crest. Frontal slope dissected by post-glacial drainage.	Rises 60-70m above Rupanco III outwash plain, but is only 10-20m above outwash to west. c. 2-3km across. Proximal slope=5-8°, distal slope=1-2°,	rampart
Rupanco III	Sharp-crested, distinct, continuous around west end of lake. Narrow crest cut by numerous meltwater channels.	10-15m above outwash, 35-40m above lake. Proximal slope=12-14°, distal slope=5-8°	ridge
	Small ridges in Pichilifaquen col form a small nested complex which can be followed continuously for c. 2km. Adjacent moraines are separated by meltwater channels.	<7m high, c.40-60m across, proximal slope=5-7°, distal slope=5-8°.	ridge

Table 2.2: Summary of the characteristics of the moraines around Lago Rupanco.

2.2.2. Ridge Moraines

Ridge moraines are single, well-defined, sharp-crested ridges a few tens of metres high with typical proximal slope angles of 12-20° (Fig. 2.5). The ridge crests are breached by channels grading into outwash plains. The moraines are asymmetric in cross-section with steep proximal slopes giving way to shallower distal flanks. This contrasts to the broad, amalgamated complexes of the rampart moraines. Ridge moraines include Puyehue III, Rupanco III and Puyehue IV. The morphology is exemplified by the Puyehue III (lakeshore) moraine. Here, the ridge can be traced for several kilometres around the lake while the Rupanco III moraine can be followed around much of the western end of Lago Rupanco. The Puyehue III and Rupanco III moraines are similar in form and dimensions.

a



b

Figure 2.5. Ridge moraines

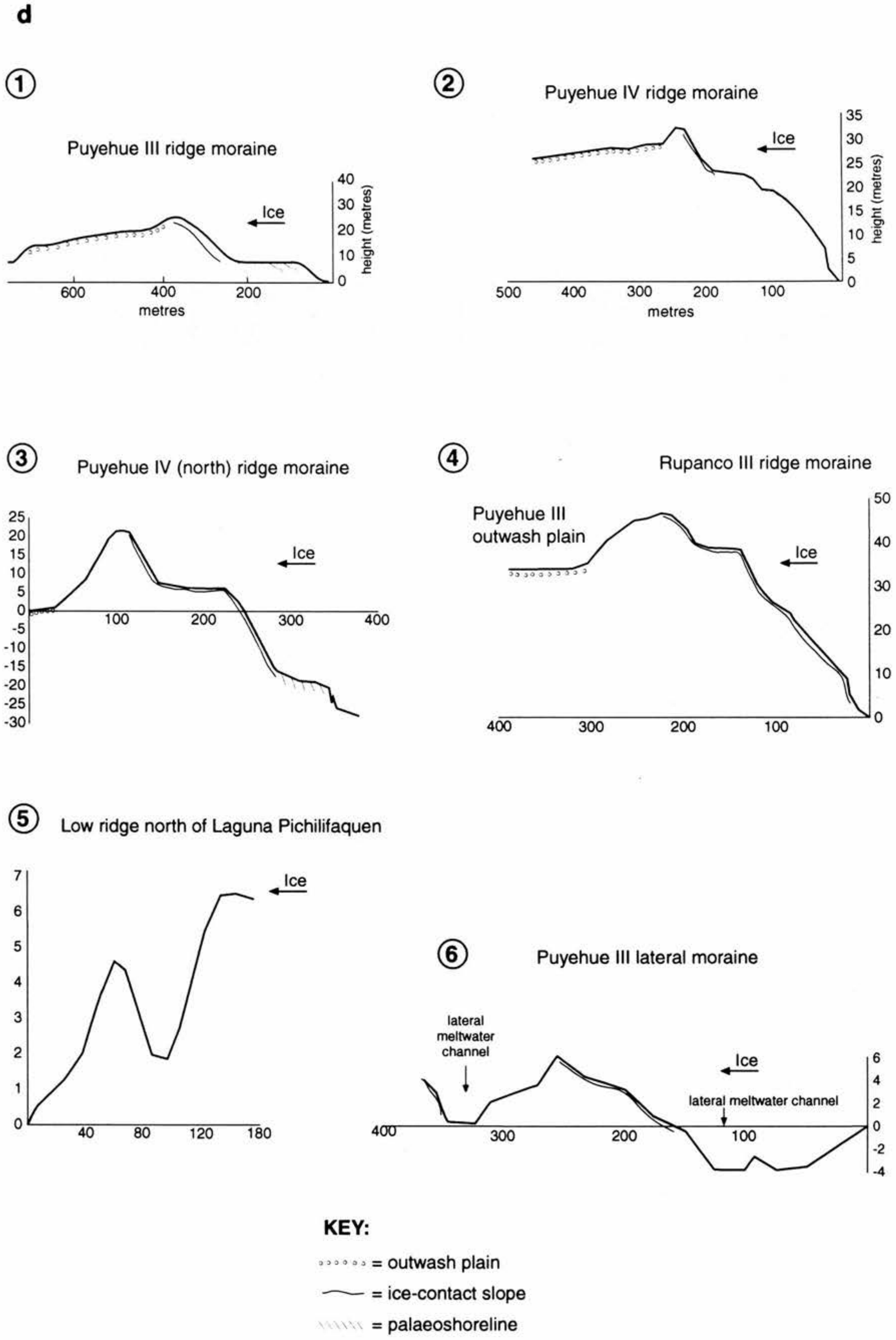
(**a**) Looking along crest of Puyehue III ridge moraine, east of Entre Lagos. Proximal slope is to right. Two meltwater channels breaching the moraine can be seen in the foreground. These grade to the Puyehue III outwash plain to the left of the photograph. Puyehue II moraine forms skyline.

(**b**) Proximal slope of Puyehue I moraine. The road lies on the Puyehue II outwash plain which is continuous on either side of the moraine. Moraine is 10m high.

(**c**) West end of Lago Rupanco. Looking from proximal slope of Rupanco II rampart moraine towards the ridge forming the Rupanco III lakeshore moraine. The Rupanco III outwash plain lies between the two moraines, and dips 0.2° towards the Río Rahue (right).

(**d**) Levelled profiles of ridge moraines around Lago Puyehue and Lago Rupanco

C


d
①
Puyehue III ridge moraine
Ice
40
30
20
10
0
height (metres)
600
400
200
metres
②
Puyehue IV ridge moraine
Ice
35
30
25
20
15
10
5
0
height (metres)
500
400
300
200
100
metres
③
Puyehue IV (north) ridge moraine
Ice
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
100
200
300
400
④
Rupanco III ridge moraine
Puyehue III
outwash plain
Ice
50
40
30
20
10
0
400
300
200
100
⑤
Low ridge north of Laguna Pichilifaquen
Ice
7
6
5
4
3
2
1
0
40
80
120
180
⑥
Puyehue III lateral moraine
lateral
meltwater
channel
Ice
lateral meltwater channel
6
4
2
0
-2
-4
400
300
200
100
KEY:
= outwash plain
= ice-contact slope
= palaeoshoreline

They both rise up to 25m above the lake level with proximal slope angles of 10-14° and 12-14°. Both grade into shallow-dipping outwash plains.

The Puyehue IV moraine occurs as two segments on the north and south shore of the lake. On the north shore of Puyehue a narrow single-crested ridge trends parallel to the lakeshore. The ridge becomes gradually lower to the west; from a height of 50m above the lake it slopes westwards with a longitudinal gradient of c. 0.5° to where it meets a 10m palaeo-shoreline. The bathymetry shows that at this point a narrow, single-crested submarine ridge trends NNW-SSE towards Isla Fresia in the middle of the lake (Fig. 2.3). On the south shore the Puyehue IV moraine consists of two closely-spaced crests that make up the north-south trending Nilque peninsula. A submarine continuation extends northwards across the lake to Isla Fresia. The moraines are breached by a number of 5-20m wide channels which flow from the moraine crest to the outwash on the distal side. With the submarine portions this moraine forms a continuous loop half-way along Lago Puyehue. The terminal moraine is delimited by the submarine sections and the ridges on the south shore whilst the ridge on the north shore marks part of the lateral extension of the moraine. The lateral extension on the south side is not seen; the north-south trending ridges abut directly against a bedrock cliff at their southern end.

The Puyehue I and Rupanco I moraines are largely buried by the outwash from the Puyehue II and Rupanco II moraines and so their morphology is not fully known. However, they are here classified as ridge type moraines on the basis of relatively sharp crests; narrow, single-ridge form; asymmetric cross-section, and similar dimensions to the other ridge type moraines: Rupanco III, Puyehue III and Puyehue IV. They only rise 10 metres above the level of the outwash plain but since they are part-buried this is a minimum figure; if similar to Puyehue III, Rupanco III and Puyehue IV then their true height is probably at least 20m.

The Puyehue V moraine forms a double ridge in a tributary valley south-east of Lago Puyehue (Fig. 2.6). It has a similar morphology to the ridge moraines but shows much steeper lateral longitudinal (3-4°) gradients and is only exposed on one side of the valley. Its location suggests it is likely to be a retreat stage of the Puyehue glacier formed during final deglaciation. The contrast in its location, lateral gradients and absence of other concentric loops excludes it from the ridge and rampart classifications.

2.3. Lateral Moraines

Both rampart and ridge moraines occur as laterals parallel to the lake axis. The same criteria used for terminal moraines have been used to identify lateral moraines except that the laterals are parallel to the long axes of the lakes rather than transverse to them. Lateral moraines are usually contiguous with the

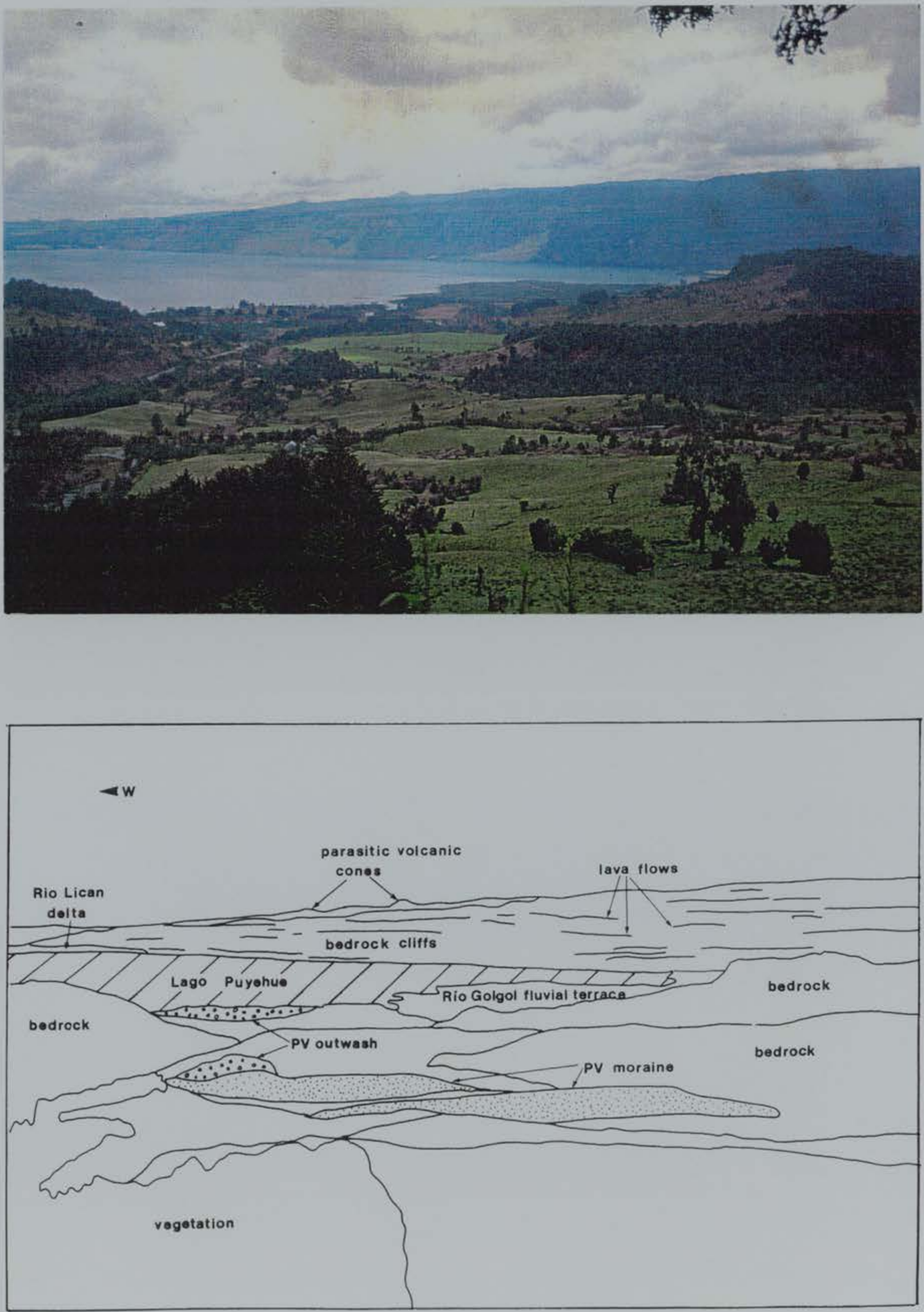


Figure 2.6. Photograph and sketch illustrating the main features at the eastern end of Lago Puyehue. The Puyehue V moraine ridges and meltwater channels run obliquely to the left and a fragment of the outwash associated with Puyehue V can be seen on the shore of Lago Puyehue. Steep bedrock walls of Lago Puyehue and the spur of Cordon Caulle are visible in the background. To the left the slopes are less steep. An areally scoured bedrock knoll can be seen at the extreme left.

terminal moraines and can be traced from the west end of the lakes to roughly half-way along the side of the lakes before they are obscured by dense vegetation, or merge into areally-scoured bedrock. The laterals provide information on marginal positions and fluctuations of the glaciers as well as their longitudinal gradients.

2.3.1. Rampart

The terminal moraines of Puyehue II and Rupanco II continue as lateral moraines on both shores of each lake. Between the two lakes a broad, high ice-contact slope can be traced continuously from the Puyehue II terminal moraine to the Rupanco II moraine. The ice-contact slope runs parallel to the south shore of Puyehue, continues on the western side of the Pichilifaquen col and then forms the topmost part of the slope above the north shore of Lago Rupanco. To the north of Lago Puyehue and south of Lago Rupanco, broad rampart laterals can be traced for several kilometres sub-parallel to the lakes.

The gradients of the lateral moraines are shallow (Fig. 2.7). From the western end of Lago Puyehue they rise eastwards with gradients of 1-2m/km (0.05-1°). Along the north shore of the lake there is a marked change about seven kilometres from the west end of the lake, where longitudinal gradients become steeper (17m/km (1°)) and the lateral moraines diverge from the lake. Rupanco lateral moraines have uniform gradients (c.12m/km (0.7°)) throughout their length.

2.3.2. Ridge

As with the rampart moraines the Rupanco III, Puyehue III and Puyehue IV ridge moraines can be traced continuously as lateral moraines. The lateral ridge moraines also have low longitudinal gradients (Fig. 2.7). The trends of the ridge laterals are parallel to the rampart laterals and include the same change in orientation and gradient on the north shore of Puyehue. To the west of this point gradients are horizontal whilst to the east they slope at angles less than 0.5°.

The lateral moraines on the north shore of Rupanco and the south shore of Puyehue are closely-spaced. To the south of Puyehue they form a sub-parallel sequence of narrow sharp-crested ridges up to 8m high superimposed on the lowest part of the ice-contact slope of the Puyehue II lateral moraine. To the north of Rupanco they have similar dimensions and form a tightly packed sequence between the foot of the main Rupanco II ice-contact slope and the present lakeshore. On the south shore of Lago Rupanco, closely-spaced Rupanco III lateral moraines run sub-parallel to the shore and have low longitudinal gradients, in a similar fashion to those on the north side. Further east all the laterals show an embayment below Laguna Bonita. A few kilometres east of this a series of about 10 ridge type

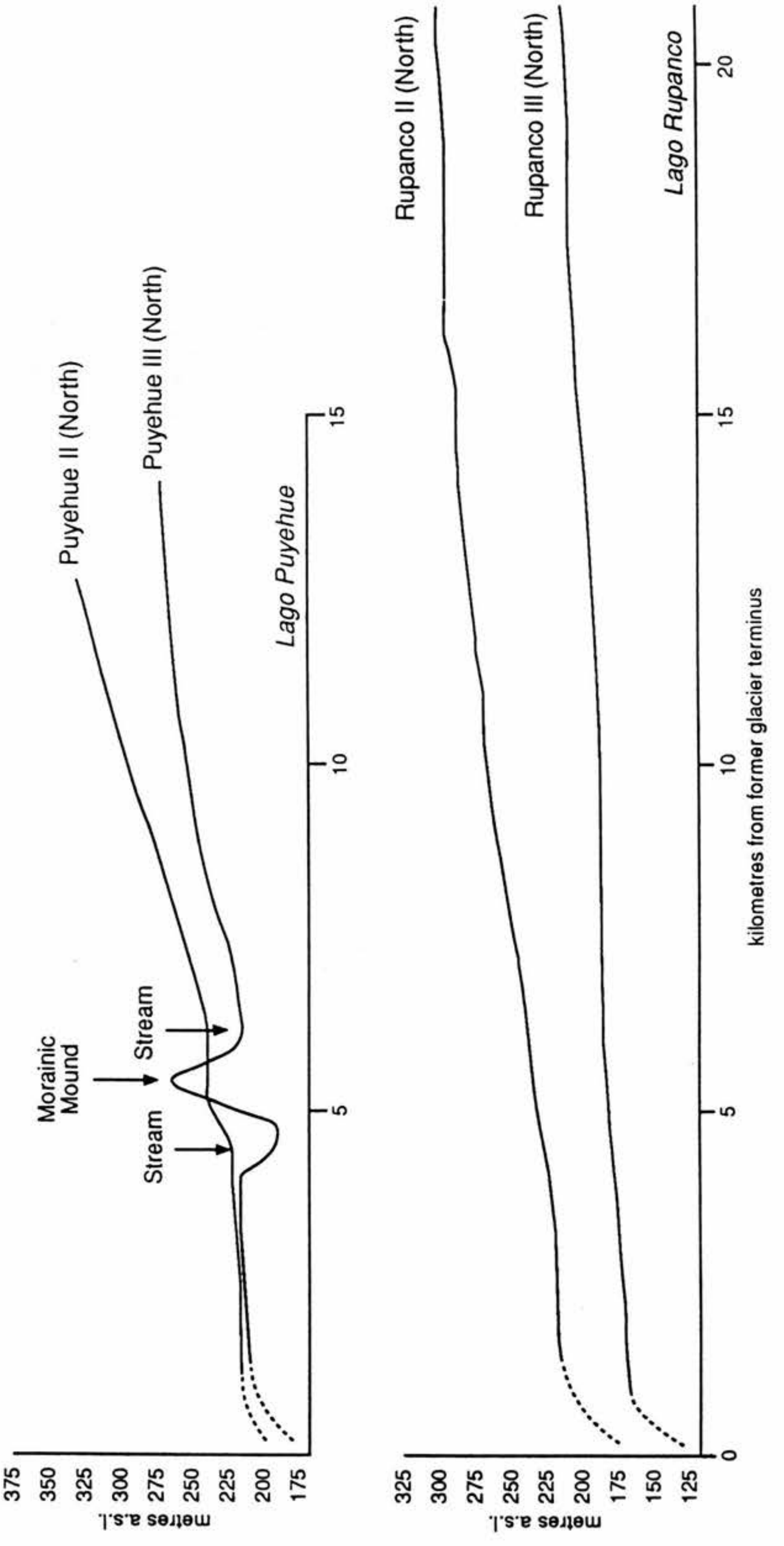


Figure 2.7. Long profiles of lateral moraines around Lago Puyehue and Lago Rupanco.

lateral moraines run oblique to the lakeshore and climb steeply up the local slope. The increase in gradient seems to mark an important change in glacier profile at this location. When the terminus was west of this point it had a relatively low angle margin whilst when it lay to the east it had a steeper profile.

2.4. Meltwater channels

Meltwater channels are ubiquitous features of the study area. Their distribution and relationships are important because the relative timing of advances of the Puyehue and Rupanco lobes can, in places, be deduced by studying the cross-cutting relationships of meltwater channels with each other and with other landforms. The channels can be broadly divided into lateral meltwater channels closely paralleling lateral moraines, and terminal meltwater channels that cut across the trend of morainic topography. The vast majority of channels contain contemporary streams (Fig. 2.8). Consequently post-glacial modification of the meltwater drainage pattern may have occurred. To minimise this potential error when mapping, channels were only mapped as meltwater channels on the basis of the following criteria:

- The channel in which the stream is contained originates at a moraine crest or the top of an ice-contact slope
- The channel flows obliquely to the local slope
- The channel shows evidence of superimposition of a V-shape (stream) incision into a former flat-bottomed channel
- The orientation, size, gradient and form of the stream-occupied channel resemble those of positively identified meltwater channels nearby without streams

In addition it is likely that once a drainage network was created during the glaciation it would not be substantially modified by post-glacial fluvial activity. Water draining from slopes would take the easiest route, in this case pre-existing glacial channels, and so modification would be limited to erosion and enlargement of some channels, downslope connection of some oblique-flowing channels, and abandonment of other channels on higher ground.

Channels generally dip from east to west, parallel to former glacier flow directions. The westward dip also corresponds to the regional gradient from the Andean Cordillera to the Pacific Coast. However, a small number of marginal meltwater channels on the south shore of Lago Puyehue dip towards the east and show truncating relationships with meltwater channels associated with the Pichilifaquen ridges.

Figure 2.8. Typical meltwater channel. Channel runs between two of the Rupanco III lateral moraines. The flat-bottomed trough dips at an angle of 0.5° to the west (left) and contains a small present-day stream (marked by line of vegetation)

Figure 2.9. Former ice-marginal lake, Bellavista. The ice-marginal lake lay in the broad vegetated depression between the high Rupanco II rampart to the left and the wooded Rupanco III moraine to the right.

2.4.1. Terminal meltwater channels

The meltwater channels which cut across moraine trends are generally confined to the terminal areas. Terminal meltwater channels vary greatly in size from a few metres across to over 150m in width, and in length from tens of metres to over five kilometres. Most lie in the range 10-30m wide and <1km long. The channels dip to the west. Gradients can be as low as 10' but range up to 1°. Most channels form part of anastamosing networks which converge towards the west and commonly feed into a single, deep channel which cuts through the outermost end moraines. Only a small number of the deep channels exist and they clearly represent major conduits for the escape of meltwater from the former Puyehue and Rupanco glaciers. Commonly the channels have 'perched' intakes in that the intake now lies significantly higher than any present-day drainage close to it. The perched channels must only have been utilised during former high lake levels or times of maximum glacial extent when glacier ice directly abutted against the intakes and fed meltwater directly into the channels. The rivers Pilmaiquen and Rahue which drain Lago Puyehue and Lago Rupanco respectively are each deeply incised into the terminal moraine sequence. There are no other channels at a low enough level to have allowed water to drain through the moraine complexes after retreat from the Puyehue II or Rupanco II position so the rivers are likely to have exploited the courses of old meltwater spillways through the moraines. The spillways have been cut down to a level sufficient to allow continued discharge of water from the western ends of the lakes.

Some of the more important terminal meltwater channels include those named in this study as the Mayelhue channel, the Bellavista channel, and the Quebrada Honda channel. The Mayelhue channel is 80m wide with a flat bottom and steep sides. Its western end grades into the Rupanco II outwash but its eastern intake is now perched 30m above the level of the Rupanco III outwash plain, so clearly it was once an important conduit through the Rupanco II moraine complex.

The Bellavista channel is not strictly a terminal channel since it begins at the top of the Rupanco II lateral ice-contact slope. However, this 30m-wide channel does cross-cut morainic topography of the interlobate area and is fed by numerous minor channels to form an anastamosing network converging northwestwards. Where it meets the Puyehue II moraine at La Huenchuta the channel turns sharply to the west and flows along a terrace eroded into the Puyehue IIB ice-contact slope. The terrace is 20-30m wide and dips at a shallow angle to the west, and also dips away from the ice-contact slope. Two kilometres further west this terrace grades into the Quebrada Honda channel. The terrace is not occupied by a present-day stream; instead the water issuing from the Bellavista channel at La Huenchuta cuts straight down the Puyehue IIB slope and onto the Puyehue III outwash plain where it joins with the Estero Chinchin.

The Quebrada Honda channel is 150m wide and 25-30m deep. The large size can probably be attributed to its position at the confluence of the Puyehue and Rupanco glacier lobes. It would thus have been a major conduit for a large amount of meltwater from the south Puyehue and north Rupanco margins. The south-eastern intake of this meltwater channel is now perched 40m above the outwash plain to the east, and 55m above the present-day lake level and currently only contains a small stream. The western end of the channel grades into the Puyehue II outwash plain.

Smaller channels which breach moraine crests occur to the east and north of Entre Lagos, where channels grade from the crest of Puyehue III to the Puyehue III outwash plain. The other sharp-crested ridge moraines are also breached by perched meltwater channels up to 10m wide, all originating close to the crest and grading into outwash plains on the distal side.

2.4.2. *Lateral meltwater channels*

Lateral channels tend to be smaller than many of the terminal channels since they are confined by closely-spaced lateral moraine ridges. Like the terminal channels they predominantly flow west but important exceptions do occur. Although they do not form anastamosing networks they are connected where individual streams have cut downhill through a lateral moraine ridge to join an adjacent, parallel channel. The steps in the channels are shown most clearly where the channels are occupied by present-day streams.

The most prominent sets of lateral channels occur along the south shore of Lago Puyehue and on both shores of the western end of Lago Rupanco. An important change in the pattern occurs on the south shore of Lago Puyehue, 4km east of Entre Lagos. Instead of the normal westwards dip the sequence of shore-parallel channels flow to the *east,* at angles of <0.5°. The channels curve around to flow south-eastwards into the Pichilifaquen col until they intersect, and are truncated by, north-east flowing meltwater channels parallel with the Rupanco III moraines. The Puyehue channels form hanging valleys on the flanks of the Pichilifaquen channels. Smaller numbers of lateral meltwater channels occur south of the Pichilifaquen col, probably associated with retreat from Rupanco III, and also occur parallel to the Puyehue V lateral moraines to the east of Lago Puyehue.

On the north shore of Lago Rupanco, some lateral meltwater channels are closely associated with the sites of former ice-marginal lakes (Fig. 2.9). The ice-marginal lakes are marked by flat-bottomed depressions surrounded by moraines, some with horizontal benches eroded into them. Exposures in the depressions expose glaciolacustrine sediments. Two lakes are particularly prominent: at Bellavista and Santa Elsa on the north shore of Lago Rupanco. The two ice-marginal lakes were dammed between Rupanco III lateral moraines and the Rupanco II rampart moraine. They are connected by meltwater channels along the palaeo-margin of the Rupanco III advance and it is likely that the lakes were filled with the meltwater draining in the channels leading southwest and west from the Pichilifaquen col.

2.5. Outwash Plains

Meltwater channels grade from moraines into areas of flat outwash. Outwash plains are recognised on the basis of the following criteria:

- Planar surfaces with a uniform gradient. The surfaces are usually extensive over several kilometres.
- Gradients less than 1°
- Channel lineations visible on the surface of the plain
- The uphill side of each plain is bordered by a moraine which usually grades into the plain

Four main outwash plains exist. Foremost amongst these is the outwash plain which stretches from the distal side of the outermost Puyehue and Rupanco moraine arcs as far as the Cordillera de la Costa, a distance of over 50 kilometres. The outwash plain is continuous from north to south so that the Puyehue and Rupanco outwash surfaces are contiguous with each other and with those associated with Lagos Ranco and Llanquihue, to the north and south respectively. Further east, areas of flat outwash occur between the Puyehue III and Puyehue II moraines and between the Rupanco III and Rupanco II moraines. Smaller outwash bodies occur on the distal side of the Puyehue IV moraine, the north side of the Pichilifaquen ridges, and small fragments associated with the Puyehue V moraine.

The size of the outwash plain associated with the Puyehue II and Rupanco II moraines dwarfs all the others. It extends tens of kilometres into the Central Valley and is contiguous with the outwash plains west of Lago Llanquihue (to the south) and Lago Ranco (to the north). The outwash plain has a concave long profile as the 2-3° distal slopes of the moraines grade into consistent shallow dips of 10'-20' to the west. The thickness of fluvioglacial material is considerable. The longitudinal Central Valley has been undergoing tectonic subsidence along normal faults throughout the Pleistocene (Paskoff, 1977). Geophysical data show that near Puerto Montt the depth to bedrock is 2000-3000m and fluvioglacial deposits west of Puyehue are known to be at least several hundred metres thick. An exposure in the gorge of the Río Pilmaiquen, 12km west of Lago Puyehue shows that the outwash here is at least 80m thick. The main features of note on this plain are the incised rivers issuing from the major meltwater channels and the lakes. The major rivers have eroded deep, steep-walled valleys with terraced sides.

The Puyehue II and Rupanco II outwash plain is contiguous through breaches in the Puyehue I ridge and relict braided channels are seen on aerial photos to converge into, and diverge from, these gaps. The relationship of the channel lineations to the moraine implies flow was constrained by the presence of the moraine. The Rupanco I moraine is also surrounded by the continuous surface of the Rupanco II outwash plain. The outwash-moraine relations also explain the subdued, discontinuous nature of the Puyehue I and Rupanco I moraines since they may have been substantially eroded and later buried by the fluvioglacial activity, such that only the topmost parts of the ridges show through.

Relict channels can also be discerned diverging from the uppermost terraces of the two major outflow rivers on the distal side of the Puyehue II and Rupanco II moraines. This supports the idea that the channels now occupied by the rivers have had a long history of providing drainage from the glacier, and later the lake.

There are also smaller bodies of outwash between some of the moraines. Between the Puyehue II and Puyehue III moraines there is a shallow-dipping crescentic outwash plain associated with the Puyehue III moraine. The Puyehue III outwash plain is fed by meltwater channels originating at the Puyehue III moraine crest but also by a small number of lateral meltwater channels which grade into the plain south-east of Entre Lagos. The network of channels located on the interlobate area between Los Esteros and the head of the Estero Chinchin also grade into the Puyehue III outwash plain. The location and dip direction of this plain show that it would have graded to the proto-Río Pilmaiquen flowing through the Puyehue II moraine complex. The Quebrada Honda channel is located 40m above this plain and so could not have been utilised. A similar crescentic outwash plain lies between the Rupanco II and Rupanco III moraines (Fig. 2.5c). A prominent lateral channel grades into the north-east corner of the outwash body. The channel forms the terminal part of the system of linked channels and ice-marginal lakes along the northern Rupanco III margin. The Rupanco III outwash grades to the highest terrace levels of the Río Rahue.

The northern and southern Puyehue IV moraine segments both grade into outwash plains. On the north shore of Lago Puyehue the Puyehue IV moraine grades northwards into a shallow outwash plain, dipping at 50' to the west. To the north the outwash plain surface is confined by bedrock cliffs and to the west it grades into a terrace 10m above present lake level. On the south shore of Puyehue the west-dipping outwash associated with the double-crested Puyehue IV moraine forms a contiguous surface with the north-dipping outwash plain associated with the Rupanco IV moraine ridges. This surface extends westward as far as Los Copihues and makes up the wide, flat peninsula forming the west side of Bahia Futacullin. Both plains grade to the same level above Lago Puyehue.

The outwash surface associated with the Puyehue V moraine has been extensively dissected by the Río Pichichanleufu and its tributaries. Consequently only two fragments remain: one forms a terrace directly in front of the moraine whilst the other exists as a small raised plateau close to the lakeshore (Fig. 2.6). When extrapolated, the two planar surfaces coincide. As with the Puyehue IV moraine, the lower outwash fragment grades to a terrace c. 12m above the present level of Lago Puyehue.

The flat bottom of the Río Golgol trough, east of Lago Puyehue, may have been formed originally by fluvioglacial infill during retreat of the Puyehue glacier. However, any clear evidence of the glacial fill has been obscured by the alluvium derived from the present-day river, and by thick tephra sequences and lava flows derived from adjacent volcanoes.

2.6. Non-aligned moraines

The interlobate area between the Pichilifaquen col and the Quebrada Honda channel is mantled with glacial deposits but shows no clear trends of moraines or meltwater channels. Numerous mounds, hollows and anastamosing channels combine to give a complex topography with relief less than 20m. The boundaries of this area are defined by the outermost crests of the well-defined Puyehue II and Rupanco II lateral moraines (Fig. 2.1). The area north of the Puyehue lateral moraines, towards Lago Ranco, is also complex and a closely-spaced network of rivers and streams dissects the inter-lake spur.

In the area south of the low ridges in the Pichilifaquen col some large-scale features can be discerned in the topography. A broad valley, running from north to south, now contains the Río Coihueco. The valley is flanked to the west by a wide south-dipping terrace on which Laguna Pichilifaquen lies, and to the east by a broad NNE-SSW trending ridge, dissected at its northern end by the upper reaches of the Río Coihueco. The point where the Río Coihueco turns from west-flowing in a narrow, incised valley to south-flowing in a broad valley coincides with a broad slope from the proximal side of the low ridges in the nadir of the col into the head of the broad valley.

2.7. Bedrock Forms

In addition to the areally-scoured bedrock in the eastern part of the study area, a number of eroded bedrock landforms occur in the otherwise largely depositional landscape to the west. Notable amongst these are the promontory of Punta Muelle de Piedra and a 15m-high roche moutoneé on the west side of Bahia Futacullin, both on the south shore of Puyehue. La Puntilla and Bahia Pescadero Grande, on the north shore of Lago Rupanco are also composed of bedrock. The bedrock features are oriented west-east with steep western faces and smoother, shallow east slopes.

At the Pilmaiquen Hydro-Electric Plant, located within the Puyehue II moraine complex, the river flows over a 15m-thick bedrock step, of columnar jointed lava, before it begins to flow through the Pilmaiquen gorge. The lava flow lava overlies a unit of unknown thickness which, although inaccessible directly, has the appearance of fluvioglacial sediment. Both the lava and outwash have been eroded by the river. There is a relict 30m-high waterfall with a 50m-diameter vertical-walled plunge pool located c. 200m downstream of the power station. The lava is overlain by the stratified sediments and rampart moraine of the Puyehue IIB stage.

The Peninsula del Islote in Lago Rupanco is composed entirely of bedrock and is markedly ice-smoothed in an east-west direction. The cliffs around the eastern ends of Rupanco and Puyehue are near-vertical, showing slight steps between different lava flows. The cliffs continue eastwards along the sides of the Río Golgol trough. On the south-east shore of Lago Puyehue the bedrock topography is more complex; kilometre-scale massifs are separated by deep valleys. The massifs show a crude east-west alignment.

2.8. Shorelines

The shores of both Lagos Puyehue and Rupanco expose evidence of former higher lake levels. Both depositional and erosional types of shoreline exist. Shorelines are recognised on the basis of three criteria.

- Benches or depositional features which are horizontal and can be traced continuously.
- Alternatively, discontinuous segments at the same altitude, or a number of features such as deltas occur at the same altitude.
- The features occur on the proximal slope of moraines or other landforms *facing* the lakes
- The features often occur close to, and are parallel with, the shorelines of the present lakes

The most prominent shoreline lies 10m above the present level of Lago Puyehue. It is marked both by graded outwash plains and erosional benches on the inner sides of the Puyehue III and Puyehue IV (northern segment) moraines (Fig. 2.5d). The 10m bench can be traced continuously on the proximal slope of Puyehue III for over 15 kilometres and five kilometres along the proximal slope of the Puyehue IV moraine. A channel runs through Entre Lagos from the lakeshore east of the town to the Río Pilmaiquen west of the town. The intake of the channel is graded to 10m above present lake level and represents the previous drainage route of the lake before the Río Pilmaiquen cut the present breach in the Puyehue III moraine at the south-west extremity of the lake. The position of the lakeshore within the Puyehue III and Puyehue IV moraines shows the lake level post-dated the formation of the Puyehue III and Puyehue IV moraines.

There is a shoreline at 8-10m above the present level of Lago Rupanco. The shoreline is marked by a combination of a narrow terrace eroded into the encircling Rupanco III moraine and higher outwash levels on the north side of the Bahia Pescadero Grande.

A number of former ice marginal lakes have been identified. Two of the lakes occur on the north shore of Lago Rupanco and are associated with the Rupanco III lateral moraines. They are recognised primarily on the basis of the presence of glaciolacustrine sediments but are also delimited by horizontal shorelines cut into oversteepened morainic slopes surrounding flat-bottomed troughs. Both ice-marginal lakes are now dry and the flat-bottomed areas enclosed by moraines are open at their western ends. Therefore, they would have required an ice dam at their western extremities in order to be maintained. The upper (Bellavista) lake was dammed on its southern side by a 20m-high flat-topped morainic mound whilst the south side of the lower (Santa Elsa) lake has a low <5m lateral moraine ridge on its southern side, so it would have required ice abutting the ridge in order to achieve any significant depth. A lateral meltwater channel runs from the Bellavista ice-marginal lake to the Santa Elsa lake. A meltwater channel also grades from the western end of the Santa Elsa lake to the Rupanco III outwash plain. The meltwater channels would have provided a route for meltwater to flow to the glacier snout when the ice-marginal lakes were not dammed. Fluctuations in the thickness of an ice dam would account for the frequent changes in lake level recorded by the erosional benches.

Evidence of another ice-marginal lake dammed by the Puyehue II moraine occurs in the interlobate area, two kilometres south-east of Entre Lagos and is marked by a flat-bottomed broad valley, flanked to both north and south by steep slopes with faint horizontal benches. The western end of the trough grades to the Puyehue III outwash plain whilst channels draining the interlobate area grade into the east end. Since the slopes with horizontal benches are oriented obliquely to the dominant moraine trends in the area and have no streams associated with them it seems that they were eroded by a former ice-marginal lake. It is probable that the lake formed when Puyehue ice lay against the Puyehue IIC ice-contact slope, and the drainage of the interlobate area was prevented from flowing west.

Another possible lake is marked by a prominent but restricted shoreline at c. 19m above Lago Puyehue on the Puyehue IV (south) moraine (Fig. 2.5). This is puzzling given that if Lago Puyehue was 19m higher the lake would extend through the gaps in the Puyehue III moraine and cut a shoreline in the Puyehue IIC moraine, which would form the west shore of the lake. There is no geomorphological or sedimentological evidence of this having happened after the Puyehue III stage. It seems most likely that the 19m shoreline records a local ice-marginal lake which formed between the Puyehue glacier and the Puyehue moraine.

A faint shoreline on the proximal side of Puyehue IIC is marked by a poorly-defined erosional bench and a number of flat-topped features lying between spurs on the Puyehue IIC ice-contact slope. Each of these features cannot be traced for more than a few kilometres but both the flat-topped inter-spur 'deltas' and erosional benches are at the same altitude (c. 232m a.s.l.) as each other and as the northern intake of the Quebrada Honda meltwater channel. The coincidence of these features at the same altitude suggests that this may be a shoreline marking a former ice-marginal lake dammed between the Puyehue IIC rampart moraine and the Puyehue glacier.

2.9. Summary of Glacial Geomorphology

The landform pattern is one of terminal and lateral moraines bounding the west ends of the lakes. The terminal moraines are closely associated with, and grade westwards into, outwash plains whereas lateral moraines are usually paralleled by small meltwater channels. Further east the landscape is dominated by bedrock features making up the foothills of the Cordillera.

The landforms record a history of fluctuations of the former Puyehue and Rupanco glaciers. Each moraine sequence consists of between four and seven stages and implies repeated advance and retreat to similar positions at the west ends of the lakes, and also to less extensive positions along the lakes. The relative timing of glacier behaviour in the two basins can be deduced from close study of the cross-cutting relationships of moraines, channels and shorelines, particularly in the Pichilifaquen col, and in the area of intersection of the two moraine arcs close to the Quebrada Honda channel. The absolute chronology can be elucidated by dating the moraine sequence using the radiocarbon technique. Before the relative and absolute chronologies are developed in Chapter 5 it is necessary to examine the glacial sediments exposed in a number of sections in the study area. The sediments described in Chapter 3 record the processes of moraine formation, whilst those described in Chapter 4 yield key information on the relative chronology.

Chapter 3: Sedimentology of rampart and ridge moraines

3.1. Introduction

The previous chapter demonstrated that the landforms around Lagos Puyehue and Rupanco record a series of glacial advances and can be used to elucidate the relative timing of the advances. However, before constructing a glacial chronology from radiocarbon dating of this sequence it is essential to establish whether these fluctuations reflect climate alone, or if other non-climatic factors such as internal dynamics might have affected the glacier system. Sediments provide an important record of processes and so by examining the sediments in detail it should be possible to identify the processes involved. This chapter describes and then draws together a synthesis of the sedimentology of rampart and ridge moraines. The following chapter presents the sedimentology of other landforms which have a bearing on the glacial chronology.

3.2. Glacial sediments

A detailed review of the interpretation of glacially-derived sediments is beyond the scope of this thesis and has already been dealt with in detail in textbooks (e.g. Eyles, 1983) and conference proceedings (e.g. Schlüchter, 1979; Jopling and McDonald, 1975; Davidson-Arnott et al, 1982). However, in a number of respects the sediments in the Puyehue-Rupanco area differ from those of a 'classic' valley glacier, such as those found in the Alps, so it is important to discuss the criteria used to recognise each sediment type. For example, one difficulty encountered was a consistent, close similarity between fluvioglacial sediments and till. The similarities between these two sediment types become important when the process of moraine formation is interpreted in Chapter 6. The moraines are formed of three sedimentary facies: fluvioglacial, glaciolacustrine and till. The following sections present the criteria for identifying each of the sediments and an explanation of how till and fluvioglacial deposits were distinguished.

3.2.1. Fluvioglacial sediment

Sedimentation by meltwater in the pro-glacial zone has been extensively studied by many workers in both contemporary and ancient environments (Boothroyd and Ashley, 1975; Rust, 1972; 1975; Jopling and McDonald, 1975; Fraser, 1982). Much of the sedimentation occurring in this zone is similar to deposition in non-glacial alluvial environments. For this reason there are few characteristics which can be used in isolation to identify a sediment as fluvioglacial; rather there is an assemblage of characteristics which must be used to arrive at this interpretation.

Fluvioglacial deposition commonly takes place in a braided river system. Pro-glacial streams show pronounced changes in regime on three timescales: diurnal, seasonal and the decades required for the retreat and advance of a glacier. They also tend to have a relatively high sediment supply. For these reasons the fluvioglacial environment tends to be unstable and highly dynamic with rapid channel evolution. On a large scale the proglacial braided system builds up low gradient fans. If unconfined, these coalesce to form sandar but, if confined, they form alluvial valley trains. Fans are constructed by aggradation of ephemeral channels and bars. Miall (1977; 1978) reviewed the braided river environment and presented a lithofacies code to describe the sediments. Braided stream deposits range from boulders to sands and minor proportions of silt and mud. Grain size tends to decrease with distance from the glacier terminus (Drewry, 1986; Fahnstock, 1963). Primary sedimentary structures include those described by Miall (1978) plus imbrication (Rust, 1975) and normal grading, particularly in gravels. Clast fabric studies have produced conflicting results. Boothroyd and Ashley (1975) found a strong orientation of oblate clasts transverse to flow direction in Alaskan outwash fans, whereas Rust (1972, 1975) found clasts tend to be oriented parallel to flow direction, although there was a high degree of variability. It seems difficult, therefore, to relate clast fabrics to former flow directions. It may be possible to do so in more recently deposited material where deposition is continuing nearby and the dominant trend can be measured, but in ancient examples fabric measurement will merely identify four possible flow directions.

In the Puyehue-Rupanco area, fluvioglacial sediments are identified according to the following criteria.

- close association with outwash plains, or distal side of moraines
- extensive stratification through unit, laterally continuous for tens of metres
- cross-stratified (tangential or planar contacts) sand lenses up to 10m across and 1m thick interbedded with the gravels
- numerous reactivation surfaces
- individual beds well-sorted
- predominantly composed of granule and pebble-sized material, with some cobbles
- most clasts are rounded to well-rounded
- sandy matrix
- matrix sometimes absent, leaving characteristic openwork gravel
- clay not present in matrix except as discrete laminae
- graded beds
- clast imbrication in gravels
- clast-supported

The most important of these criteria are the extensive stratification, cross-stratification, grading, sorting, and the absence of clay from the matrix.

3.2.2. Tills

The identification and interpretation of till is a subject that has spawned a huge literature including many volumes dedicated to the subject. The controversy largely arises from the intermediate position in which till lies in the sedimentary system; between purely glacial processes, proglacial water-lain deposition and non-glacial processes. The wide variety of processes which affect tills makes a sedimentological classification difficult and most authors use a genetic classification. For example, Boulton (1976), and Boulton and Deynoux (1981), classified tills into primary till which is affected only by processes occurring in direct contact with glacier ice, and secondary till which is deposited directly from glacier ice but with subsequent modification by other agents, particularly meltwater. Dreimanis (1976; 1982), and most authors subsequently, used a three-fold classification of lodgement till, melt-out till, and sediment gravity flows (sometimes called 'flow till'). These till types have been described in detail at a number of contemporary glaciers (e.g. Lawson, 1981). More recent work on sub-glacial tills has begun to move away from the term 'lodgement' till as there is some doubt as to the importance of the process of clast lodgement, except on rigid beds. Instead, tills formed by sub-glacial deformation of unconsolidated sediments are termed soft bed till (Hart, 1994) or deformation till (Elson, 1988). The definition of deformation till is '..unconsolidated sediment....detached from its source, the primary sedimentary sources distorted or destroyed, and some foreign material admixed' (Elson, 1988). Deformation till is regarded as broadly equivalent to the deforming bed of Boulton and Jones (1979). Other authors have suggested more detailed classification with up to 12 or even 30 separate till facies (Levson and Rutter, 1988; Lundqvist, 1984). However, it is generally recognised that it is only in rare cases of extremely detailed sedimentological studies of well-exposed sections that such classifications become possible and even then the usefulness of such methods is questionable. Often, the only distinction that may be made is between subglacial and supraglacial tills (e.g. Haldorsen and Shaw, 1982).

In the Puyehue-Rupanco area, it is possible, in places, to subdivide the tills. Table 3.1 presents the criteria for identifying three till types, namely deformation (or subglacial soft bed) till, melt-out till, and glacigenic sediment gravity flows. As with the fluvioglacial sediments it is the assemblage of characteristics which allow identification of the till types rather than any single diagnostic feature. Most of the tills in the area are diamicts (poorly-sorted clast-sand-mud admixtures (Eyles et al, 1983)). The sections described in this chapter demonstrate that deformation till is the most important till type in the field area.

	TILL TYPE		
Characteristic	**Deformation (subglacial) till**	**Melt-out till**	**Glacigenic sediment gravity flows**
Geomorphological association	sub-glacial, (particularly associated with basins or where glacier flows up-slope, can form part of moraine)	ice-marginal	ice-marginal landforms, often fills hollows or channels
Unit dimensions	usually extensive, laterally consistent sheets (can form small patches on slopes), usually <5m thick but can be up to 20m	few cm to 2m	few metres thick, laterally discontinuous, may form lobate fans a few metres across
Structures	usually massive (few relict structures, most destroyed by deformation), can show shear banding, recumbent folds (noses often boudinised), sheath folds, thrusts, deformed primary bedding may be evident	may be massive or show stratification reflecting orientation of basal debris in glacier, sediment drapes over clasts	usually structureless, but may contain lenses of well-sorted sands and silts, loading structures ('ball-and pillow' or 'flames' common), 'flow lineations' around obstructions, deformed intraclasts, deformed/overturned slump folds, faulted
Contacts: lower	usually erosional, can be in contact with abraded bedrock or truncate underlying unconsolidated sediment, may show graded zonation from deformed zone to sheared zone, overturned zone and a basal undeformed zone	interbedded with meltwater deposits	depositional or minor erosional unconformity, often interbedded with other proglacial sediments
upper	often overlain by meltwater deposits but can be uppermost glacial sediment	may grade into flowtill	often uppermost glacial sediment
Clasts	various - can be unmodified from parent material but some authors argue for importance of clast modification during deformation of till. Clasts poorly sorted, may be imbricated with up-glacier dip, soft sediment clasts sheared	poorly sorted, angular to sub-rounded	depends largely on parent material, may be sorted
Matrix	clay-silt, poor sorting, no grading, compact	poor in silts and clays because of winnowing, poorly sorted but may be locally well-sorted, can be reverse or normal graded	depends on parent material, often rich in silt and clay
Fabric	can be strong or weak depending on degree of deformation, parallel or transverse to former ice movement	parallel or transverse to former ice movement, sub-horizontal	weak, transverse or parallel to former ice movement
Support	matrix	clast or matrix	usually matrix
Other	shows little lateral or vertical variation (except vertical gradient in degree of deformation) Clast pavements occur within units, sub-parallel to upper and lower boundaries	low lateral variation but may be highly variable vertically in composition and structures	highly variable laterally and vertically

Table 3.1. Criteria for distinguishing deformation till, melt-out till and glacigenic sediment gravity flows. Criteria from several sources (Boulton, 1975; 1982; Kruger, 1982; Hart and Roberts, 1994; Hart and Boulton, 1991; Elson, 1988; Lawson, 1979; 1981; Haldorsen and Shaw, 1982)

A consistent problem in the Puyehue-Rupanco area is distinguishing melt-out tills and gravity flows from fluvioglacial deposits incorporated within moraines. This is for two reasons. First, there is a continuum of deposition between ice-marginal melt-out, glacigenic sediment gravity flows and proximal fluvioglacial sediment. Consequently, the criteria for identifying the sediments overlap. Secondly, the descriptions of the sections show that there is abundant fluvioglacial sediment in the field area and repeated glacial advances over the same material have continually reworked the sediment. As a result, the two sediment types typically have the same colour, and contain clasts with similar size distribution, roundness, and shape characteristics. These similarities are discussed further in the synthesis of the sedimentary evidence at the end of this chapter. It is therefore necessary that a number of key criteria for distinguishing the two in this area are defined. The most important features for distinguishing the till are the presence of clay and striated clasts. The most important features of fluvioglacial sediment are the *extensive* stratification and cross-stratification plus the absence of clay and striae (Table 3.2). Additionally, the individual fluvioglacial beds are much better sorted than the tills and are graded.

Criteria	**Fluvioglacial**	**Tills**
Structures	extensive stratification and cross-stratification	generally massive or crudely bedded
Matrix	clay and silt absent	dominated by clay and silt
Clasts	no surface features	rare striated clasts
Sorting	good to excellent	poor
Grading	normal	absent
Support	clast	usually matrix

Table 3.2. Criteria for distinguishing fluvioglacial sediment from tills deposited in the presence of abundant meltwater.

3.2.3. Glaciolacustrine sediments

Glaciolacustrine sediments are useful in the field area for identifying former levels and spatial extent of the existing lakes as well as establishing the existence of former ice-marginal lakes. The sediments associated with former lakes can be broadly divided into two types. First, those deposited distally by settling-out from the water column, and second, those deposited under the influence of both lacustrine and fluvial processes close to the lake shore. The diagnostic characteristics of distal glaciolacustrine deposits are listed below:

- Dominated by clay and silt
- Finely laminated, usually in normally graded silt-clay couplets. Laminae usually sub-millimetre but can be up to 1cm thick

- Dropstones: isolated granule to cobble-sized clasts which deform underlying strata and are draped by overlying laminae. Dropstones are usually sub-angular to rounded.
- Iceberg-rafted debris: lenses of diamict which fine upwards into silt and clay. The diamict lenses often extend laterally from dropstones
- Loading structures
- Association with present-day lakes or relict lakebeds

At the point where glacial meltwater streams enter a lake there will be a progressive gradation from glacio-fluvial deposits through delta topsets, foresets, and bottomsets to distally-deposited lacustrine sediment. These deltas are useful since the altitude of the topsets provides a clear marker of former lake level (Gilbert, 1885; Church and Gilbert, 1975). The deltas themselves differ little from non-glacial deltas apart from the possibility of overlying fluvioglacial sediment and glaciotectonic deformation by later advances. Recognition of deltaic sediments is therefore based on the following three-fold division which applies to both lateral and vertical sequences.

- Gently dipping bottomsets (usually <5°), often graded, merging with lake sediments
- Steeply dipping foresets (max c.30° if material is coarse, c. 15° for sands)
- Near-horizontal topsets truncate top of foreset beds as delta progrades. In glacial environments these usually form an extension of a braided stream system.

3.2.4. Aeolian sediments

In addition to the glacial sediments described above, most of the sections in the field area expose aeolian silt. The accumulations of glacial sediment are capped by up to two metres of relatively massive orange-yellow to grey silt. This is very well-sorted and contains only a small number of clasts, which are typically similar to those in the underlying sediment. Since the sorting is otherwise very good most of the large clasts seem likely to be derived from post-depositional processes within the sediment. For example, frost heave may move clasts upwards through overlying sediment. The silt grades into a grey silty soil which is largely derived from volcanic dust (Veit, 1993). Rootlets from the soil commonly penetrate down into the silt. The silt is interpreted as aeolian in origin and may correlate to a thin loess layer on the Argentinian side of the Andes (Wintle, *pers. comm.*). The Argentinian (or Pampean) loess originates largely from volcanic ash blown from the Peru-Bolivia-Argentina Altiplano (Bloom, 1990).

3.3. Descriptions of sections

Using the criteria described above, 18 sections exposing ridge and rampart moraines in the Puyehue-Rupanco area were studied in detail (Fig. 3.1). Descriptions of individual units at each site are presented and these have been interpreted to establish the sedimentary history at each location. The sections are presented according to whether they expose rampart or ridge moraines and are further ordered from west to east. Some of the sections contain organic material suitable for radiocarbon dating. This material has been sampled and the sites described in detail.

3.3.1. Sections cut into rampart moraines

Several sections in the proximal ice-contact slopes of rampart moraines demonstrate similar sediment associations.

Pilmaiquen (Puyehue IIB)

A large quarry cut into the Puyehue IIB ice-contact slope close to the Pilmaiquen Hydro-Electric Power Station shows many of the features common to the moraine sections (Fig. 3.2, Table 3.3). The dominant sedimentary unit (unit 1, Fig. 3.2a) consists of 20m of grey, horizontally-stratified gravels with cross-bedded sand lenses up to 10m wide and 0.6 to 1m thick. Clasts are predominantly cobble and pebble sized but there are a few boulders up to 2m across. These are sub-rounded and aligned parallel to bedding whereas most clasts are rounded to well-rounded. The cross-beds in each sand lens show asymptotic (depositional) contacts with underlying strata but the upper contacts are strongly truncated at reactivation and scour surfaces by the overlying gravels. Individual beds are laterally continuous for tens of metres. Towards the east side of the quarry, close to the Puyehue II proximal slope, one of the sand lenses and the gravel beds above and below are folded into symmetrical, open, upright folds. Fold hinges are aligned north-south and the amplitude of the folding decreases to the west.

At the extreme east end of the quarry the stratified gravels are overlain by a diamict (unit 2) with an observed maximum thickness of 5m. The sediments within the diamict are very similar to those in the stratified unit in terms of colour and clast characteristics but are poorly sorted and unstratified. In contrast to the strata below, the diamict matrix contains clay and silt. The roundness and shape characteristics of the two units are also similar. The clay and silt occurs as pale brown, deformed laminations in small pockets around larger clasts and dispersed through the matrix. The diamict contains several clasts larger than those in the stratified gravels; some of these boulders are sub-angular. The contact between the diamict and stratified unit dips to the east but is not sharply defined.

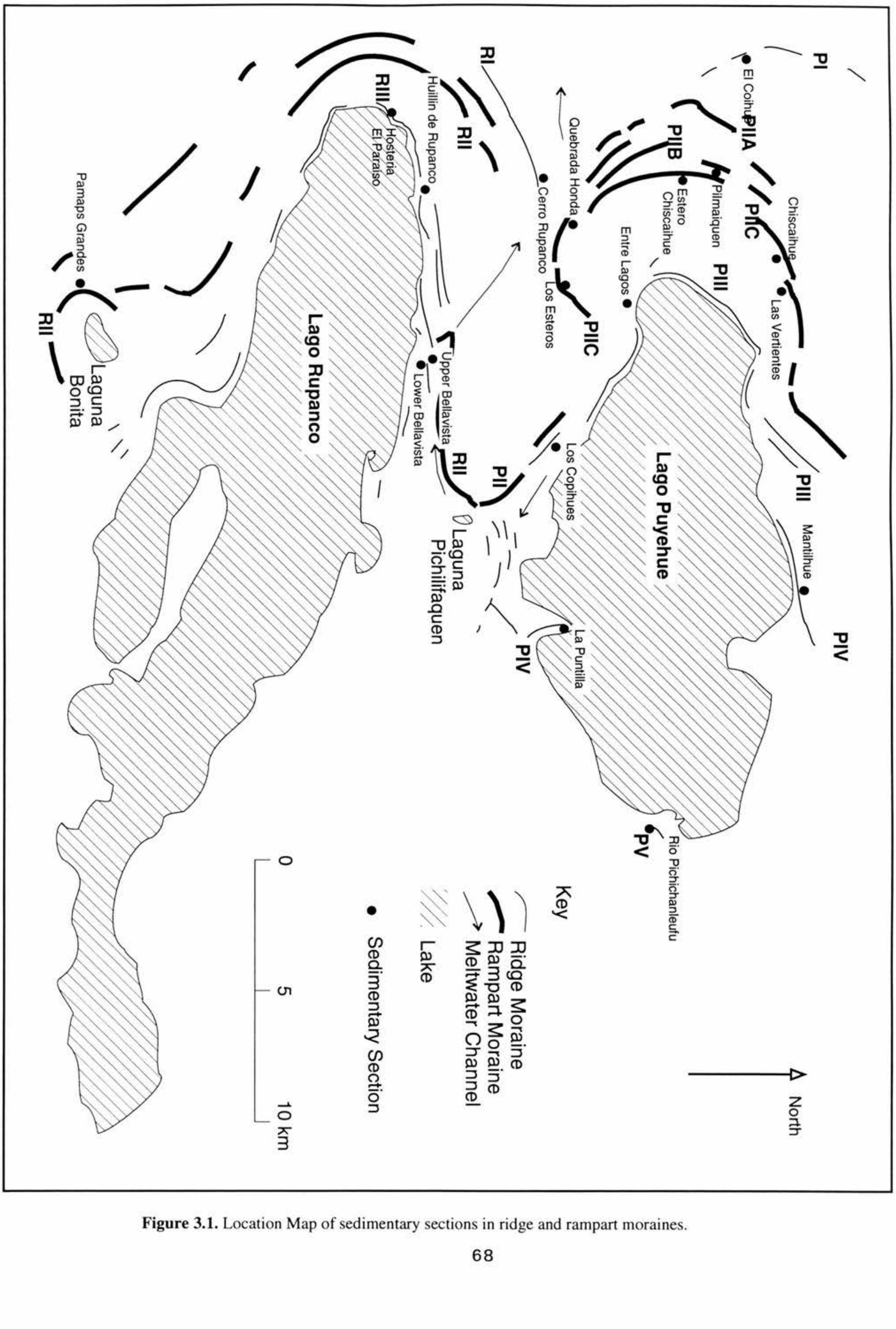


Figure 3.1. Location Map of sedimentary sections in ridge and rampart moraines.

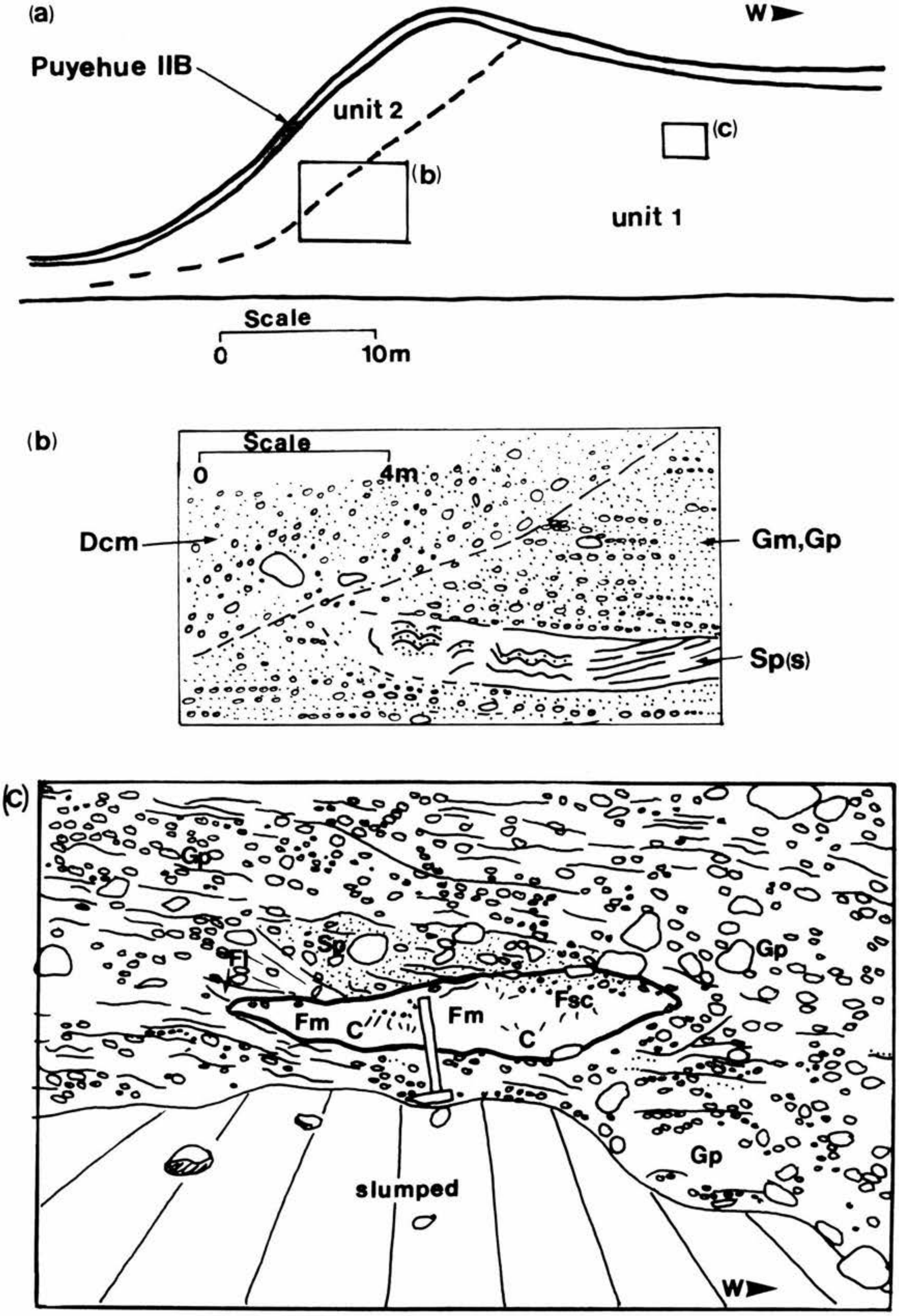


Figure 3.2. Section in the Puyehue IIB ice-contact slope at Pilmaiquen.
(a) Relations of the different units to the ice-contact slope. A columnar-jointed lava flow of unknown age underlies unit 1.
(b) Sketch of the contact between diamict and stratified gravels with a sand lens. The contact truncates the lower unit and is parallel to the ice-contact slope.
(c) Sketch of a clast of organic silt contained within strata of unit 2. The clast has fine gravel embedded in its outer surface which has provided an armouring effect. Plant macrofossils within the silts are labelled. Some of the macrofossils were radiocarbon dated (A-7566). The hammer is 30cm long.

Table 3.3. Sedimentological data from Pilmaiquen Hydro-electric Power Station
Geomorphological Context: Puyehue IIB ice-contact slope
Section Dimensions: 30m high, 100m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
2 [2-5]	dark grey	gen. massive, folded clays occur in pockets	l: tectonic u: depositional	2-500 [cobbles]	poor, sub-angular (large clasts) to rounded, various	coarse sand-clay, poor, none	crude strat. parallel to slope	matrix	deformation till
1 [15-20m]	dark grey	horizontal stratification, sand lenses with x-bedding, folding	l: not visible u: tectonic gradational (E), or depositional(W)	2-300 (one 2m clast) [cobbles]	good in indiv. beds, sub-angular to rounded, various	coarse sand-silt, locally good, thin cycles	none	clast	glaciofluvial

Table 3.4. Sedimentological data from Los Esteros
Geomorphological Context: Crest of Puyehue IIC ice-contact slope
Section Dimensions: 4m high, 30m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
2 [2-3]	pale grey-brown	gen. massive, blocks of lam. clay and silt are folded + thrust faulted	u: depositional l:erosional	2-200 (400 rare) [cobble]	poor, sub-angular to rounded, various	clay-coarse sand, poor, none	soft sed clasts slope parallel	matrix	deformation till
1 [>1]	dark brown	stratification, x-stratification	u: erosional l: not visible	2-50 [granule]	good in indiv. beds, sub-rounded to rounded, various	silt-coarse sand , good, normal	none	clast	glaciofluvial

Table 3.5. Sedimentological data from Estero Chiscaihue
Geomorphological Context: Foot of Puyehue IIC ice-contact slope
Section Dimensions: 6m high, 10m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
2 [4.5]	grey	massive	l:erosional u: ground surface	2-150 [pebble]	poor, sub-angular to well rounded, various	clay to coarse sand, poor, none	weak, sub-horiz.	matrix	deformation till
1 [1.5]	dark grey	bedded	l: not exposed u: erosional	2-130 [pebble]	locally good, sub-angular to well rounded, various	fine sand -coarse sand, locally good, normal	none	clast	fluvioglacial

Below the contact are the folded sand lens and undulating gravel beds, whilst above is the massive, poorly sorted diamict. At the extreme east end of the section, directly underlying the ice-contact slope itself, the diamict has a crude slope-parallel fabric defined by alignment of the larger clasts.

Unit 1 contains a 1.5 metre-long clast of massive, brown silts and clay (Fig. 3.2c). The clast is in the shape of an elongate teardrop and is armoured by fine gravel. It overlies stratified gravels and is overlain by clays and a sand lens. Within the silts are numerous plant macrofossils, probably reed stems. These are two to four millimetres in diameter and occur in a variety of orientations. The macrofossils have been sampled for radiocarbon dating and provide a maximum date for the deposition of the outwash.

Interpretation

The clast support, extensive stratification, complex truncating relationships, presence of sand lenses and conglomeratic units of unit 1 in the Pilmaiquen section show that it is an accumulation of fluvioglacial sediment. The fluvioglacial sediment is overlain with an erosional contact by diamict which is composed of clasts with similar characteristics to the fluvioglacial sediment below. Despite the similarities in clast composition the diamict is unstratified, shows poor sorting, contains clay and large angular clasts and has a weak fabric parallel to the dip of the ice-contact slope. All these characteristics plus the location of the unit directly below an ice-contact slope suggest the diamict is a till. Moreover, the lack of structures, the erosional lower contact, the similarity of the clast characteristics to the underlying unit, the matrix support, low vertical and lateral variability, and the close association with an ice-contact slope imply that it is probably a deformation till. The folding below the contact and the truncation of bedding in the lower sediments demonstrate that glaciotectonic activity accompanied the deposition of the till. The orientation of the folding shows that a lateral compressive stress was directed to the west. The similarities in clast characteristics and the nature of the truncating contact between the fluvioglacial strata and till suggest that the till is largely derived from glacial reworking of the fluvioglacial sediment.

The clays and silts within the deformation till are finely laminated and contain dropstones and so are glaciolacustrine sediments. They occur as deformed, variously-oriented blocks or in pockets associated with larger clasts. The obvious source for this glaciolacustrine sediment is the Lago Puyehue basin, two kilometres to the east of the Pilmaiquen section. Therefore, the glacier advance to the Puyehue IIB ice-contact slope incorporated underlying glaciolacustrine sediment into the deforming bed. The deformed bed of the glacier extended to close to the snout of the glacier where the deforming till incorporated pre-existing fluvioglacial sediment. Thus, the glaciolacustrine sediment was entrained in basal till, and deposited both as discrete blocks and dispersed through the till.

The Pilmaiquen section records deposition of a thick sequence of fluvioglacial sediment followed by a glacier advance to the ice-contact slope. No diamict occurs beyond the crest of the slope so the glacier advanced no further than this point. The advance of the glacier deformed and reworked the topmost fluvioglacial sediment and mixed it with glaciolacustrine clays and silts transported from Lago Puyehue to the east.

Los Esteros (Puyehue IIC)

A quarry near Los Esteros, at the top of the Puyehue IIC ice-contact slope, south of Entre Lagos, exposes stratified sands and gravels (unit 1, Table 3.4, Fig. 3.3). These are cross-stratified and individual beds display strong normal grading. The stratified gravels are overlain by a diamict (unit 2). The contact between gravels and diamict is erosional and sharply truncates the topmost inclined beds of the gravels. The diamict is similar to that in the Pilmaiquen quarry but with a greater abundance of fine-grained sediment. The clasts in the diamict are similar to those in the underlying stratified unit. The diamict is generally massive but contains blocks of deformed, laminated clays and silts. These blocks occur in several orientations but are commonly aligned such that the top and bottom edges are parallel to the ice-contact slope. The clays and silts are finely laminated on a millimetre scale with alternating dark brown and pale brown laminae and contain abundant rounded dropstones up to 15cm across. The laminae within the blocks are reverse-faulted and show minor folding. Also included within the diamict are small pockets of deformed, laminated clays and silts. The pockets of fine sediment occur in the voids between larger clasts. The section is capped by a number of >2m striated erratic boulders lying at the crest of the ice-contact slope.

Interpretation

The lower cross-bedded gravel unit is clearly fluvioglacial sediment that has been overridden. The deformed clasts, boulders, erosional lower contact, matrix support, abundant clay, lack of grading or any structures in the overlying massive diamict suggests it is a deformation till deposited during advance to the Puyehue IIC limit. The similarity of the clasts in the till to those in the unit below suggest that the fluvioglacial sediment was the parent material for much of the till. The clays and silts within the till are finely laminated and contain dropstones and are typical of glaciolacustrine sediments. At the Los Esteros section they sit 45m above present lake level, so they must have been emplaced at that altitude by glacial deformation. The obvious source for the glaciolacustrine sediment is the Lago Puyehue basin, located a few kilometres from the section. The glacier advance to the Puyehue IIC limit overrode the glaciolacustrine sediment in the Puyehue lake basin and incorporated blocks into a deforming bed below the glacier. This deformation till extended as far as the snout of the

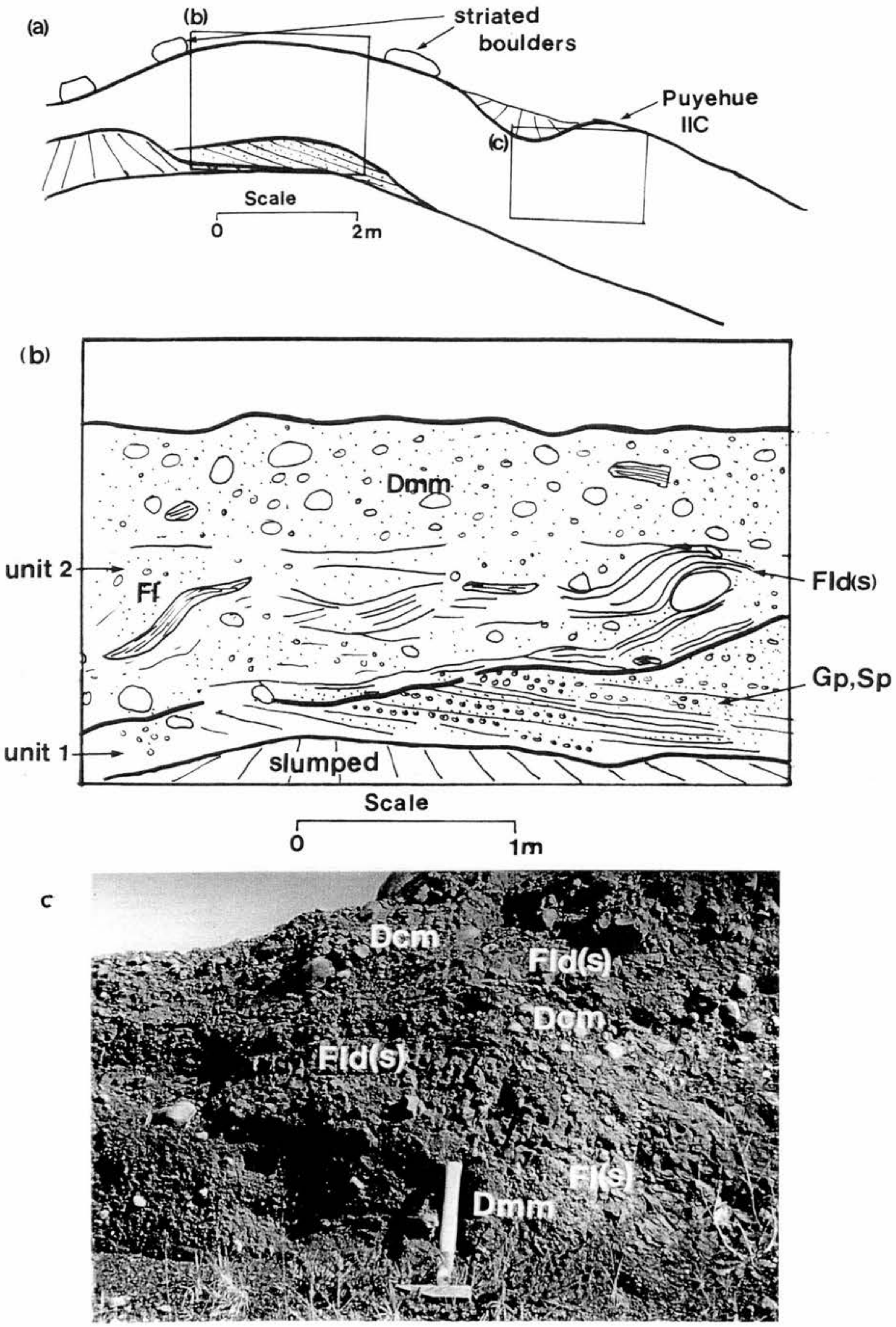


Figure 3.3. Section in the Puyehue IIC ice-contact slope at Los Esteros.

(**a**) Relations of the different units. A lower stratified unit is overlain unconformably by a thick diamict which mantles the ice-contact slope. The diamict has a number of erratic boulders on its upper surface.

(**b**) Sketch of the contact between diamict and stratified gravels and sands. The strata are truncated by the diamict which contains inclusions of finely laminated silts and clays.

(**c**) Photograph of blocks of clays and silts with dropstones contained within the diamict. The blocks are aligned sub-parallel to slope and have thrust faults and faults within them. Hammer is 30cm long.

glacier at the Puyehue IIC limit. The thrust structures in the blocks of glaciolacustrine sediment and their alignment sub-parallel to the ice-contact slope support this view. These blocks were transported relatively intact but some were deformed such that the fine sediment was dispersed through the till. The thrust faults show that the blocks of sediment also underwent brittle deformation which suggests that they may have been frozen.

Estero Chiscaihue (Puyehue IIC)

This small section occurs at the foot of the Puyehue IIC ice-contact slope (Table 3.5). It exposes a well-stratified, clast-supported clay-free unit of gravels composed of pebble- and cobble-sized material, overlain by a massive diamict. The contact between the two units is sub-horizontal and truncates the beds of the lower unit. The diamict occurs as a tabular sheet and is matrix-supported, contains abundant clay and is very compact. Clasts are rare and there are no structures in the diamict. It forms the lowermost part of the Puyehue IIC ice-contact slope. Clasts in the diamict show a weak fabric parallel to the lower contact and to the slope.

Interpretation

This section is similar to those at Los Esteros and Pilmaiquen: that is, a clay-rich diamict, overlies a stratified clast-supported unit. The lack of clay and the stratification in the lower unit mean that it is interpreted as fluvioglacial sediment. The unit above is a clay-rich deformation till which overlies the fluvioglacial deposit with an erosive contact. There are too few clasts in the till to obtain a representative sample so it is not clear where they derive from. However, the clay and silt fractions show similar distributions to sediment sampled from palaeo-shorelines of Lago Puyehue, suggesting that the till was formed largely from sediment in the lake basin. This is a similar interpretation to those for the Los Esteros and Pilmaiquen sites except that the deformation till at Estero Chiscaihue contains far fewer clasts. This may be because this site is much closer to the lake and so contains a higher proportion of the fine-grained glaciolacustrine sediment.

Las Vertientes (Puyehue IIC)

This section cuts into the foot of the proximal slope of the Puyehue IIC moraine where it turns from a N-S orientation to a more E-W (lateral) orientation. Three units are exposed (Table 3.6). The lowermost unit is a massive, hard grey diamict with a clay-rich matrix. Only 1m thickness of the unit is exposed and no structures are visible. Above this is a thicker exposure of well-stratified pebbles, gravels and cross-bedded sands with scour features. A 1-2m thick tabular unit of massive orange-brown diamict lies over these strata, and sharply truncates the bedding at an abrupt SE-dipping

Table 3.6. Sedimentological data from Las Vertientes
Geomorphological Context: Proximal slope of fronto-lateral part of Puyehue IIC moraine
Section Dimensions: 6m high, 20m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
3 [0.8]	orange-brown	crude stratification, deformed lens of silty sand	l: erosional u: parallel to ground surface	2-300 (pebble)	poor, sub-rounded to sub-rounded,	clay-coarse sand, poor, none	weak, slope-parallel	matrix	(deformation) till
2 [>4]	pale grey	bedded, folded close to upper contact	l: not exposed u: erosional	2-300 (pebble)	locally good, sub-rounded to rounded	fine sand-coarse sand, good, normal	imbrication	clast	fluvioglacial
1 [1]	dark grey	massive	l: not exposed u: depositional	2-210 (granule)	poor, sub-rounded to sub-angular	clay-coarse silt, poor, none	none	matrix	till

Table 3.7. Sedimentological data from Chiscaihue
Geomorphological Context: Proximal edge of Puyehue IIC, northwest of Lago Puyehue
Section Dimensions: 6m high, 30m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
3 [1-2]	orange-brown	stratified, folded	u:ground surface l: erosional	2-150 [granule]	poor, sub-angular to well rounded, various	coarse silt to coarse sand, poor, none	none	matrix	(deformation) till
2 [2.5]	orange-brown	bedded, x-bedded, folded	l:depositional u: erosional	2-200 [pebble]	locally good, sub-angular to sub-rounded	fine sand to coarse sand, locally moderate, normal	none	clast	glaciofluvial
1 [>1]	dark grey (weath. to grey-white)	laminated clay intraclasts, deformed bedded gravel lens	l: not exposed u: depositional	2-100 soft sed clasts up to 400 [pebble]	poor, sub-angular to sub-rounded, various	clay-coarse silt, poor, none	foliated	matrix	till

(38/150°) planar contact (Fig. 3.4). The bedded strata show minor folding, directed to the NW, within 20cm of the contact. The folds are upright and symmetrical but diminish in amplitude away from the contact such that the majority of the sequence is undeformed. The upper diamict contains a high proportion of grey clay dispersed in the matrix and also contains a lens 20cm thick and 40cm long of laminated clay and silt. The diamict is weakly stratified, sub-parallel to the slope. The diamict grades upwards into a 30cm-thick orange massive silty layer containing pumice clasts. The diamict thins upslope until it pinches out close to the crest of the moraine ridge.

Interpretation

The sedimentological characteristics of the lower diamict and its correspondence to a till at the nearby Chiscaihue site suggests it is probably a till but this is difficult to confirm without a thicker exposure. The stratification and cross-bedded sands of the overlying unit are typical of fluvioglacial sediment. The geomorphological context, unit dimensions, truncation and deformation of the underlying unit, clast fabric, contacts and tabular sheet-like form, of the upper diamict imply that this is a till. The weak stratification means it is difficult to establish whether it is a melt-out till or a deformation till. If the stratification is tectonic this suggests a deforming bed origin but if it is primary depositional layering then an origin by melt-out is likely. Since the stratification is inclined and parallel to the slope a deformation till seems more likely; melt-out debris would be unlikely to be stable on a slope such as this. The truncation implies that some of the fluvioglacial strata has been reworked; some of this may now be incorporated into the till. The origin of the silty layer at the top of the till is unclear. It may be the topmost parts of the till where it incorporated pumice-rich sediment, or alternatively may derive from subsequent sediment gravity flows or slope deposition down the proximal slope of the Puyehue IIC moraine.

Chiscaihue (Puyehue IIC)

This section occurs where a quarry has been cut into a low mound at the foot of the Puyehue IIC ice-contact slope, close to the Las Vertientes section. The section exposes two diamict units with a cross-bedded gravelly unit sandwiched between them (Table 3.7). The lower diamict is dark grey, massive, hard and clay-rich. This is similar to unit 1 at the Las Vertientes site. It contains a single folded lens of alternating beds of sand and gravel. The diamict also incorporates blocks of intensely deformed laminated clays and silts containing dropstones. Blocks are up to 40cm across and show no clear dominant orientation. Clay is also dispersed throughout the matrix. The diamict constitutes the lowermost part of the whole quarry. In the NW wall of the quarry it is overlain by a well-bedded unit of pebbly gravel interbedded with sandy pumice-rich horizons. The sands and gravels are folded throughout much of the unit. The contact with the underlying diamict is conformable except for one

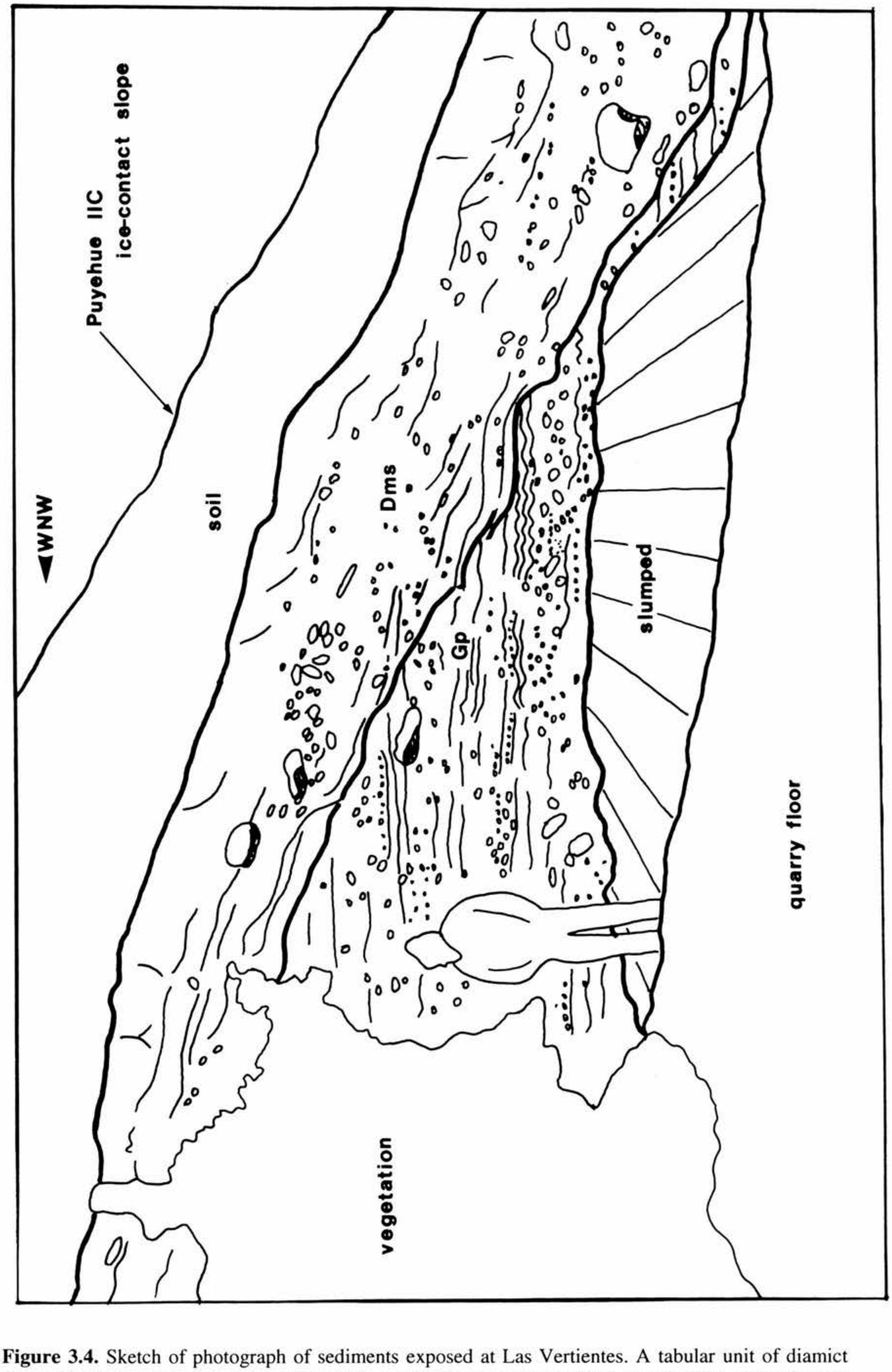


Figure 3.4. Sketch of photograph of sediments exposed at Las Vertientes. A tabular unit of diamict dipping to the east-southeast unconformably overlies horizontally bedded gravels. The strata close to the contact are folded. (Note unit 1 is not visible). Figure is 1.8m high.

location where the beds onlap a steeply-dipping (40°/100°) contact. The beds above this contact dip 34°/052° and are largely undeformed.

An unconformable contact separates the well-bedded gravels from an orange-brown stratified diamict. On the south side of the quarry the gravels are absent and the diamict directly overlies the lower diamict with an irregular contact. The upper diamict is better sorted than the lower one and contains more angular clasts. It has no clear fabric and is rich in orange/yellow pumice clasts up to 1cm across.

Interpretation

This section records two glacial advances separated by a period of meltwater activity. The lower diamict is a till as shown by the sorting; lack of bedding; matrix-support; clay content; deformed, chaotic, laminated clasts of clay; and foliation. Clay clasts are glaciolacustrine sediments almost certainly derived from Lago Puyehue, 1km to the SE. The upper diamict is a little better sorted and shows some stratification, a small number of flat-iron clasts and is matrix-supported. These features plus its position underlying the foot of the Puyehue IIC ice-contact slope imply that it is also a till. The upper till has similar sedimentological characteristics and unusual orange-brown colour to the upper till (unit 3) at Las Vertientes. The till would have been deposited by a glacier advance which reached the Puyehue IIC ice-contact slope. The advance was immediately preceded by meltwater activity which caused localised deposition of the bedded gravels on top of the lower till. It is not possible to establish from such limited exposure whether this deposition occurred on an outwash plain or directly from the glacier snout. The lower till was probably deposited during advance to one of the more extensive moraine limits to the west of this locality. It is correlated here with the lower till (unit 1) at Las Vertientes. Both have similar colour and sedimentological characteristics and are markedly different from the upper orange diamict. The lower till at this site and Las Vertientes probably represents a more extensive advance since it extends under the Puyehue IIC moraine whereas the orange till is seen to pinch out below the crest of the Puyehue IIC ice-contact slope. The marked colour difference between the two tills is probably due largely to the high content of pumice of the upper till - implying that at some point between the two advances a volcanic eruption deposited pumice on the glacier foreland. This conclusion is supported by the presence of abundant pumice layers in unit 2.

Quebrada Honda (Puyehue IIA/IIB/IIC)

This section is cut into the proximal face of the Puyehue II moraine directly south of the inlet of the Quebrada Honda channel. A lower unit of massive sandy diamict contains bullet-shaped sub-rounded clasts and deformed laminated clays and silts (Table 3.8). It is onlapped on its north side by a 4m thick

Table 3.8. Sedimentological data from Quebrada Honda
Geomorphological Context: Margin of meltwater channel through Puyehue II moraine
Section Dimensions: 10m high, 30m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
3 [3]	pale grey	bedded	l: depositional u: ground	2-300 (pebble)	moderate, sub-rounded, various	fine sand to coarse sand, moderate, none	none	clast	fluvioglacial
2 [4]	yellow	laminated in lowest 1m, massive above	l: depositional onlap u: depositional	n/a	n/a	silt to fine sand, moderate, none	none	matrix	overbank deposits
1 [3]	pale grey	massive diamict, contains deformed blocks of laminated clay and silt	l: not exposed u: onlapped	2-300 (pebble)	poor, sub-rounded, bullet	clay-coarse sand, poor, none	none	matrix	till

Table 3.9. Sedimentological data from Pampas Grandes
Geomorphological Context: Rupanco II moraine
Section Dimensions: 8m high, 80m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
4 [3]	grey	bedded, lenses	l: depositional u: ground surface	2-200 (pebble)	good, sub-rounded, various	fine sand to coarse sand, good, normal	weak imbrication	clast	fluvioglacial
3 [1]	grey	massive, contains stringers of units 2a and 2b	l: erosional u: depositional	2-160 (pebble)	poor, sub-rounded, various	clay to coarse sand	none	matrix	till
2b [0.2]	khaki brown	laminated, preserved fold nose	l: erosional u: erosional	n/a	n/a	fine silt to coarse sand	none	matrix	lake / kettle hole
2a [2]	brown-grey	stratified, folded, faulted, contains wood	l: erosional u: erosional	20-80 (pebble)	poor, sub-rounded, various	clay to fine sand, moderate, none	none	matrix	lake / kettle hole
1 [2]	brown	massive	l: not exposed u: erosional, irregular	2-200 (pebble)	poor, sub-rounded, sub-spherical	clay to coarse sand, poor, none	none	matrix	till

lens of compact silt and fine sand. At the base, the silts are laminated and drape over the topmost clasts in the diamict whilst the upper half of the lens is massive. A unit of well-bedded pebbly gravel overlies the silt lens and the diamict.

Interpretation

The lower diamict is interpreted as a till. As with other sites in the ice-contact slopes of the Puyehue II moraine the till contains deformed fine clays and silts, probably derived from glaciolacustrine sediment. The lens overlying the till extends from the Quebrada Honda channel and its formation was probably associated with meltwater activity in the channel. The most likely explanation for the onlapping sequence and change from laminated to massive character is that it represents increasing amounts of overbank sedimentation, possibly due to aggradation of a stream in the meltwater channel. The channel eventually aggraded to the extent that a well-bedded pebbly gravel unit was deposited over the top. The inlet of the channel lies 40m above the Puyehue III outwash plain and this section is 10m above the inlet. Thus, the channel can only have been used for meltwater discharge when ice was directly against the Puyehue IIC ice-contact slope. Geomorphological relationships show that this channel was also used for the discharge of meltwater which flowed from the Rupanco lobe and along a terrace which leads into the intake of the channel. Activity in the channel would have ceased after glacier retreat from the Puyehue IIC ice-contact slope.

<u>Pampas Grandes</u> (Rupanco II)

This section was first described by Mercer (1976) and the deformed organic-rich units were used by him to provide a date for the Last Glacial Maximum in southern South America. The quarry has been worked extensively since that time but still provides an important section into the Rupanco II moraine.

The lowermost unit is a structureless sandy diamict with sub-rounded clasts up to 20cm and weathered clasts of a granitoid lithology (Table 3.9). Above this are two sub-units predominantly composed of silt and fine sand with black gyttja and abundant woody material. Unit 2a consists of laminated, heterogeneous sands and silts with a few pebble and cobble-sized clasts and layers of sticky grey clay. It has been intensely deformed and numerous small (<5cm displacement) normal and reverse faults are exposed within it. This deformation extends right down to the abrupt irregular contact with the lower diamict. The black gyttja layers in unit 2a contain wood branches up to 30cm long and 8cm diameter and stringers of yellow clay (Fig. 3.5). A sample of the wood was taken for radiocarbon dating. Unit 2b is a west-directed fold nose of laminated brown silts and sands contained within unit 2a.

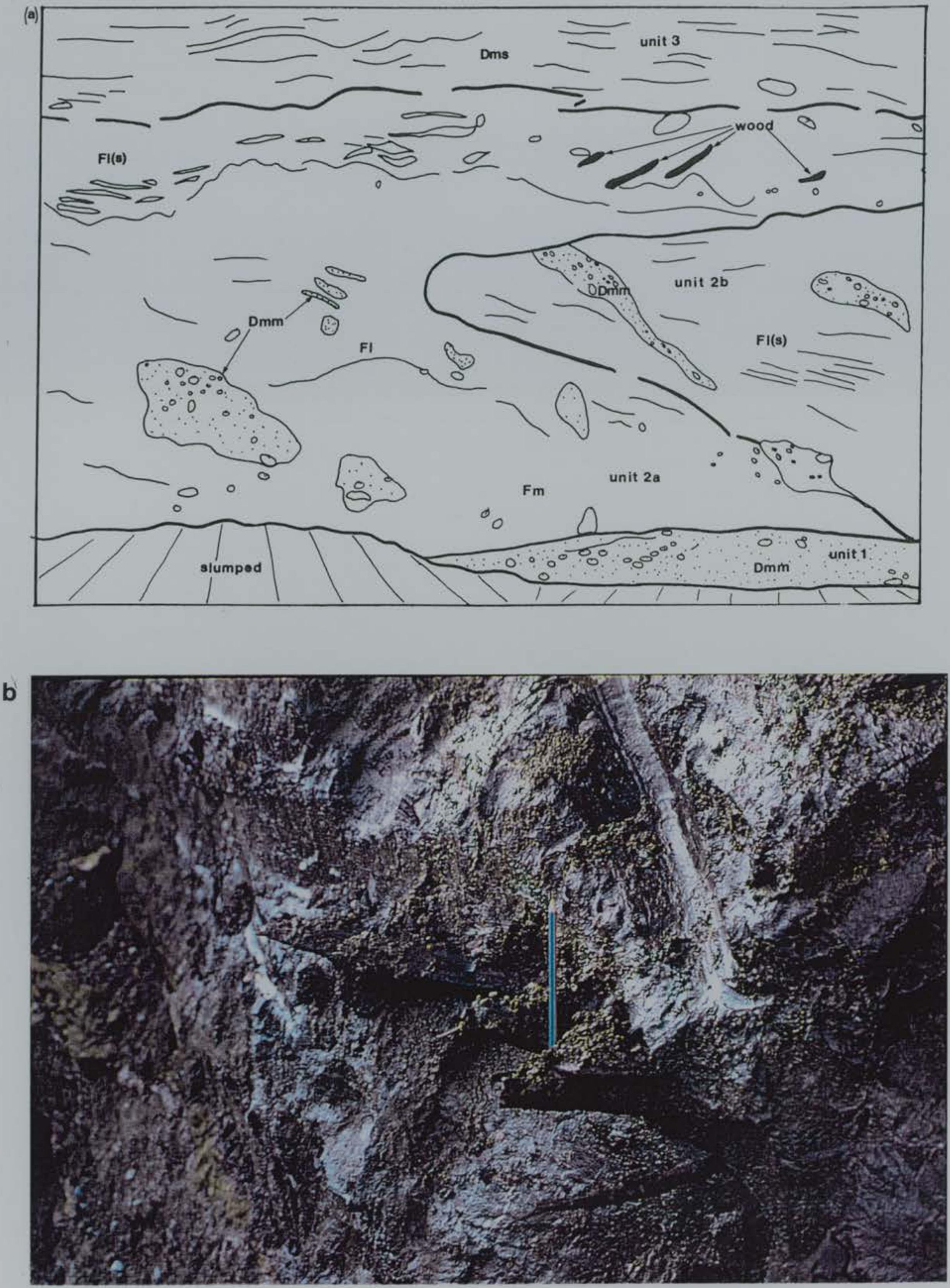


Figure 3.5. Section in the Rupanco II moraine at Pampas Grandes.

(a) Sketch of sedimentary unit relations. A lower diamict is overlain by deformed gyttja and organic clays which contain wood and pockets of diamict.

(b) Photograph of wood in unit 2a. The branches are up to 50cm long, 6cm in diameter and are largely intact. The internal structure of the wood resembles tesselated diamonds; this is characteristic of *Nothofagus* species in Chile and implies that conditions prior to Rupanco II were suitable for growth of at least one of the Nothofagus species. A sample of the wood has been radiocarbon dated (AA-10315)

Above the deformed silty units is a massive compact diamict which erodes the top of unit 2a and contains deformed inclusions of it. This diamict is thin and pinches out on the west side of the quarry. It is overlain by a bedded unit of weakly imbricated, clast-supported gravels which dip at a shallow angle to the west. These directly underly the present land surface and extend well beyond the limit of the diamict below. A number of cross-bedded sand lenses are exposed in the unit.

Interpretation

This section records the glacial overriding of a small basin, either lacustrine or a kettle-hole. The lower unit is probably a till from an earlier advance. The clasts are more weathered than in the overlying units so it may significantly predate the upper part of the section. The two organic-rich units overlying this till with an erosional contact were probably deposited in a small basin some distance to the east. The abundant wood and organic gyttja point to deposition during an interstadial and the clay layers suggest this may have been in a minor lake basin. The fold nose of 2b and the folding within 2a show that this unit was subjected to westwards-directed compression and the extent of deformation right down to the irregular contact with the lower diamict suggests that the unit has been thrusted into this position. The fold nose is characteristic of glacially-overridden sediment. The diamict which has eroded the top of unit 2 is probably a till. It contains a wide variety of clast sizes including clay and stringers of unit 2. If these had been reworked by meltwater the diamict would show bedding but it is homogeneous and massive, so mechanical reworking during glacial advance seems more likely. The bedded clast-supported pebbly gravels and cross-bedded sand lenses overlying the till are probably fluvioglacial sediments deposited close to the ice front in a sheet extending over the till. Thus, a glacier advanced over an infilled minor basin, thrusted and folded the basin sediments, left a thin till above and deposited a sheet of fluvioglacial gravels as it retreated.

3.3.2. Summary of rampart moraine sedimentology

There are a number of important similarities in the sedimentation and deformation histories of the rampart moraine sites. Recognition of the characteristics which different sites have in common enables the key elements in moraine construction to be identified. Three significant similarities can be recognised.

- By far the greatest volume of the moraines is made up of sorted, stratified fluvioglacial sediments. These strata are sometimes folded, sheared, or both, particularly on the proximal (east) side of the moraines.

- The stratified sediments are commonly overlain with an erosional contact on the proximal side of the moraine by deformation tills. The tills are composed of clasts with similar characteristics to the fluvioglacial sediment.
- The tills contain glaciolacustrine clay and silt, both dispersed within the matrix and as laminated clasts containing dropstones. The clasts are deformed and aligned parallel to the proximal moraine slopes.

3.3.3. Sections cut into ridge moraines

Despite the morphological differences between ridge and rampart moraines, the sediments and structures making up the ridge moraines show similar relationships to those of the ramparts. A number of sections into the Puyehue I, Puyehue III, Puyehue IV and Rupanco III moraines illustrate these similarities.

El Coihue (Puyehue I)

This section cuts through the crest of the Puyehue I moraine. It exposes up to 8m of compact clay-rich grey diamict containing sub-rounded to well rounded clasts up to 50cm across. Approximately a quarter of the clasts are striated or faceted, or both. The diamict is extremely hard and rings when struck with a hammer. This contrasts strongly with most diamicts in the field area which can be easily disaggregated with a spade. A faint stratification can be seen on the proximal side of the moraine but cannot be traced for more than a few metres. Most clasts show no evidence for weathering when cracked open. Weathering rinds are virtually absent from volcanic clasts in the diamict and individual crystals in the rocks are fresh (Fig. 3.6). A few clasts have narrow orange rinds but these rinds are as hard as the fresh lithology.

Interpretation

The diamict is a till deposited during formation of the Puyehue I moraine. It is anomalously hard and the clasts within it are far less weathered than the clasts in the Rupanco I moraine. No fluvioglacial deposits are exposed below the till but much of the moraine has been buried by the Puyehue II outwash plain which is contiguous through the gaps in the Puyehue I moraine.

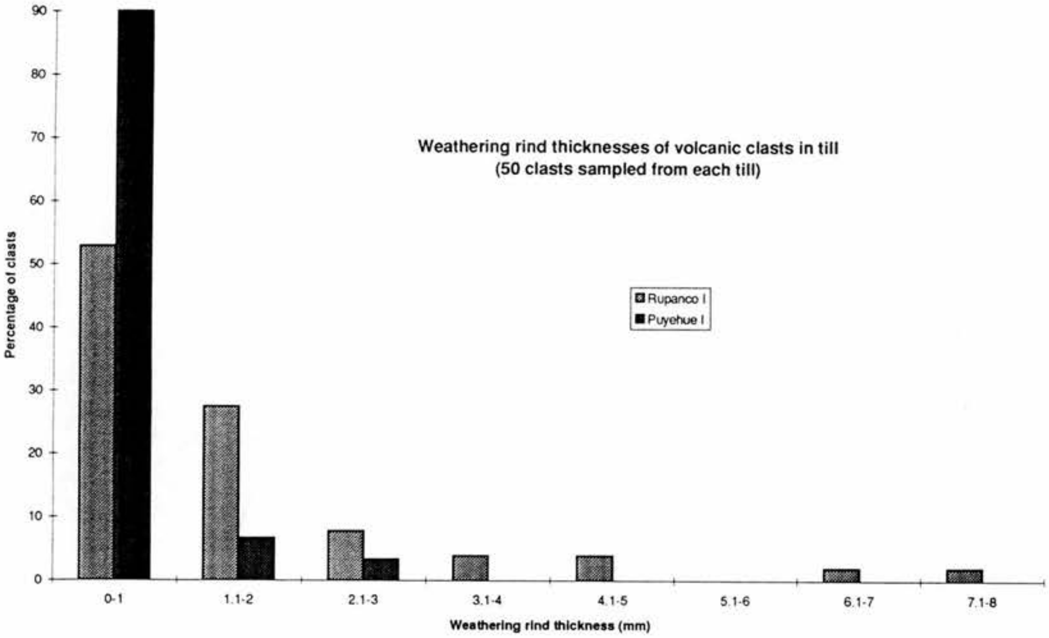


Figure 3.6. Weathering rinds of volcanic clasts in tills.
The majority of clasts in the Puyehue I till at El Coihue are unweathered. Clasts in the Rupanco I till at Cerro Rupanco have weathered rinds up to 8mm thick. This contrasts to the other tills in the field area which are unweathered, and implies that the Rupanco I till may be older than the others.

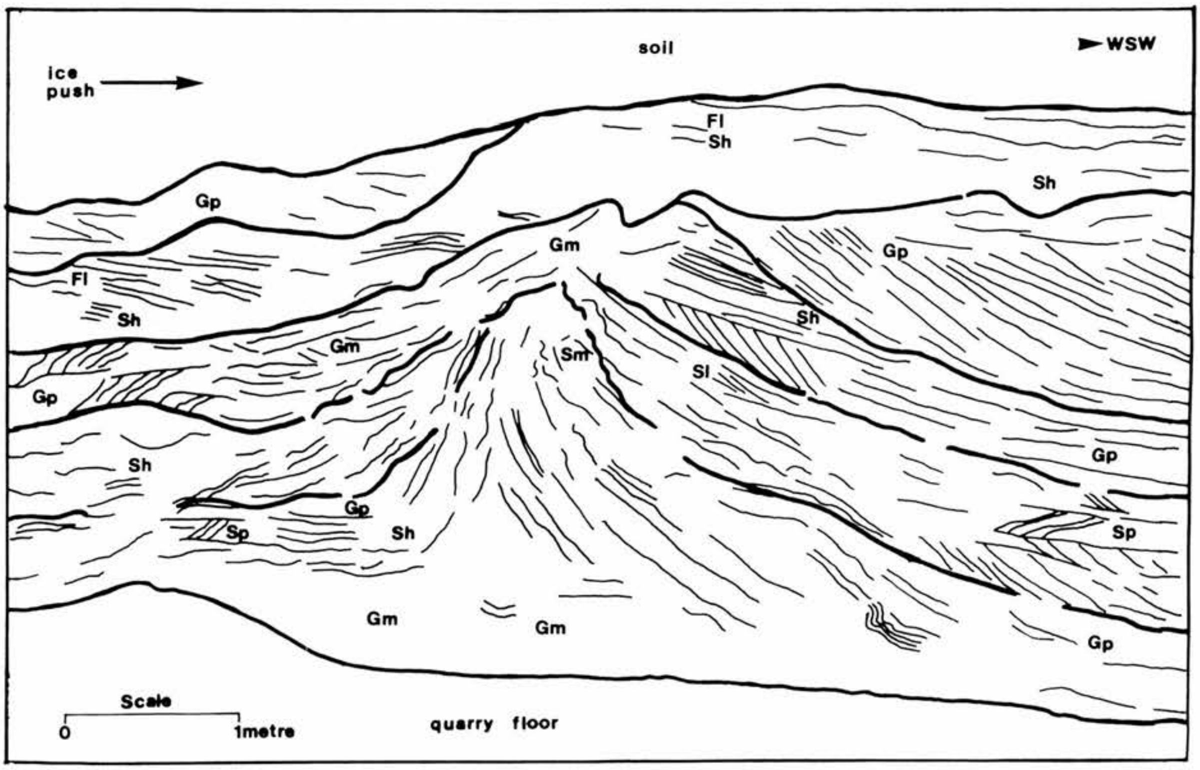


Figure 3.7. Sketch of bedding relations in fluvioglacial sediment on distal side of Puyehue IV moraine. The lowermost sub-unit has been folded into an antiform and the stratification partly lost. Above this, the sub-units of sands and gravels are progressively less deformed but each overlies the previous with an erosional unconformity (bold lines). The uppermost planar cross-bedded gravels and horizontally bedded sands are undeformed. The implication of this section is that formation of Puyehue IV moraine was accompanied by syndepositional glaciotectonism of the outwash plain. To the left of this sketch, charcoal was sampled from silt clasts in the outwash for radiocarbon dating (AA-9423, AA-10929)

Entre Lagos (Puyehue III)

The sediments of the Puyehue III moraine and its outwash plain are exposed in Entre Lagos. The proximal slope of the moraine is made up of a massive, tabular, silty, matrix-supported diamict with rounded to sub-rounded clasts up to 20cm across. Boulders up to 2m across lie on the proximal slope and crest of the moraine. The diamict contains thin, folded stringers of laminated clays and silts up to 30 cm long which are aligned sub-parallel to the slope. In places, the silt matrix of the diamict has a closely-spaced foliation which is also sub-parallel to the slope.

On the distal side of the moraine a section exposes sediments directly underlying the Puyehue III outwash plain. These are well-bedded sand and gravels with complex truncating relationships (Fig. 3.7). In the upper part of the section individual beds can be traced for c. 50m. The beds on the lakeward side of the section are folded into broad upright antiforms. The folds are unconformably overlain by bedded and cross-bedded sands and sandy gravels which form the upper part of the section. Within the bedded gravels there are a small number of clasts of silt and silty peat. Within these clasts are 1-2mm fragments of charcoal. Samples of this charcoal from one silt clast and one silty peat clast have been radiocarbon dated to provide two maximum ages for the Puyehue III outwash.

Interpretation

The diamict of the moraine is a till and like other sites in the area has incorporated clasts of clay, probably glaciolacustrine in origin. Lago Puyehue lies directly inside the Puyehue III moraine so the clays may not have been transported more than a few hundred metres. The clay and silt content, matrix-support, foliation and deformation within the till suggest it is a deformation till. The sediment of the outwash plain is fluvioglacial; it underlies the plain, is well-bedded, contains no clay and the upper parts show extensive horizontal bedding. The folding of the sediment close to the lake shows that it has been deformed. The multiple angular unconformities between the different outwash units demonstrate that the deformation occurred *during* build-up of the fluvioglacial sequence. As each unit was deposited, the deformation caused by the glacier snout buckled up the sediment such that subsequent outwash deposition truncated existing strata. The latter stages of outwash deposition are undeformed, implying syn-depositional deformation had ceased by that time.

Mantilhue Quarry (Puyehue IV)

Along the north shore of Puyehue there is only one well-exposed section into the Puyehue IV moraine. This occurs two kilometres east of the hamlet of Mantilhue. The quarry is cut parallel to the axis of the moraine, on its distal (north) side and exposes both the edge of the outwash plain and the sediments of the moraine (Fig. 3.8a). The top of the quarry is only a few metres below the crest of the moraine and so the exposure provides a useful near-complete section through the distal side of the moraine .

The lowermost unit consists of well-bedded coarse sands, and fine gravels (Table 3.10). These are horizontally bedded on the north side of the quarry and extend under the sub-horizontal outwash plain surface. Individual beds can be traced laterally for up to 20 metres and vary from well sorted coarse granules with no matrix, to beds of yellow-brown sand (largely pumice), to cobbles and granules in a sandy matrix. The majority of the clasts are sub-angular. The sediments have been deformed: in the north wall of the quarry the beds are horizontal but become increasingly steeply tilted and folded to the northwest towards the moraine (Fig. 3.8b). They are also thrust-faulted, but the thrust planes (SE-dipping) are not themselves folded. Towards the contact with unit 2 the bedding is less well-defined and the gravels contain rare boulders, some up to 30 centimetres across. The contact between units 1 and 2 is marked by a 20 centimetre layer of unstratified sand containing granule-sized clasts. The sand layer directly overlies the unit 1 gravels, grades upwards into the gravel-rich diamict of unit 2 and can be traced laterally for the entire length of the section. It contains thin (1cm) pale brown clay-rich layers, all with sharp upper and lower contacts. The layers have irregular margins and are folded. Although there is usually only one layer present, there may be two or three locally . Unit 2 is predominantly composed of sandy, pumice-rich diamict with pebbles and granules but also contains a single clast pavement of cobbles. The clast pavement is 10 centimetres thick, sub-horizontal, clast-supported and contains very little matrix. The clasts within the unit 2 diamict are similar to the clasts in unit 1, and are dominated by sub-angular clasts. The upper contact of unit 2 with unit 3 is also marked by a clast pavement, less well-defined than below but also composed of sub-horizontally oriented cobble-size material. The majority of the section is occupied by the pale brown unit 3 diamict. This diamict can be divided into two sub-units: a lower (0.5-5m) massive clast-supported sediment made up of coarse granules, cobbles and occasional boulders, and an upper sub-unit containing folded sand lenses interbedded with cobble-rich material. The sand lenses have complex truncating relationships (Fig. 3.8c). The upper half of the section is almost wholly sandy diamict and the topmost sands are yellow, hard and compact.

Interpretation

A fluvioglacial origin is interpreted for the unit 1 sediments, not only from their position extending under the outwash plain but also the sorting characteristics and the lack of matrix material. They have clearly undergone a compressional event; the fold and thrust structures are consistent with this deformation being directed towards the northwest. Since the thrust contact is itself unfolded the folding must have preceded the thrusting. The deformation probably derived from the advance(s) that built-up the moraine itself. The unit 2 diamict is almost certainly till since it contains striated clasts and

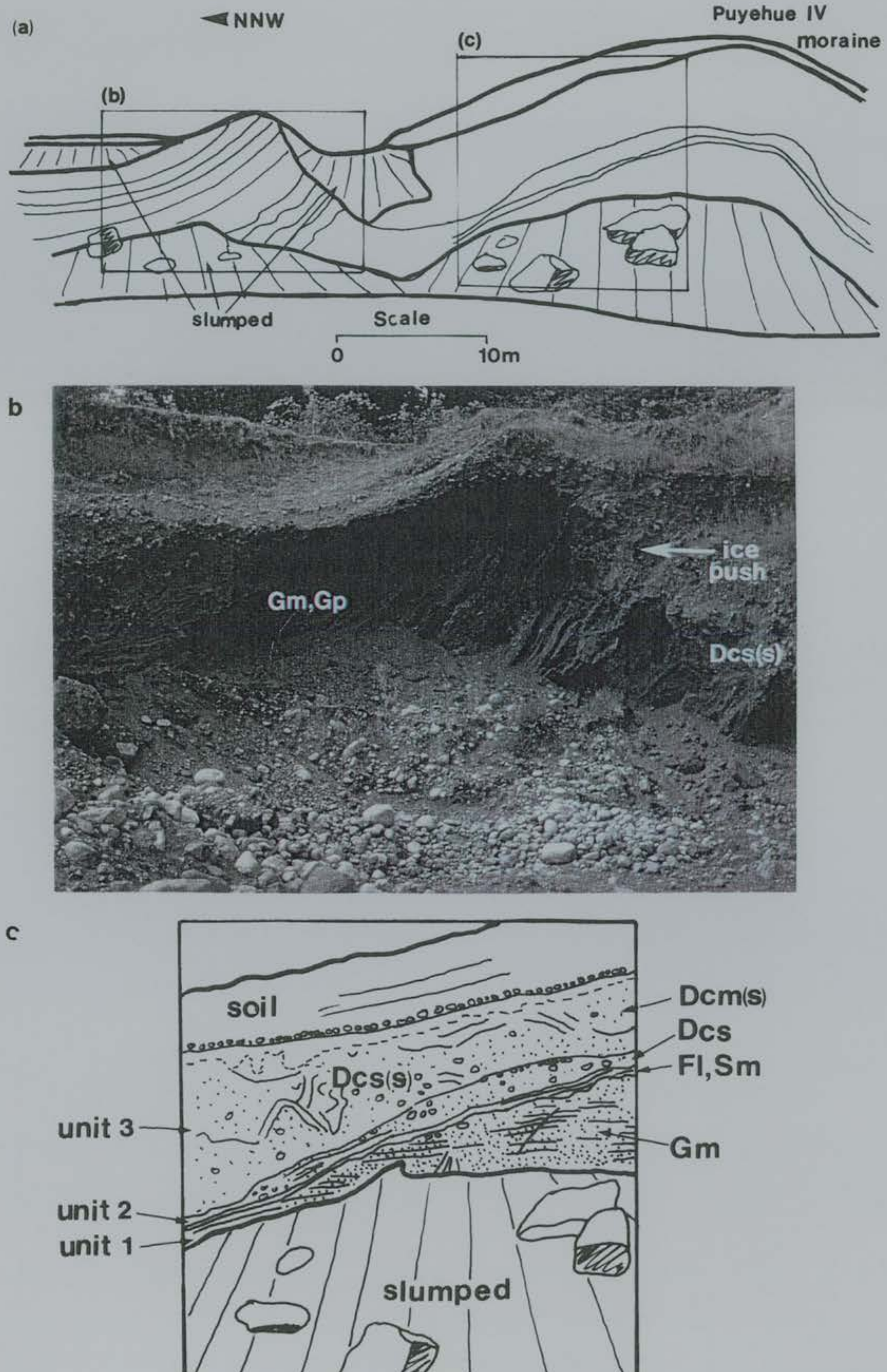


Figure 3.8. Section in Puyehue IV moraine at Mantilhue.

(a) Sketch showing relation of deformed fluvioglacial sediment to moraine ridge.

(b) Photograph of deformed fluvioglacial strata. The outwash plain (to the left) has been bulldozed during moraine formation and the beds are buckled up and cut by a low angle thrust.

(c) Sketch of sediments making up the Puyehue IV moraine. The lowermost fluvioglacial strata are truncated by the overlying till. A layer of clay lies along the contact between the two units. The uppermost till contains deformed lenses of sand.

Table 3.10. Sedimentological data from Mantilhue
Geomorphological Context: Puyehue IV lateral moraine, north shore of Lago Puyehue
Section Dimensions: 15m high, 60m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
3 [3-10]	pale brown	massive in lower parts, stratified and folded lenses higher up	u: depositional l: uncertain	2-650 (pebbles)	poor, predominantly sub-rounded, some blocky	coarse sand-clay, poor, none	large clasts sub-parallel	clast	sediment gravity flow or proximal outwash
2 [0.6-1]	dark brown	stratified, clast pavements, folding	u: uncertain, marked by clast pavement l: erosional	2-300 (medium granule)	poor, rounded to angular, fines gen. more angular, various	clay-coarse sand, poor, none	bedding-parallel, crude imbrication dips SE	matrix	deformation till
1 [>3]	grey	well-bedded, x-bedded, folded, thrust faulted	u: erosional, sheared l: not exposed	2-300 (medium granule)	locally good, fines gen. sub-angular, coarse gen. sub-rounded, (overall angular to rounded), various	coarse sand-fine sand, locally excellent, indiv norm cycles, overall fines upwards	none	clast	glaciofluvial

Table 3.11. Sedimentological data from Los Copihues
Geomorphological Context: Small lateral moraine banked on Puyehue II ice-contact slope, lies above Puyehue III moraine.
Section Dimensions: 4m high, 20m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
3	pale grey	none	l:erosional u:erosional	2-2000 [granule]	poor, sub-angular to sub-rounded	fine silt to coarse sand, poor, none	none	matrix	till
2 [0.4]	dark brown	laminated, thrust fault	l: depositional u: erosional	2-80 [granule]	poor, sub-rounded	clay to coarse sand, moderate to good in indiv. layers, normal	none	matrix	glaciolacustrine
1 [>1]	pale brown	none	l: not exposed u: depositional, undulating	2-100 [granule]	poor, clasts are rotten and friable	clay to coarse sand, poor, none	none	matrix	?

constitutes part of the moraine. It also shows evidence of deformation including the folded clay layers. The similarity of the constituent material to that in the stratified gravels below along with the evidence of shearing suggests that this unit may be made up of the deformed topmost parts of unit 1 along with a small component of glacially transported sediment. If this is the case then the irregular clay layers probably represent inhomogenities in a deformation till. Interestingly, clasts in both units are dominantly sub-angular. The departure from the more rounded clasts found in other fluvioglacial units may be due to a down-moraine increase in clast rounding such as has been described in Norway (Matthews and Petch, 1982). The Mantilhue section is located up-glacier, closer to the bedrock cliffs at the east end of Puyehue. Above the lower parts of unit 2 there is a clast pavement which implies some change in depositional conditions, probably a minor retreat with winnowing of finer material from the till surface. Unit 3 has a complex structure but its position close to the crest of the moraine and the presence of syn-sedimentary deformation in its upper parts suggests it is also a till. However, the sediment has some of the features associated with deposition in the presence of abundant water such as numerous sandy lenses, clast support mechanism and proximity to the outwash plain. A possible explanation is that the sub-units of unit 3 lie on the continuum between proximal proglacial outwash and sediment flow deposits. Thus unit 3 probably represents the latter stages of moraine formation after the retreat interpreted at the top of unit 2.

The sequence exposed in the Mantilhue quarry can be broadly summarised as recording the process of glacier advance into an outwash plain, deformation of the pre-existing fluvioglacial sediment and mixing with glacially-transported material. This was then overlain by sediment deposited from the abundant meltwater close to the ice margin - either as sediment flow or proglacial outwash - but giving rise to a series of deformed, stacked lensoid sands.

La Puntilla (Puyehue IV)

The Puyehue IV moraine on the south shore of the lake forms the peninsula of La Puntilla. A section into the crest of the moraine shows it is made up of a massive, ungraded, dark grey, compact diamict. The diamict is clay-rich and contains clay and silt dispersed throughout the matrix along with sub-rounded cobbles and occasional boulders up to 25cm across. The lower contact of the diamict is not exposed.

Interpretation

The diamict is a till, probably composed largely of reworked glaciolacustrine sediment. Unlike most of the other tills around the two lakes this till is composed almost wholly of dispersed fine-grained material rather than glaciolacustrine sediment contained in reworked fluvioglacial sediment. This may be due to its position halfway along the lake. The tills of Puyehue II, Puyehue III, Rupanco II and Rupanco III have all been formed close to the ends of the lake where pre-existing fluvioglacial material would be available for reworking. Here, the moraine forms a peninsula protruding into the lake and the only potential proximal sources of sediment would be the glacier itself and the lake floor. Extensive reworking of glaciolacustrine deposits by the glacier would have produced the silty diamict which constitutes this moraine.

Los Copihues (Puyehue II)

The sediments of the closely-spaced lateral moraines along the south shore of Lago Puyehue are only exposed in a small number of poor sections but one relatively well-exposed section does exist in the crest of a moraine near Los Copihues (Table 3.11). This lateral is located on the upper part of the Puyehue II ice-contact slope, well-above the Puyehue III lateral and so seems to mark a possible retreat stage from the Puyehue IIC limit.

The lowermost sandy diamict unit is poorly exposed and no structure is visible. Unit 2 overlies the diamict with a depositional contact. Finely laminated clays and silts are interbedded with thicker (<10cm) diamict horizons and onlap the diamict below. The clays contain dropstones up to 6cm across, mostly sub-rounded to well-rounded. The diamict layers contain abundant pumice and grade upwards into clay and silt. The whole horizontally laminated unit is cut by a shallow thrust which dips 10°/170° and has a displacement of 95cm. To the north (proximal) side of the moraine similar laminated sequences are intensely folded and thrusted.

The uppermost unit overlies the laminated sediments with an erosional contact. It is a pale grey diamict containing faceted and bullet-shaped clasts up to 2m across. It is massive and contains abundant clay in the matrix. The thrust fault in the underlying sediments displaces the contact between units 2 and 3 but cannot be traced further into unit 3.

Interpretation

The three units record the latter stages of lateral moraine construction along the shore of Lago Puyehue during the Puyehue III glacial event. The lowermost unit is difficult to interpret because of the poor exposure and pervasive weathering. The poor sorting suggests a till but a fluvioglacial origin cannot be ruled out since any structures and fabrics may have been obscured by weathering. What is clear is that the glaciolacustrine sediments of unit 2 were deposited over this existing sediment. Iceberg-rafted debris was deposited as isolated dropstones and accumulations of diamict which settled differentially through the water column to form graded units. The laminated unit implies the existence of an ice-marginal lake 30m above the present level of Lago Puyehue prior to the advance which deposited the upper till unit and constructed the moraine. Either during or after till deposition the top two units were cut by a thrust fault. This tectonic event probably correlates to the intensely deformed clays of unit 2 on the proximal side of the moraine. Interestingly, the south-dipping thrust has a contrary orientation to what might be expected from a glacier margin impinging from the north. This is puzzling given that glacier advance from any other direction was unlikely.

Río Pichichanleufu (Puyehue V)

The only section into the Puyehue V moraine at the east end of Lago Puyehue is a large quarry cut into the distal side of the ridge. Two contrasting units are exposed (Table 3.12, Fig. 3.9). The majority of the section is occupied by a thick sequence of bedded granules, pebbles and cobbles with sand lenses. The stratification is extensive and many of the gravels and sand lenses are also cross-bedded. Numerous local reactivation surfaces interrupt the sequence. The upper third of the bedded unit is made up of interbedded fine gravel, sand and silt. These strata can be traced across most of the section and grade upwards into coarser pebbly gravel. Thin (<1cm) pumice-rich sand horizons are ubiquitous throughout the unit.

The stratified unit is overlain with a strongly erosional contact by a massive, yellow diamict. The diamict is largely composed of yellow silt very similar to the material which overlies most of the sections in the area. As well as clasts of basaltic lithologies the diamict contains sub-angular intraclasts of diamict and of silt. The diamict clasts are grey, hard and contain clasts up to 1cm across, whilst the silt intraclasts are rich in pumice. The unit contains numerous small rootlets in various orientations but it is not clear if they are reworked or derived from plant growth on the quarry walls. Some rootlets penetrate the top of the diamict but their extent cannot be traced.

Interpretation

This unit demonstrates a glacier advance into outwash.. The lower unit is clearly a fluvioglacial sequence deposited in an aggrading channel environment. The silty diamict which has eroded this unit also forms the proximal side of the moraine, and contains numerous intraclasts of different types. It is probably a till deposited during the construction of the Puyehue V moraine. Its unusual friable, silty character may be due to incorporation of a large amount of windblown material which is extensive throughout the field area as a cap over sedimentary sections, directly underlying the soil. The silty till has also incorporated silt clasts, probably derived from reworking of the fluvioglacial sediment.

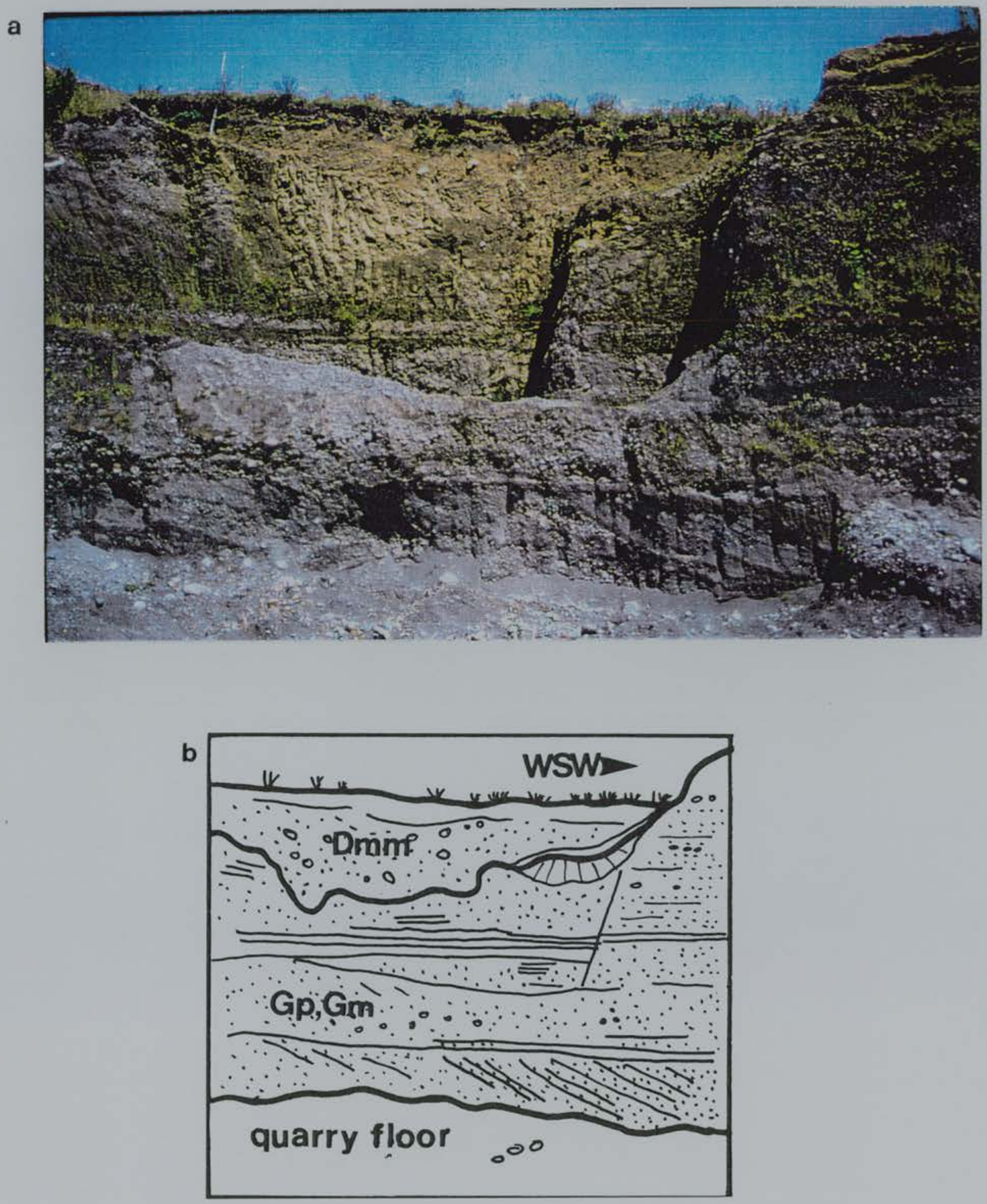


Figure 3.9. Section in Puyehue V moraine at Rio Pichichanleufu.
(a) Photograph
(b) Sketch of massive silty diamict which has eroded up to 5m of the topmost fluvioglacial beds. The fluvioglacial beds are extensively bedded and cross-bedded and underly the fragments of the Puyehue V outwash plain which can be traced to the north-northwest. Section is 20m high.

Table 3.12. Sedimentological data from Rio Pichichanleufu
Geomorphological Context: Puyehue V moraine at east end of Lago Puyehue
Section Dimensions: 20m high, 50m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
2 [1-5]	yellow brown	massive, contains silt intraclasts, clasts of grey diamict and rootlets	l: erosional u: forms ground surface	2-500 [pebble]	poor, sub-angular to sub-rounded, various	fine silt-coarse silt, poor, none	none	matrix	till
1 [>15]	dark grey	bedded, lenses	l: not exposed u: erosional	2-300 [granule]	moderate, sub-angular to well-rounded, various	fine sand to coarse sand, moderate, overall normal	imbricatio n	clast	fluvioglacial

Table 3.13. Sedimentological data from Hosteria El Paraiso
Geomorphological Context: Ice-contact slope of RIII moraine, west shore of Lago Rupanco
Section Dimensions: 11m high, 10m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts	Clasts		Matrix	Fabric	Support	Interpretation
				Size(mm) [Range(Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
3d [3]	pale grey	poorly stratified	u:depositional l: depositional	2-500 (pebble)	poor, sub-angular to sub-rounded, various	clay-coarse sand, poor, none	crude horiz. alignment	clast	proximal glaciofluvial
3c [0-2]	pale grey	stratified, x-stratified lens	u: depositional l: depositional	2-30 (granule)	good, sub-rounded to well-rounded, various	fine sand-coarse sand, good, normal	none	clast	channel, proximal glaciofluvial or gravity flow
3b [0.75]	pale grey	crude bedding	u: depositional l: depositional	2-100 (granule)	poor, sub-rounded to well-rounded, various	med.sand-coarse sand, poor, none	none	clast	till or proximal glaciofluvial
3a [1.5]	pale grey	crude bedding, clasts of brown clay	u: depositional l:depositional	2-60 (cobble)	poor, sub-angular to sub-rounded, various	fine sand-coarse sand, poor, none	crudely aligned with bedding	clast	proximal glaciofluvial
2 [1.5]	grey-brown	gen. massive but laminated (<1mm thick) at base	u: erosional l: depositional	rare clasts up to 100mm in silt and clay	poor, sub-angular to sub-rounded, blocky	clay-silt, locally good at base, laminae graded silt -clay	none	matrix	glaciolacustrine transformed into deformation till
1 [>1.5]	dark brown	stratified, x-stratified, lenses	u: depositional l: not visible	2-100 (pebble)	locally good, angular to sub-rounded, various	med. sand-coarse sand, good, sands occ. grade into clay	parallel to bedding	clast	glaciofluvial

Cerro Rupanco (Rupanco I)

This section cuts through a Rupanco I moraine fragment located on the high ground between the two lakes. It exposes 4m of a massive yellow friable diamict which constitutes the moraine ridge. The degree of weathering means that it is not possible to discern structures within the diamict. It contains angular to sub-rounded clasts which are intensely weathered; no surface features such as striations are visible. The clasts have significantly thicker weathering rinds than anywhere else in the field area (Fig. 3.6). A few clasts have rinds up to seven or eight millimetres thick but most are weathered to less than three millimetres deep.

Interpretation

The interpretation of this diamict is difficult because of the small size of the exposure and intense weathering. Since it makes up the Rupanco I moraine it is probably a till. Whatever its origin the key feature is the greater degree of weathering compared to most other glacial deposits in the study area, suggesting the Rupanco I till is older.

Hosteria El Paraiso (Rupanco III)

At the foot of the proximal slope of the Rupanco III ridge moraine which forms the west shore of Lago Rupanco, 3 sedimentary units are exposed in an 11m-high section (Table 3.13, Fig. 3.10). The lowermost sediments (unit 1) consist of lakeward-dipping cross-bedded sands with pebbles and cobbles. The unit becomes more massive in the topmost 15cm. The basal 2cm of unit 2 comprise planar laminated clays and silts, the lowermost laminae of which drape over the clasts in the unit below. Above this the laminae are folded, sheared and discontinuous until about 20cm up into the unit where individual laminae cease to be discernible. Dropstones are present throughout the sediment. Unit 2 is massive to its upper contact which is marked by a layer of cobbles and sand. Unit 3 is a highly variable assemblage with four sub-units. The lowest (3a) of these is a series of crudely bedded, poorly sorted, sands and gravels with a sharp upper contact. Clasts of pale brown clay, very similar to the clays in unit 2, as well as cobble-sized dropstones occur. The sediments of unit 3b are similar in most respects to those below but are predominantly composed of gravel rather than sand. Unit 3c comprises a lens of bedded and cross-bedded gravels and sands, pinching-out to either side but reaching a maximum thickness of 2m. The top consists entirely of stratified fine sands. Sub-unit 3d is composed of crudely stratified and clast-supported pebbles and cobbles and is separated from the unit below by a line of cobbles.

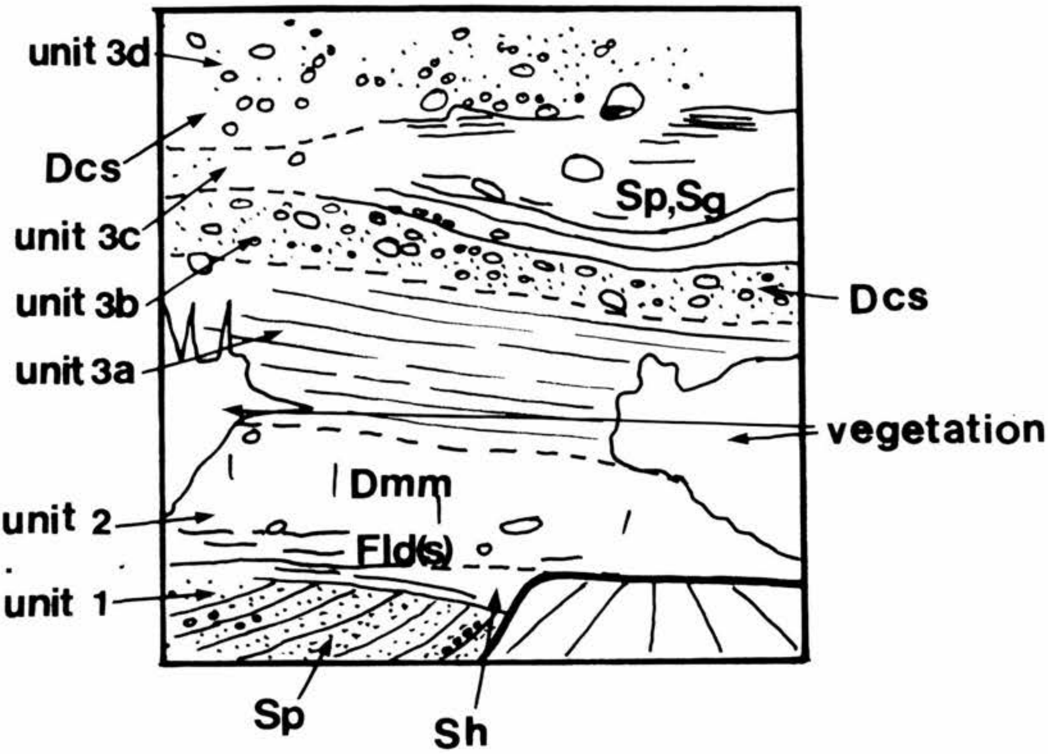


Figure 3.10. Sketch of sediments exposed in proximal slope of Rupanco III moraine at Hosteria El Paraiso. A unit of cross-bedded sands is overlain by laminated clays containing dropstones. These have been deformed into a massive clay-rich diamict. Above the diamict are a series of sub-units of stratified gravels and sands. Section is 11m high.

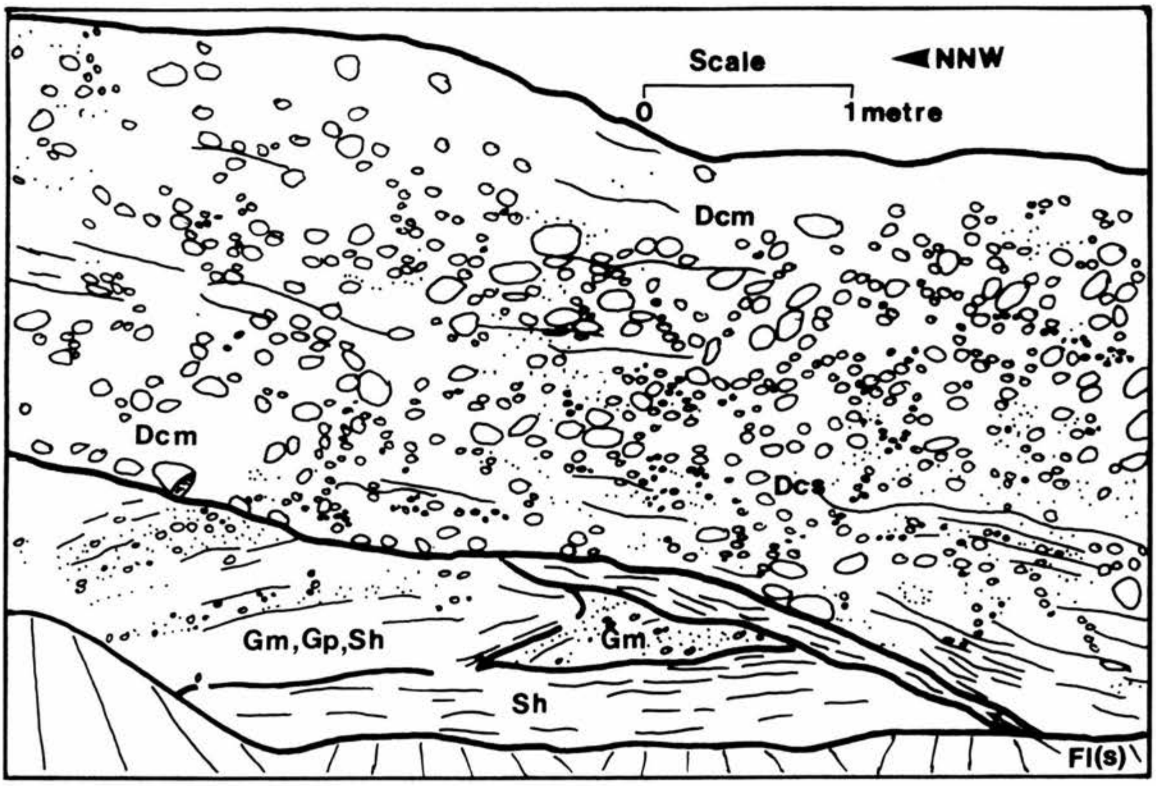


Figure 3.11. Sketch of sediments in Rupanco III lateral moraine at Lower Bellavista. Bedded sands and gravels overly a unit (visible where it has been streaked out along thrust contact) of laminated clays. The two units have been overthrust by a 2m thick unit of diamict.

In a section 50m away along the proximal side of the moraine unit 3 is absent and unit 1 is overlain by a much thicker accumulation of the sheared clays of unit 2. Elsewhere along the proximal slope of the moraine shallow sections expose folded and faulted finely laminated clays containing dropstones. In places the lamination has been replaced by a platy, tectonic foliation dipping parallel to the proximal moraine slope.

Interpretation

The lower two units show that glaciolacustrine sediments were deposited over cross-bedded fluvioglacial sands. These were overthrust by a glacier, resulting in a deformation till (unit 2) overlying sheared clays. The till was overlain by unit 3 which consists of a number of sub-units lying in the continuum between proximal fluvioglacial deposits and tills deposited in the presence of meltwater. The deposition of these deposits was fairly localised, as evinced by the absence of unit 3 in a section close by. At the Hosteria El Paraiso locality the over-thrusting of the glaciolacustrine deposits by glacier ice was sufficient only to shear the topmost parts of the clays and form a thin deformation till. Elsewhere along the proximal slope the deformation was more pervasive and transformed the laminated glaciolacustrine sediment into a layer of clay-rich, foliated deformation till. The foliation is not axial planar to the folding and is likely to be shear-induced banding.

Lower Bellavista (Rupanco III)

This is a small exposure into the foot of one of the major lateral moraines associated with the Rupanco III advance along the north shore of the lake. The section occurs close to the lip of a channel draining a flat area between the Rupanco II ice-contact slope and the Rupanco III lateral moraine (Table 3.14).

Three units are exposed. The lowermost unit is a thin sequence of finely laminated brown clay and silt containing dropstones. Laminae are 1mm to 3mm thick. This is overlain by 50cm of horizontally-laminated well-sorted fine sands which have no cross-bedding or other structures (Fig. 3.11). The sands are overlain by interbedded sands and gravels with some cross-bedding. The lower two units are separated form the uppermost unit by an abrupt thrust contact parallel to the proximal slope of the moraine. The laminated silts and clays extend towards the north-northwest along the base of the contact. They are foliated and pinch-out along the thrust. The upper unit is a massive diamict made up of granule, pebble and cobble clasts in a sandy matrix which also contains some clay. The boundaries of the unit parallel the proximal slope of the moraine.

Table 3.14. Sedimentological data from Bellavista Channel
Geomorphological Context: Section into wall of channel through RIII lateral moraine, north shore of Lago Rupanco
Section Dimensions: 3m high, 10m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
3 [2]	grey-brown	faint stratification	l: erosional, weakly developed clast pavement u: ground surface	2-150 [pebble]	poor, sub-angular to sub-rounded, various	clay-coarse sand, poor, none	none	matrix	till
2 [0.75]	pale brown	horizontally bedded sands and stratified gravels, laminated, folded	l: depositional u: erosional	2-40 (granule)	good, sub-angular to sub-rounded	fine sand to coarse sand, good, none	none	clast	fluvioglacial
1 [0.15]	khaki brown	none	l: uncertain u: erosional	n/a	n/a	clay to fine silt, good, none	intermittent foliation	matrix	glaciolacustrine

Table 3.15. Sedimentological data from Huillin de Rupanco
Geomorphological Context: Crest of Rupanco III lateral moraine, north shore of Lago Rupanco
Section Dimensions: 3m high, 50m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
4 [1.2]	grey	lens of sediment fines upwards, thrust faults	l:depositional u:ground surface	2-70 [granule]	poor, sub-angular to sub-rounded, various	clay to coarse sand, poor, normal	none	varies	iceberg-rafted debris
3 [0.8]	brown	laminated, dropstones, loading structures, minor lenses of diamict	l:depositional u:depositional	2-80 [pebble]	poor, sub-angular to sub-rounded, various	clay to fine silt, locally good, silt-clay couplets normally graded	none	matrix	glaciolacustrine (?varves)
2 [0.4]	yellow-grey	lens of sediment fines upwards	l:depositional u:depositional	2-80 [granule]	poor, sub-angular to sub-rounded, various	clay to coarse sand, poor, normal	none	varies	iceberg-rafted debris
1 [0.6]	brown	laminated, dropstones, loading structures, minor lenses of diamict	l: not exposed u:depositional	2-100 [pebble]	poor, sub-angular to sub-rounded, various	clay to fine silt, locally good, silt-clay couplets normally graded	none	matrix	glaciolacustrine (?varves)

Interpretation

The lower unit is a thin glaciolacustrine sediment which has been overlain by laminated sands. The sorting and lamination of the sands suggests they were deposited in either a fluvioglacial channel or form part of a delta. The latter seems more likely since there is evidence for a lake at this site. Firstly, they directly overly glaciolacustrine sediments suggesting the sands may be bottomsets. Secondly, the low flat area to the north of the moraine resembles other ice-marginal lakes in the field area. However, more evidence would be needed to confidently ascribe this origin to the sediment.

The upper unit is a till deposited during construction of the Rupanco III lateral moraine. It has overthrusted and deformed the lower units along a well-defined contact which has dragged the clays along the thrust for almost a metre and imposed a foliation. The till may be a deformation till. Thus, the section records glacial advance over an ice-marginal lake during construction of the Rupanco III lateral moraine.

Upper Bellavista (Rupanco III)

This section at the foot of the distal slope of the Rupanco III lateral moraine exposes 10m of interbedded sands, gravels, clays and silts overlain by a gravelly horizon. The lower unit is a sequence of extensively stratified sands and gravel up to 7m thick. Cross-bedded lenses of sand occur throughout the unit. This is depositionally overlain by sub-horizontally laminated clays and silts containing dropstones. Thin (<1cm) layers of diamict are interbedded with the finer sediments. Towards the south side of the section the laminae have been gently folded into upright antiforms. Above an abrupt erosional unconformity they are overlain by a further sequence of extensively cross-bedded pumice-rich sands with numerous scour features. These strata are folded and faulted at the south end of the section. Above this faulting the sands are overlain by a thin (20cm) gravelly diamict with cobbles and pebbles. This unit is massive and shows no structures or preferred clast orientations. The diamict pinches out to the north where the cross-bedded sands grade directly into orange-yellow silt and soil.

Interpretation

Both cross-bedded sandy units are interpreted as fluvioglacial sediments. The cross-bedding and scours are due to continual aggradation of channels in which the sands accumulated. The clays and silts which lie between are glaciolacustrine as shown by the dropstones and layers of ice-rafted debris. Thus two episodes of fluvioglacial activity were separated by a period of glaciolacustrine sedimentation. Subsequent to this the sediments were deformed from the south and overlain by a unit representing a final pulse of either coarse fluvioglacial sediment or a sediment gravity flow. This was derived from the south i.e. upslope on the distal side of the moraine.

This section can be correlated with the Lower Bellavista section to establish the way in which this lateral moraine was constructed. Fluvioglacial sedimentation was succeeded by the formation of an ice-marginal lake. Since there is no other evidence for a former level of Lago Rupanco at this altitude (80m above present) this lake was probably ice-dammed along the northern margin of the Rupanco lobe. Further advance of the lateral margin with deltaic and fluvioglacial sedimentation overran the margin of the lake at Lower Bellavista and constructed the moraine. The sediments on the distal side of the moraine were deformed and overlain by thin flows of proximal fluvioglacial deposits.

<u>Huillin de Rupanco</u> (Rupanco III)

This section cuts into a lateral moraine bounding the lakeward margin of an extensive flat area on the north shore of Rupanco. The flat area is bounded on its north side by the Rupanco II ice-contact slope which leads westwards into a meltwater channel leading into the Rupanco III outwash plain. The lowermost unit is composed of finely laminated silts and clays with dropstones up to 10cm (Table 3.15, Fig. 3.12). The dropstones often occur within normally graded sand and gravel lenses up to 10cm thick. The laminae directly below these lenses are deformed by the dropstones and loading structures are common. The laminae occur as ca. 210 silt-clay couplets with dark brown silt grading upwards into pale brown clay. Overlying the 210 couplets there is a thick lens of sandy diamict which fines up from poorly sorted striated pebbly gravel to grade into the overlying silt-clay lamination. Above this are c. 105 silt-clay couplets of unit 3 which is sedimentologically similar to unit 1. The basal pebbly sands of unit 4 deform the topmost laminae of unit 3. The sandy diamict unit is composed of several weakly graded sub-units but its topmost part is obscured by tailings from the quarry. Each of the graded sub-units is capped by a wavy discontinuous thin (<0.5cm) layer of clay and fine silt. Several low angle thrust fault cut this lamination near the top of the section.

Interpretation

The section exposes glaciolacustrine sediments laid down in an ice marginal lake during the Rupanco III advance. Units 1 and 3 are glaciolacustrine clays and silts with dropstones. The lenses associated with the large clasts are iceberg-rafted diamicts. Single depositional events would have dumped the diamicts which then settled through the water to form graded lenses. Units 2 and 4 are simply thicker iceberg-rafted diamicts. The thrust faults in unit 4 shows that the section has been deformed and it is likely that this deformation occurred during the formation of the low lateral moraine. The geomorphology shows that in order to be maintained this lake would have required an ice-dam at its

Figure 3.12. Photograph of glaciolacustrine sediments in Rupanco III lateral moraine at Huillin de Rupanco. Finely laminated silt-clay couplets are interbedded with thin diamict units which are laterally discontinuous. The diamict units are commonly lensoid and grade upwards into the silt laminae. Dropstones which deform underlying laminae and are draped by overlying laminae are associated with the diamict lenses.

western end. The close association of the lake sediments with the Rupanco III moraine suggest that the glacier advance to this limit dammed the lake. The thrust deformation may date from the same event; the deformation was mild so was probably due to minor marginal fluctuations rather than a significant readvance.

3.3.4. Summary of ridge moraine sedimentology

A number of key features emerge in the ridge moraine sedimentary histories. These are similar to those identified for the rampart moraines.

- Ridge moraines are dominantly composed of fluvioglacial sediment on their distal sides.
- The fluvioglacial sediments are commonly overlain erosionally by massive diamicts. Most of these are deformation tills.
- The tills contain reworked glaciolacustrine sediment, generally smeared on the proximal slope.
- Sedimentary sequences are sometimes capped by sediment flows or proximal fluvioglacial sediment.

However, some of the lateral ridge moraines and the Puyehue V moraine show significant differences.

- The sections at Los Copihues, Huillin de Rupanco, Lower Bellavista and Puerto Chalupa all show advances of lateral glacier margins into ice-marginal lakes, with only limited fluvioglacial deposition. The lateral moraines at these sites were all constructed during the Puyehue III and Rupanco III advances.

- The Puyehue V moraine at Río Pichichanleufu is anomalous since the diamict it is made of does not contain glaciolacustrine sediment. This may be due to its unique position in a tributary valley to the east of Lago Puyehue where no source of such sediment existed. Instead the diamict contains a high proportion of material interpreted as aeolian silt. Elsewhere this silt overlies sediments deposited during earlier glacial advances. This suggests that the Puyehue V moraine may have been formed at a very late stage when the area was virtually deglaciated and aeolian silt was already widespread.

- The Rupanco I and Puyehue I moraines are not well-exposed; both are largely buried by the outwash from later advances and sections reveal little information. The Puyehue I moraine is composed of a hard compact till very different to any other till in the field area, whilst the Rupanco I moraine is made of relatively friable till containing clasts more intensely weathered than elsewhere.

3.4. Synthesis of the Sedimentological Evidence

At each of the sections in the ridge and rampart moraines, the tills, fluvioglacial and glaciolacustrine sediments occur in broadly similar associations. Fluvioglacial sediments comprise the bulk of each moraine and form thick sequences which can be traced distally where they grade into the shallow-dipping outwash plains. Glaciolacustrine sediment occurs as blocks within the tills and as a thin, deformed layer at the foot of the proximal slope of some moraines. The tills occur only on the proximal slopes of moraines where they form a layer 0.5m to 5m thick overlying the fluvioglacial sediment. The contact between the till and fluvioglacial sediment can be sharp and erosional but is sometimes gradational and marked only by a progressive increase in clay content and decrease in stratification and sorting of the fluvioglacial sediment. Close to the contact the fluvioglacial beds are commonly folded. A sketch of the sediment patterns is shown in Figure 3.12A.

Most of the tills on the proximal slopes of the moraines are deformation tills. A number of lines of evidence lead to this conclusion. Primarily, they have been recognised on the basis of their tabular form and the fact they are massive and relatively uniform throughout their thickness. They are also clay-rich, ungraded, matrix-supported, contain sheared soft sediment clasts and have weak fabrics and occasional clast pavements. The parent materials of the deformation tills can be identified by examining the clast size distributions, clast shape and roundness characteristics of the different sedimentary facies. Firstly, there is a clear relation between the deformation tills and the blocks of deformed glaciolacustrine sediment. Most of the tills contain clays and silts characteristic of glaciolacustrine material, either as blocks or dispersed material, or both. In addition, at a number of sites there is a close similarity between the clasts of the fluvioglacial sediment and the tills. This relationship, together with the truncation of the fluvioglacial strata by the tills, suggests that the origin of the deformation till is also closely linked to the fluvioglacial sediment.

Particle-size analysis of the sediment matrices implies reworking of the fluvioglacial and glaciolacustrine sediments to form the tills (Fig. 3.13). The matrix of the fluvioglacial sediment is dominantly composed of sand with little silt or clay. The glaciolacustrine sediments are rich in silt and clay but contain little sand-sized material. Some till samples show closely similar matrix compositions to the fluvioglacial sediment but others contain higher proportions of silt and clay. The compositions of the till samples lie on a mixing line between the fluvioglacial sediments and the glaciolacustrine clays and silts. Those till samples which have the same composition as the fluvioglacial material have been deformed enough to obliterate the stratification but have not been mixed significantly with fine-grained material whereas others have been mixed with glaciolacustrine sediment. The general position of the diamicts near the fluvioglacial end of the mixing line reflects the higher volume of pre-existing fluvioglacial sediment than transported glaciolacustrine material.

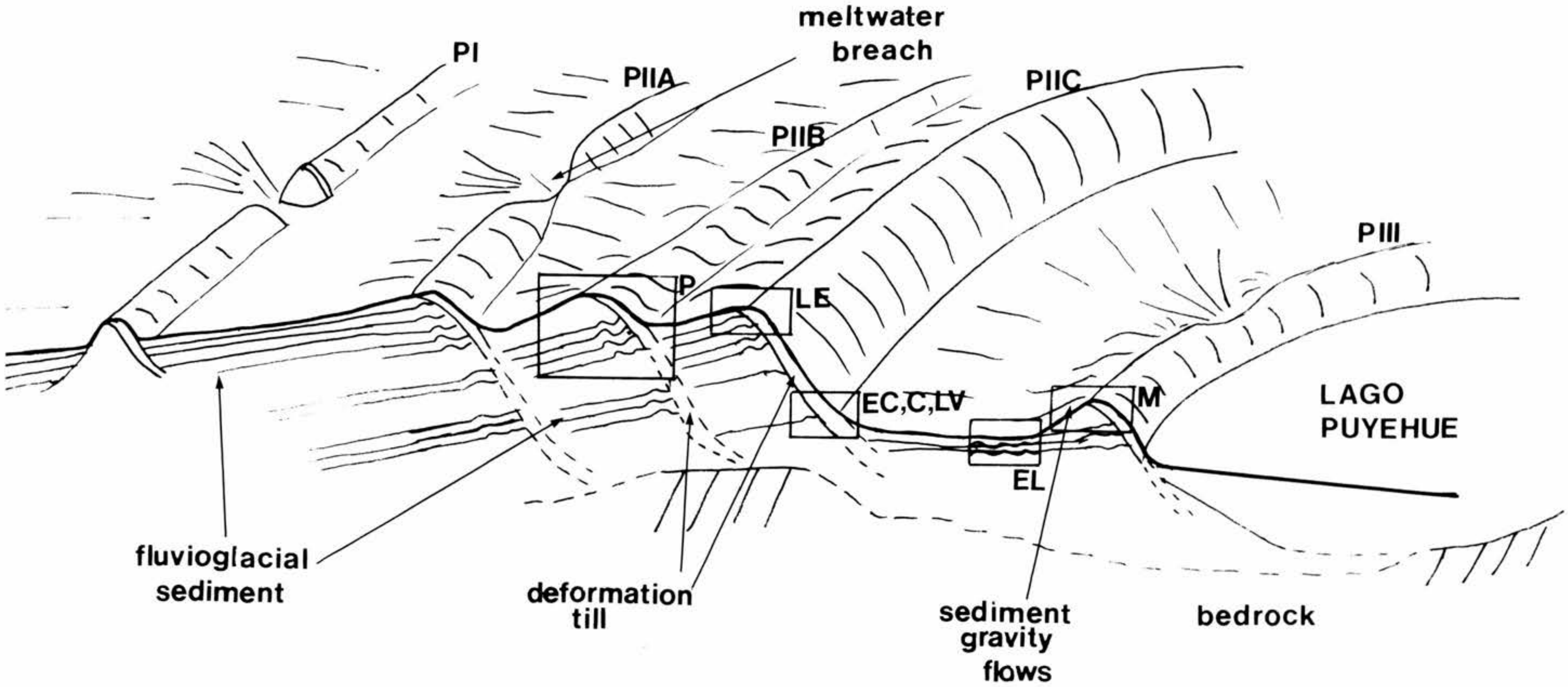


Figure 3.12A. Sketch of sediment patterns and relations between key sections along a transect through the rampart and ridge moraines around Lago Puyehue. Sites P (Pilmaiquen), LE (Los Esteros), EC (Estero Chiscaihue), C (Chiscaihue), LV (Las Vertientes), EL (Entre Lagos) and M (Mantilhue) are described in the text. Similar relations occur in the moraines around Lago Rupanco. Diagram not to scale.

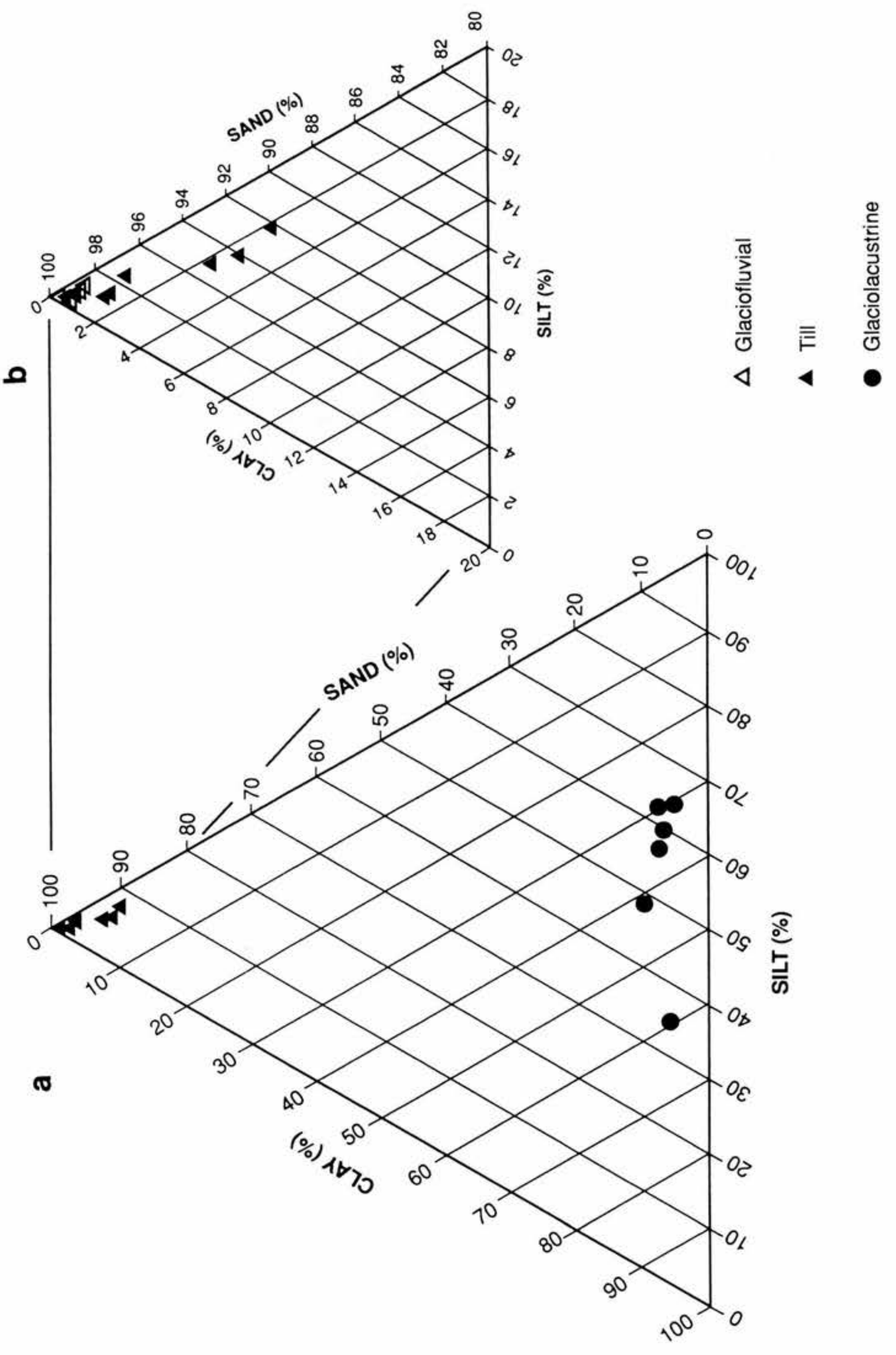


Figure 3.13. Composite grain size analysis of the matrix fraction of fluvioglacial, till and glaciolacustrine sediment from sites described in the text.

(a) The till and fluvioglacial sediment contrasts with the clay- and silt-rich glaciolacustrine sediment. The analysis for entrained blocks of laminated sediments show them to be dominated by silt (c.35-65%) and clay (c.30-60%) but with little sand content (<9%) so the compositions lie close to the silt-clay axis.

(b) Fluvioglacial sediments are composed dominantly of sand (98-100%) with little silt (<2%) and clay (<2%). On the sand-silt-clay plot they tend to cluster close to the sand apex. The results for the tills from the same localities show a wider spread of values with more silt (<10%) and clay(<4%) but still dominated by sand. Many till compositions are very similar to the fluvioglacial material but the rest lie along a line extending towards the silt-clay axis.

Clast roundness data from the three best-exposed sites also show that the fluvioglacial sediment and till at each site are very similar. At the Mantilhue site the fluvioglacial sediment and till show similar clast roundness distributions (Fig. 3.14a). Both show a predominance of sub-angular clasts with approximately symmetrical distributions either side of this peak. The similarity implies that the till was probably formed by reworking of the fluvioglacial sediment as it was folded and deformed by the glacier. At the Pilmaiquen site the fluvioglacial sediment is composed predominantly of clasts which are rounded to sub-angular (Fig. 3.14b). The till shows a similar dominance of sub-rounded clasts but slightly higher proportions of sub-angular and angular clasts than the fluvioglacial sediment. This difference is related to the presence of the large sub-angular clasts in the till; the mixing of the fluvioglacial and glaciolacustrine sediment was also accompanied by the addition of a number of sub-angular clasts, probably glacially-transported. At the Los Esteros site the till shows a greater proportion of sub-rounded and sub-angular clasts than the fluvioglacial sediment (Fig. 3.14c). However, only a few clasts large enough to be measured for shape and roundness data were found in the fine gravels at the Los Esteros site so this difference may reflect the small sample size of the fluvioglacial sediment. In summary, the roundness data show that the two sediment types contain similar populations of clasts.

On the basis of clast shape data the fluvioglacial sediments and tills are virtually indistinguishable. At the Pilmaiquen site most clasts in both the till and fluvioglacial sediment have equant shapes. The overall range of clast shape in each sediment type is very similar (Fig. 3.15a). A similar pattern exists at the Los Esteros site although the till contains slightly more bladed and tabular clasts (Fig. 3.15b). As with the clast roundness data the small difference may be because the small sample size of fluvioglacial clasts is unrepresentative of the sediment. At Mantilhue the ranges of clast shapes of the two sediment types is again similar but at this site it is the fluvioglacial sediment which shows slightly more bladed clasts (Fig. 3.15c). The shape characteristics of the till and fluvioglacial sediments in the moraine sections demonstrate that the two sediment types contain similar clast populations.

The folding of the fluvioglacial sediment is upright and usually symmetric, suggesting that the glacier termini deformed the outwash longitudinally from a position east (up-glacier) of the fluvioglacial sediment. Much of the outwash was also deformed sub-glacially, below the deforming layer. Deformation of the fluvioglacial sediment, such as the bulldozing of the Puyehue IV outwash plain, was more intense close to the proximal side of the moraine. This would be expected as the proximal slope would be the point of maximum contact with the glacier. In places, the deformation continued during further sedimentation, resulting in folded sand lenses within the till forming at the glacier snout and syndepositional folding in the fluvioglacial material as longitudinal stresses were transmitted from the glacier.

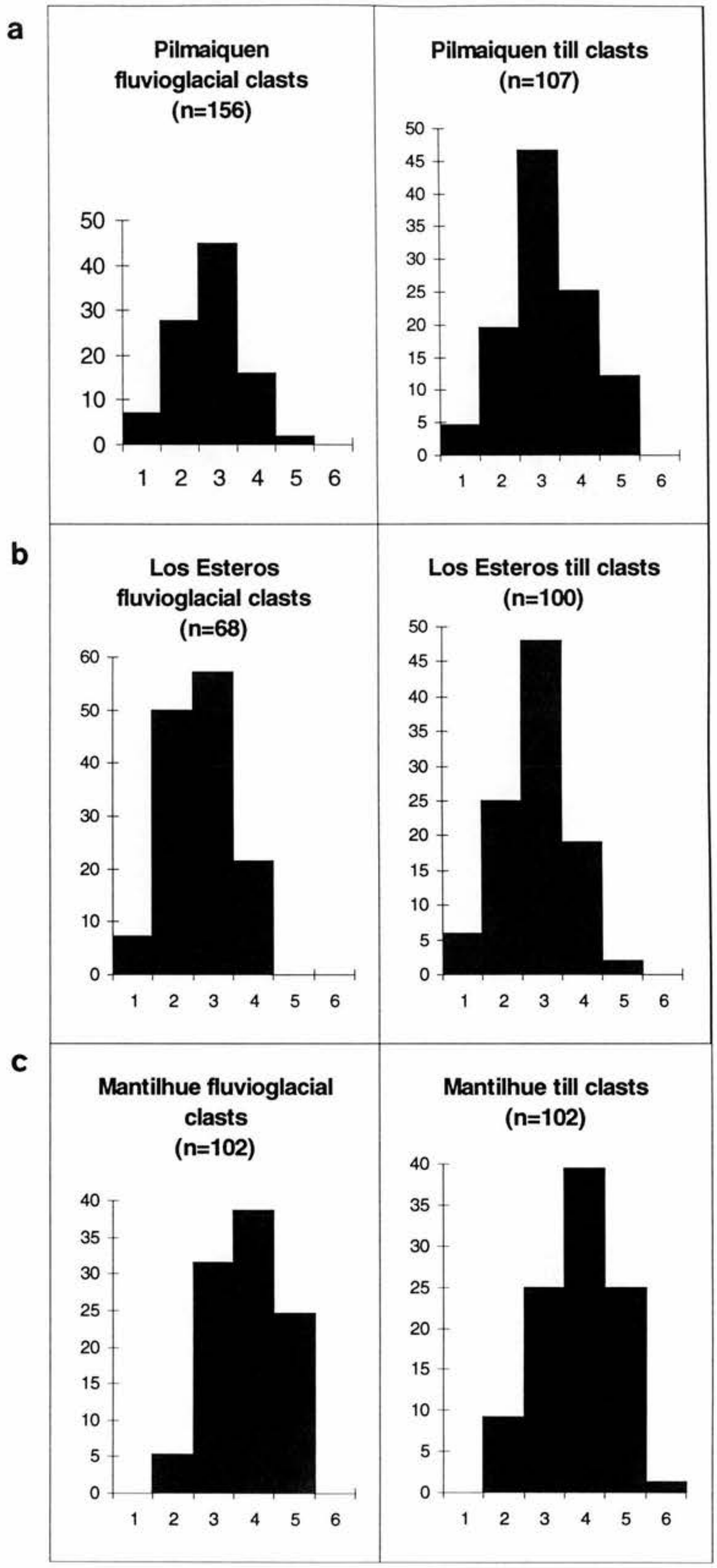


Figure 3.14. Clast roundness characteristics of tills and overridden fluvioglacial sediments. Roundness is plotted as a percentage of clasts in each of 6 categories (1=Well-rounded, 2=Rounded, 3=Sub-rounded, 4=Sub-angular, 5=Angular, 6=Very angular).
(a) Pilmaiquen
(b) Los Esteros
(c) Mantilhue
All three sites show clasts with similar roundness distributions in the two sediment types.

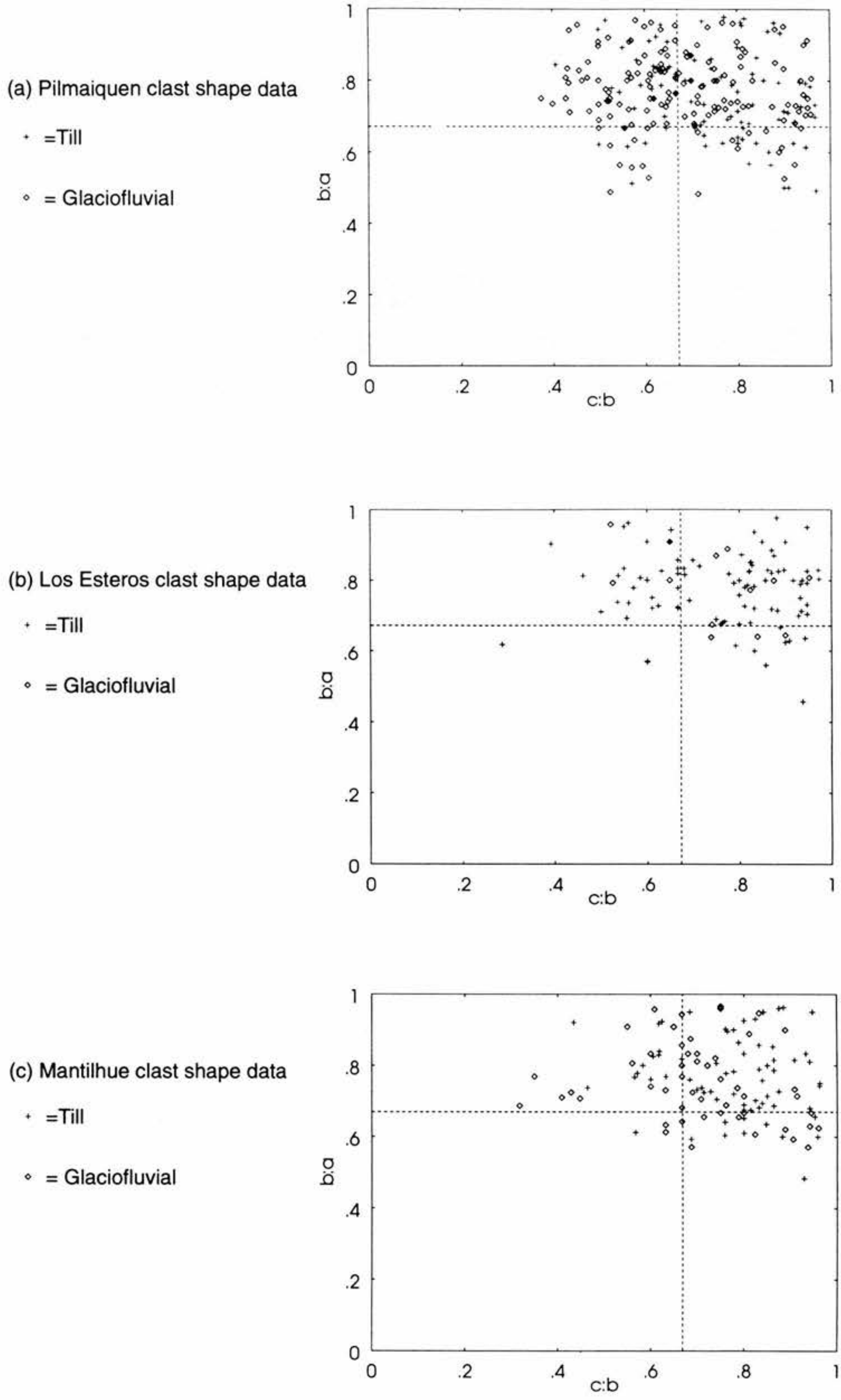


Figure 3.15. Zingg diagrams showing the similarity in clast shape between tills and fluvioglacial sediments. The ratios b/a and c/b are plotted against each other for each clast. Most clasts in both sediment types tend to have relatively equant shapes (top-right quadrant).

The blocks of glaciolacustrine sediment contained in most of the tills lie several tens of metres above the present level of the lakes. The obvious source for this glaciolacustrine sediment is the Lago Puyehue or Lago Rupanco basins, no more than a few kilometres from any of the sections in which the glaciolacustrine sediment occurs. The brittle deformation of the blocks in some section suggests that some of the glaciolacustrine sediment may have remained frozen during transport. Moreover, the continuum of fine-grained sediment in the till from intact blocks to dispersed clay and silt suggests that some of the entrained glaciolacustrine sediment was deformed or re-distributed during transport or deposition.

The contrast in several of the moraines between intact blocks of glaciolacustrine sediment in till at the crest and homogeneous clay-rich till at the base suggests that the chance of preserving undeformed glaciolacustrine sediment may have been greater at the crest of the slope than at the base. At the base the sediment would have been subject to greater subglacial shearing. The Rupanco III moraine shows that the deposition of the till could be fairly localised, as evinced by its absence in several sections along the proximal slope. The deformation of the glaciolacustrine sediment in Rupanco III varied from shearing and recumbent folding of the topmost parts of the unit to pervasive deformation which transformed the laminated glaciolacustrine sediment into a layer of clay-rich, foliated till.

3.5. Summary

In summary, the till and fluvioglacial sediments making up the moraines contain clasts with similar shape and roundness characteristics to each other. The clasts in the tills are derived from mixing of clasts in the fluvioglacial sediment with glaciolacustrine clays and silts. These features plus the deformation of the fluvioglacial strata suggest that the tills are deformation tills derived from reworking of the fluvioglacial sediment with the addition of fine-grained material in the form of glacially-transported glaciolacustrine sediment. Further accumulation of fluvioglacial sediment continued after the initial glaciotectonic deformation.

Minor differences from this general pattern occur in places but most of these can be explained by the local topography of the sites. For example Puyehue I and Rupanco I appear to be made of homogeneous deposits but these sites are located at the outer edge of the moraine sequences and only the topmost parts of each moraine are exposed. Thus, the full depositional history may not be exposed. The Puyehue V moraine is in an unusual location east of the lake basin. The differences between this moraine and the others can probably be attributed to the absence of any influence of the lake on the glacier which formed the moraine.

Chapter 4: Sedimentology of landforms with specific relevance to glacier chronology

4.1. Introduction

Sediments within the rampart and ridge moraines yield important information on the processes operating during construction of the moraines. The sediments of landforms other than moraines can also provide useful information. In particular, the sediments can help determine the glacial history of the interlobate area where there are no clear morainic trends, the lake level histories in each basin, and the interaction of glacial and volcanic processes. In addition there are two sites where sections into the Puyehue II outwash yield radiocarbon dates. This chapter describes the sedimentology of landforms at nine sections which relate to the glacial chronology (Fig. 4.1).

4.2. Sections in outwash plains

La Capilla (Puyehue II outwash plain)

The constituent material of the Puyehue II outwash plain is exposed in a 10m-deep section at La Capilla, 16 kilometres west of Lago Puyehue. The surface of the outwash plain grades from this site to the distal side of the Puyehue II rampart moraine to the east. The fluvioglacial sediment is extensively stratified and cross-stratified. The dominant material is gravel but lenses of cross-bedded sand are common and clasts up to cobble-size are present. The fluvioglacial sediments here contain reworked clasts containing organic material which provide maximum dates on the outwash. The clasts are made of yellow-brown, pumice-rich silts and finely laminated clays (Fig. 4.2). Within the silts and clays there are abundant casts of wood macrofossils and some wood fragments up to 10cm long. Each clast is up to 80cm long and they occur in a single metre-thick layer. Each clast is armoured by fine gravel, embedded firmly into the silt. The layer of silt clasts lies between two layers of cross-stratified gravels.

The coating of gravel around the silt and clay clasts shows they have been transported from their original site of deposition. However, the clasts occur close together in a single layer and are not present anywhere else at the site which implies they probably have not been transported far. The sediment type and the presence of wood are suggestive of a pond or small bog.

Puente Treguaco (Puyehue II outwash plain)

The lowermost unit at this site is made up of laterally extensive, stratified gravels and cross-bedded sand lenses. Individual beds can be traced for up to 8m, are well-sorted and contain clasts up to cobble

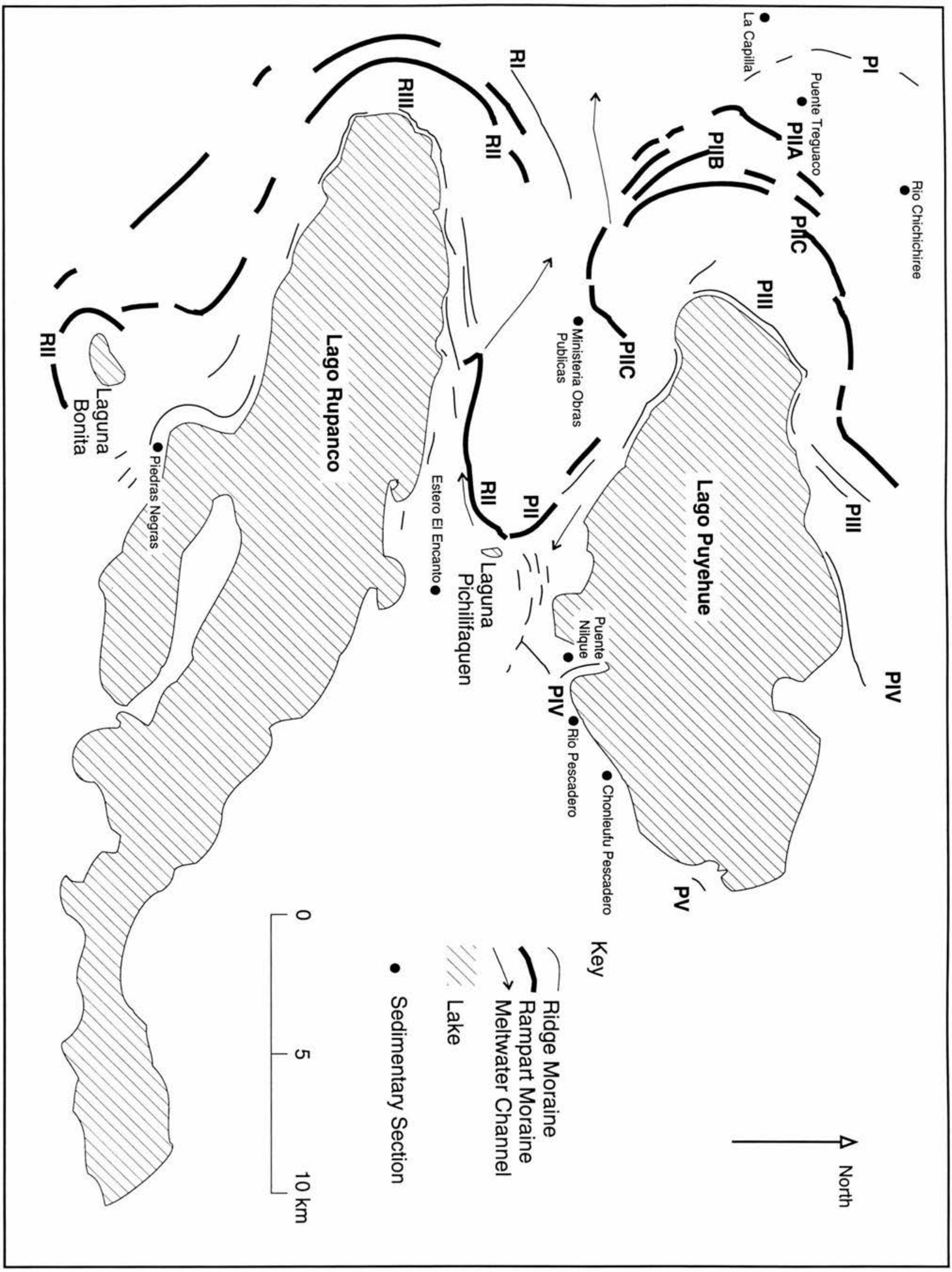


Figure 4.1. Map showing locations of sedimentary sections in non-morainic landforms.

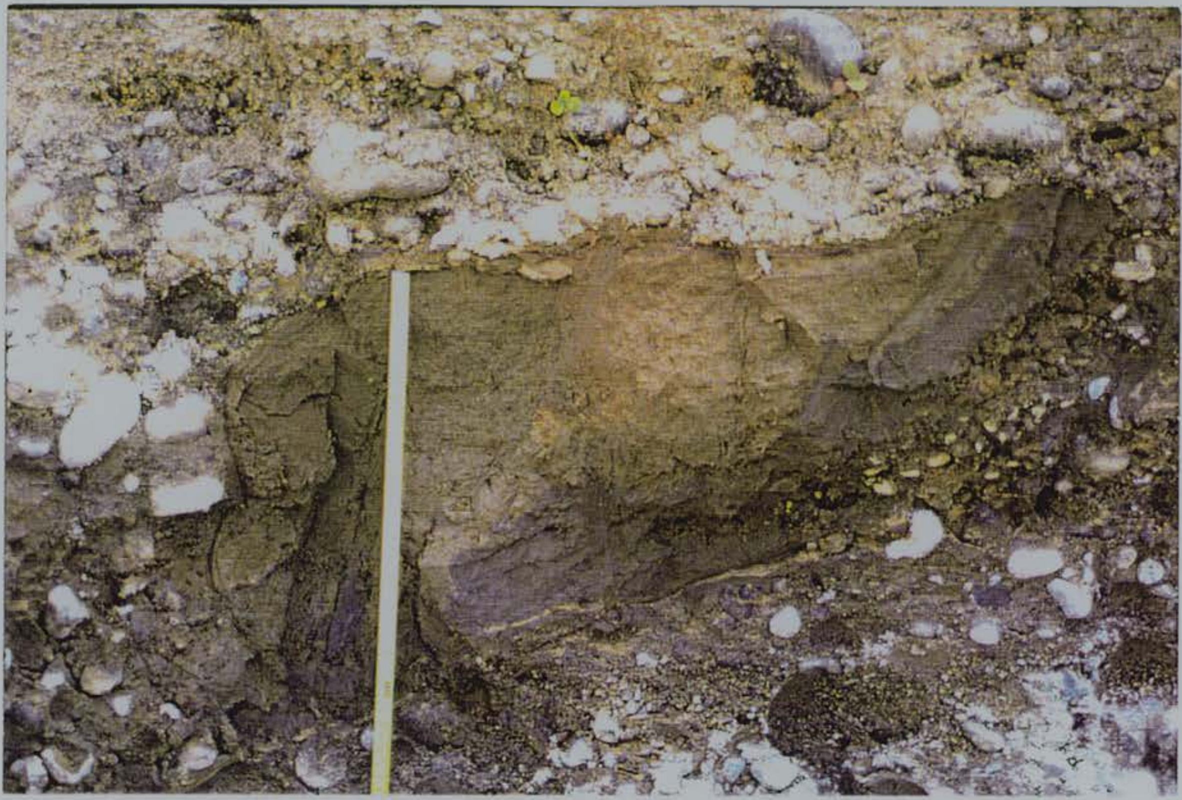


Figure 4.2. Photograph of silt clast in Puyehue II outwash plain at La Capilla. All the clasts occur along a single bed in the fluvioglacial strata. Each clast is armoured by a coating of fine gravel, and contains abundant plant macrofossils, including some casts of wood. Three samples of wood from this clast have been radiocarbon dated (AA-10316, AA-11751, AA-9959).

size. The unit is at least 5m thick and is overlain by a 1.5m-thick unit of clays and silts. The lowermost parts of the fine-grained unit are composed of blue-grey clay containing fine gravel. The clay fills the interstices of the topmost beds of the unit below. The clays grade upwards into massive, orange-brown clays and silts. The silty clay contains abundant plant macrofossils. These are stems up to 5mm thick, oriented vertically, and spaced <1cm apart. The stems are hollow and have the appearance of reeds. Above the silty clay the unit grades into interbedded clay, silt and sand lenses. These are overlain by a 3-4m thick unit of stratified gravels and cross-bedded sand lenses similar to the lower stratified unit. The contact is irregular and truncates the bedding at the top of the silty clay unit. The top of the upper unit forms the Puyehue II outwash plain and grades to the Puyehue IIA moraine to the east.

Interpretation

This section records two episodes of fluvioglacial deposition separated by an interval when lower energy deposition of clays and silts took place. The initial outwash deposition is not tied to a particular moraine. The presence of upright, apparently undisturbed reeds in clays and silts suggests that a pond developed on the former outwash plain. This probably occurred during an interstadial when the braided stream network of the outwash plain was relatively inactive and conditions were stable (and warm) enough for plants to develop. The topmost pond sediments were then eroded and overlain by further fluvioglacial deposition associated with the Puyehue II moraine but it is not clear which of the Puyehue II sub-stages was responsible for depositing the sediment. Several stems were sampled in order to yield limiting dates for the outwash units. The date gives a minimum date for the lower outwash unit and a maximum date for the upper unit.

4.3. Sections in the interlobate area between Lago Rupanco and Lago Puyehue

Ministerais Obras Publicas (MOP) Quarry

The MOP Quarry exposes a section into the undulating topography of the area midway between the two lakes. The quarry is not cut into any distinct geomorphological feature but to the east there is a broad, poorly-defined relict meltwater channel whilst to north, south and west there are mounds and hollows with a relief of less than 15 metres. The south wall of the quarry displays the most complete section where the characteristics and inter-relationships of the 5 units can be deduced (Table 4.1). The lowermost unit consists of bedded (36°/190°) pebbly gravels. Individual beds are normally graded from pebbles to fine granules and are occasionally topped by thin clay or silt layers (Fig. 4.3). The lower contact is not visible but beds become less distinct and slightly folded towards the upper contact. The overlying massive diamict of Unit 2 thins towards the west and has a faint, localised sub-horizontal foliation. There is a slight increase in clay content from bottom to top. Elongate clasts in the

Table 4.1. Sedimentological data from Ministerias Obras Publicas
Geomorphological Context: Undulating topography of interlobate area betweeen Lagos Puyehue and Rupanco.
Section Dimensions: 7m high, 50m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
5 [<0.4]	Pale brown	stratified faulted	l:depositional u:depositional	n/a	n/a	clay-silt, very good, normal (silt-clay couplets)	n/a	n/a	glaciolacustrine
4 [2-3]	Grey	gen. massive, (but some deformed lenses, drapes, sediment rafts, + interbedding with unit 3)	l:sheared u: depositional	2-300 (pebble)	poor, sub-rounded to sub-angular, bullet	silt-medium sand, poor, none	none	matrix (locally clast)	melt-out till
3 [1-2]	Dark brown	stratified, x-stratified, isoclinal folding, poss. sand lenses	l: depositional u: sheared	2-8 (granule)	nd	silt-coarse sand, good in indiv. beds, overall reverse grading of unit	n/a	n/a (unit is almost entirely matrix)	fluvioglacial (transformed to deformation till)
2 [0.5-2]	Grey-brown	massive	l: sub-horiz., planar u: depositional	2-500 (cobble)	poor, sub-rounded, bullet + blocky	clay-coarse sand, poor, none	weak, parallel to top surface	matrix	deformation till
1 [>2]	Mid-grey	stratified (beds c.10cm thick) x-stratified	l: not seen u: sharp, topmost beds sheared	2-200 (pebble)	moderate, sub-rounded, various	silt-coarse sand, moderate, normal (silt layer tops each cycle)	clasts parallel to bedding	clast	fluvioglacial

Table 4.2. Sedimentological data from Estero El Encanto
Geomorphological Context: Section into interlobate area, in Pichilifaquen col north of Lago Rupanco
Section Dimensions: 6m high, 40m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
2 [2-5]	grey-brown	stratified, clasts of laminated clay	l: erosional u: depositional	2-200 [granule]	poor, sub-angular to well-rounded, various	coarse silt to coarse sand, poor, none	weak clast orientation	matrix (locally clast)	melt-out till
1 [1-4]	pale grey	stratified, folded, normal and reverse-faulted	l: not exposed u: erosional	2-150 [pebble]	poor, sub-rounded, various	coarse silt to coarse sand, moderate (locally good), normal	none	matrix	fluvioglacial

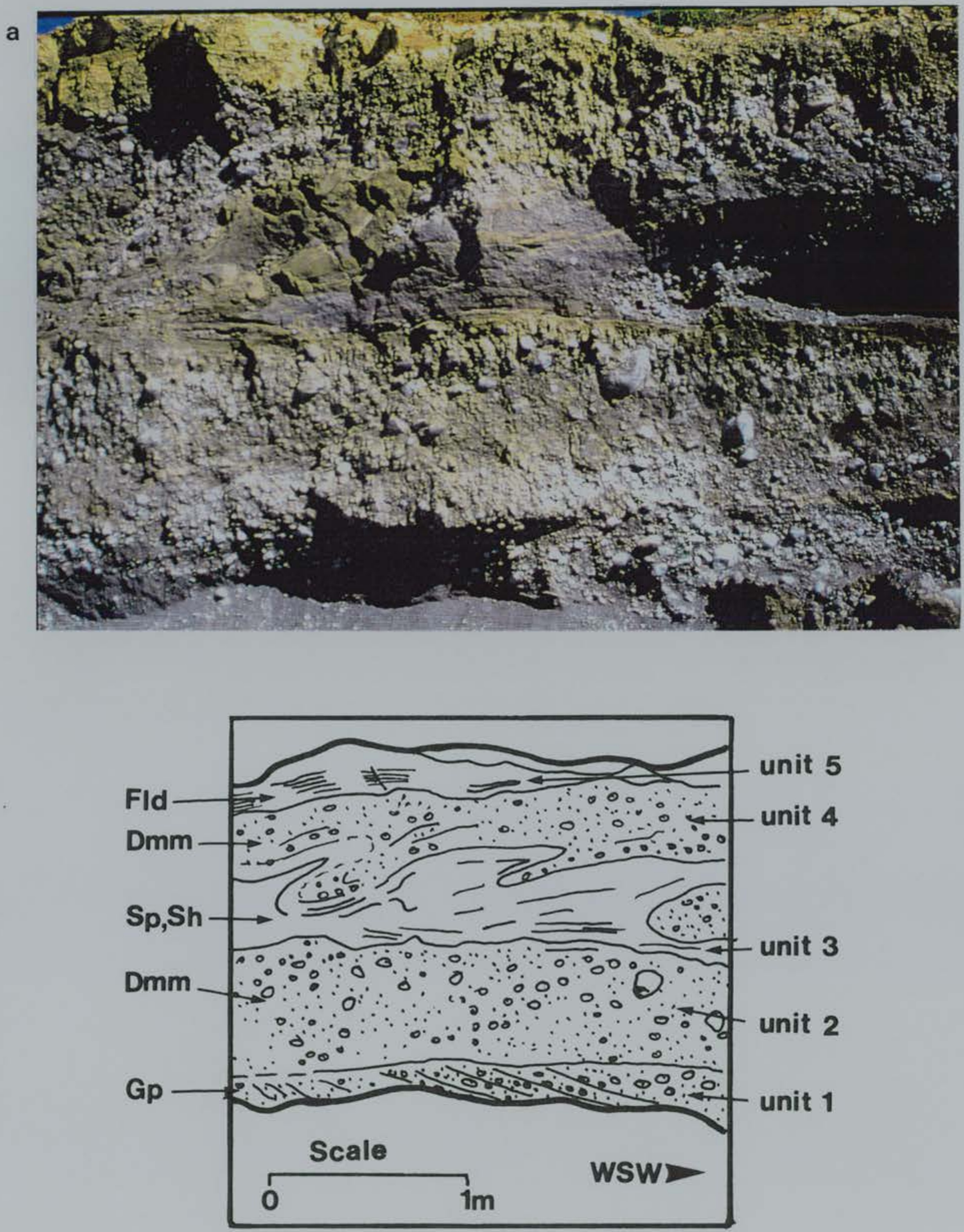


Figure 4.3. Ministerias Obras Publicas site
(a) Photograph and sketch of south wall of quarry showing lower fluvioglacial gravels overlain by a massive till. The till is overlain by one metre of laminated silts which have been recumbently folded to the west-southwest and extend into the overlying till. Small pockets of glaciolacustrine sediment are interbedded with, and overly, the upper till.
(b) Ice wedge cast of pebbly till in fluvioglacial silts and fine gravels.

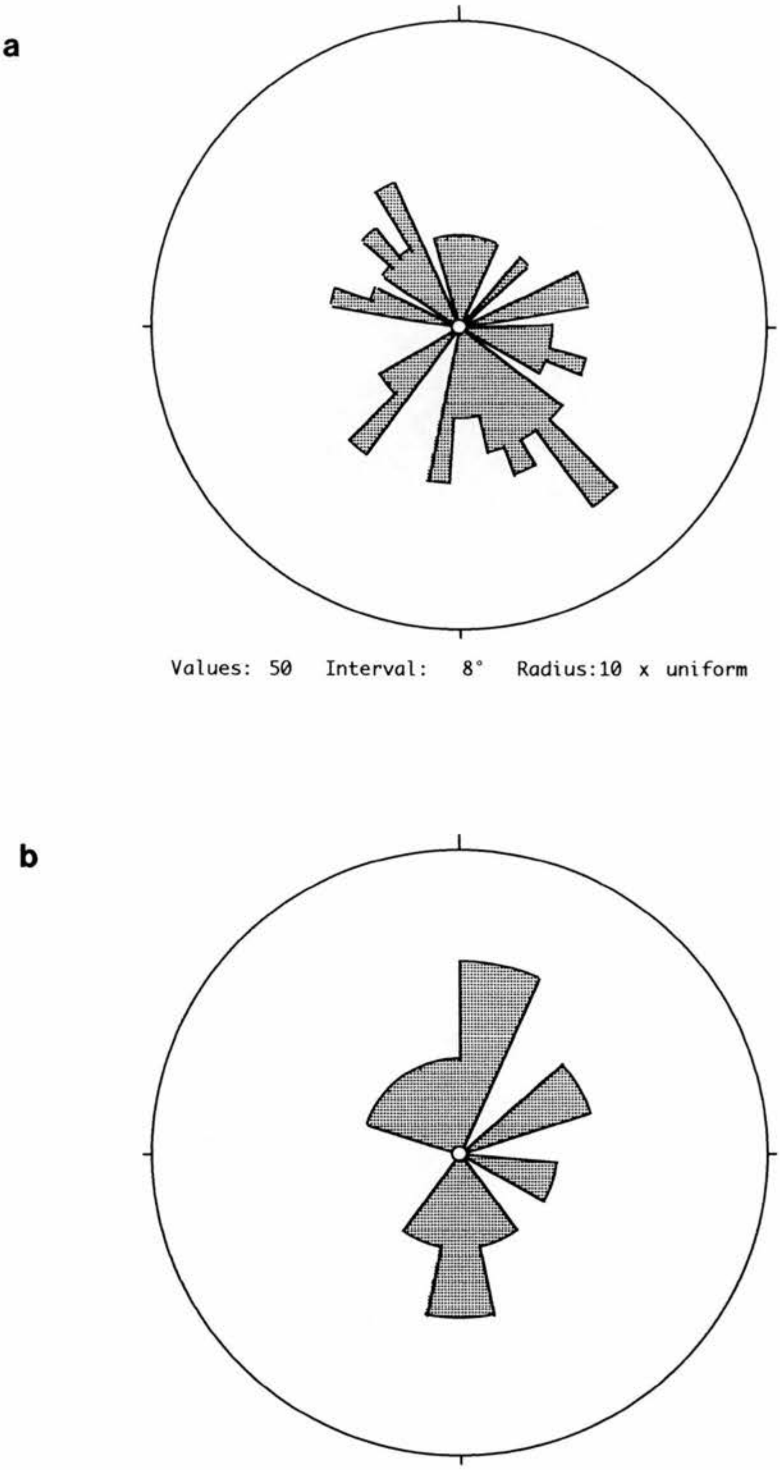
b

unit are dominantly oriented in a northwest-southeast direction with a weaker transverse orientation (Fig. 4.4a). The hard, basal silts of Unit 3 depositionally overly the topmost clasts of Unit 2 but grade upwards into increasingly coarse sands and the topmost layers are composed of cross-stratified pumice-rich gravels. Several silt layers interrupt this overall reverse-graded sequence. Unit 3 is intensely deformed; westward-directed isoclinal folding is ubiquitous at both metre- and centimetre-scales. Large fold structures protrude from the upper surface into the overlying Unit 4 diamict and give rise to a complex interbedding relationship of the two bodies (Fig. 4.3a). The hinges of most of these folds have near-horizontal dips and are oriented in a south-southeast or north-northwest direction. In addition, small (<1m) 'rafts' of Unit 3 occur within the Unit 4 diamict west of some of the protruding fold noses. Elongate clasts in Unit 4 show a north-south orientation plus a weak east-northeast trend (Fig. 4.4b). Unit 4 contains folded sand lenses in its lower parts whilst higher up it encloses discrete lenses of Unit 5. These lenses also occur above unit 4 and cap the section in places. The lenses are up to 40cm thick and consist of silt-clay couplets each from <1mm to 10mm thick. with occasional sand interbeds and thin layers of Unit 4 diamict. Laminae are usually sub-horizontal but also show sag structures and are cut by normal-faulting. Faults are c.10mm apart and have throws of 2-5mm. Rare thrust-faulting of the laminae is visible at the base of the sag features. In the east wall of the quarry unit 3 is cut by a downward-pointing vertical cone of massive pebbly diamict. The cone is 70cm wide at the top and extends 1.2m into the stratified sediment (Fig. 4.3b).

Interpretation.

The stratification and cross-stratification, rounding, normal grading and clast support mechanism all suggest a fluvioglacial origin for the gravels of Unit 1. A massive, matrix-supported diamict overlies the fluvioglacial gravels with an erosional unconformity. It contains a large size range of bullet and blocky stones with facets and rare striae; together with the poorly-defined foliation, poor sorting, presence of clay in the matrix and the parallel orientation of elongate clasts the characteristics suggest that it is a subglacially-deposited till. The clast fabric implies that it was deposited by ice flowing towards the northwest. This is consistent with an extension of the Rupanco lobe over this area. The erosional unconformity and the shearing of the gravels below the till record an erosional event after deposition of the fluvioglacial sediment. This erosion most likely accompanied deposition of the till but it is possible that one or more events occurred between the deposition of these two units.

The overlying sands and gravels are well-sorted in individual beds and display cross-bedding, suggesting deposition in flowing water. Unit 3 therefore probably represents fluvioglacial deposition subsequent to the till deposition. This may have been later in the same advance or part of a separate advance. Unit 4 above again shows the poor sorting, wide range of sub-rounded to sub-angular clast sizes, bullet clasts, and matrix support mechanism typical of many tills. Parts of the till have a clast



Values: 50 Interval: 8° Radius:10 x uniform

Values: 15 Interval: 24° Radius:10 x uniform

Figure 4.4. Clast fabrics in tills and fold structures at Ministerias Obras Publicas site.
(a) Rose diagram showing orientation of elongate clasts in lower till (unit 2). A northwest-southeast fabric is superimposed by a weaker transverse trend.
(b) Rose diagram showing orientation of elongate clasts in upper till (unit 4). A north-south fabric is visible with a weaker northeast trend.

support mechanism and with the small lenses of material draping over clasts and the close association with meltwater deposits suggest that this is a melt-out till. However, the style of deformation of the underlying sands to form recumbent folds implies that the glacier advance to this point deformed the underlying sediment subglacially. Thus, unit 4 and the deformation of unit 3 suggest that a second glacial advance over this site formed a deformation till closely followed by deposition of a melt-out till. The clast fabric is aligned weakly north-south which does not allow discrimination between the likely flow directions of the two glaciers. However, the folding in the sands and silts of unit 3 was directed towards the west-southwest which implies the overlying sediment was probably deposited by the Puyehue lobe.

Unit 5, which is interbedded with, and overlies, Unit 4 represents localised glaciolacustrine accumulations. The two units record the last stages of waning ice, with deposition of melt-out till and small ponds forming on the surface of the ice. Settling of this material as the ice surface lowered led to faulting. Later periglacial activity resulted in an ice-wedge cast (Fig. 4.3b).

In summary the sequence represents two or more glacial advances over this part of the interlobate area. The first of these was an advance of the Rupanco lobe which sheared pre-existing fluvioglacial deposits and deposited a deformation till. The latter advance, probably by the Puyehue lobe, overrode and deformed more fluvioglacial material, this time leaving a melt-out till on top. These advances were extensive in comparison to most of the glacial advances recorded by moraines in the area. The moraines associated with the Puyehue II and Rupanco II advances do not impinge on this area; rather the lateral moraines simply run east-west along the north and south margins of the interlobate area. Therefore the tills described above are not derived from the Puyehue II or any younger advances. They must have been deposited during an advance to the Puyehue I and Rupanco I moraines.

Estero El Encanto

A 6m high section exposes two heterogeneous units which record glacial overriding in the area between Lago Puyehue and Lago Rupanco. The lower unit is made up largely of stratified sand and fine gravel with some coarser horizons (Table 4.2, Fig. 4.5). Layers of sand-sized pumice clasts are also common in the unit. At least one laminated clay horizon containing dropstones occurs near the top of the unit but only extends 40cm laterally. The unit is folded and faulted; normal faults occur with a spacing of c.50cm and mean throw of 50cm. The beds are also cut by minor thrusts directed to the NNW. The contact between the two units is listric and truncates bedding and folds in the lower unit. The maximum dip of the contact is 42°/166° but this decreases to a sub-horizontal orientation to the SSE and eventually fades away. The contact is also marked by a layer of cobbles at the base of the upper unit. The upper unit is stratified, sub-parallel to the lower contact. Beds are predominantly made

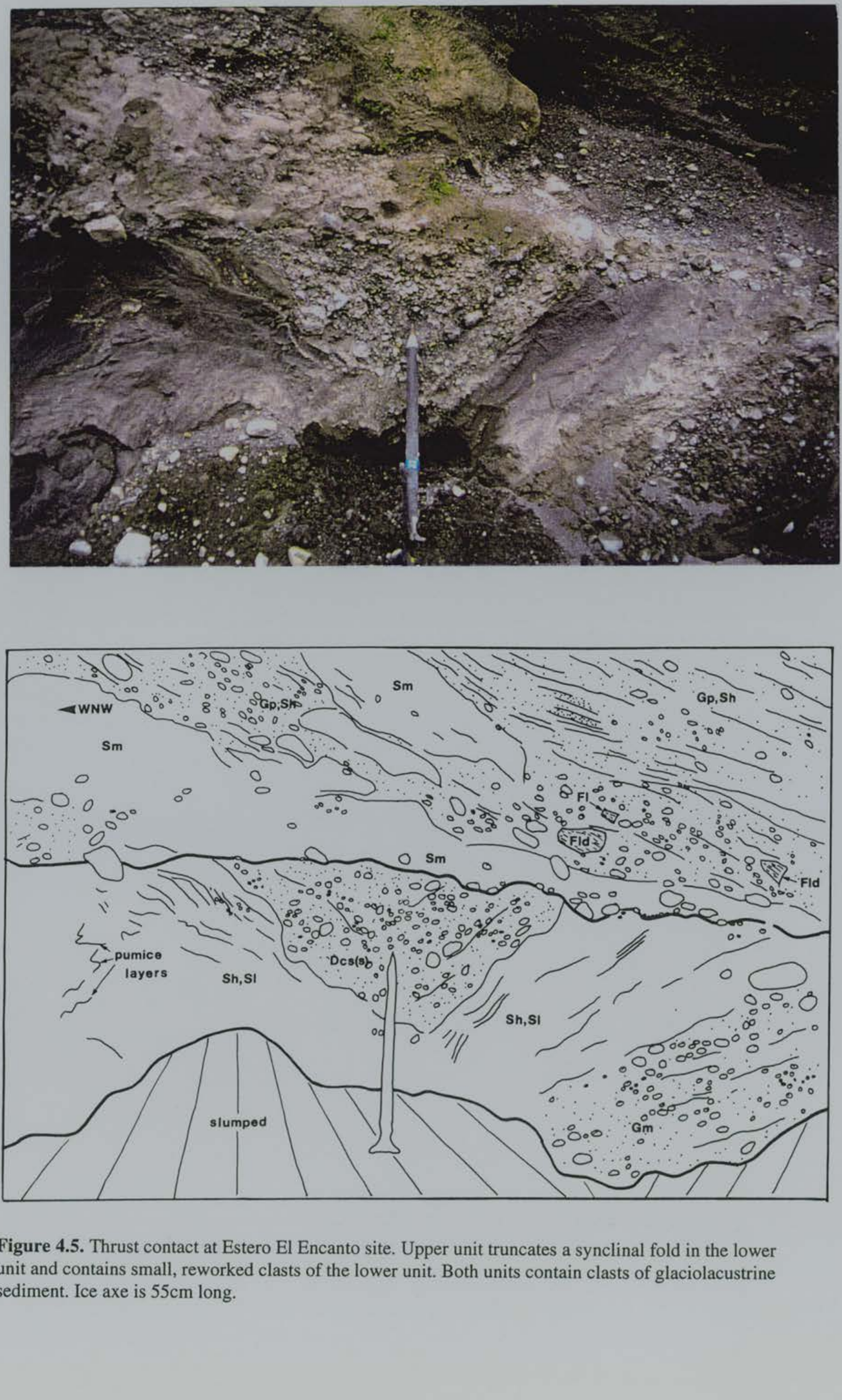


Figure 4.5. Thrust contact at Estero El Encanto site. Upper unit truncates a synclinal fold in the lower unit and contains small, reworked clasts of the lower unit. Both units contain clasts of glaciolacustrine sediment. Ice axe is 55cm long.

up of pebbly gravel . This unit also contains clasts of laminated clay very similar to those in the underlying unit. The clasts have no dominant orientation and are concentrated near the contact.

Interpretation

The interpretation of this section is difficult since both units have ambiguous features. The lower unit has several fluvioglacial characteristics such as extensive stratification, sand-rich matrix, clast support, good sorting in individual beds, and normal grading. However, the presence of clay laminae with dropstones implies some glaciolacustrine sedimentation. A possible explanations for this is that the unit was actually deposited by largely stagnant ice with abundant reworking by meltwater. Minor pools of water with melting ice blocks might have led to isolated pockets of glaciolacustrine sediment. It is unlikely that the unit is composed exclusively of melt-out till since the glaciolacustrine sediment implies subaqueous, rather than subglacial or subaerial, deposition. The key point is that this unit records glacial melting and retreat from this site.

The upper unit is probably a melt-out till. Deformation of the underlying unit, truncation of bedding and inclusion of clasts all point to glacial overriding at this site. This was then followed by melt-out of the ice and accumulation of gravel and sand sequences. Some of the better sorted and stratified horizons were probably also reworked by meltwater. The contact between the two units is a thrust plane, formed as the glacier overran the lower unit, partially eroding its topmost layers.

Río Coihueco

On the south side of the Río Coihueco there is a 20m-high section where the valley side is incised by the river. The lower 16m of this section is made up of bedded clast-supported sandy gravels, with clasts of pebble and cobble size. The finer beds show truncating relationships and there are also a number of cross-bedded sand lenses. Clasts are sub-angular to well-rounded and imbricated. Numerous, northwest-directed recumbent folds deform the gravel beds. At the top of the unit, the upper limb of one of these folds has been truncated by the overlying unit. Small thrusts cut some of the cross beds and other depositional contacts in the finer-grained beds near the top of the sequence. Above this is a 4m-thick unit of massive, grey, clayey diamict showing a strong sub-horizontal clast fabric. Clasts range up to small boulder size and some are striated and faceted. The unit extends over the top of the whole bedded unit. It forms an undulating ground surface which can be traced for several hundred metres to the northwest. The contact between the two units is undulating and sharp.

Interpretation

The lower unit is interpreted as fluvioglacial sediment which has been overridden, shearing the top of the sequence and emplacing a till directly above. The northwest-oriented folding of the fluvioglacial gravels implies they were overridden by ice flowing to the northwest. This is consistent with a logical extension of the former Rupanco lobe into the Pichilifaquen col. Since the till is not overlain by any other glacial sediments it seems likely that the overriding occurred during the advance to the Rupanco III moraine in the col, before final deglaciation of the Rupanco basin.

Summary

The interlobate area has had a complex history of glacial overriding and retreat. The chaotic nature of the mounds, channels and other landforms which make up the area plus the high lateral and vertical variability of the sediments all imply sedimentation was dependent on local topographic conditions and the input of meltwater. Topographic lows are occupied by late-stage glaciolacustrine sediment overlying interbedded tills and fluvioglacial sediments. Despite this, at least two advances over the interlobate area have been recognised, the first of which was by the Rupanco lobe. Fluvioglacial sediments south of the Pichilifaquen col were overridden and deformed by the advance to the Rupanco III moraines in the col.

4.4. Sections recording former lake levels

Puente Nilque

The Puente Nilque section is cut into a terrace graded to the Puyehue IV ridge moraine on the south shore of Lago Puyehue. The surface of this outwash plain grades to 12m above present lake level. Two units separated by an unconformity are exposed (Fig. 4.6, Table 4.3). The lower unit is composed of bedded sand dipping 24°/312°. The sands contain granules and pebbles and show normal grading. Individual beds are 1cm to 10cm thick and listric (concave-up). The bedded sands are unconformably overlain by horizontally stratified granules, pebbles, cobbles and sand lenses. The unit coarsens upwards from coarse granules with pebbles to cross-bedded cobble and pebble beds (Fig. 4.6a). The clasts in the unit are sub-rounded to well-rounded and moderately sorted. Clast imbrication is not strong in any single direction but there is a marked absence of clasts dipping to the northwest quadrant (Fig. 4.6b).

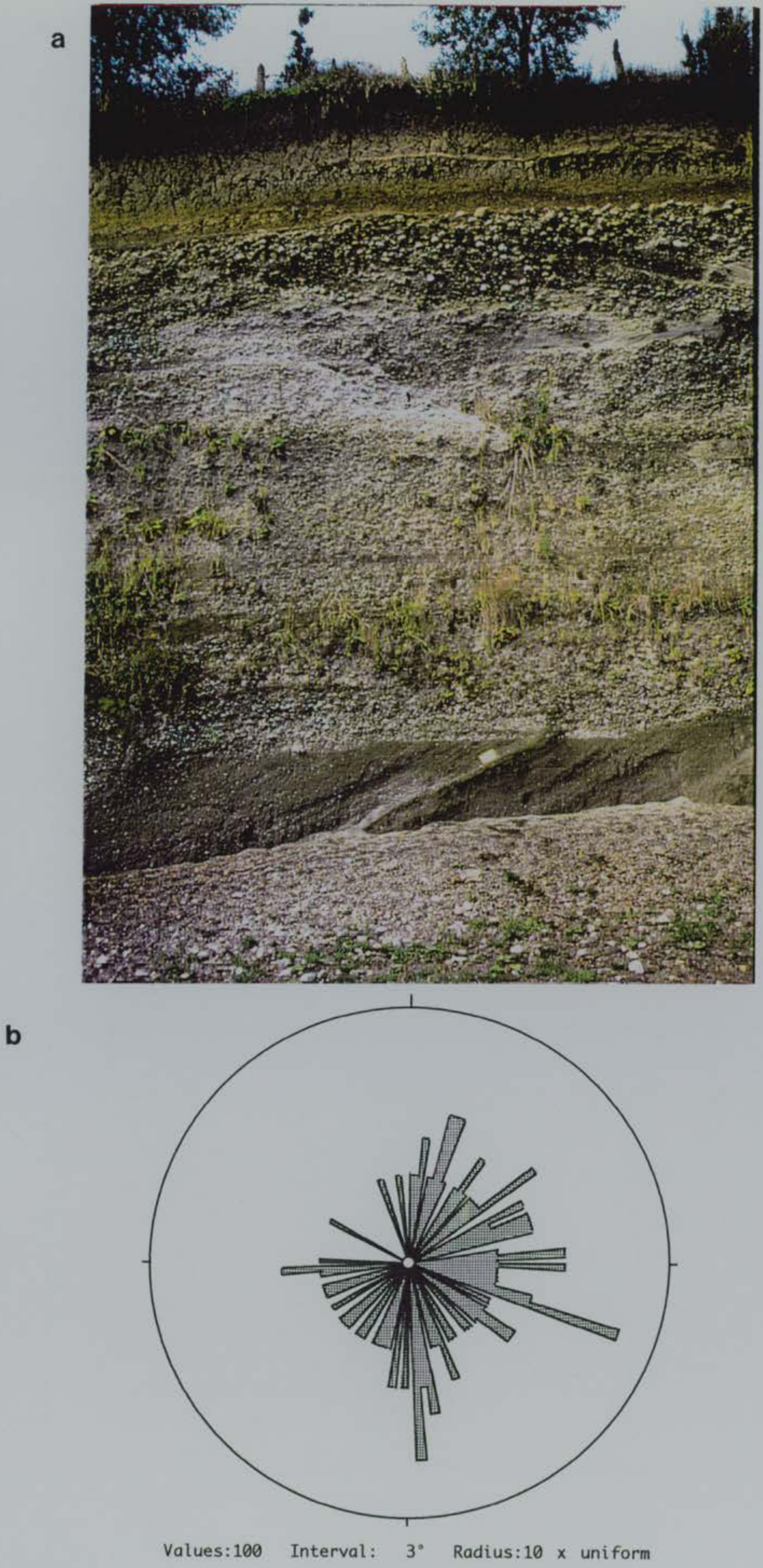


Figure 4.6.. Puente Nilque site
(a) Photograph of deltaic foresets overlain with an erosional unconformity by horizontally stratified fluvioglacial sediment. The top outwash surface grades to both the Puyehue IV moraine and the Rupanco III moraine in the Pichilifaquen col.
(b) Stereogram of imbrication in the fluvioglacial sediment. No dominant trend is visible but there is a marked absence of clasts dipping to the northwest quadrant. This suggests palaeocurrent may have been directed towards the northwest.

Table 4.3. Sedimentological data from Puente Nilque
Geomorphological Context: Section into outwash plain which grades to the Puyehue IV moraine and Rupanco III moraines on the south shore of Lago Puyehue.
Secction Dimensions: 12m high, 80m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
2 [8-10]	grey	bedded, lenses	l: unconformable u: parallel to ground surface	2-80 [granule-pebble]	poor, sub-rounded to well-rounded	medium sand to coarse sand, moderate to poor, none	imbrication	clast	fluvioglacial (delta topsets)
1 [3]	grey	bedded	l: not exposed u: unconformable	2-16	moderate, rounded	fine sand to coarse sand, moderate, normal	none	matrix	delta foresets

Table 4.4. Sedimentological data from Puerto Chalupa
Geomorphological Context: Section into north shore of Lago Rupanco, 20m above present lake level
Section Dimensions: 3m high, 30m long

Unit No. [Thickness] (m)	Colour	Structures	Contacts (1=lower, u=upper)	Clasts		Matrix	Fabric	Support	Interpretation
				Size (mm) [Range (Mode)]	Sorting, Roundness, Shape	Size, Sorting, Grading			
5 [1]	grey	fines upwards	l:depositional u: ground surface	3-50 [pebbles]	excellent, well-rounded,various	n/a	strong horizontal alignment	clast	beach
4 [0.8]	grey	none	l:depositional u: depositional	2-100 [pebble]	moderate, sub- to well-rounded, some bullet-shaped	fine sand to coarse sand, locally well-sorted, none	horizontal alignment of clasts	matrix	till
3 [0.6]	yellow	bedded	l: depositional u: depositional	2-40 [pebble]	moderate, sub-angular, various	fine sand to coarse sand, locally well-sorted, none	none	matrix	(glacio)fluvial
2 [0.6]	yellow	bedded, x-bedded	l: depositional u: depositional	n/a	n/a	fine sand to coarse sand, locally well-sorted, none	none	matrix	(glacio)fluvial
1 [2]	brown	laminated, intensely normal and reverse faulted, dropstones	l: not exposed u: depositional	20-50 [pebble]	poor, sub-rounded, various	clay to fine silt, locally excellent, normal	none	matrix	glaciolacustrine

Interpretation

This sequence is interpreted as a prograding delta. The lower unit shows many of the features of delta foresets such as a consistent lakewards dip, predominantly sand-sized material and graded bedding. The topset beds are composed of fluvioglacial material, probably derived from Puyehue IV and the Pichilifaquen low ridges. Progradation is shown by the thick foreset sequence as well as the coarsening-up in the fluvioglacial unit. Since so few clasts are imbricated to the northwest this suggests that palaeocurrents were probably directed towards this direction. This delta is useful for reconstructing former lake levels since it shows that at the time when the Puyehue IV moraine and the Laguna Pichilifaquen moraines were formed Lago Puyehue was c. 12m above its present level.

Río Pescadero

To the east of the Puyehue IV moraine, where the Río Pescadero discharges into Lago Puyehue there is a section exposing a similar sequence to the Puente Nilque section. It is cut into a flat-topped landform whose surface lies 22m above Lago Puyehue and dips towards the lake. Six metres of lakeward-dipping pebbly sands are overlain unconformably by a 4m sequence of horizontally stratified and cross-stratified pebbly gravel, with cobbles and sand, which coarsens upwards from pebbly sand to bedded pebbles and cobbles. The sequence is undeformed.

Interpretation

Like the Puente Nilque section this section records a prograding delta. However, this delta cannot be linked to any particular glacial event - it lies within the Puyehue IV limit as an isolated feature and is not graded to any glacial landforms. The Río Pescadero carries very little bedload and it is unlikely that it would construct a delta under present conditions. Therefore, the sediment was probably derived from a stream reworking recently deposited glacial sediments, soon after a glacial advance. This is supported by the fact that the deltaic sediments are undeformed and thus are likely to post-date an ice advance to Puyehue IV. It was probably deposited by the Río Pescadero where it discharged into a lake c. 22m above present. A reconstructed Lago Puyehue at 22m above its present level would extend westwards through several gaps in the Puyehue III moraine and would only be dammed by the Puyehue II moraine. There is no sedimentological or geomorphological evidence for this. Thus, it seems unlikely that the delta records a former level of Lago Puyehue. Rather, a small ice-marginal lake may have developed on the south side of the glacier, dammed between the glacier terminus and the Puyehue IV moraine. This is supported by the presence of an erosional bench on the proximal slope of the adjacent moraine at 19m above Lago Puyehue. No other landforms around the lake record any shoreline at this level.

Piedras Negras

The shoreline of Lago Rupanco shows a number of features recording higher lake levels. The most prominent of these is a 15-20m thick sequence of sandy gravels at Piedras Negras, on the south shore of the lake. These sands have listric bedding and dip of 16°/310°. Most clasts are sub-angular and oriented parallel to bedding. The whole sequence is undeformed and shows no grading. The top of the sequence is a lakeward-dipping planar surface 30m above present lake level.

At Puerto Chalupa on the north shore, 20m above present lake level there is an exposure of matrix-free granules, pebbles and cobbles which are dominantly well-rounded (unit 5 in Table 4.4). The clasts show a strong horizontally-aligned fabric and fine upwards from cobbles to fine granules through the 1m thickness of the unit. This unit overlies a sequence of till and fluvioglacial sediments.

Interpretation

The Piedras Negras site is interpreted as the foreset sequence of a delta which has built-out into a former Lago Rupanco 30m above the level of today. A higher lake level is also recorded by the unit at Puerto Chalupa which is interpreted as beach sediment. However, this is at a slightly lower altitude and may have formed as the level of Lago Rupanco dropped. Both sites are within the Rupanco III limit so the 20-30m shoreline must post-date this advance.

Summary

Both Lago Puyehue and Lago Rupanco were formerly at higher levels during the last glaciation. The deltaic sediments at Puente Nilque can be linked to a particular glacial event when the Puyehue glacier lobe reached the Puyehue IV moraine, contemporaneous with the advance of the Rupanco lobe to the Pichilifaquen low ridge moraines. The higher level of Lago Rupanco post-dated the Rupanco III advance as undeformed deltaic sediments occur within this limit.

4.5. Sections recording relationship of glacial and volcanic activity

Río Chichichiree

The Río Chichichiree section exposes 2-3m of coarse sediment of the Puyehue II outwash plain overlying a yellow laminated unit (Fig. 4.7). The lower unit is composed predominantly of clay but contains clasts up to fine granules. Fragments of pumice are common but a variety of clast lithologies

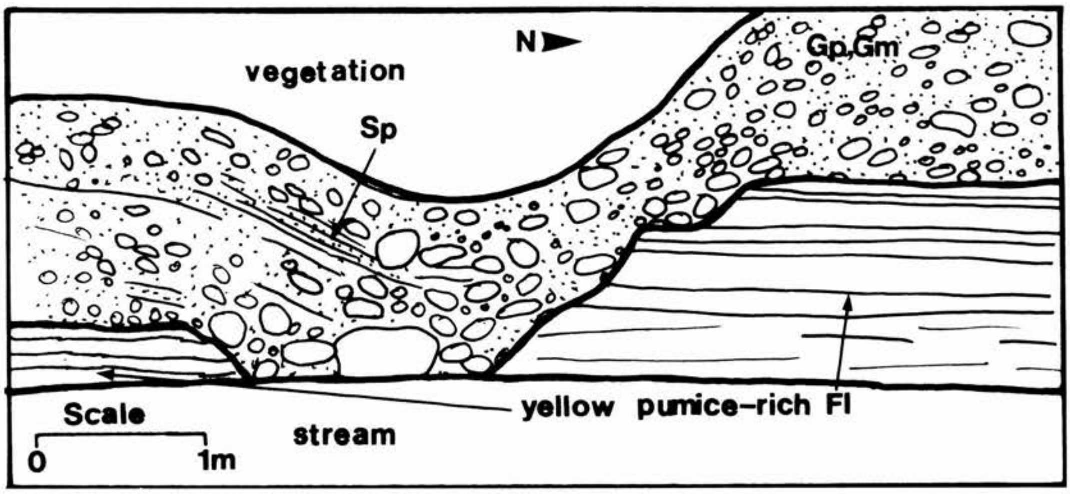


Figure 4.7. Sketch of Lahar at Rio Chichichiree site. Yellow-brown laminated lahar is sandwiched between two fluvioglacial units. Topmost outwash grades to the Puyehue II moraine. The lahar can be traced to the south.

are also present. The laminations are from 1-8mm thick and are unconformably overlain by the unit above. This is composed of sandy gravel, including pebbles and cobbles plus some boulders up to 50cm across. Clasts are predominantly sub-rounded to rounded but some of the smaller particles are angular. Clasts in the lower part of the unit are coated in yellow clay. The unit is cross-bedded shows strong imbrication and is clast-supported.

To the south of the Río Chichichiree section there is an area of undulating mounds and hollows with a relief of 5-10m. This is directly underlain by an extensive >5m thick yellow deposit containing abundant fragments of pumice clasts up to 10 cm across and some rounded clasts of volcanic lithologies similar to those in nearby glacial deposits. The topmost parts of the unit are finely laminated but no overall grading exists.

Interpretation

The morphology of the top surface of the yellow unit, its distribution over an extensive part of the area to the northwest of Lago Puyehue, its pumice content and the variation between a massive lower part and laminated upper part imply that the yellow unit is probably a lahar. The low relief mound and hollow topography is particularly diagnostic of lahars in this part of Chile and has been termed 'cerillos' (MacPhail, 1973). The overlying sediment at the Río Chichichiree site is fluvioglacial. It makes up the outwash plain, is cross-bedded, imbricated and clast-supported. The early stages of deposition of the unit eroded the top of the lahar and this probably explains the yellow clay on the clasts. The outwash plain grades to the Puyehue IIA moraine but it is not clear which of the Puyehue II sub-stages deposited the outwash. Meltwater from Puyehue IIB and/or Puyehue IIC may have discharged through the Puyehue IIA ice-contact slope and reused the outwash plain. Thus, the lahar must predate the Puyehue IIC advance but may have predated the Puyehue IIA advance. Corvalan (1974) described a lahar exposed over a wide area northwest of Lago Puyehue and close to Osorno. Geochemical analysis showed the lahar was derived from Volcan Puyehue. Geophysical soundings also detected a 13m-thick lahar below 10m of fluvioglacial outwash at El Coihue, close to the Puyehue I moraine. This was attributed to the same eruption but was not directly sampled. A mastodon tooth enclosed in the lahar near Osorno yielded a radiocarbon date of 18,700±900 (Corvalan, 1974). If the lahar detected at El Coihue is the same unit then this provides a maximum limiting date for deposition of the Puyehue II outwash. Similarly, if it could be tied to the lahar at the Río Chichichiree site then this would also provide a maximum for the overlying outwash. However, no published geochemical data for the dated lahar exist so these units cannot yet be correlated.

4.6. Summary

Sediments in the interlobate area have shown that the area was overridden by at least two glacial advances, the first of which was by the Rupanco lobe. These imply an ice extent greater than that indicated by most of the moraines. In addition there is evidence of higher lake levels than present. Lago Puyehue was maintained at a level 10m higher than present after the Puyehue III advance, and a small ice-marginal lake may have developed against the southern part of the Puyehue IV moraine. Lago Rupanco was at a level 30m higher than present after the Rupanco III stage. Volcanic activity also occurred between sub-stages of the Puyehue II moraine and at least one lahar was deposited northwest of Lago Puyehue.

Chapter 5: Chronology of the Puyehue and Rupanco glaciers

5.1. Introduction

This chapter presents a glacial chronology of the Puyehue and Rupanco glacier lobes. It draws on the geomorphological and sedimentological data presented in earlier Chapters to establish a relative chronology of advance and retreat of the two glaciers. The relative chronology is well-constrained and the positions of the glacier margins during successive advance and retreat can be established. Radiocarbon dating of the sequence then allows some of the glacial advances to be dated.

The retreat behaviour of the glaciers is more difficult to establish than the timing and extent of advances. For many of the glacial events recorded in the Puyehue and Rupanco basins there are commonly more lateral moraines than terminal moraines. This is probably because the lateral moraines record positions of the ice margin during the initial stages of glacier retreat, while geomorphic evidence of former retreat positions of the termini is now obscured by the lakes. Any geomorphic evidence of retreat after the early advances has been obliterated by subsequent advances. To judge from the last retreat phase of the Puyehue glacier, deglaciation was accompanied by stillstands and minor readvances within, and immediately east of, the lake basin. In the Rupanco basin there is little evidence of significant stillstands during retreat.

5.2. Relative chronology of the Puyehue and Rupanco glaciers

5.2.1. Puyehue I and Rupanco I Stages

The consistent alignment of discontinuous fragments delimits the extent of the advance of the Puyehue I stage and allows the margin to be reconstructed with some confidence (Fig. 5.1a). The nature of the advance is difficult to establish because of the degree to which segments of the moraine have been removed. The glacier extended several kilometres further than any subsequent advance and covered the interlobate area with ice. The Rupanco I limit is less well-defined than Puyehue I but the glacier extent can still be reconstructed from the remaining moraine fragments (Fig. 5.1a). Like Puyehue I this is the most extensive advance and the two moraine arcs intersect close to the Quebrada Honda Channel.

On the basis of relative weathering, the Puyehue I and Rupanco I tills apparently have different ages. The weathering rinds of volcanic clasts in most moraines around Puyehue and Rupanco are <1 mm. The exception to this is Rupanco I which contains clasts with rinds up to 8 mm and a mean rind thickness of 1.5 mm. Porter (1981) observed that deposits of the last glaciation are essentially

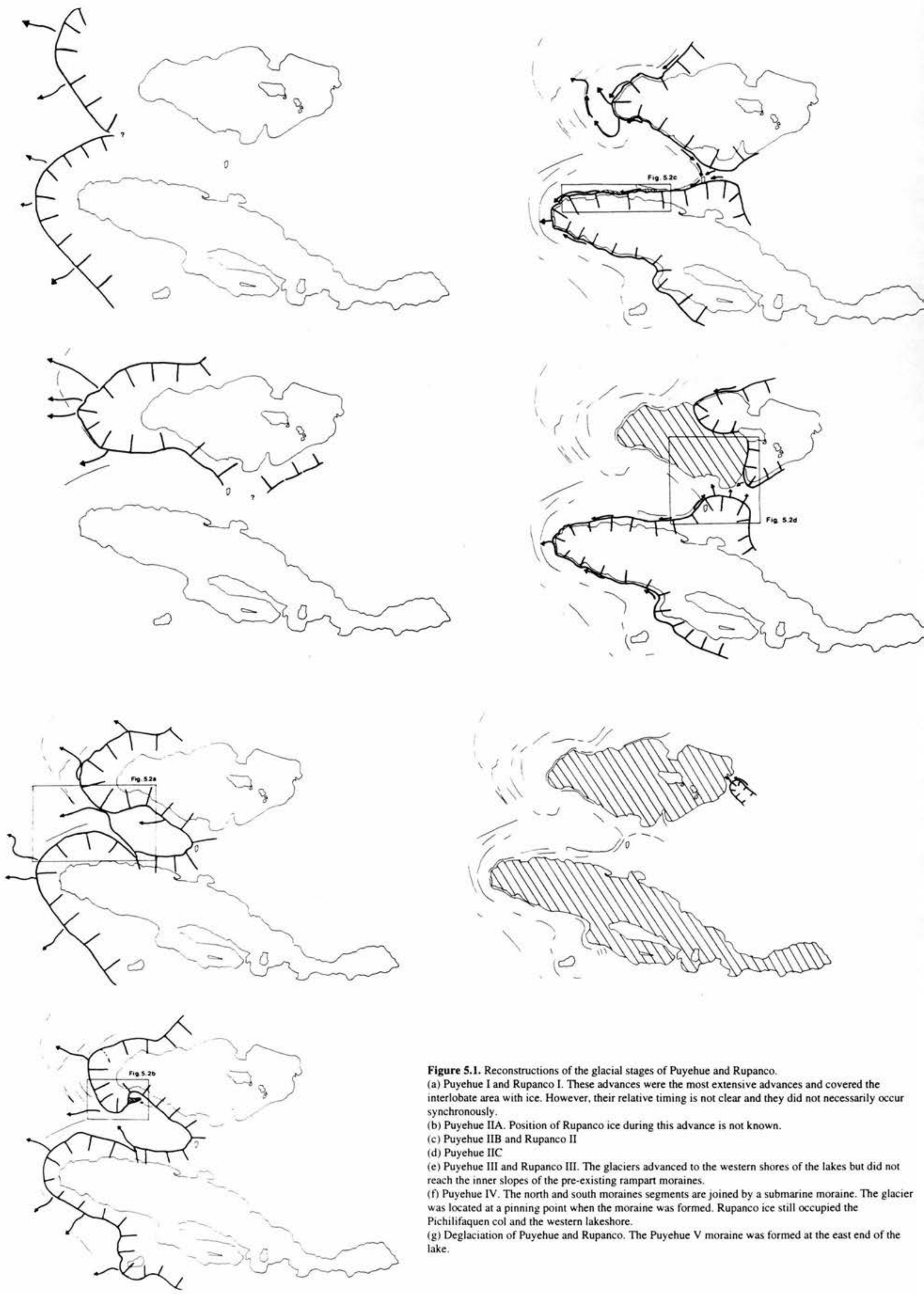


Figure 5.1. Reconstructions of the glacial stages of Puyehue and Rupanco.
(a) Puyehue I and Rupanco I. These advances were the most extensive advances and covered the interlobate area with ice. However, their relative timing is not clear and they did not necessarily occur synchronously.
(b) Puyehue IIA. Position of Rupanco ice during this advance is not known.
(c) Puyehue IIB and Rupanco II
(d) Puyehue IIC
(e) Puyehue III and Rupanco III. The glaciers advanced to the western shores of the lakes but did not reach the inner slopes of the pre-existing rampart moraines.
(f) Puyehue IV. The north and south moraines segments are joined by a submarine moraine. The glacier was located at a pinning point when the moraine was formed. Rupanco ice still occupied the Pichilifaquen col and the western lakeshore.
(g) Deglaciation of Puyehue and Rupanco. The Puyehue V moraine was formed at the east end of the lake.

unweathered (Table 5.1) and so on this basis all of the moraines, with the possible exception of Rupanco I, date from the last glaciation. Volcanic clasts in the Puyehue I till have no visible weathering rinds and ring loudly when struck with a hammer. The till is indistinguishable from the other Puyehue tills and outwash on the basis of relative weathering so probably derives from the same (Llanquihue) glaciation. The thicker rinds of Rupanco I suggest that it may be of substantially different age to Puyehue I and to the rest of the Rupanco moraines. Comparison with Porter's (1981) weathering criteria for distinguishing deposits of different glaciations shows that it may date from the Santa Maria glaciation, but the results do not preclude the possibility it dates from early parts of the Llanquihue glaciation.

Glaciation		Llanquihue	Santa Maria	Río Llico	Caracol
Weathering rind thickness (mm) of volcanic clasts in upper parts of till (n=20)	Mean	0.5	2	10	17
	Range	0-2	1-6	6-14	13-21

Table 5.1. Relative weathering criteria for distinguishing drifts of different glaciations (from Porter (1981)).

In summary the relative timing of Rupanco I and Puyehue I is not entirely clear but it is possible that the Rupanco I moraine substantially pre-dates all other Puyehue and Rupanco moraines. Due to the poor dating control on these moraines they are difficult to compare to the other advances in the Puyehue and Rupanco basins and to chronologies elsewhere in the Lake District.

5.2.2. Puyehue II and Rupanco II Stages

The Puyehue II and Rupanco II moraines are rampart moraines with similar morphologies. They are both constructed from closely-spaced moraines, forming amalgamated sequences. Geomorphological relations demonstrate that some of the advances which constructed the two ramparts were synchronous. One key difference between the two moraine complexes is that Puyehue II was constructed by more advances than the Rupanco II moraine. The Puyehue II moraine has been divided into 3 ice contact slopes (A, B and C). Each of these is discussed separately because there were significant changes in glacier behaviour and extent between the three stages. The Rupanco II moraine is made up of two, or possibly more, ice contact slopes but these are closely superimposed one on the other and cannot be clearly sub-divided.

Each of the three Puyehue II stages constructed a terminal moraine limit. Where these moraine limits are continuous the glacier terminus position can be reconstructed confidently. There are gaps between some moraine segments but the gaps are relatively small and the moraines have a consistent alignment on either side so the glacier extent can be interpolated easily. The lateral limits of the glacier during each advance are more difficult to identify separately. A broad ice-contact slope can be traced around the interlobate area, from the Puyehue II terminal limits eastwards along the south shore of Lago Puyehue and through the Pichilifaquen col into the Rupanco basin. The continuity of this limit, the convergence of each of the terminal limits towards it, and the absence of any other rampart lateral moraines mean that it was probably occupied during each of the Puyehue II stages. There are two implications of this reconstruction of the lateral limit. First, during the Puyehue II stages the Pichilifaquen col was covered with ice derived from Puyehue or Rupanco, or both. The second implication is that the glacier did not override the interlobate area during the Puyehue II stages.

The Puyehue IIA moraine demonstrates that during the earliest advance to the Puyehue II moraine the glacier extent was significantly less than the Puyehue I advance but the southern part of the terminus impinged upon, and was parallel to, the Puyehue I moraine (Fig. 5.1b). This is particularly evident in the zone of confluence of the Rupanco and Puyehue moraine belts close to the Quebrada Honda channel where the moraine limits are coincident. The extent of the Puyehue IIB stage was less than Puyehue IIA but the glacier margin paralleled the previous advance (Fig. 5.1c). The Puyehue IIC ice-contact slope is the innermost of the Puyehue II rampart moraine and so its precise extent is well-defined by a continuous morphological limit (Fig. 5.1d). At the former southwest margin of the glacier the ice-contact slope has a prominent embayment which shows that the glacier had a prominent lobe which pushed southwest towards the Los Esteros site. To the east of this embayment there is a series of horizontal benches on Puyehue II adjacent to a flat-bottomed depression. The benches around the flat-bottomed basin imply that the lobe of ice pushing south dammed a lake (Fig. 5.2a). In summary, the Puyehue II rampart moraine was constructed by 3 or more advances to similar positions to the west of the present-day lake.

Each of the Rupanco II advances reached similar limits. The terminal limits grade into a single lateral limit in the same way as the Puyehue II moraine. The northern margin of the glacier occupied the steep ice-contact slope along the north shore of Lago Rupanco and can be traced continuously to its confluence with the Puyehue ice in the Pichilifaquen col. Along its southern margin the glacier had a lobe extending into the depression now occupied by Laguna Bonita. At the Pampas Grandes site the organic sediments incorporated into the moraine show that the lobe overrode a small lake or bog, possibly a forerunner of Laguna Bonita formed between glacial advances.

The meltwater channels around the Quebrada Honda channel show that the maxima of the Puyehue IIC stage and one of the Rupanco II stages were synchronous. The fluvioglacial terrace banked up against the Puyehue IIB ice-contact slope and grading into the Quebrada Honda channel was fed by a meltwater stream from the crest of the Rupanco II rampart at Bellavista (Fig. 5.2b). When the glacier

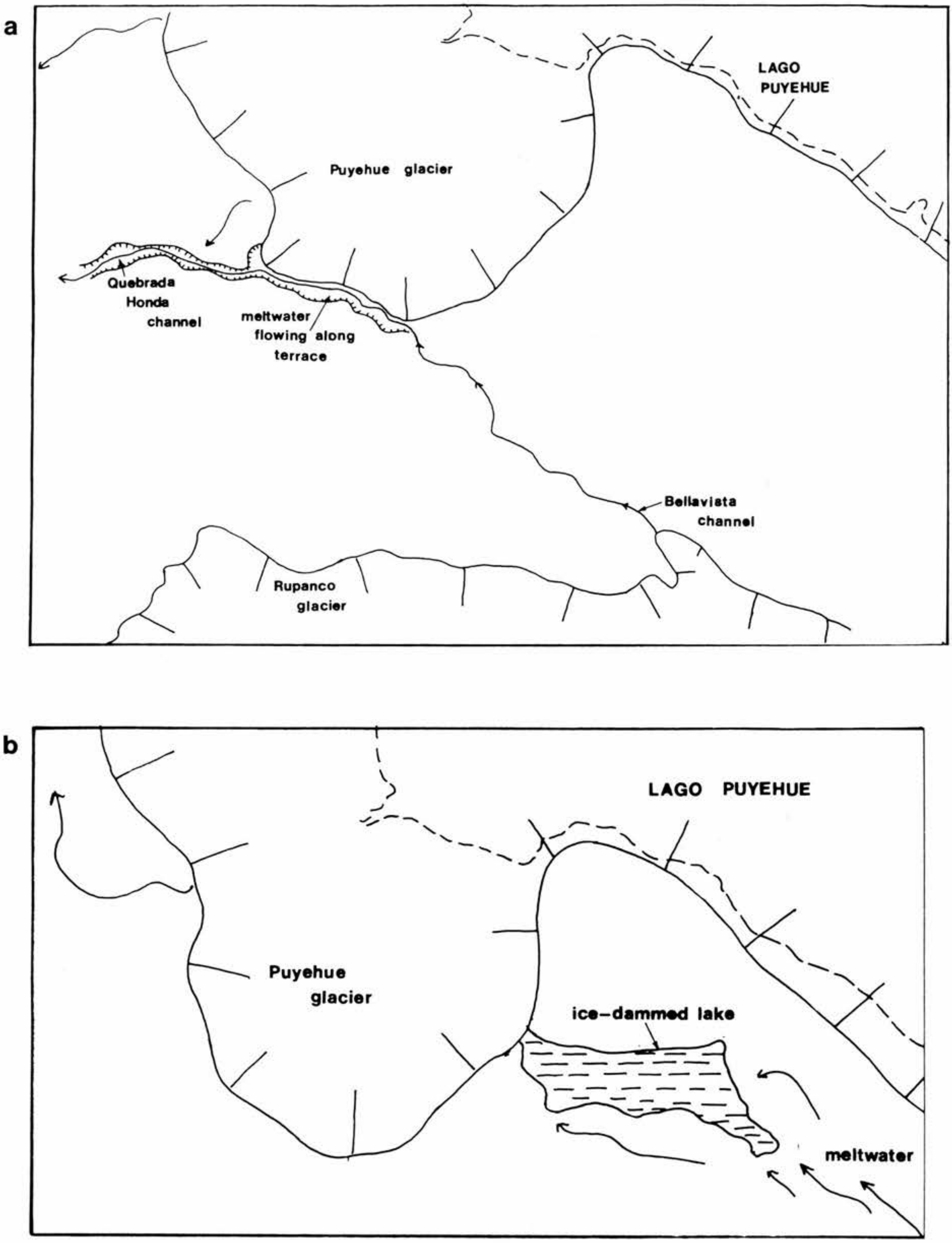
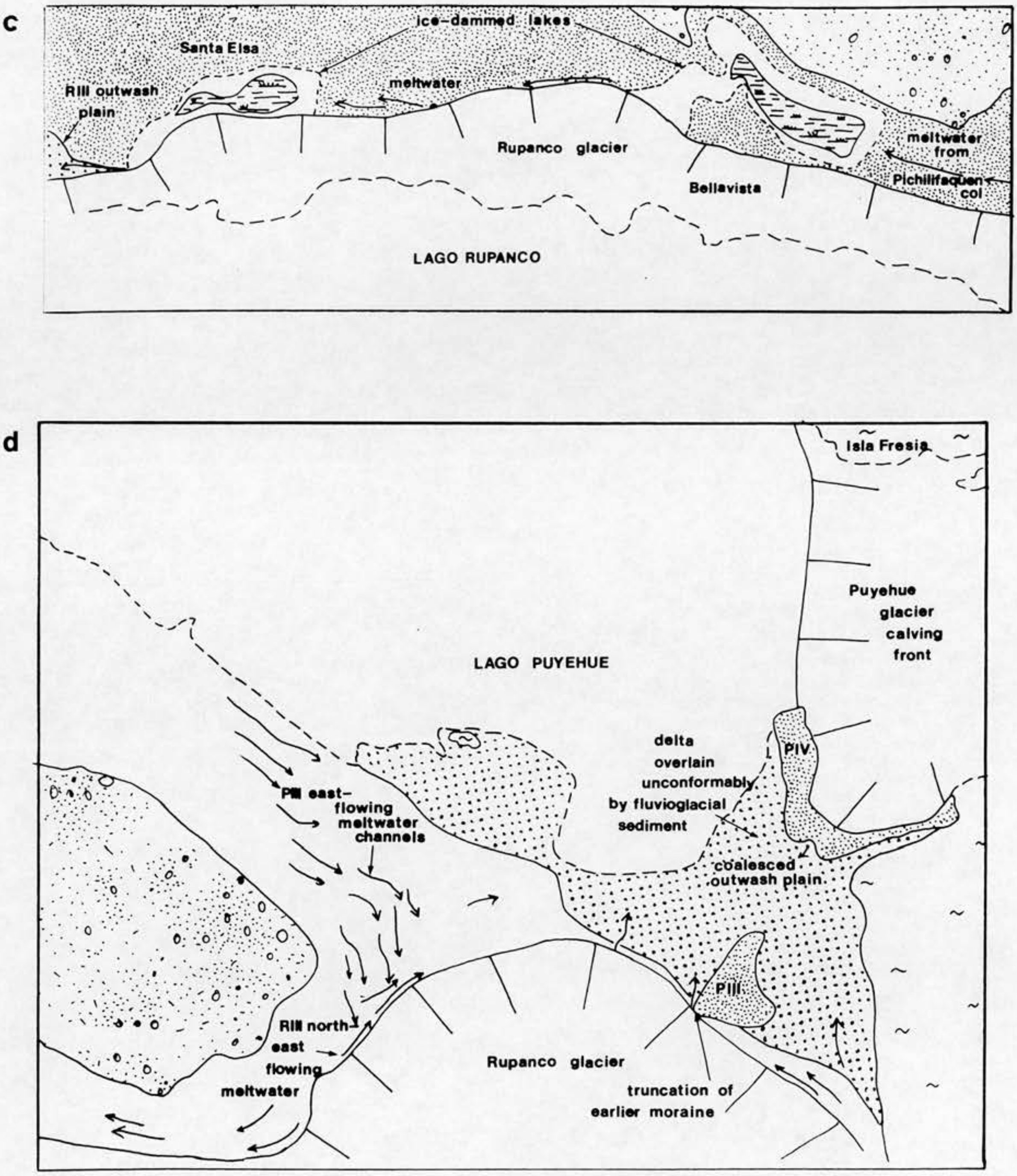


Figure 5.2 Detailed reconstructions of key parts of the relative chronology of the Puyehue and Rupanco glaciers.
(a) Geomorphological relations demonstrating synchrony between the Puyehue IIB and Rupanco II stages. The channel leading from the Bellavista ice contact slope grades into a narrow lateral terrace cut into the proximal slope of Puyehue IIB. This terrace grades into the mouth of the Quebrada Honda channel. Water only flowed along this terrace when the Puyehue glacier was directly against it, otherwise the water flowed directly down the Puyehue IIB slope. Thus, meltwater was discharged from the Rupanco glacier during the Rupanco II stage and flowed along the front of the Puyehue glacier during the Puyehue IIB stage.
(b) Ice-dammed lake south of Entre Lagos during the Puyehue IIC stage.



(c) Ice-marginal lakes on the north shore of Lago Rupanco. The lakes were dammed between the Rupanco II moraine and the Rupanco glacier during the Rupanco III stage. Lakes are recorded by flat-bottomed depressions surrounded by slopes with horizontal benches, and by glaciolacustrine sediments.

(d) Geomorphological relations in the Pichilifaquen col demonstrating asynchronous behaviour of the Puyehue and Rupanco glaciers. The Rupanco III moraines truncate the Puyehue III lateral moraine and meltwater channels. The outwash plain associated with Rupanco III is contiguous with the outwash from the Puyehue IV moraine and grades to the same level above Lago Puyehue.

retreated from the Puyehue IIB slope a new channel was cut directly downslope, bypassing the terrace and Quebrada Honda channel. The main channel intake could have only been used when the Puyehue glacier margin was directly abutting it since the intake is perched c.20m above the foot of the Puyehue IIB ice-contact slope.

In summary, both the Puyehue II and Rupanco II rampart moraines were constructed during a number of glacial stages. Meltwater relationships between the Bellavista channel and the Quebrada Honda channel show that at least one of the Puyehue II stages and Rupanco II stages were synchronous. However, the relative timing of the other stages is not known and there is no direct evidence to suggest they were synchronous.

5.2.3. Puyehue III and Rupanco III Stages

The Puyehue III stage is delimited by a single continuous ridge moraine at the west end of the lake (Fig. 5.1e). The glacier was significantly less extensive than during the Puyehue II stages. During the Puyehue III stage, a small number of lateral moraines and meltwater channels were formed along the shores of the lake and banked up at the base of the Puyehue II ice-contact slope. Most of the meltwater channels flow west and grade into the Puyehue III outwash plain but some flow east along the Puyehue III lateral moraines into the Pichilifaquen col. The Puyehue III outwash plain was deposited between the Puyehue III and Puyehue IIC moraines. All meltwater flowing across this plain continued into the proto-Río Pilmaiquen; the intakes of other channels through the moraines lie above the level of the plain and so must have been abandoned. The relict channel through present-day Entre Lagos grades to the same level as the prominent 10m shoreline around the lake. Thus, the proto-Río Pilmaiquen discharged from the lake through a slightly more southerly route than it does today. This channel would have been used after retreat from the Puyehue III moraine and may also have been used by meltwater flowing from the glacier during the Puyehue III stage.

The Rupanco III event formed a single ridge moraine along the lakeshore (Fig. 5.1e). Along the shores of the lake a series of closely-spaced lateral moraines was deposited on the existing Rupanco II ice-contact slope. Channels parallel to the lateral moraines show that meltwater flowed westwards down both north and south margins and was discharged onto the Rupanco III outwash plain and out through the proto-Río Rahue. Two flat-bottomed depressions containing glaciolacustrine sediment show that at least two ice-dammed lakes were formed along the northern margin of the Rupanco glacier during the Rupanco III stage. These are linked by a meltwater channel which can be traced continuously along the north shore of Lago Rupanco (Fig. 5.2c). The channels and lakes along this margin were probably partly supplied by meltwater derived from the southern margin of the Puyehue glacier. At some late stage the northern margin of the Rupanco glacier pushed into the Pichilifaquen col and formed the low moraines there (Fig. 5.2d). These moraines truncate a fragment of the Puyehue III lateral moraine. Moreover, the meltwater channels associated with the moraines truncate the east-flowing Puyehue III meltwater channels

5.2.4. Puyehue IV and concurrent Rupanco behaviour

The segments of the Puyehue IV moraine on the north and south shores of Lago Puyehue are linked by a submarine ridge. Bathymetric data show that the ridge runs from where the west end of the northern moraine segment reaches the lake, across to Isla Fresia in the middle of the lake and to the northern tip of the southern Puyehue IV moraine segment (Fig. 2.3). This ridge is probably a submarine moraine. The reconstruction of the Puyehue IV stage therefore shows the glacier had a calving front about halfway along Lago Puyehue (Fig. 5.1f). This calving front was in two segments, split by Isla Fresia. Puyehue IV outwash plains on both sides of the lake grade to 10m above present lake level demonstrating that the lake still maintained its higher level during the Puyehue IV stage.

The relations of the outwash from the Puyehue IV moraine and from the small Rupanco III moraines in the Pichilifaquen col can be used to infer the relative timing of the moraines. The two outwash units grade to the same former level of Lago Puyehue and have coalesced, implying they were formed at the same time (Fig. 5.1f). Moreover, the intersecting meltwater channels and moraines confirm that the Rupanco III moraine post-dates the Puyehue III moraine. Therefore the Rupanco and Puyehue glaciers displayed strikingly different behaviour. The Puyehue glacier had retreated from the Puyehue III limit to a new limit half-way up its lake basin whilst the Rupanco glacier was still advancing into the Pichilifaquen col to its Rupanco III limit (Fig. 5.2d).

The onshore and submarine parts of the Puyehue IV moraine are located at a 'pinning point' in the lake (Mercer, 1961). Pinning points are locations where calving glacier termini are stable. Calving glaciers cannot change their altitudinal extent in response to changes in the Equilibrium Line Altitude (ELA) and so respond by advancing or retreating to points where channel geometry changes such that the calving rate increases or decreases sufficiently to compensate for the change in ELA. At the Puyehue IV moraine location there was a step in the potential for calving where two narrow calving fronts on either side of Isla Fresia were more stable than a single, broad calving front across the full width of the lake. Thus, during retreat from Puyehue III or possibly as part of a later readvance the Puyehue glacier halted at this pinning point. The deformation of the northern part of the Puyehue IV moraine implies relatively high proglacial compression. Therefore, even if the moraine resulted from a stillstand during retreat there must have been at least a minor readvance.

5.2.5. Deglaciation of Puyehue and Rupanco

There are no terrestrial limits or bathymetric features along the lake east of the Puyehue IV moraine to suggest further stillstands. Any geomorphological evidence of the Puyehue glacier behaviour east of the lake has been obscured by subsequent fluvial activity and volcanic eruptions which have filled parts of the valley with fluvial sediment and up to 20m of lava. However, in a tributary valley close to the east end of the lake basin, leading up to Termas de Puyehue and Volcan Casablanca the Puyehue V moraine and a series of parallel meltwater channels shows that there was a stillstand during late-stage deglaciation of the Puyehue basin (Fig. 5.1g). This could have been related to temporary stabilisation of the glacier front as it withdrew from the lake and the rate of ablation was sharply reduced as a consequence. The outwash plain associated with this moraine grades to the 10m level of Lago Puyehue and shows that the higher lake level was maintained for some time after retreat from Puyehue IV.

There is only one site at which moraine limits were formed during deglaciation of the Rupanco basin. The series of oblique lateral moraines situated within the Rupanco III limit above Piedras Negras show that the glacier gradient steepened at this point. The oblique moraines were probably related to stabilisation of the southern margin at Peninsula del Islote, a potential pinning point, after calving retreat from the Rupanco III moraine. The moraines are steeper than other lateral moraines which is probably due to glacier thickening when a reduced calving rate was attained at the pinning point. After this the Rupanco glacier retreated with no stillstands. The eastern portion of the lake is deep and parallel-sided so the calving retreat was probably rapid. Unlike Puyehue there is no evidence of stillstands east of the lake so rapid deglaciation of the entire basin probably continued unabated after the lake became ice-free. Perched deltas, beach sediments and a bench cut into the proximal slope of Rupanco III show that following retreat from Rupanco III Lago Rupanco was maintained at a level 20-30m above present.

5.2.6. Post-glacial modification

Significant modification of many of the glacial landforms followed deglaciation and led to the present-day landscape. Incised terrace sequences and perched channels show that the level of both lakes lowered as their present outlets cut down through existing outwash terraces. Drainage from the main inter-lake spur cut through the Pichilifaquen col and joined the course of the Río Coihueco. Many former meltwater channels were further eroded by streams and many were linked by downslope erosion through the lateral moraines to give rise to the present step-like drainage network. The Río Lican formed a large delta on the north shore of Lago Puyehue, fed by streams from the southwest flank of Volcan Puyehue. Streams flowing into the north side of the lake eroded deep channels through the Puyehue III lakeshore moraine (e.g. Fig. 2.7). The Río Golgol deposited a thick sequence of fluvial gravels which is covered in places by lava flows derived from the valley flanks. The outwash terrace formed by the Puyehue V moraine was incised by the Río Pichichanleufu leaving only two fragments.

5.2.7. Summary and conclusions of relative chronology

The glacial landforms record at least 7 fluctuations of the Puyehue glacier and at least 4 fluctuations of the Rupanco lobe. The relative chronology demonstrates that the sequences are broadly similar but there are some key local differences in the behaviour of the glaciers:

- The moraines around both lakes are essentially unweathered and so date from the last glaciation. The main exception is the outermost Rupanco moraine fragment which may be older than the other moraines.

- The Puyehue and Rupanco moraine complexes are alike in their extent and some moraines have strikingly similar locations, morphologies and dimensions, specifically Puyehue III and Rupanco III.

- The relations of the Bellavista and Quebrada Honda meltwater channels to moraines in the two basins show that at least one of the advances to the Puyehue II and Rupanco II ramparts was synchronous

- The difference in the number of moraine ridges shows that the Puyehue lobe fluctuated more frequently than Rupanco, particularly during the formation of the Puyehue II rampart moraine.

- Landform relationships in the Pichilifaquen col show there was a lag between the initial retreat of the Puyehue lobe and that of the Rupanco lobe from their maximum positions after the Puyehue III/Rupanco III advance.

- The two lobes showed asynchronous behaviour during the Puyehue IV stage in that the Puyehue lobe had retreated half way up Lago Puyehue at the same time as the Rupanco lobe was advancing to its maximum Rupanco III extent.

- The pattern of moraines shows retreat of the Puyehue lobe was marked by stillstands or minor readvances whilst the Rupanco glacier retreated with only one stillstand.

Thus the landform relationships reveal both similarities and differences in behaviour which provide information on the relative responses of two closely adjacent glaciers which must have experienced the same climatic changes.

5.3. Radiocarbon chronology of the Puyehue and Rupanco glaciers

In order to gain a temporal dimension on glacier behaviour and to allow the results from the Puyehue-Rupanco area to be compared to other glacial chronologies, exposures were sampled for organic material to be radiocarbon dated. A total of 19 radiocarbon dates were obtained on material from sites around Lago Puyehue and Lago Rupanco (Table 5.2, Fig 5.3). Date determinations were carried out using either conventional techniques ('A'-prefix) or accelerator mass spectrometry (AMS) techniques ('AA'-prefix). Dates are reported uncalibrated and with errors of one standard deviation so there is a 68% probability that the measured age of the sample lies within the range given. The $\delta^{13}C$ values are quoted as departures from the Peedee belemnite and provide a measure of the ^{14}C fractionation between different materials. Thus, they allow the dates to be corrected for fractionation effects and all the raw dates have been normalised to $\delta^{13}C$= -25‰ (wood). Even for those samples showing the extreme lowest and highest $\delta^{13}C$ values this correction only amounts to c.90 years. The percentage of modern carbon is the actual value measured on the accelerator relative to the activity of 'modern' carbon (defined as 1950 AD carbon, or more precisely as 95% of the ^{14}C activity of carbon in the NBS oxalic-I standard (Tim Jull, *pers. comm.*)). Dates are identified as maximum or minimum limiting dates. Clearly, basal core dates are minimum estimates but several maximum dates were obtained from organic material overridden or reworked during glacigenic sedimentation. The geomorphological context of each date is also given and in particular the glacial stage with which it is associated. Individual core stratigraphies and the depths of each radiocarbon sample are given in Figure 5.4.

5.3.1. Puyehue I

There are no radiocarbon dates on this advance so its age can only be estimated from relative weathering criteria. These suggest a last glaciation age but it is not possible to constrain this more closely.

5.3.2. Puyehue II

The outwash graded to the Puyehue II moraine has been dated at three localities. The outwash directly in front of the Puyehue IIB moraine at Pilmaiquen contains a 1m-long clast of clays and silts with plant macrofossils (Fig. 3.2c). These yield an age of 19,355 BP, implying that the deposition of Puyehue IIB outwash was occurring after this date.

Laboratory Number	Sample Number	Site Name	Age (years B.P.)	$\delta^{13}C$, ‰ PDB	% Modern Carbon	Minimum or Maximum Limiting date	Geomorphological Context
AA-10316	C/21.1/1	La Capilla	12,810±110	-26.1	-	Maximum	Puyehue II outwash
AA-11751	C/21.1/6	La Capilla	15,890±175	-	0.1383±0.0030	Maximum	Puyehue II outwash
AA-9959	C/21.1/7	La Capilla	17,795±135	-	0.1091±0.0018	Maximum	Puyehue II outwash
AA-10317	C/23.1/1	La Mosqueta (Core)	11,110±100	-28.5	-	Minimum	Puyehue IIB kettle hole / moraine abandonment
A-7566	C/79.1/1	Pilmaiquen	19,355+905 -810	-23.2	-	Maximum	Puyehue IIB Outwash
A-7565	C/78.3/1	Puente Treguaco	19,700+180 -175	-24.6	-	Maximum	Lattermost stages of Puyehue II outwash (also minimum for lower outwash)
AA-10315	C/26.2/1	Pampas Grandes	32,460±600	-28.8	-	Maximum	Rupanco II moraine
AA-12149	C/65.1/3	Mayelhue (Core)	8,510±70	-30.5	0.3468±0.0029	Minimum	Rupanco II meltwater channel
AA-10929	C/1.3/1	Entre Lagos	≥47,000	-	0.0005±0.0011	Maximum	Puyehue III moraine
AA-9423	C/32.2/1	Entre Lagos	23,380±210	-	0.0544±0.0014	Maximum	Puyehue III outwash
AA-10320	C/24.6/2	Entre Lagos (Core)	10,630±95	-27.5	-	Minimum	Puyehue III outwash
A-6355.1	9/1/D	Entre Lagos (Core)	11,440±150	-28.3	-	Minimum	Puyehue III outwash
A-6823	C/27.1/7	Los Copihues I (Core)	16,390+415 -395	-29.2	-	Minimum	Puyehue II lateral meltwater channel
AA-11754	C/67.1/2	Los Copihues II (Core)	16,105±185	-	0.1347±0.0031	Minimum	Puyehue II lateral meltwater channel
AA-10318	C/41.1/1	Rio Rahue	6,860±130	-27.2	-	Maximum	Rupanco III moraine
A-6820	C/25.1/2	Pichilifaquen (Core)	8,950±200	-27.3	-	Minimum	Rupanco III meltwater channel + Rupanco deglaciation
AA-9960	C/40.5/1	Puente Nilque	3,235±55	-27.4	0.6684±0.0046	Maximum	Puyehue IV moraine
AA-11753	C/66.1/3	Termas de Puyehue (Core)	12,230±100	-	0.2181±0.0027	Minimum	PuyehueV lateral meltwater channel
AA-13760	C/23.7/6	Santa Ines (Core)	15,225±125	-28.4	-	Minimum	Interlobate area - minimum for Puyehue I and Rupanco I

Table 5.2. Radiocarbon Dates on material from sites around Lago Puyehue and Lago Rupanco.

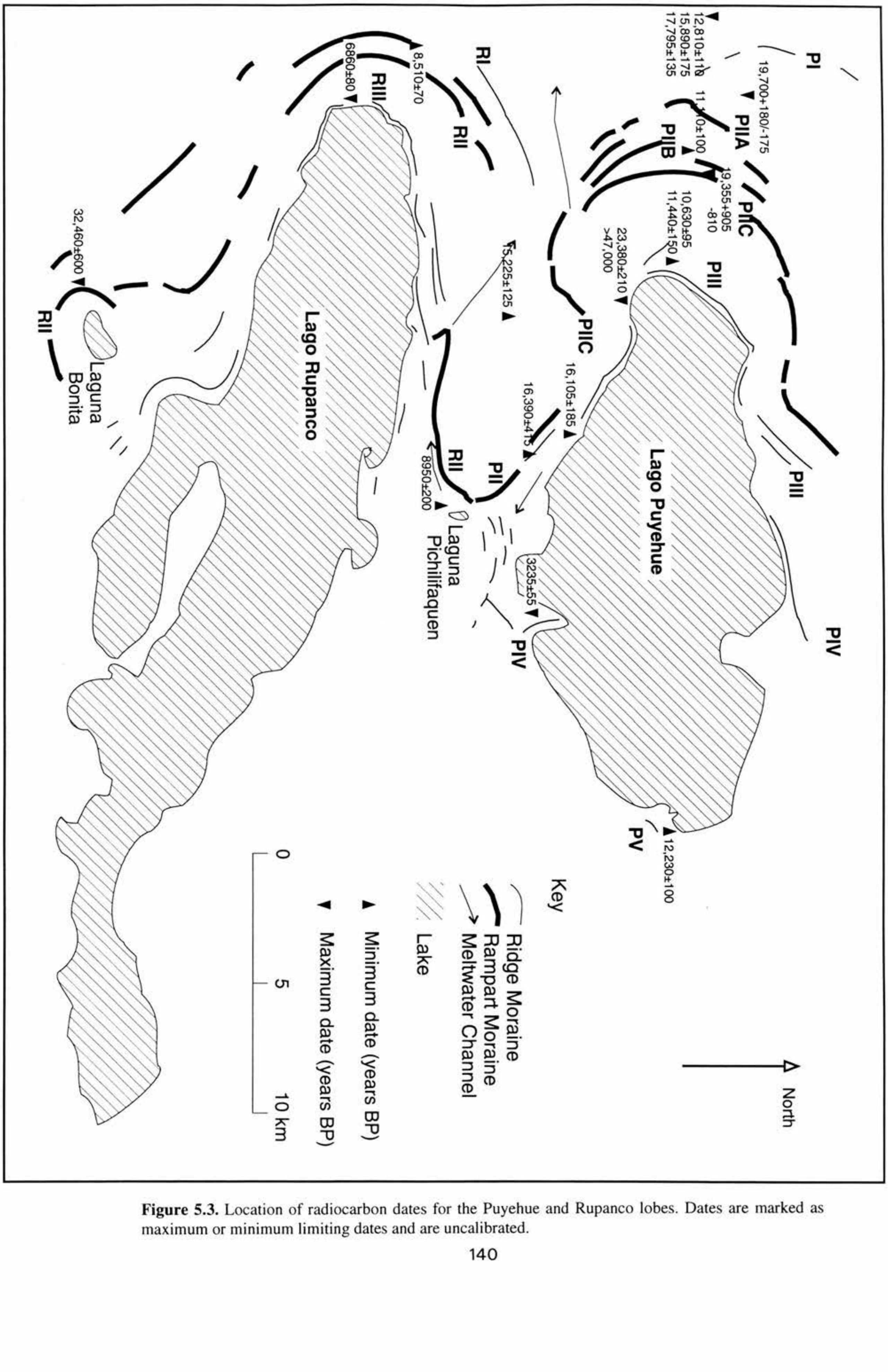


Figure 5.3. Location of radiocarbon dates for the Puyehue and Rupanco lobes. Dates are marked as maximum or minimum limiting dates and are uncalibrated.

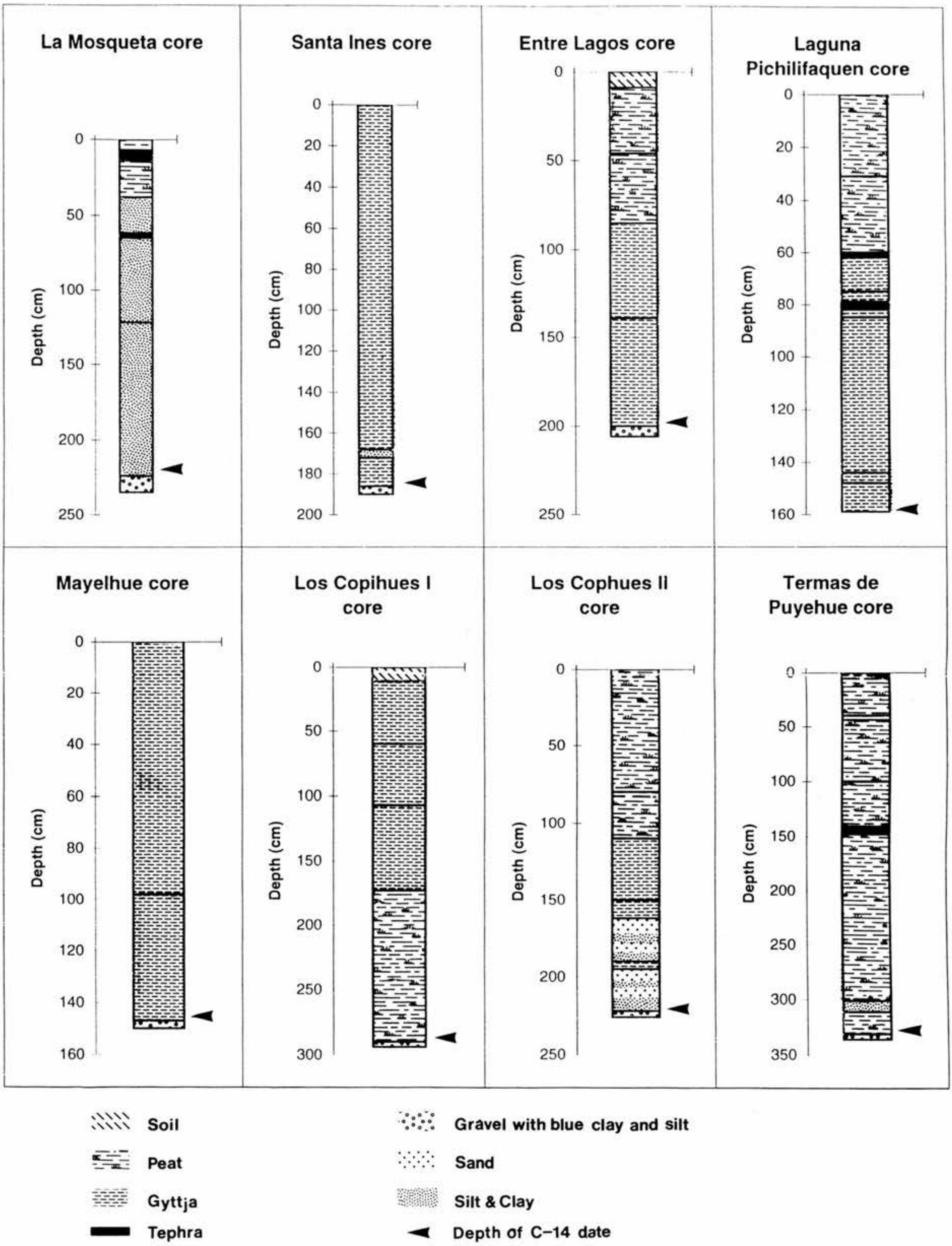


Figure 5.4. Core stratigraphies. The depths of samples taken for radiocarbon dates are marked.

Further west, at Puente Treguaco, two outwash units graded to the outer part of the Puyehue II moraine are separated by a unit of clays and silts with hollow-stemmed plant macrofossils, possibly reeds, in life position. The reeds at the base of the clays yield a date of 19,700 BP. The implication is that the lower outwash was deposited before this date and the upper outwash unit was deposited after this date. Thus, outwash deposition from Puyehue II was occurring both before and immediately after 19,700 BP. Since the reeds are in life position they have not been transported. If growth of the reed bed was terminated by deposition of the upper outwash unit then the date is a close maximum limiting age on the overlying outwash. It is difficult to trace the individual components of the Puyehue II outwash plain associated with each of the Puyehue II moraine stages. This is because meltwater discharging from each of the inner moraine stages flowed through a complex network of channels before forming an outwash plain beyond the outer parts of the moraine. The similarity of the date at Puente Treguaco to the date from the Pilmaiquen section suggests that the upper outwash could be associated with the Puyehue IIB advance even though it is not possible to trace this outwash back to a particular moraine.

The third site, at La Capilla on the Puyehue II outwash plain, five kilometres west of the Puyehue II moraine exposes fluvioglacial sediment containing armoured clasts of brown silt and fine sand. These clasts are up to 80cm along, occur strung along a single bed, and contain abundant casts of woody material (Fig. 4.2). Three samples close together in the same clast have afforded significantly different radiocarbon ages of 12,810, 15,890, and 17,795 BP. The range of c.5000 years from the same sample suggest that these dates are suspect. The surface of the clast was cleaned back over 20cm in the field but it is possible that rootlets of moss growing on the section face may have contaminated the samples, yielding anomalously young dates.

Minimum limiting dates for the Puyehue II moraine have been obtained from three sites. A kettle hole on the crest of the Puyehue IIB rampart yielded a basal date of 11,110 BP directly above blue clay and gravel. Older minimum ages come from two cores taken from near Los Copihues on the south side of Lago Puyehue. Basal dates taken from two different lateral meltwater channels which mark retreat from the Puyehue II stage yield dates of 16,105 BP and 16,390 BP. The younger of these dates is taken from a unit of organic sediment above coarse gravel but below undeformed and finely laminated clays, silts and fine sand (Fig. 5.5). The laminated sediment is probably derived from ice-marginal activity associated with the subsequent Puyehue III advance. The upper site lay up-slope, beyond the influence of the Puyehue III margin.

In summary, at least one advance to the Puyehue II rampart moraine occurred before 19,700 BP. A subsequent advance which occurred soon after may have been the Puyehue IIB advance which post-dates 19,355 BP. Ice had retreated from the Puyehue II complex by 16,390 BP.

5.3.3. Puyehue III

The timing of the Puyehue III stage has been bracketed by two maximum and two minimum limiting dates. The fluvioglacial sediment directly in front of the Puyehue III moraine at Entre Lagos includes a small number of silt intraclasts and peat balls. Charcoal fragments within these reworked clasts yield dates of 23,380 BP and ≥47,000 BP. These imply that the Puyehue III outwash was deposited after 23,380 BP. However, the charcoal could substantially pre-date the actual reworking of the silt intraclasts so these are unlikely to be close bracketing ages. Minimum dates for Puyehue III have been obtained from basal dates in a meltwater channel graded to the frontal part of the Puyehue III moraine. Samples of gyttja lying directly above basal gravel and pebbles in two cores in the channel afford dates of 10,630 BP and 11,440 BP. Therefore, the advance to the Puyehue III moraine culminated after 23,380 but before 11,4440 BP.

5.3.4. Puyehue IV

One date exists for the Puyehue IV stage. The outwash at Puente Nilque contains a 30cm-diameter silt ball with dispersed organic material. Samples of the organics affords an age of 3,235 BP which is a maximum date for deposition of the Puyehue IV outwash. Although the sample was *in situ* it is possible that it was contaminated by younger material whilst sitting exposed in the section face. In addition no recognisable macrofossils could be seen in the sample.

5.3.5. Puyehue V

A minimum date of 12,230 BP for recession from the Puyehue V limit is derived from a basal sample of a core in a lateral meltwater channel close to Termas de Puyehue, at the eastern end of Lago Puyehue. The date was derived from organic fragments in clays which directly overly outwash. Since there is no evidence for readvances after Puyehue V the date provides a minimum estimate for the time of deglaciation of Puyehue and shows that the lake became free of ice sometime before 12,230 BP. It is also important because it provides a minimum age limit for the whole moraine sequence to the west, much of which does not have close minimum dating control.

5.3.6. Rupanco I

As with Puyehue I this event is undated by radiocarbon but relative weathering criteria suggest a substantially older age than the rest of the Rupanco and Puyehue moraines.

5.3.7. Rupanco II

A maximum date for the Rupanco II advance has been afforded by a piece of wood from the Pampas Grandes site near Laguna Bonita. The date shows that the bog sediments in which it lies must have been overridden sometime after 32,460 BP. Material from the same site has also been dated in previous studies, Mercer (1976) interpreted a date of 19,450 BP as a close maximum for the advance. Lowell *et al* (*in press*) also sampled glacially-overridden peat and gyttja from the site which yielded dates of 22,650±95, 20,605±880, 22,745±295 and 25,680±330 BP. Clearly, Mercer's date is the youngest maximum and provides the closest limiting age on the Rupanco II stage. A minimum date for the Rupanco II advance comes from a core in the Mayelhue meltwater channel where dispersed organics in the basal material affords a date of 8,500 BP. Thus, the Rupanco II moraine was constructed between 19,450 BP and 8,500 BP.

5.3.8. Rupanco III

A maximum date of 6,860 BP for the Rupanco III advance is derived from dispersed organic fragments in a silt ball contained in outwash close to the Río Rahue. As with the silt ball sampled from the Puente Nilque site to date the Puyehue IV stage this clast was sitting exposed in an open section face so may have been contaminated by younger material. A minimum for recession of ice from the outermost Rupanco III limits is given by a basal date of 8,950 BP from gyttja in a meltwater channel in the Pichilifaquen col. This channel would have been abandoned after retreat from the Pichilifaquen moraines.

5.3.9. Interlobate area

A core was taken at Santa Ínes to try to date abandonment of the high ground between the lakes. Since the geomorphic evidence implies that the area has not been covered by glacier ice since Puyehue I or Rupanco I it was hoped to obtain a minimum for the Puyehue I/Rupanco I advance(s). Samples of gyttja directly overlying blue clays at the base of the core yield a date of 15,225 BP. However, this date does not help to constrain the timing of Puyehue I since the dates on Puyehue II demonstrate that advances were occurring around and after 19,500 BP and so provide older minima.

5.3.10. Discussion

The radiocarbon dates provide firm constraints on some of the advances and allow most of the glacial advances to be dated to some degree. However, a number of dates are inconsistent with the rest and significantly at odds with previous regional chronologies. Before drawing together the relative and absolute chronologies to establish a meaningful chronology for the Puyehue and Rupanco glaciers it is necessary to discuss which of the dates have internal inconsistencies or other anomalies, and so should not be included in the chronology.

The dates from the La Capilla are all derived from the same clast but yield a 5000 year range of dates from 12.8 ka to 17.8 ka. In addition they are inconsistent with other dates on the Puyehue II advance which suggest it culminated after 19.4 ka and minimum dates suggesting retreat had occurred by 16.4 ka. It seems probable that the material has been contaminated by younger material, despite having been carefully cleaned. The most likely source of contamination is deep rootlets from the moss growing on the section face. These dates therefore seem unreliable and are not considered in the final chronology for the Puyehue glacier.

The maximum date of 3,235 BP on the Puyehue IV advance is inconsistent with both the minimum date for Puyehue V and with all previous evidence of glaciation in the region which concludes that the lakes have been ice-free since the Late-Glacial. This material must have been substantially contaminated whilst in the section face and the date cannot be considered realistic. The maximum date of 6,860 BP for the Rupanco III advance is inconsistent with the minimum date of 8.9 ka obtained on the north side of Rupanco. It is also markedly inconsistent with the glacial history of Puyehue and with previous evidence of glaciation in the region.

All the dates which have been discarded are anomalously young. In the case of included organic material such as from La Capilla, Río Rahue and Puente Nilque this is probably due to rootlet contamination. Only a small fraction of modern carbon is needed to have a huge influence on the final date (Pilcher, 1991). The age variations of the La Capilla samples may be due to differing amounts of contamination in the same clast. The dates of 3,235 BP and 6,860 BP from silt clasts at Río Rahue and Puente Nilque suggests that dispersed organic material in silt balls does not yield reliable dates. For this reason these dates are excluded from further discussion.

5.4. Comparison of the Puyehue and Rupanco glacier chronologies.

The glacial chronologies of the Puyehue and Rupanco lobes are shown in Figure 5.5. Key minimum and maximum dates with their associated errors are shown and stages which have been linked in the

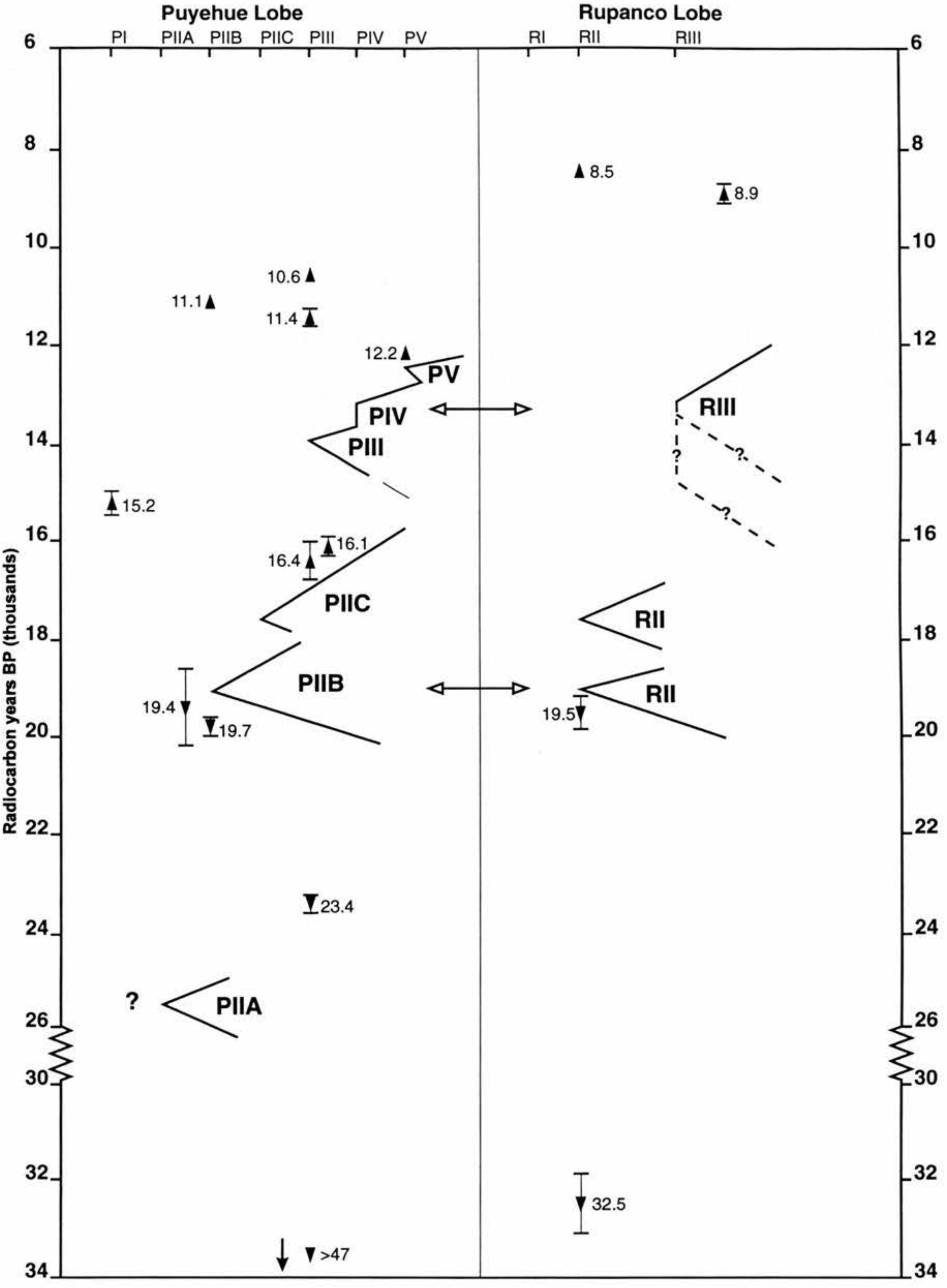


Figure 5.5. Time-distance diagram for the Puyehue and Rupanco glaciers. Limiting dates are plotted with errors of 1σ. In addition, intervals where the behaviour of the two glaciers has been linked by geomorphological relations are shown by arrows. Distance scale is schematic only.

relative chronology are marked. Before discussing the features of the chronology there are aspects of the dating control worth noting.

5.4.1. Discussion of dating control

In places, the *closest* limiting ages for the glacial advances are not associated directly with the landforms derived from that glacial event. For example, minimum ages from some cores are younger than the minimum ages for glacial advances that occurred subsequently. Similarly, some reworked material yields older maximum ages than the maximum ages for glacial events which occurred earlier. This section establishes which are the closest limiting dates for those events where such contrasting results exist.

Both of the maximum dates on the Puyehue III stage are older than the Puyehue II maximum of 19,355 BP. Therefore the latter date is a more appropriate maximum date for the Puyehue III stage since it occurred after the Puyehue II stage. The Puyehue III advance is likely to be younger than the dates of 16.1 ka and 16.4 ka from Los Copihues because the core from which the former date comes shows evidence of a subsequent advance above the depth of the date. There are no direct dates on the Puyehue IV stage so the only reliable dating control on the moraine is that it pre-dates Puyehue V and occurred after Puyehue III. As with all the core sites it is not known if the minimum date of 12.2 ka for Puyehue V is a close limiting date but it agrees closely with previous estimates of deglaciation from Lago Ranco at 12.2 ka (Mercer, 1976) and areas further south at 12.3 ka (Lowell *et al*, *in press*). This date also provides a useful minimum date for the Puyehue III advance, constraining it more closely than the 11.4 ka date from the Puyehue III outwash plain.

In addition to the maximum dates for Rupanco II afforded directly from the Pampas Grandes site on the south side of the lake, Porter (1981) correlated the site directly to nearby sites at Llanquihue where an advance culminated shortly after 20,100 BP. The youngest maximum is still the 19,450 BP date obtained by Mercer (1976) and so this is the most appropriate constraint on the maximum age of the Rupanco II advance. The minimum date of 8,500 BP from the Mayelhue terminal meltwater channel is unlikely to be a close minimum for Rupanco II, judging from the chronology for Puyehue and the rest of the region. Similarly, the minimum date of 8.9 ka in the Pichilifaquen col is unlikely to be a close minimum limiting age for deglaciation from Rupanco III. Since the Rupanco III minimum date probably does not closely pinpoint retreat from Rupanco III the date of final deglaciation of Rupanco is not closely-constrained.

The date of 15,255 BP from above the basal blue clay and gravel in the core sampled from the interlobate area suggests that the basal sediments were probably deposited during the Puyehue

II/Rupanco II advance to the limits outside the interlobate area. At this time slopes would have been unstable because of lack of vegetation and abundant meltwater. Similarly, the blue-grey silt layer at c.168cm may record the Puyehue III/Rupanco III stage since it is consistent with a Puyehue III advance between 12.2 ka and 16.1 ka.

A number of basal core dates appear not to provide close minimum limiting ages. This may be for a number of reasons. Firstly, basal dates may not closely date an event such as meltwater channel abandonment if there is a significant lag before vegetation colonises the site. Secondly, the date may actually relate to a younger, possibly non-glacial, event such as stream aggradation, landslide or slope movement. Additionally, subsequent glacier advances may have caused increased slope wash and sedimentation in pre-existing basins. This is analogous to the Loch Lomond Stadial in Scotland when further sedimentation occurred in kettle holes which had formed during the preceding glacial maximum, giving rise to two layers of glacial clay. (In all cases cores were taken on flat ground away from slopes and as far from present stream courses as possible so as to try to minimise this problem.) A third reason is that contamination from higher in the core may have occurred. This seems unlikely since the samples were extracted carefully and cleaned thoroughly.

5.4.2. Similarities and differences of the Puyehue and Rupanco chronologies

The two glaciers show a broadly similar pattern of glacial advance and retreat although the timing of the earliest advances remains unclear. Despite the general agreement of the two chronologies they do show discordant behaviour. It is important to examine both the similarities and differences in order to fully understand the palaeoclimatic significance of these chronologies. The most important features to emerge from the chronology are:

- The Puyehue and Rupanco lobes both advanced at least once before 19.5 ka. The relative and absolute timing of these advances is not known.

- Both glaciers advanced to maxima sometime after 19.5 ka. Maximum dates for both lobes suggest that the Puyehue II and Rupanco II advances may have been broadly synchronous. This agrees with the geomorphological evidence of synchrony between the Puyehue IIB stage and one of the Rupanco II stages.

- A subsequent advance to the Puyehue II limit occurred between 19.4 ka and 16.1 ka.

- The Puyehue III moraine is dated to between 16.1 ka and 12.2 ka.

- The *initial* glacier advances to form the Puyehue III and Rupanco III moraines may have been synchronous but the Puyehue glacier had reached its culmination and retreated as far as the Puyehue IV limit whilst the Rupanco lobe was advancing to, or still at, the Rupanco III limit.

- Deglaciation of Puyehue was complete by 12.2 ka. Deglaciation of the Puyehue basin began before Rupanco. The timing of Rupanco deglaciation is loosely constrained to before 8.9 ka but was probably complete at a similar time to Puyehue.

5.5. Synchronous and asynchronous behaviour of the glaciers

The similarities of the two glacier chronologies suggest that the glaciers were controlled dominantly by climate, as would be expected. The similar numbers of advances to equivalent positions at comparable times can be attributed to climate forcing. In particular, the advances at c. 19.5 ka and between 16.1 and 12.2 ka were probably a common response to climatic deterioration at these times. Therefore, most of the moraines around the two lakes probably record intervals of climatic deterioration and so have palaeoclimatic significance. Both lakes were deglaciated at similar times which suggests the glaciers also had a common response to climatic amelioration.

The chronologies do show differences which imply that other controls were superimposed on the first order control of climate forcing. In order to investigate reasons for, and the significance of, differences in timing between the Puyehue and Rupanco glacier fluctuations it is important to know not only which glacier was leading but also by how much. The relative behaviour of the glaciers has already been demonstrated by the chronologies. The magnitude of leads and lags can be estimated in a number of ways. Firstly, comparison of the radiocarbon chronologies may indicate some of the differences. However, the limited dating control on the Rupanco lobe means that the only meaningful comparison is between the Rupanco II and Puyehue II stages. The dates on these show that they may have been synchronous, both occurring shortly after 19.5 ka. Geomorphological relations show that the limits were both occupied at the same time for at least some of the glacial event. Since no minimum dates exist on the Rupanco II moraine it is not possible to discern any lags or leads.

An alternative approach to investigating leads and lags between the glaciers is to apply calving theory to the two former lobes. Using such calving relations can demonstrate which glacier led the other and also provide estimates of the maximum possible lag induced between the two by differences in their calving rates. Water depths in the lakes are well known and estimates of likely calving rates are possible from the empirical relations developed for freshwater calving by Funk and Rothlisberger (1989) and Warren *et al* (*in press*). Figure 5.6 shows theoretical advance and retreat times for the Puyehue and Rupanco glaciers as a function of ice velocities. These assume an average water depth of

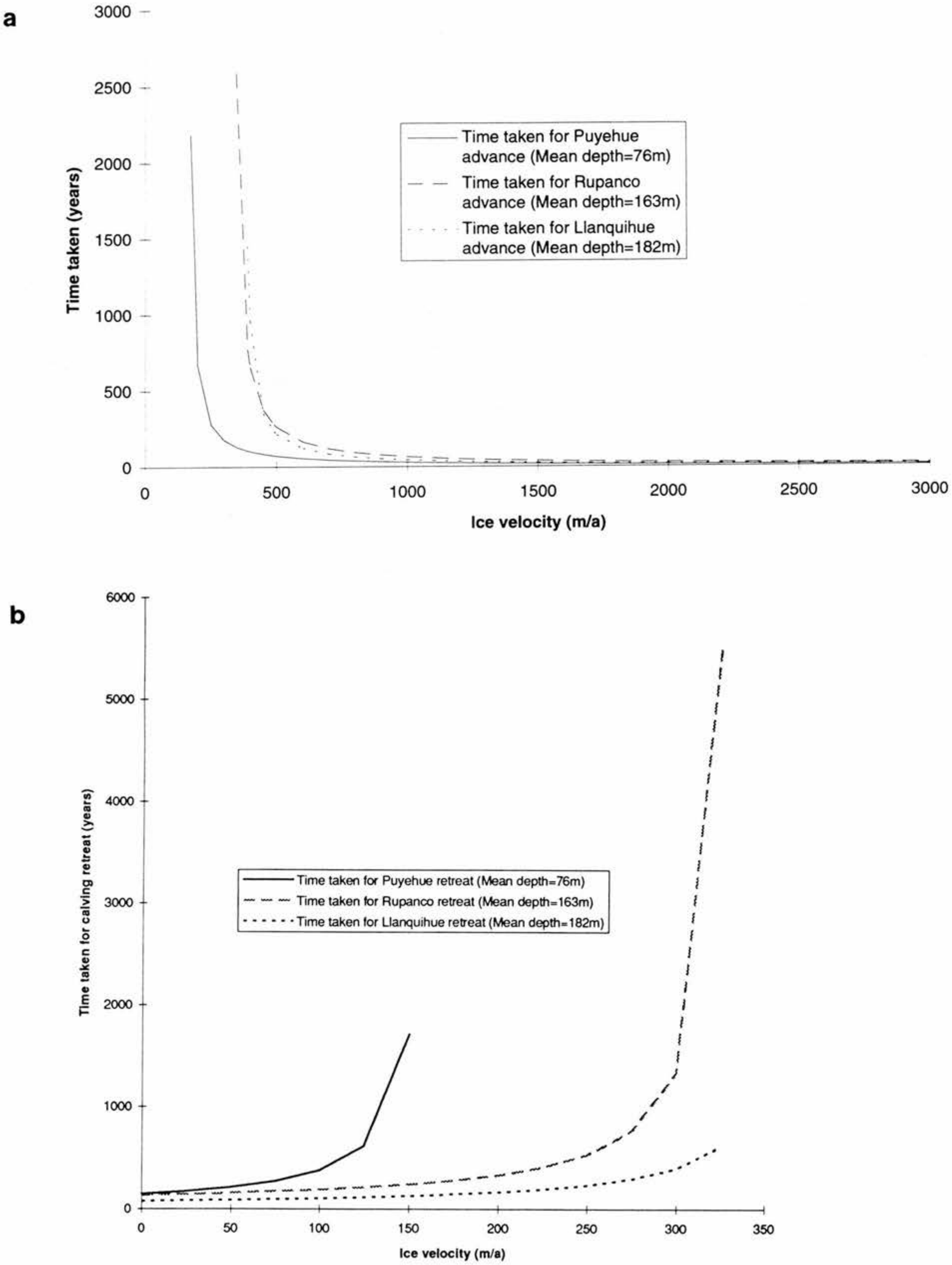


Figure 5.6. Calving relations for the Puyehue, Rupanco and Llanquihue glaciers. Times for calving advance and retreat have been calculated using the empirical relation between water depth and calving rate derived by Funk and Rothlisberger (1989). Mean depths are taken from Campos *et al* (1988; 1989; 1992)

(a) Advance times. There is a strong dependence of advance time on ice flow velocity; for low ice velocities (<500 ma^{-1}) calving advance can take up to 2500 years and can differ by as much as 1000 years for different glaciers. For a given ice velocity, the Puyehue glacier reaches the west end of the lake more rapidly than the Llanquihue and Rupanco lobes which show similar behaviour.

(b) Retreat times. The Rupanco and Llanquihue glaciers retreat more rapidly than the Puyehue glacier.

76m in Lago Puyehue and 163m in Lago Rupanco (Campos *et al*, 1989; 1992). The times for advance may be underestimates since the ability of calving glaciers to advance often depends on their ability to reduce effective water depths by constructing a submarine moraine shoal which will be dependent on proglacial sedimentation rates. The graphs demonstrate the strong contrast between the Puyehue and Rupanco glaciers. The Puyehue glacier would have led the Rupanco glacier during advance. On the basis of different water depths and for ice velocities less than 500ma^{-1} the Rupanco glacier may have taken up to 1000 years longer to advance the full length of the lake than the Puyehue glacier (Fig. 5.6a). For greater ice velocities the difference would be measurable in decades. During retreat the situation would have been reversed with the Rupanco glacier retreating more rapidly, up to 1000 years earlier than Puyehue (Fig. 5.6b)

Another approach to estimate the lag is to apply advance and retreat rates measured on present-day glaciers in similar environments and of similar dimensions to the Puyehue and Rupanco glaciers. However, data on glaciers calving into freshwater are limited, especially those calving into water depths greater than 70m. Tidewater glaciers are thought to calve much more rapidly and so the more abundant data from this type cannot be applied. The maximum recorded advance rate for a freshwater glacier is 132ma^{-1}, at the Pio XI glacier, Chile but only three measurements on advancing glaciers exist in total and this may not be representative (Warren *et al*, in press). Thus, using measured rates of advance is not possible. However, estimates can be made for the lag during retreat. One example of this is the Puyehue IV stage when the Puyehue lobe had retreated to a position midway along the lake whilst simultaneously the Rupanco glacier was reaching its Rupanco III maximum at the end of the lake. An estimate of the lag between the culmination of Puyehue III and eventual culmination of Rupanco III can be made from the time required for the Puyehue lobe to calve back to the Puyehue IV limit. The distance from Puyehue III to Puyehue IV is 15 kilometres and maximum measured retreat rates on freshwater calving glaciers this century are up to 440ma^{-1}, measured on the Upsala glacier, Argentina (Warren *et al*, in press). On this basis, it could have taken the Puyehue lobe as little as 35 years to retreat back to the latter position. Therefore, on the basis of likely retreat rates the *minimum* lag between Puyehue and Rupanco during the Puyehue III/Rupanco III stage was probably of the order of decades. A significant unknown factor in the calculation which prevents estimation of the maximum likely lag between the two glaciers is the length of time the Puyehue terminus lay against the Puyehue III limit before retreating. The time it was situated at the moraine would add to the lag between the two glaciers. The sizes of the Puyehue III and Rupanco III moraines are very similar so as a crude approximation it could be argued that they sat against their respective limits for similar lengths of time and that any differences were probably in the order of decades rather than hundreds of years.

In summary, simple theoretical considerations imply that there may have been maximum lags up to the order of 1000 years or more between the Puyehue and Rupanco glaciers during advance. During retreat, lags of decades or possibly centuries were more likely. If lags as large as these occurred during the last glaciation then it has important implications. The timing of the advances of each glacier could differ significantly and show a systematic variation from the actual timing of climatic change.

5.6. Modelling the leads and lags of the Puyehue and Rupanco glaciers

Another approach to investigating the lag between the two glaciers is modelling. Models are an excellent way to investigate the relative behaviour of glaciers since they can simulate glacier response to climate change. A study run in parallel with this one developed a one dimensional flowline model which calculates the mass balance at equally spaced points on the base topographic grid and then determines the ice thickness at each point, and the flow of ice between points. The flow calculation includes terms for internal deformation, basal sliding and also incorporates the effect of longitudinal deviatoric stresses on ice velocities (Hubbard, *submitted*; *unpublished*). The model was run on the Puyehue and Rupanco basins using a 1 km grid and forced by stepped changes in Equilibrium Line Altitude over a period of 9000 simulated years. The simulated years are not directly equivalent to calendar years; their conversion depends on a number of assumptions about temperatures, and therefore flow parameters. The two timescales are, however, comparable with each other on an order of magnitude basis. Model experiments were used to investigate the climatic deterioration necessary to simulate the glacial maximum and the effect of valley geometry on the sensitivity and response of the glaciers. Glacier response depends on a number of controls including the variables of valley geometry, climate, flow mechanics and associated basal processes. By modelling two closely adjacent glaciers of differing morphologies the effect of valley geometry can be isolated and explored whilst holding the other controls constant.

Firbush and Andrews (1984) and Oerlemans (1989) have shown that the shape and longitudinal bed profile of a glacier exerts an important control on the sensitivity and response of the glacier. The frontal position of a glacier on a shallow slope is more sensitive to climate because of the way mass balance changes are accommodated at the glacier terminus. For a glacier on a shallow slope, a given depression of the ELA will affect a greater area of the glacier, and so the terminus will advance further to accommodate this than would occur in a steeper glacier. However, glaciers on shallower slopes have a slower response time compared to those on steeper slopes. The change in mass balance can be transmitted to the glacier terminus more quickly if slopes are steeper and therefore velocities are greater. Analysis of the geometrical differences between the Puyehue and Rupanco valleys reveals a number of features which may be significant in controlling their response to climatic fluctuations. First, Puyehue has a larger accumulation area which should result in faster ice build-up during climatic deterioration. Puyehue also has a more uniform, steeper longitudinal bed slope and should experience a faster and more linear response to forcing. On the other hand, Rupanco has an over-deepened basin with a small bed slope. Thus a slower response should be expected once initial rapid advance into this basin has occurred. The valleys have similar orientations and have been subject to the same general climate through time; they are underlain by similar materials and so similar basal conditions and flow processes are likely to have applied.

5.6.1. Modelling results

The modelled behaviour of the two glaciers shows several interesting features, a number of which recall the geomorphological record:

- Both glaciers reach stable positions at the end of the lakes and are stable there for a fairly wide range of mass balance conditions. In effect, the glaciers are partially decoupled from climate when they reach the westward end of the lake basins. Glacier advance in response to further ELA lowering is negligible. This matches well the empirical evidence of closely spaced moraine loops and large volumes of sediment around the western end of the lakes.

- During the initial build-up from no-ice conditions the Puyehue glacier responds more rapidly to climate deterioration than Rupanco. The Puyehue glacier builds up in c. 2000 years, half the c. 4000 years taken by the Rupanco lobe. This contrast is directly related to the bed profile differences with the steeper bed of Puyehue causing it to have a faster response. Even after substantial ice has accumulated in each basin, the Puyehue glacier shows a greater likelihood to advance to the end of its lake than the Rupanco glacier (Fig. 5.7). For example, during the triple ELA drop used between 300 and 3300 simulated years to force the model the Puyehue lobe advances in response to each drop whilst the Rupanco lobe only advances twice. Again, this closely matches the geomorphological evidence of more ice-contact slopes making up the Puyehue II limit than the Rupanco II limit. This is also what would be expected from the geometrical considerations given above; although the precise frontal position of the Rupanco lobe may be more *sensitive* to climatic forcing, its *response time* as a whole is so slow that it fails to respond sufficiently to climatic signal below a certain frequency. The differences in response mean there is a lag between culmination of advances of the Puyehue lobe and the Rupanco lobe. For example when ELA is dropped to 600m shortly after 4500 years the Puyehue lobe responds rapidly but the Rupanco lobe reaches its maximum limit up to 700 years later. Similarly, after 1800 years the ELA drop to 600m results in a differential response with the Rupanco lobe reaching its culmination 200 years later.

- The Puyehue lobe retreats from its terminal limit before the Rupanco lobe. When the ELA is raised after 2100, 3100 and 6000 simulated years the Puyehue lobe retreats first. Between 6000

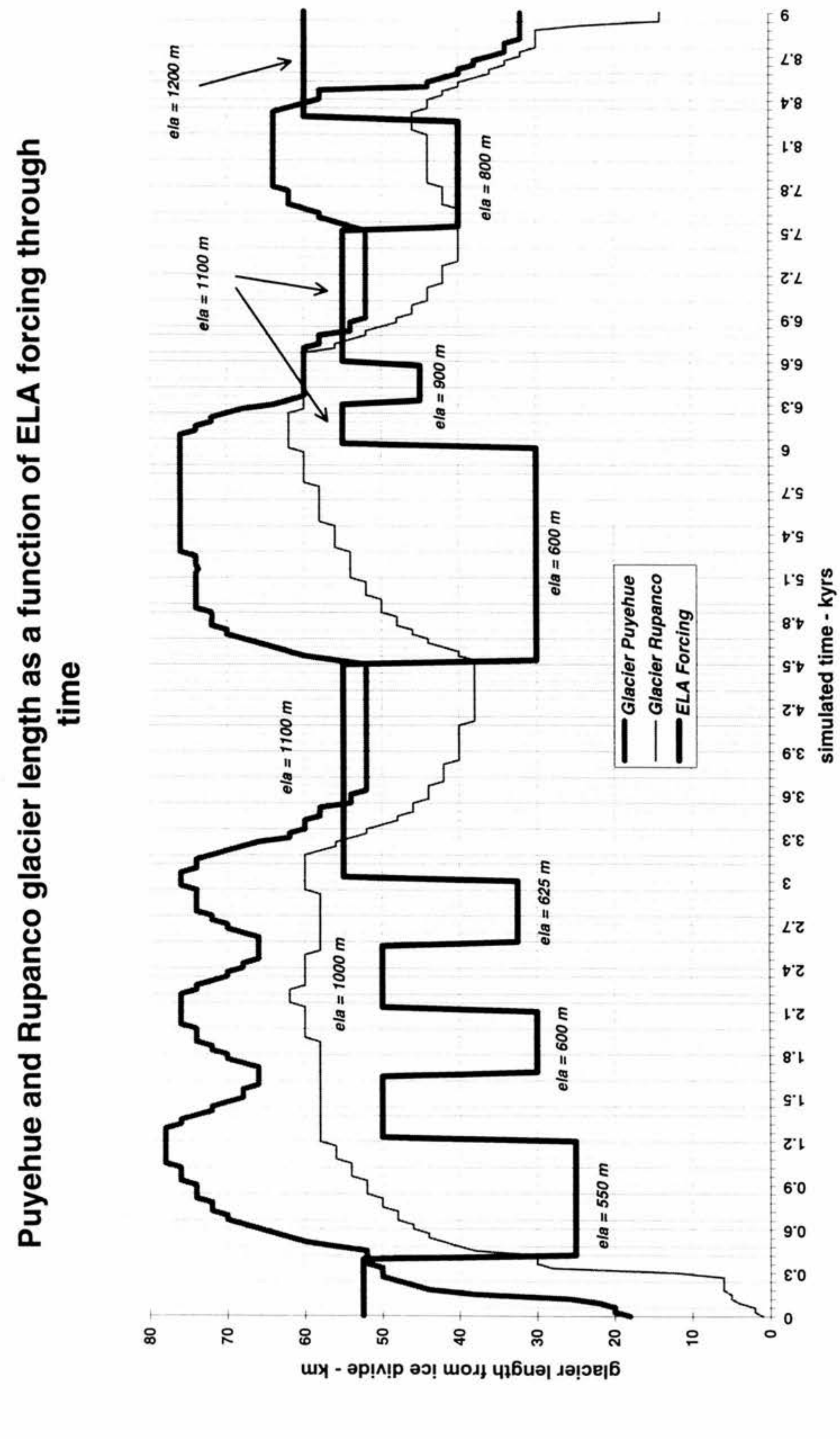


Figure 5.7. Modelled behaviour of the Puyehue and Rupanco glaciers. The graph of ELA forcing shows the hypothetical changes in Equilibrium Line Altitude used to drive the model. The response of the two glaciers to the climate forcing is shown in terms of their distance from the ice divide. The distance of the two glaciers from the ice divide in response to ELA forcing is shown over a period of 9000 simulated years. The two glaciers show the same broad pattern of advance and retreat in response to the climate forcing. Differences in behaviour are due to the geometry of their basins (see text for discussion). From Hubbard (*submitted*).

and 6500 years Puyehue responds to a 300 year period of climatic amelioration by retreating 20 km from its limit. In this same period Rupanco remains within 2 km of its maximum limit. This behaviour agrees with the empirical evidence that the Rupanco III lateral moraine and Puyehue IV moraine were formed at the same time after retreat from Puyehue III.

- The retreat of Puyehue is markedly stepped. This matches the empirical evidence of stillstands (Puyehue IV and Puyehue V) in Lago Puyehue. However, the model also shows stepped retreat of Rupanco, for which there is no empirical evidence. The mismatch between model and field results in the presence and number of steps during deglaciation may be because the model does not allow for calving behaviour which could overcome and smooth out other effects during glacier retreat

These results show that the similarities and discordant behaviour of the two lobes which are recorded by the empirical evidence are what might be expected from glaciological theory. The close match of the field evidence to the modelling results implies that the local differences in behaviour are related to inherent features of the glaciers and their basins and not to external climatic factors. Minor mismatches between empirical evidence and the model can be explained by calving effects which are not incorporated in the model.

Given realistic ice flow parameters the model can also provide estimates of the lags in timing between the glaciers. The empirical evidence does not record when build-up from no-ice conditions occurred so the model result showing an initial 2000-year difference between the two glaciers cannot be discussed in the context of the glacial advances under consideration. However, subsequent behaviour of the glaciers demonstrates that lags in the order of centuries occur, with a maximum lag of c.700 years during advance of the two glaciers. This is a similar magnitude to the crude estimate of the 1000-year lag which might be introduced by calving effects. More importantly, both modelling and consideration of calving relations suggest the difference was in the same direction. Puyehue leads Rupanco in advance and retreat.

5.7. Conclusion

The relative and absolute chronologies of Puyehue and Rupanco demonstrate a similar pattern of glacial fluctuations in both basins. Superimposed on this underlying pattern are differences in glacier behaviour. The similarities and differences in behaviour are shown both by field evidence of intersecting landforms and by experiments with a flowline model.

Both glaciers advanced a comparable number of times to closely similar limits. A number of these advances were synchronous. For example, the two glaciers both advanced at the same time after 19.5

ka. Both the lakes were probably deglaciated at similar times; in Puyehue this was complete by 12.2 ka.

There is also empirical evidence of differential behaviour. Specifically, the Puyehue glacier led the Rupanco glacier during advance and retreat. Modelling studies suggest the difference between the two glaciers may have been as much as 700 years during initial ice build up with lags of the order of decades or centuries for much of the retreat cycle. The close match of field and model evidence demonstrate that most of the short-term differences in behaviour can be explained in terms of the contrasts in valley geometry of the two basins.

Chapter 6: A model for the formation of ridge and rampart moraines.

6.1. Introduction

This chapter develops a model for formation of the rampart and ridge moraines around Puyehue and Rupanco. The geomorphological data in Chapter 2 and the sedimentological data in Chapter 3 show that the two moraine types display certain similarities and differences. The key similarities are that both moraine types have the same sediment facies associations and their lateral moraines have low longitudinal gradients. Chapter 5 shows that the moraines mark the limit of glaciers fluctuating every few thousand years and possibly even more frequently.

6.2. Origin of the Moraines

The synthesis of the sedimentological data discussed some of the processes responsible for the formation of the moraines. Each glacier snout apparently advanced into pre-existing outwash, with consequent mild glaciotectonism. The tectonism, and the formation of till seems to have been largely restricted to the proximal sides of the moraines, implying that once the glacier impinged on the outwash it did not advance very much further. The tectonism was accompanied by reworking of fluvioglacial strata to form an overlying till. In many cases, the till has several characteristics of a deformation till. This is particularly true for some sites located east (up-glacier) of the major moraines. The till contains deformed glaciolacustrine clays and silts derived from the up-glacier lake basin.

6.2.1. Deforming beds

One possible explanation for the low gradients of the lateral moraines, the deformed sediments within the moraines, and the presence of glaciolacustrine sediments is that the glacier was advancing over a deforming bed. Boulton and Jones (1979) highlighted the importance of a deforming substrate below temperate ice. They observed that a large proportion of the forward movement of a glacier can be due to deformation of the sediment rather than the glacier. This led to the development of a model in which the glacier surface profile and forward movement are controlled by the strength and hydraulic properties of the bed sediments although other factors such as subglacial hydrology and bedrock 'sticky spots' may also play a significant role (Kamb, 1991; Humphrey *et al*, 1993; Iverson *et al*, 1995). When hydraulic transmissibility is high, subglacial water pressures are relatively low and deformation of the bed is unlikely. If, however, the sediment has a low hydraulic transmissibility then pore water pressures build up and the shear strength of the subglacial sediment is reduced. Eventually, a point is reached where the shear strength of the bed is lower than the driving stress at the base of the glacier and deformation of the bed material occurs. Thus, the bed contributes a component to the forward motion of the glacier. The deformation of the bed leads to a lower glacier surface profile. For example, glacial geological studies of the southern margin of the Laurentide Ice Sheet have shown that gradients may have been as little as one sixth those of typical profiles from present-day ice sheets. This view has been supported by seismic observations on Ice Stream B, Antarctica which suggest that ice is moving on a subglacial sediment layer deforming at an extremely low effective stress (Alley *et al*, 1986; Blankenship *et al*, 1986).

The criteria necessary for bed deformation are high subglacial water pressures and sediment with low shear strength. Pore water pressures tend to be raised in saturated impermeable sediments; for example, clays and fine silts tend to be relatively impermeable and susceptible to deformation whereas gravels commonly have high permeabilities and are resistant to shear deformation. Thus, glaciolacustrine sediment is ideal for bed deformation since there is abundant water lying over the sediment of the lake bed and this sediment is usually fine-grained and impermeable so little pore water can escape. The material will be saturated and, if a load is applied, pore pressures will rise and the sediment will deform easily. The fine-grained glaciolacustrine silts and clays of the Puyehue and Rupanco moraines would have been ideally suited to bed deformation. Any direct observation of deformed sediment in the former subglacial zone is prevented by the lakes but the remarkably low gradients of lateral moraines around both lakes demonstrate shallow glacier profiles, whilst the tectonised glaciolacustrine clays and silts on the proximal sides of moraines, and the deformation tills forming the moraines suggest that the glaciers advanced over, and deformed, a bed of fine-grained sediment. Therefore, a deforming bed origin agrees with the existing evidence.

Furthermore, the sediment associations within the moraines, where diamicts overly and incorporate pre-glacial sediments with some deformation is similar to the 'constructional deformation' of bed materials described by Hart *et al* (1990). The constructional style is characteristic of a deforming bed at ice margins where stresses are compressive and conservation of mass requires that there is a net thickening of sediment. The deformed fluvioglacial sediments in Puyehue and Rupanco moraines correspond to the 'overturned zone' while the diamicts containing a mix of local and 'exotic' material are typical of the 'sheared zone' (Hart *et al*, 1990). The correspondence between the location of the moraines and the tills composed dominantly of fluvioglacial sediment implies that the glacier halted and formed a moraine in response to a change in the bed materials it was advancing over. It follows from a consideration of the behaviour of subglacial sediments that as permeability rises then pore pressures will decrease. Thus, the shear strength of the sediment will increase as meltwater is drained more effectively. Perhaps when the glaciers advanced from deformable, saturated, impermeable clays and silts of the lake basin over coarser, more permeable fluvioglacial sediment the abrupt change in basal shear strength caused the glacier to halt. The thickness and surface slope of the glacier were not sufficient to produce the driving stress for the glacier to advance further.

6.2.2. Ice-marginal processes

The possible range of processes operating at the change in bed conditions is illustrated in Figure 6.1. The glacier advances over a deforming bed which thickens towards the ice margin. Close to the margin there is a transition from clay-rich deformation till which is flowing, to fluvioglacial sediments which are being deformed along shear planes. Bedrock protuberances ('sticky spots') through the till may provide resistance to flow in the lake basin. The glacier experiences strongly compressive flow due to the retardation of flow over the well-drained deposits beyond the lake basin, and the longitudinal compressive stress caused by the slope at the west end of the lake basin. The compression leads to thrusting at the base of the ice so debris is raised to higher levels within the glacier, and possibly to the surface. If so, then it adds to the pre-existing supraglacial debris, which is transported by surface meltwater and deposited at the glacier snout either as proximal fluvioglacial sediment or sediment gravity flows. Eventually, it is likely to be transported into the braided river system of the outwash plain beyond. The net upwards movement of debris at the margin means that there is little input of debris into the moraine from the basal zone of the glacier. At the glacier terminus, local freezing-on of bed materials may occur during winter. This can occur when a winter 'cold wave' penetrates the thin ice at the margin and depresses the 0°C isotherm into the subglacial sediment, freezing it to the base of the glacier. Basal freezing-on of debris at the ice margin has been interpreted for temperate glaciers in Iceland (Kruger, 1993). Such a mechanism is only likely to occur where the ice is a few tens of metres thick, that is at the extreme 'feather edge' of the ice margin. This may explain why intact blocks of glaciolacustrine sediment occur near the crests of the Puyehue-Rupanco moraines whilst homogeneous foliated clay-rich tills occur near the base of the moraines. Small amounts of glaciolacustrine sediment may have survived at the edge of the lake basin and were then locally frozen-on as blocks during winters. Summer melting would have released them into the sediment which forms the proximal slope of the moraine (Kruger, 1993). An alternative mechanism for the emplacement of the blocks is that they were frozen-on in the lee of bedrock protuberances at the base of the glacier further behind the margin. This seems unlikely given that the bed was deforming and would be unlikely to yield intact laminated sediment. The glacier progressively thickens with time at the margin. The thickening is matched by further deposition of fluvioglacial sediment which is syn-depositionally deformed by the ice. The thickening of the terminus will migrate up-glacier.

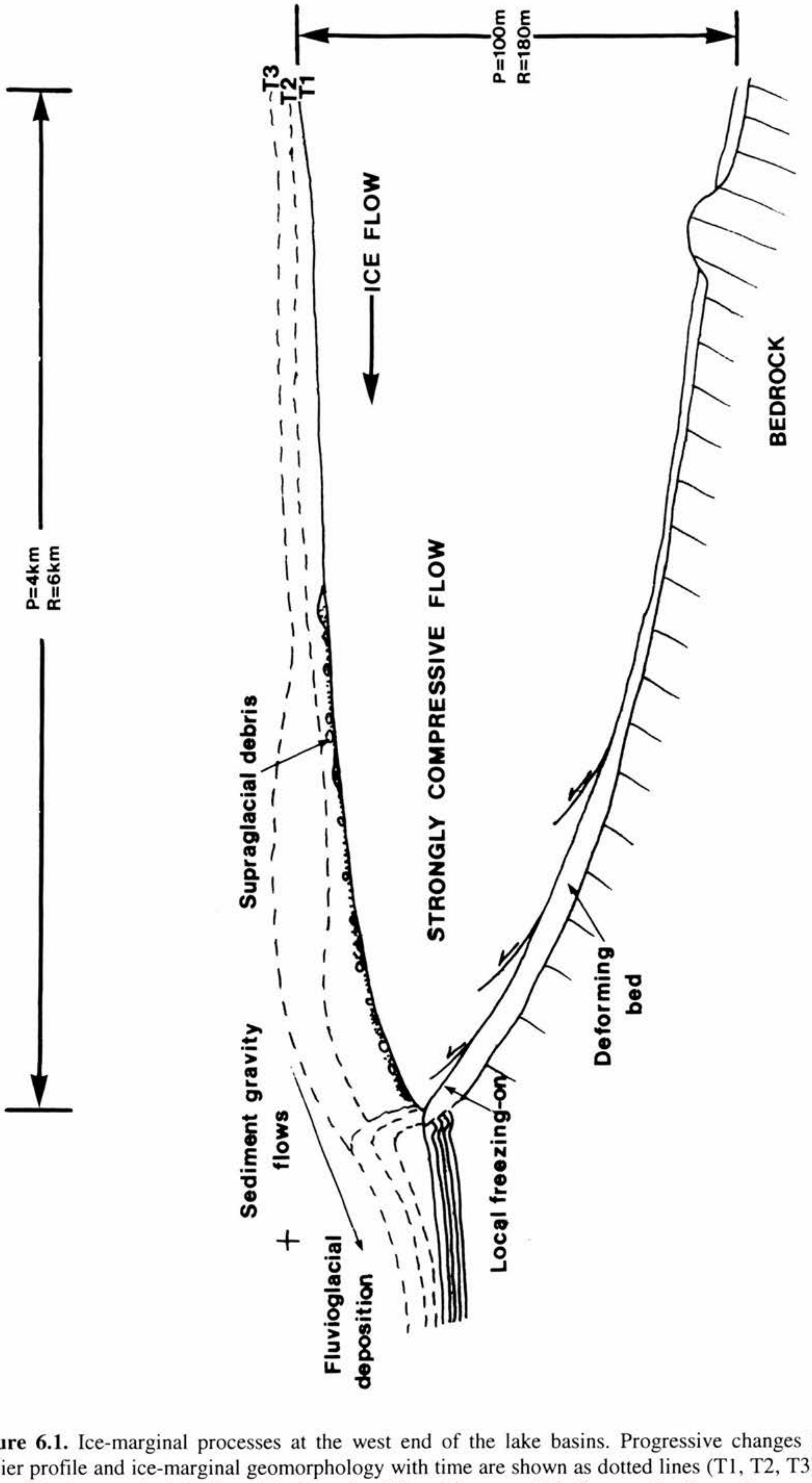


Figure 6.1. Ice-marginal processes at the west end of the lake basins. Progressive changes in the glacier profile and ice-marginal geomorphology with time are shown as dotted lines (T1, T2, T3). The scale of the ice margin is indicated for Puyehue (P) and Rupanco (R). See text for discussion.

6.2.3. Discussion of alternative explanations

Alternative explanations for the moraines could be surging glaciers, push moraines, or ice shelves. The Puyehue and Rupanco moraines show few of the features commonly associated with surges, such as looped and accordion-style folding, *extensive* glaciotectonism, normal faulting in moraine cores, water escape structures and chaotic 'dead ice' topography (Sharp, 1988) and so this origin can probably be discounted. The ridge and rampart moraines are unlikely to be push moraines since there is no evidence of large-scale nappe structures or stacking of thrust faults to form large duplex zones, as has been described for typical push moraines such as the Dammeberge and Lamstadt moraines in North Germany and Thompson glacier on Axel Heiberg Island in the Canadian Arctic (van der Wateren, 1987; Kalin, 1971).

Horizontal moraines formed by existing and former ice shelves have been reported from the Arctic (England et al, 1978) and Antarctica (Sugden and Clapperton, 1981). However, the location of the Puyehue and Rupanco glacier termini at a low altitude in a mid-latitude area with high precipitation means they would have been temperate glaciers and the ability of temperate ice to form floating shelves is controversial (Warren, *pers. comm.*; Powell, 1991). The apparent lack of temperate ice shelves and the effect of intercrystalline water films on the strength of ice suggest that temperate ice is simply not strong enough to form an ice shelf (Powell, 1991). Post (*pers. comm.*) refutes this and argues that there are examples of apparently floating temperate ice tongues (eg Bering glacier) and it is the fracturing of fast-moving ice and the higher temperatures of temperate seas which explain the lack of temperate ice shelves. A change in glacier behaviour is suggested along the north shore of Puyehue where gradients alter down-glacier from shallow to near-horizontal. The pronounced bend in the Puyehue III moraine on the north shore of the lake is coincident with a change in longitudinal profile of the moraine. West of the bend the moraine is near-horizontal whereas to the east it extends up the valley with a low gradient. The Puyehue III moraine is similar to ice-shelf moraines both in terms of its horizontal, narrow, single-ridge form and the mixture of exotic and local sediment (Sugden and Clapperton, 1981), so it is possible that near its terminus the Puyehue ice may have been sufficiently thin to float and form a horizontal moraine around the shoreline. However, until the debate on floating temperate ice is resolved it is difficult to interpret confidently an ice shelf origin for the Puyehue III moraine.

6.3. A model for the formation of rampart and ridge moraines

A single model incorporating the processes of advance over a deforming bed into outwash and glaciotectonism can explain the formation of both rampart and ridge moraines. The model can be divided into a six stage cycle (Fig. 6.2).

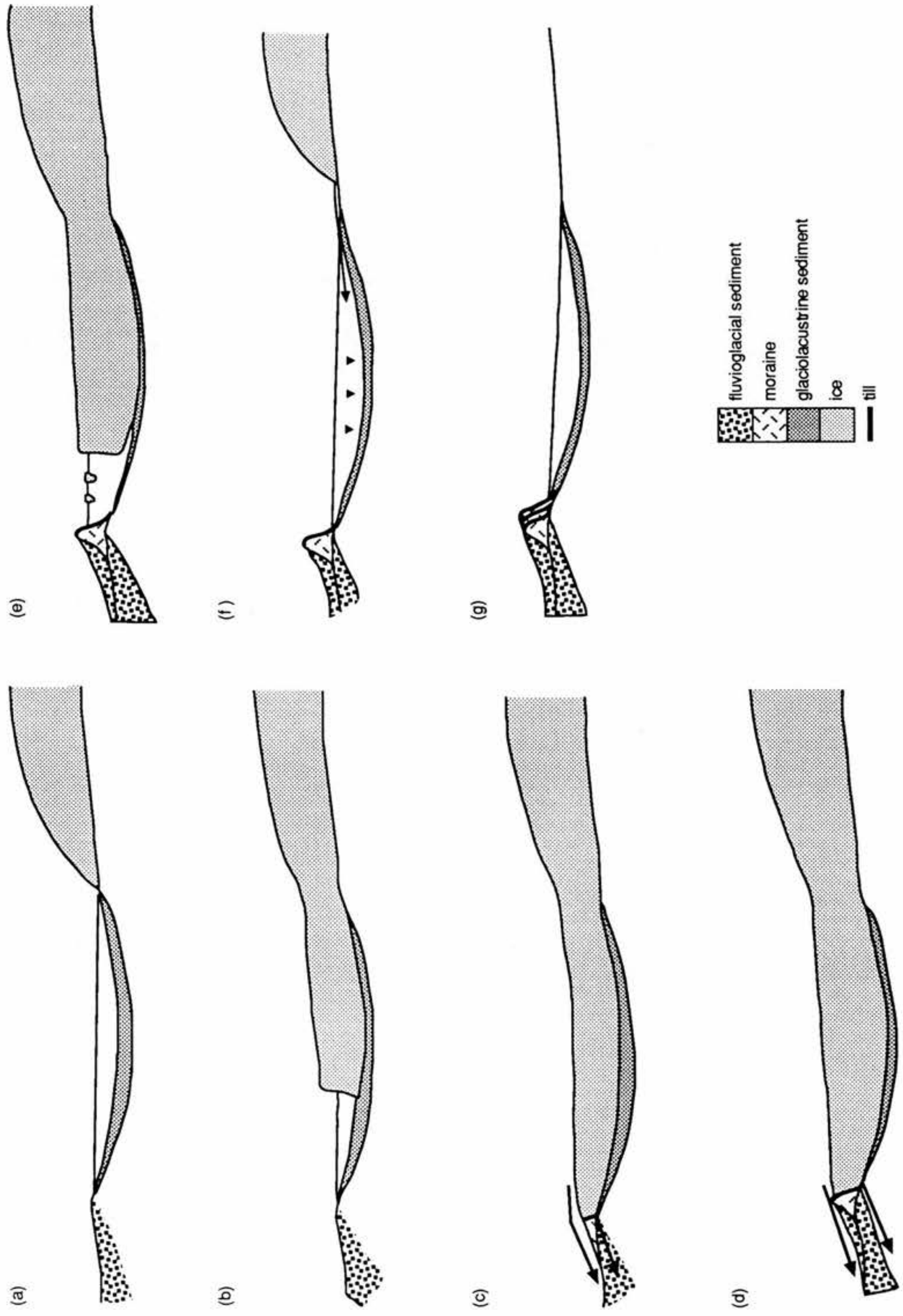


Figure 6.2. A model for the formation of ridge and rampart moraines. The sequence of cross-sections refers to a single cycle of glacier advance and retreat.

(a) The glacier advances down the trough towards the lake with a 'conventional' convex glacier profile.

(b) The glacier advances into the lake and encounters a bed of saturated impermeable sediment. This wet sediment with high pore pressures is deformed and the surface profile lowered.

(c) The snout reaches the west end of the lake where pre-existing fluvioglacial deposits are more resistant to deformation. Basal water drains easily so pore pressures are lower, bed deformation does not occur and the snout halts. Mild glaciotectonism occurs.

(d) Positive mass balance causes the glacier to thicken. Glaciotectonism continues as fluvioglacial sediment builds-up. The glacier may actually leave the basin given sufficient climatic forcing.

(e) The onset of retreat with calving into the lake leading to rapid retreat with halts only at pinning points.

(f) The snout lies upvalley of the lake and lacustrine sediments are topped-up by distal sedimentation.

(g) Feedback can lead to the formation of amalgamated moraines.

Stage 1: In the early stages of advance the glacier lobe moves down the glacial valley towards the lake. It has a conventional longitudinal profile with angles behind the snout of 2-3°.

Stage 2: When the glacier reaches the lake it encounters a bed of saturated, fine, impermeable sediment. This material is more readily deformed than the ice itself and allows the glacier to advance easily with very little internal deformation of the ice (Boulton and Jones, 1979). Thus the portion of the glacier in the lake adopts a flatter longitudinal profile with gradients of less than 1°. Any calving at the glacier front is insufficient to offset the amount of forward movement over the deforming bed and so the snout advances. If the ice becomes sufficiently thin then it may achieve flotation to form an ice shelf.

Stage 3: At the west end of the lake the snout encounters pre-existing coarse-grained deposits. In the Puyehue and Rupanco examples these are fluvioglacial sediments deposited during retreat from previous glacial advances. Basal water drains more easily through these gravels so pore pressures are lower and the bed is less susceptible to deformation than the glaciolacustrine sediment over which the glacier has been advancing. Surface gradients are so low that the basal shear stresses are insufficient to deform the ice internally and allow its further advance, at least until the lobe thickens massively. In this zone of compressive flow from advance over saturated, deforming clays to retardation over well-drained outwash a small amount of deformation occurs. The pre-existing fluvioglacial strata are folded and, in places, thrusted. In the course of this deformation fluvioglacial gravels and clays derived from the lake basin are reworked to form a thin veneer of deformation till. The deformation tends to be restricted to the proximal side of the moraine. The glacier tongue now provides a direct conduit for meltwater onto the outwash plain to the west. In this way the zone of outwash deposition is localised and as more fluvioglacial strata are deposited then the barrier to further advance thickens.

Stage 4: The longitudinal compression at the snout causes the glacier to thicken and the profile to steepen at the west end of the lakes. Eventually the glacier may thicken sufficiently to leave the basin but this possibility is restricted by the simultaneous build-up of fluvioglacial material on the distal side of the moraine. Small amounts of deformation may continue as shear stresses increase so the tills formed in Stage 3 may be further deformed. Syn-depositional deformation of fluvioglacial material will also occur as deposition of the outwash plain continues.

Stage 5: Once the glacier retreats from its position at the west end of the lake it will calve into deeper and deeper water. This is likely to have a runaway effect and the glacier will experience rapid calving retreat until it stabilises at the east end of the lake, or at a suitable pinning point (Mercer, 1961;

Kirkbride, 1993). This leaves a lake shoreline moraine with low lateral gradients, made up largely of outwash and an overlying melange of glaciolacustrine and fluvioglacial sediments.

Stage 6: During the time the glacier terminus lies at, or beyond, the east end of the lake the clays and silts will be 'topped-up' by further sedimentation. This sedimentation could be in a glacier-contact or distal lake, depending on the position of the terminus relative to the lake (Ashley, 1988).

The six-stage cycle will be repeated for each glacial advance and after the first moraine has formed there is strong potential for feedback during the formation of subsequent moraines. There are two reasons for this. Firstly, the presence of a ridge at the end of the lake forms a topographic barrier to advance, in addition to the contrast in bed conditions. Secondly, the lake allows the further deposition of saturated fine-grained sediment which contrasts strongly with the permeable sediments at the west end. Thus, any subsequent advance is likely to reach the same place, even for a wide range of mass balance conditions. This self-reinforcing process leads to the construction of an amalgamated moraine in a location determined by the initial lake shoreline position.

If retreat from a previous moraine position is accompanied by partial infilling of the western end of the lake by coarse, permeable sediment then this moves the grain-size and permeability boundary into the lake. Thus the next moraine location is likely to be developed further up-glacier. Such a change in the deforming/non-deforming boundary could occur if the glaciers showed a similar type of transition from melting to calving retreat as described for some temperate glaciers in New Zealand (Kirkbride, 1993). In this process, the debris cover of a glacier terminus becomes perforated and sink holes form. The resultant increased melting causes the lakes to coalesce and the debris mantle of the glacier is gradually lowered as the glacier surface disintegrates. Eventually, the lakes coalesce sufficiently that the glacier begins to calve into a terminal lake and so rapid retreat occurs. Clearly, much of the sediment initially located on the surface of the glacier terminus will be deposited in the terminal lake. There is no direct geomorphological evidence of this process having occurred in either the Puyehue and Rupanco basins. However, shorelines and small delta forms banked against the Puyehue IIC and Puyehue IV moraines suggest that there were local ice-dammed lakes situated between the glacier termini and these moraines. It is possible that these lakes were derived from a similar process to that described by Kirkbride (1993).

Although the exact mechanism is not evident, a shift in the deforming/non-deforming boundary apparently occurred in the case of the Puyehue III and Rupanco III advances. During these advances the glaciers did not reoccupy the inner ice-contact slopes of the Puyehue II and Rupanco II amalgamated moraines. Instead they formed new single ridges several hundred metres up-glacier. The shift in moraine position also demonstrates the close similarity of the two moraine types. In effect, Puyehue II is a special case of Puyehue III in which several advances of the same type have formed a large amalgamated complex. Each rampart moraine is formed from several ridge moraines. Alternatively, the ridge moraine (e.g. Puyehue III) can be viewed as being in the incipient stages of forming a rampart moraine. Whichever way it is viewed it is crucial to realise that despite their outwardly dissimilar appearances, the two moraine types were constructed by the same process of glacier advance over a deforming bed of lake sediment.

6.4. Implications of the model

The model of moraine formation has two immediate implications for the field area. The first implication is that feedback between the glacier and the bed influences its subsequent behaviour. The formation of a lake basin will create a distinction between (glacio)lacustrine and fluvioglacial sediments where there are marked contrasts in permeability and shear strength. An initial glacier advance through the lake is likely to halt at the downglacier end of the lake and form a moraine there. Subsequently, it is this moraine which largely dictates the extent of the next advance and so the position of subsequent moraine accumulation. Therefore, the position of the first moraine is crucial in determining the location of the moraine sequence. The more moraines formed at this location, the greater the control it exerts on later glacial advances. This feedback control will only be overcome by prolonged, large glacial advances. Moraines formed during earlier glaciations which extended west of the field area apparently did not form rampart/ridge complexes. This is likely to be because the climatic deterioration was sufficiently large that the glaciers extended beyond any sediment contrast. That is, the glaciers thickened sufficiently to leave the lake basins. In addition, during earlier parts of the glaciation the lake basins may not have been excavated or the advances were sufficiently extensive and prolonged to scour all sediment from the lakes. This would mean the lakes did not have the potential to determine moraine position early in the glaciation.

The second implication is that moraine sediments and locations in this area were clearly subject to non-climatic controls. A climatic trigger is still necessary to cause a glacier to advance as far as the lake but how far it gets beyond this depends largely on the distribution of sediment. This is another example of the way in which topography and the nature of the glacier bed can influence glaciers. In this case a glacially-eroded lake basin, acting as a trap of fine sediment, has smoothed-out any differences that existed in the magnitude of successive glacier advances by creating a threshold at which it is favourable for a glacier to terminate, but beyond which is extremely difficult to advance. This may explain why the moraine sequences around each of the Chilean Lakes are so similar and so clustered.

6.5. Summary

This chapter has developed a model for ridge and rampart moraine formation, drawing on the geomorphology and sedimentology of the moraines around Lagos Puyehue and Rupanco. In this model the glaciers advance over deforming beds in the lake basins and halt at the lakeshore transition to coarser, more permeable sediment. The role of the lakes is crucial in determining glacier extent and thus moraine position. The next chapter discusses the wider implications of this model of moraine formation and of the Puyehue-Rupanco glacier chronology.

Chapter 7: Wider implications

7.1. Introduction

This chapter discusses two main implications of this research on the former Puyehue and Rupanco glaciers. The first of these implications concerns the moraine-forming model and its relevance regionally, in the Lake District, and in a wider sense. The second implication concerns the correlation of the glacial chronology to the 'type' Llanquihue chronology. Following on from this comparison, some of the difficulties inherent in making interhemispheric correlations are explored.

7.2. Implications of the moraine-forming model

The work around Puyehue and Rupanco has showed that there is a characteristic landform association around both lakes and that this is the result of a moraine-forming process where the presence of a lake basin plays a strong role. During advance through such a lake basin the glaciers may be relatively insensitive to climate and the location of moraines is controlled by non-climatic factors. This process is likely to operate in situations where active temperate glaciers discharge from a mountain range into lakes filled with potentially deformable sediment. These conditions were probably fulfilled by the former Llanquihue lobe so it is worth examining the moraines to see if there is evidence that this process was operating and if so to discuss the possible influence on the Llanquihue glacier.

7.2.1. Moraine-forming processes around the Llanquihue glacier

The Llanquihue moraine belt demonstrates several similarities to those around Puyehue and Rupanco. The moraines are all closely-spaced; all the last glaciation moraines are within c.5 km of each other and the different drifts are stacked on top of each other. Most moraines are broad, several tens of metres high, and occur as amalgamated series of ice-contact slopes or broad ridges which are graded to extensive outwash plains to the west. This is the same morphology as the rampart moraines around Puyehue and Rupanco. The moraines are composed largely of reworked outwash with thin tills on their proximal slopes (Lowell *et al, in press*). The tills lie over outwash units, or earlier tills, with thrust contacts. Additionally, pockets of glaciolacustrine clay occur in till at several sites, such as Frutillar Bajo. There are two differences in the pattern of moraines compared to Puyehue and Rupanco. One is that there is no lakeshore ridge around Lago Llanquihue. Instead of a lakeshore moraine for the 14.5 ka advance there is a prominent terrace made up largely of glaciolacustrine sediment topped by lahars derived from Volcan Calbuco. Thus, the west shore of the lake is formed by a steep slope rather than a single sharp-crested ridge with an associated outwash plain, as at Puyehue and Rupanco. A second difference is that the outermost ridges are not morainic in origin. A number of the outermost ridges of the moraine belt appear superficially similar to the ridge moraines around the two lakes to the north and were mapped as the Llanquihue I moraine limit by Mercer (1976) and Porter (1981). They are discrete ridges, discontinuous, and of similar dimensions to the ridge moraines. However, sections into the core of these ridges show that they are actually constructed from outwash which has been folded into antiforms and extensively faulted. The folding may be derived from simple compressive stresses or may be a surface expression of blind thrusting. No till is present in the ridges and the fluvioglacial strata can be traced into the shallow-dipping outwash plains on each side.

The close similarities between the pattern, dimensions, morphology and constituent sediments of the Llanquihue moraines to those around Puyehue and Rupanco implies a similar process was operative around all three lakes. Thus the characteristic landform association shows that the glaciers may have been partially decoupled from climate by interactions with their beds and feedback controls created by the deposition of moraines. The ridges of folded fluvioglacial strata in the Llanquihue outwash plain may be further evidence of the control of pre-existing moraines on the limits of subsequent glacier advance. The ridges imply substantial compressive stresses were transmitted through the outwash plain, probably due to the Llanquihue lobe pushing against the lakeside ice-contact slope. This corresponds to Stage 4 of the moraine-forming model where the glacier has reached the far end of the lake and is beginning to thicken with consequent increasing driving stresses but is not able to override the topographic barrier of pre-existing moraines. Since the moraine-forming process can also be applied to Llanquihue the model provides an explanation for the stacked drifts. It also emphasises the need for good lithostratigraphic and morphostratigraphic criteria to distinguish advances recognised on the basis of dates from overridden organic material in stacked drifts.

7.2.2. Wider implications

There are three major implications of the moraine-forming model which apply beyond the field area. First, the role of lakes in glacial fluctuations is important. The lake is controlling glacier dynamics at a local scale and can exert a stronger control on glacier position than the mass balance. This local lake effect can be compared to tidewater calving, where a calving cycle can dominate regional mass balance (Mercer, 1961). Also, the intuitive assumption that moraine locations define and dam lakes can be challenged. Here, it is the initial lake shoreline that determines the position of the subsequent moraines and not vice versa. Where glacial chronologies are to be derived from moraine sequences in areas where strong differences in sediment grain size, strength or permeability exist it is important to investigate the internal structure of moraines to establish whether they have been formed by repeated advances, not necessarily closely associated in time. In such cases, geomorphological mapping alone cannot determine the number of glacial stages and detailed sedimentological and stratigraphical studies are likely to be required to distinguish the stacked drifts and allow dating of the fluctuations. An approach based primarily on dating may not recognise all the glacier advances.

The second implication is that conditions favourable for shoreline moraines are most likely to exist at the snouts of temperate glaciers where large amounts of meltwater build large barriers of fluvioglacial outwash and enhance the grain-size contrasts by depositing coarse sediment in front of the glacier during stadials and fine-grained sediment in the lake during interstadials. Glaciers in temperate environments with high debris content are also more likely to form such moraines because of the greater likelihood of forming substantial proglacial sediment sequences as a result of high rates of summer melting. Lake shoreline moraines would be less likely to form in deep valleys where sidewall drag would exert a strong control on glacier movement. Possible Pleistocene analogies for the moraines described in the Chilean Lake District include the moraine loops around the southern ends of the North American Great Lakes, the loops around the Italian and South German Lakes, and some termini on the east side of the Southern Alps, New Zealand. All these lie in climates which are or were relatively mild.

A third implication of this type of moraine formation is its effect on the extent of glacier fluctuations. The composite moraines constructed at the down-glacier end of the lakes form significant topographic barriers to subsequent glacier advance. Thus, the effect of lakes may partly explain why several areas have experienced progressively less extensive glaciations through time.

7.3. Implications of the chronologies of Puyehue and Rupanco

Any discussion of the wider implications of this study of the Rupanco and Puyehue glaciers must involve comparison with the impressive work of George Denton's team in the Llanquihue area. One important step in such a comparison is to review critically the conclusions and assumptions of the Lowell *et al* work. In particular, it is interesting to see whether the southern lobes also exhibit leads and lags of up to c.700 years. If it is established that there is room for leads and lags, then this is not intended as a criticism of the Lowell work. Rather, it shows to what extent the evidence is consistent with a slightly different approach.

7.3.1. Discussion of dating control for the Llanquihue chronology

A time-distance diagram, plotted from the 'raw' radiocarbon dates, for the Llanquihue, Seno Reloncavi and Castro lobes is shown in Figure 7.1. The diagram shows the dating control for each of the advances of the three lobes. The possible range of time which the maximum and minimum dates

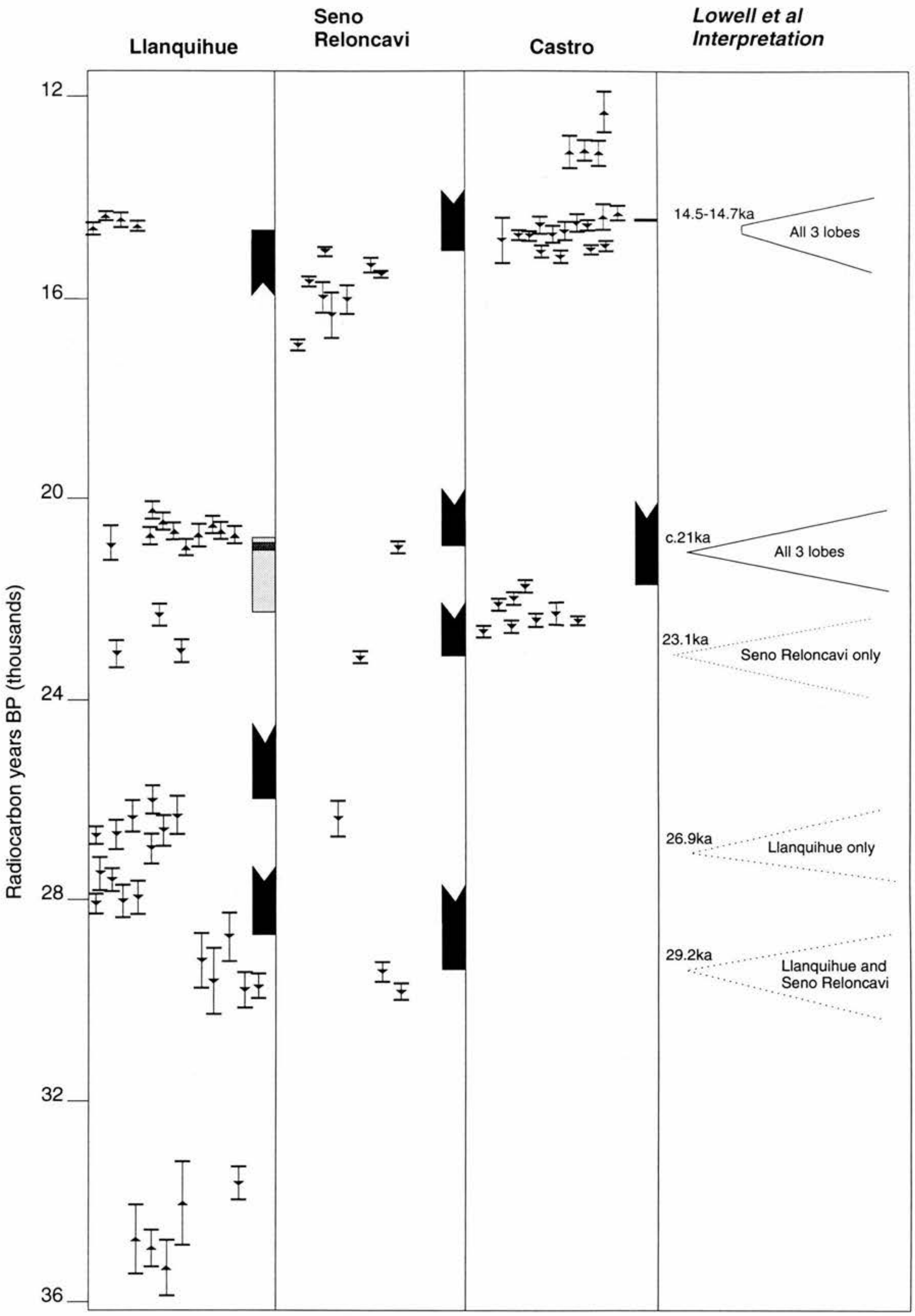


Figure 7.1. Radiocarbon dates for the Llanquihue, Seno Reloncavi and Castro glacier lobes. The dates are plotted according to which lobe they relate and whether they are maximum or minimum dates. The interpretation of this data by Lowell *et al* is given in the right-hand column. The individual columns for the glacier lobes has a shaded bar indicating the possible time range for each of the glacier advances. The toothed ends of some bars indicate the dating control is 'open-ended'; that is, there is no bracketing date associated with that advance. For example, the 14.5-14.7 ka advance of the Llanquihue lobe is constrained by four minimum dates to sometime before 14,570 BP while the corresponding advance of the Seno Reloncavi lobe is constrained by several maximum dates to sometime after 15,200 BP. The c.21 ka advance of the Llanquihue lobe is constrained by maximum and minimum dates. However, two of these overlap so the shading of the bar shows the central zone of overlap and the possible range of the advance if one or both of the dates are discarded. All dates from Lowell *et al* (*in press*).

indicate for each advance are shown along with the interpretation of Lowell *et al* (*in press*). Four main features are apparent from the data.

Firstly, advances of the three lobes at comparable times have been 'averaged' to produce a single advance date. This is a useful way of dealing with a large amount of data to produce a 'type' chronology but it runs the risk of masking minor differences in behaviour of the individual lobes which may be significant. Secondly, many dates, particularly from overridden organic material, are described as 'close' limiting dates. For example, the 26.9 ka advance of the Llanquihue lobe is dated by grass and leaf litter from the top of an organic silt bed below a till. The relatively undisturbed nature of such easily transported material suggests it was unlikely to have been deposited substantially before the glacial advance. Thus, this example may be a relatively close limiting date. Several advances have maximum or minimum limiting dates, but are not bracketed by a combination of the two. For example the culmination of the advance described around 21 ka may have occurred any time after 20,900 BP for the Seno Reloncavi lobe, and any time after 21,700 BP for the Castro lobe. These are the dates on shells and wood buried or deformed by glacial sediments during the advances of the two lobes. Similarly, the 26,900 BP and 29,200 advances are only constrained by maximum dates and may have occurred significantly later than the dates given. The 29.2 advance is dated by an organic silt layer, with apparently little evidence of it providing a close limiting date. The 29.2 ka advance interpreted for the Seno Reloncavi lobe is constrained by a folded peat clast, which is incorporated into the moraine and yielded a date of 29,080 BP. The 21 ka advance of the Llanquihue lobe is better constrained by maximum and minimum dates but the oldest minimum and youngest maximum overlap. If one or both of these overlapping dates are discarded then the dating control on the Llanquihue lobe advance constrains the advance to sometime between 20,700 and 22,250 BP (Fig. 7.1).

Thirdly, the stratigraphy presented by Lowell *et al* is based largely on radiocarbon dates rather than morphostratigraphic and lithostratigraphic criteria. Although the Llanquihue and Seno Reloncavi lobes were mapped in detail the results are not presented with the palaeoenvironmental data and the radiocarbon dates so it is not always possible to elucidate the relation of the sites to each other. An important example of this is the 23,120 advance of the Seno Reloncavi lobe, which is based on only one maximum date and could be a maximum for the 21 ka advance. Other examples of this are the Frutillar Bajo and Puerto Octay sites which yield clusters of maximum dates for the 26,900 and 29,200 advances respectively but without details as to why they are *separate* advances. As given, the Puerto Octay and Frutillar Bajo dates might all be maximums for an advance after 26,900 BP.

Finally, although not explicitly stated, two of the sites which yield multiple dates have had these dates combined to give an arithmetic mean, using the method described in Lowell (1995). For example, the Puerto Octay site yields five dates between 28,550 and 29,600 BP with a mean of 29,200 BP. The

Frutillar Bajo site affords 12 dates between 25,853 and 27,900 BP with a mean of 26,900 BP. This is in contrast to all other sites where the youngest maximum or oldest minimum has been taken as the limiting date. The problem of whether to use individual dates or averaged dates has been discussed by Lowell (1995). He showed that multiple dates from samples at the same stratigraphic level vary by up to 1000 years and that inter-sample variability is often outside the one-sigma confidence level commonly quoted. Multiple samples from the same geological unit show a range of up to 5000 years and also that inter-sample comparison is usually outside the one standard deviation level. For these reasons Lowell (1995) and others (e.g. Baillie, 1990) recommend several analyses for each stratigraphic level to ensure that any individual age is representative. These dates should be combined to provide a 'best age' from the data set, either visually, or by an arithmetic mean, or by combining their probability distributions.

In the treatment of multiple dates the averaging approach may be better for minimising the influence of contaminated samples on the date of a glacial advance, but if all the dates are averaged then the total range of the samples becomes important in determining the limiting date. For example, there may be different 'generations' of reworked organic material in the same stratigraphic unit. If dates are obtained on samples of the material and the results averaged, then the older material assumes the same importance as the youngest generation material. Taken alone, the younger material would provide a more representative maximum limiting date. This may result in a significantly older maximum date. The averaging of the dates at Puerto Octay yields a maximum date 650 years older than the youngest single maximum date, and at Frutillar Bajo there is a 1000 year difference. Averaging the dates has also removed up to 2000 years variability. An alternative approach would be to average the three oldest maximum (or youngest minimum) dates. In this way, the effect of 'extreme' contaminated samples would still be minimised but the total range of ages in the whole sample would be less influential in determining the limiting date. This approach results in a maximum limiting age of 29,000 BP for the Puerto Octay section, and 26050 BP for Frutillar Bajo. These dates are, respectively, 200 years and 850 years younger than the average values using the approach of Lowell (1995). Moreover, they are within only 450 years and 200 years of the youngest maximum dates at each of the sites. Clearly, the approach to multiple dates can significantly influence the interpretation of the timing of a glacial advance. Where only single dates exist then they have to be treated as limiting dates.

From this consideration of the work of Lowell *et al*, a number of conclusions can be drawn about the Llanquihue chronology. Firstly, the 21 ka and 14.5 ka advances are well established for each of the three lobes but the exact timing of the advances of each lobe may have been different. For example the Castro lobe may have reached its 21 ka limit 750 years or more before the Seno Reloncavi lobe. The 14.5 ka advance is closely bracketed for the Castro lobe and the other two lobes may have been synchronous. The dates suggest that the Llanquihue lobe advanced at least 100 years earlier than the

Castro lobe but this is probably not significant given that the standard deviations for the dates are of the order of 100 years. The other advances are less securely constrained. The 23,120 BP advance has already been highlighted as based on only one date whilst the 26,900 and 29,200 BP advances are not recorded for all lobes and the dating control does not preclude the possibility that they may have been markedly asynchronous. The possibility also remains that the clusters of dates at 26.9 ka and 29.2 ka do not represent two separate advances, but relate to the 26.9 ka advance. Earlier advances are still constrained to pre-35,000 BP

7.3.2. Comparison of the Puyehue and Rupanco chronologies to the Llanquihue chronology

Bearing these limitations in mind the Puyehue and Rupanco chronologies can be compared to the Llanquihue glacial history. An immediate conclusion from this comparison is that the pattern is similar and that the dates of many of the glacial stages are consistent. Although not necessarily synchronous with each other, the dating control on the Puyehue III and Rupanco III stages shows they are entirely consistent with the 14.5-14.7 ka advance of the Llanquihue lobe. The Puyehue III advance occurred subsequent to 16.1 ka but before 12.2 ka whilst geomorphological relations suggest that the Rupanco III advance may have been approximately synchronous. The Puyehue IIA stage is not well-dated. It occurred prior to 19.4 ka so may be an equivalent of the Llanquihue 21 ka, 23.1 ka, 26.9 ka, 29.2 ka or even pre-35 ka advance(s). Puyehue I and Rupanco I are undated but may be equivalent to the pre-35 ka advance(s) described for the Llanquihue lobe. Deglaciation from the Puyehue and Rupanco lake basins was complete before 12.2 ka. Again, the dating control is consistent with, but cannot confirm, the deglaciation after 14 ka inferred for the Llanquihue lobe. None of the glaciers left evidence of a climatic deterioration of equivalent age to the Younger Dryas event of northern Europe. This agrees with earlier work which discussed the absence of geologic evidence for advances during the very closing stages of the glaciation in this region (Mercer, 1976).

There is also evidence for discordant behaviour of the Puyehue and Rupanco lobes compared to the three lobes to the south. This is manifest in both the timing and number of glacial events. For example, the sequence of advances to the Puyehue II and Rupanco II moraines do not match the evidence further south of a single advance at c.21 ka. The maximum in the Rupanco basin apparently occurred after 19.5 ka (Rupanco II). Advances to closely similar limits in the Puyehue basin occurred once before 19.4 ka and once shortly afterwards (Puyehue IIB). Therefore, the maximum Rupanco advance and at least one of the Puyehue advances occurred substantially later than the Llanquihue maximum at 21 ka. Another advance of the Puyehue and Rupanco glaciers occurred between 19.4 ka and 16.4 ka (Puyehue IIC and Rupanco II). The Llanquihue lobe apparently did not advance at all in this interval since no moraines were formed between 21 ka and 14.5 ka. Other differences exist in earlier parts of the sequence where there is a mismatch between the number of moraine stages in Puyehue-Rupanco and the three lobes to the south. The chronology of the Puyehue and Rupanco glaciers shows that prior to 19.4 ka there were apparently only two advances of the Puyehue lobe and one advance of Rupanco. Therefore, at least two of the Llanquihue advances at 23.1, 26.9, 29.2 and pre-35 ka are apparently not recorded by either the Puyehue or Rupanco glaciers. This apparent difference in behaviour is puzzling given the existence of apparently more complex behaviour of the Puyehue and Rupanco lobes after 16.4 ka when there were two stages (Puyehue IV and Puyehue V) not recorded by the Llanquihue lobe.

The magnitude of the lags between the different glaciers can be estimated from a comparison of the radiocarbon chronologies. However, because of the limited dating control on the Puyehue and Rupanco lobes this method only allows a crude estimate of *maximum* possible lags between the different basins. The main conclusion to emerge from this comparison is that the Rupanco and Puyehue equivalents of the 21 ka advance in the Llanquihue basin occurred 1500 years later than in Llanquihue. This is potentially a significant anomaly. However, at present it rests on one key date for Rupanco and two for Puyehue so it needs to be tested further. Comparison of the other advances is less informative. For example the Puyehue III and Rupanco III stages are likely to be equivalent to the 14.5 ka lakeshore advance of the Llanquihue lobe but the only control on their timing is that they occurred subsequent to 16.1 ka and prior to 12.2 ka.

7.3.3. The effect of valley geometry on the response of the Llanquihue glacier

The good match between field evidence and the glaciological model has demonstrated that most of the differential behaviour of the Puyehue and Rupanco glaciers can be explained on the basis of geometrical differences and glaciological theory. Minor mismatches between the model and the field evidence, for example the style of retreat of Rupanco, may be explained by calving effects which are not incorporated in the model. Since morphological differences appear to have played an important role in the differential response of Puyehue and Rupanco, it is important to examine the geometry of the Llanquihue basin and its possible influence on glacier response.

The present bathymetry of Llanquihue resembles an oyster shell opening to the west with an overdeepened basin up to 317m deep in the east and a shallower, relatively flat-bottomed basin between 100 and 200m deep in the west. There is also evidence of a submarine ridge across the mouth of the southwestern embayment of the lake. The morphology of the former Llanquihue ice catchment during the last glaciation is difficult to establish because of changes in topography caused by volcanic activity. The overdeepened basin in the east part of Lago Llanquihue marks a former deep connection to Lago Todos Los Santos which is over 300m deep at its western end. During the last glaciation this connection was the major route for ice flowing west to form the moraines around Lago Llanquihue, but during the Holocene lavas from Volcan Osorno flowed into the trough, separating the two lakes

(Campos *et al*, 1990). The possibility of substantial changes in topography means that the Llanquihue lobe cannot be modelled confidently, but it is possible to make some qualitative observations about the likely effects of basin geometry on the response of the former Llanquihue glacier. A substantial volcanic edifice existed through much of the Quaternary on the eastern shore of Lago Llanquihue (Moreno, 1974). This would have been ice-covered during the last glaciation but any glacier derived from the volcano is unlikely to have had sufficient volume and mass balance excess to overcome the high calving rates and advance across the lake alone. Instead, this glacier would have acted as a feeder to the main glacier flowing from the mountains through Lago Todos Los Santos. The morphology of the present basin through which the main glacier would have advanced is complex with several tributary arms feeding into the lake from the surrounding mountains. These valleys are relatively short and steep so the glaciers probably responded rapidly to climate during initial ice build-up. Despite this, they are located a substantial distance east of Lago Llanquihue so would have taken a relatively long time to reach its western shore. Valley geometry and calving relations then both point towards a slower response to climate compared to Puyehue and Rupanco. This is in direct contrast to the empirical evidence of an earlier 21 ka advance in Llanquihue than in Puyehue or Rupanco. However, two features of the morphology of the Llanquihue glacier basin may explain the difference.

First, all of the tributary valleys feed into a narrow basin now occupied by Lago Todos Los Santos. During glaciation the tributary glaciers would have coalesced to produce a considerable thickness of ice in the basin. The confluent ice might have reached sufficient thickness to intersect the Equilibrium Line and so accumulation would have increased sharply and the glacier would maintain a higher volume. For the same climatic conditions there would be two possible stable states, with substantially different ice volumes. Which of these was adopted would depend on whether the glacier was in the initial stages of growth (small volume) or had already grown to a sufficient altitude to maintain a higher volume. This is analogous to the behaviour described for the Scottish Ice Sheet by Payne and Sugden (1990). The high accumulation - high volume scenario would be likely to lead to a more extensive frontal position than the low volume state. This is because the glacier would have to advance significantly further in order to ablate the excess mass. The effect of the altitude-mass balance feedback on the frontal position would be further magnified by the fact that the basin feeds through a relatively narrow trough into Lago Llanquihue (Firbush and Andrews, 1984). It therefore seems likely that during the last glaciation the Llanquihue lobe maintained a large volume of ice which was relatively independent of the effects of valley geometry in the Todos Los Santos basin. The altitude - mass balance feedback may have led to a relatively quick response to climate. Only prolonged warming could reduce the lobe to its low volume state and slow the response to subsequent cooling.

Secondly, the discontinuous submarine ridge across the southwestern embayment of the lake may be a submarine moraine shoal which would suggest that, at times, the Llanquihue glacier front sat close to the western shore of the lake without leaving any onshore moraine record. If so, then this would provide another explanation for the quicker response of the Llanquihue glacier in the glacial record. In effect, the Llanquihue glacier may have responded quickly to climate because it did not have far to advance to reach the western shore.

The two geometrical factors discussed above may have operated together during the 21 ka advance so that the Llanquihue glacier responded more quickly than either Puyehue or Rupanco. However, if the Llanquihue glacier was in its low volume state, such as during early last glaciation advances then the lobe may have responded more slowly to climate. The glacier would also be unlikely to reach the western shore of the lake in response to any cooling event after it was deglaciated at 14.5 ka. If there was such a cooling, then any associated moraine(s) would be located in the tributary valleys.

The geometry of the Llanquihue basin would have also influenced the calving dynamics of the Llanquihue glacier. The considerable depth of the eastern portion of the lake suggests that calving rates would have been large as the glacier advanced into the lake (Fig. 5.6a). The Llanquihue lobe had a wider terminus than Puyehue or Rupanco so this would also have increased the total ablation. Thus, from a consideration of probable calving rates the Llanquihue lobe should have responded relatively sluggishly to climatic forcing. It is possible that in the case of Llanquihue the geometrical effects and calving effects acted in opposite directions and that geometrical effects dominated, causing the glacier to respond rapidly. During retreat however, the glacier would have calved into progressively deeper water and retreat is likely to have been rapid (Fig. 5.6b).

The basins of the former Castro and Seno Reloncavi glaciers do not have the same morphologies as the Llanquihue basin, although both are surrounded by more tributary valleys than Puyehue and Rupanco. As with Llanquihue the basins are relatively long and steep so the glaciers may have showed an initial quick response. However, the considerable distance they had to advance and the high calving rates in seawater means this response may have slowed towards the western limits. The Gulf of Ancud is shallow but it is not known if there are any submarine ridges. Therefore it is not known if the same factors affected these two lobes as the Llanquihue lobe. However, as discussed above, the minimum ages of the 21 ka advances of these two lobes are not constrained and so they may have occurred as late as Puyehue and Rupanco.

7.4. Comparison of the glacier chronologies to other proxies

One way of testing the palaeoclimatic significance of the glacial chronolgies is to compare them to independent proxies of climate. For example, the palynological record of climatic changes in the Lake District spans much of the Late Pleistocene interval in question. Although the 21 ka and 14.5 ka advances seem securely established, the precise timing for each glacier varied. Perhaps the pollen record can be used to establish the onset of the climate signal responsible for this advance. Additionally, the pollen record might be used to test the glacial geologic evidence of advances at 29,200, 26,900, and 23,120 BP.

The pollen record identifies cold conditions which lasted for much of the interval from 40,000 BP until 14,500 BP when temperatures warmed abruptly. This agrees well with the geologic evidence of glacial advances until c. 14,500 when abrupt deglaciation occurred. However, within this interval the pollen record does not show much resolution of climatic events. In particular there are no marked changes at the key dates highlighted by the glacial evidence; namely 21-19, 29.2, 26.9 and 23.1 ka. The Alerce core shows moderate increases in precipitation at c.22 ka, c.26.4 ka and c.31.8 ka but these were short-lived and are within the error limits of the method used to calculate precipitation (Heusser *et al*, 1981). The Río Negro site shows a slight cooling and increase in precipitation at c.26 ka but these conditions were maintained unchanged until c.14 ka. None of the other pollen sites record significant climate variation in the interval 32,000 to 16,000 BP. The record from north of the Lake District, at Laguna Tagua Tagua (34°S), shows a transition from cold dry conditions to a cold wet climate at c.29 ka (Heusser, 1984) but this climate apparently then remained constant until c.11.5 ka. In summary, the pre-15 ka pollen record does not appear to provide the necessary sensitivity to determine the precise timing of the climatic deterioration recorded by the glacial advances.

The pollen record of the interval 15-14 ka does show more evidence of climatic variation. At Puerto Octay, Moreno (*submitted*) interpreted a short-lived cooling at c.15.8 ka and another at c. 14.8 ka. These were followed by rapid warming. Heusser's (1974) interpretation of cores from Puerto Octay and Puerto Varas showed a slight cooling at c.15 ka which was maintained until rapid warming at 12 ka. Therefore, the advance of the Puyehue and Rupanco glaciers between 16.4 ka and 12.2 ka were likely to have been in response to one of these cooling events. At present, the dating control is not sufficient to determine which.

The apparent low sensitivity of the pollen record may be for a number of reasons. First, the magnitude of the changes in temperature and precipitation which caused glaciers to expand were too small to cause changes in vegetation assemblages. Second, the vegetation may have changed but the changes were subtle and not sufficient to allow them to be detected in the pollen record. A third possibility is that any changes in climate were too short-lived to cause a response in vegetation. A fourth factor that may have been important is the distribution of the ecological zones. During the glaciation the ecological zones of Chile migrated northwards, and the Lake District was colonised by subantarctic parkland vegetation. Changes from the background conditions of the glaciation to colder stadials may not have been sufficiently large for the next ecotone southward to advance north into the Lake District. In effect the spatial extent of ecotones may have smoothed out the record of changes in climate.

Equilibrium Line Altitudes have been reconstructed from a number of sources. An additional result of the flowline modelling experiment is that an ELA lowering of at least 1000m is required to simulate the glacial maximum (Hubbard, *in press*). This result agrees with the c.1000m of ELA depression inferred from different lines of empirical evidence by both Moreno (*submitted*) and Porter (1981). Porter's estimate is from glacial geological evidence and reconstructed glacier elevations whilst Moreno's estimate is based on pollen evidence of a 6°C cooling and an inferred 0.6°C/100m lapse rate. However the figure of 1000m from the flowline model is in marked contrast to the results of modelling the entire Patagonian ice cap on a 20km grid (Hulton *et al*, 1994). Both models used a similar mass balance curve developed from regional meteorological data by Kerr and Sugden (1994). This discrepancy is mainly due to the size of the grid in the regional model which smooths out individual valley basins, and to the lower estimate of the present-day ELA (Hubbard, *in press*).

In summary, the pollen record does not appear sufficiently sensitive to resolve some of the apparent disparities between the chronologies of the Puyehue, Rupanco, Llanquihue, Seno Reloncavi and Castro glaciers. However, the pollen-derived estimate of ELA depression during the last glaciation agrees well with estimates based on glacial geology and a glaciological model.

7.5. Implications of the glacier chronologies for interhemispheric correlation of glacial events

Our understanding of the timing of glacial advances is obviously dependent on the availability of samples for radiocarbon dating and on the problems associated with this dating technique. The dating control on glacial events is unlikely ever to be ideal so it is particularly important to be aware of the limitations of radiocarbon chronologies. Glacial chronologies can show the pattern of glacial advance and retreat and raise important ideas and palaeoclimatic questions, but the possibility of short-term asynchronous behaviour of glacier lobes should be incorporated in order to distinguish local noise from the climate signal. This is particularly important in a key area such as the Lake District where 'type' chronologies of the last glaciation have been established.

This leads to the question of whether the modulation of the glacier response in the Lake District by non-climatic influences was significant in the context of the 'type' glacial chronology. The chronology developed by Lowell *et al* (*in press*) has been compared to the glacial record in New Zealand to produce a composite record for the Southern Hemisphere. This in turn has been compared to the record of ice-rafting events in the North Atlantic. The close match between the hemispheres has been interpreted as due to interhemispheric synchrony of climate change, an important result with far-reaching implications for mechanisms of climate change. This thesis shows some of these events may indeed be synchronous, particularly glacier advances at c.21 ka and 14.5 ka. However, some of the Chilean glacier advances are not so well established and so their correlation is more difficult.

7.5.1. The difficulties of interhemispheric correlation

In addition to the specific discussion of the Lowell *et al* chronology, it is worth exploring interhemispheric correlation in a wider sense. Many studies attempt to correlate proxy records over long distances and there are a number of difficulties associated with this. Global correlation of glacial events, such as ice-rafting pulses or glacial advances, which are separated by a few millenia is made difficult by three factors. First, there is a clear potential for introducing delays in glacier response which mean that no single glacier will necessarily record the 'true' date of the climatic event and each glacier may reach its maximum extent at different times. Added to this uncertainty is the dating control on individual glacier lobes which is not always close and may sometimes allow as much as one thousand years of 'slack'. Thirdly, without careful consideration of the first two problems the timing of events may be correlated over-optimistically when combining the dates of advances from each of these lobes.

The importance of dating control for confident correlation can be illustrated, using the correlation of the Chilean glacial chronology with the North Atlantic ice-rafting record as an example. The Heinrich events towards the end of the last glaciation occurred at an interval of between 6000-7000 years (Fig. 1.1). Between these major ice-rafting events there were a number of smaller ice-rafting pulses (events *a, b, c, d, e, f, g* of Bond and Lotti, 1995) which recurred at intervals of 2000 to 3000 years. Each of these events has an associated dating precision. Broecker (1994) suggests that it is reasonable to assume a precision of c.300 years for such events. This study has shown that glacial advances of individual glacier lobes in the Lake District may have differed by up to 1500 years, which raises the question of how easy is it to correlate the Chilean glacial chronology to the North Atlantic ice-rafting record.

The question can be addressed using a simple computer program which matches two sequences of events. The following section gives a brief description of the operation of the program and its results (full details of the program are given in Appendix A). The program creates a sequence of *n* dates, each representing the 'true' date of a glacial event. These dates are *random*, generated internally by the computer. The dates are then compared to the dates of the Heinrich events, which are taken from Figure 3 of Bond and Lotti (1995). The comparison is repeated with progressive, stepped increase in the precision of the dates in both sequences of events. In effect, the range of time represented by each event is increased by an equal amount in both the positive (maximum date) and negative (minimum

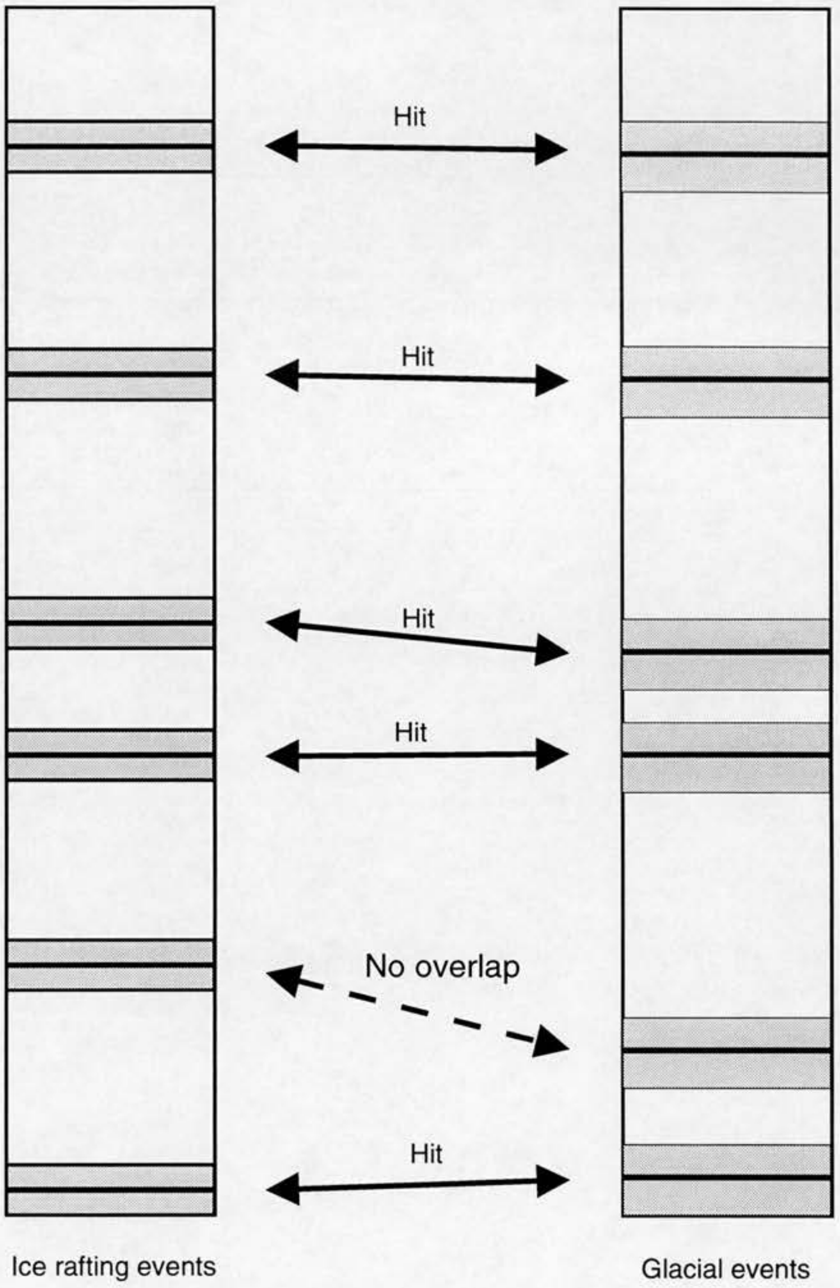


Figure 7.2. Operation of the correlation program. Two sequences of events are compared, each with an associated precision. Any overlap between the time ranges of the two events is counted as a 'hit'. The example given is an illustration of a run of the program which resulted in 83% hits. That is, 5 of the 6 possible glacial events matched an ice-rafting event.

date) directions (Fig. 7.2). Any overlap between the time ranges of a Heinrich event and a glacial event is counted as a 'hit'; that is, a sufficiently close match to regard the two events as synchronous. This is analogous to the situation in reality where overlap between the dates of two events (such as a glacial event and a Heinrich event) is commonly interpreted as evidence of synchrony. The percentage of hits between the two sequences is calculated for each set of error values (Fig. 7.3). In order to smooth the results, the comparison is run 100 times for each set of error values. Each of these runs generates an entirely new sequence of random numbers. The mean percentage of hits is then a representative measure of the degree of match between two sequences of events with the given errors.

The results show a relatively high degree of match between the two sequences of events. For example, when correlating 3 random events to 15 ice-rafting events, an average match of over 70% occurs when the precision is 750 years on the glacial events and 300 years on the ice-rafting events (Fig. 7.4a). The program can be applied to the Lowell *et al* scenario in the Chilean Lake District. For this, eight random (glacial) events in the interval 9200 BP to 30600 BP are compared to the eight ice-rafting events at 10,200, 14,500, 18,000, 19,000, 21,000, 23,000, 26,000 and 29,000 BP. The results show that a greater than 50% match occurs when Heinrich errors are as small as 100 years and the precision on glacial advances is 550 years (Fig. 7.4b). This means that, on average, more than half of the glacial events are matching ice-rafting events in each run. Many of the runs result in a 'perfect' correlation (all glacial events match an ice-rafting event) or very close match (all but one or two events match ice-rafting episodes).

The implication of the results from the program is that without relatively tight dating control the probability of obtaining a good correlation between two records is high, whether or not there is a causal link between the records. It does not necessarily imply that the correlation obtained by Lowell *et al* is spurious, but rather that the confidence of the match would be improved by a measurable amount if the dating control on some of the advances was closer. This thesis has illustrated that one way to achieve this might be to examine the topographic controls in more detail so that the glaciers with the most rapid response to climate change could be identified.

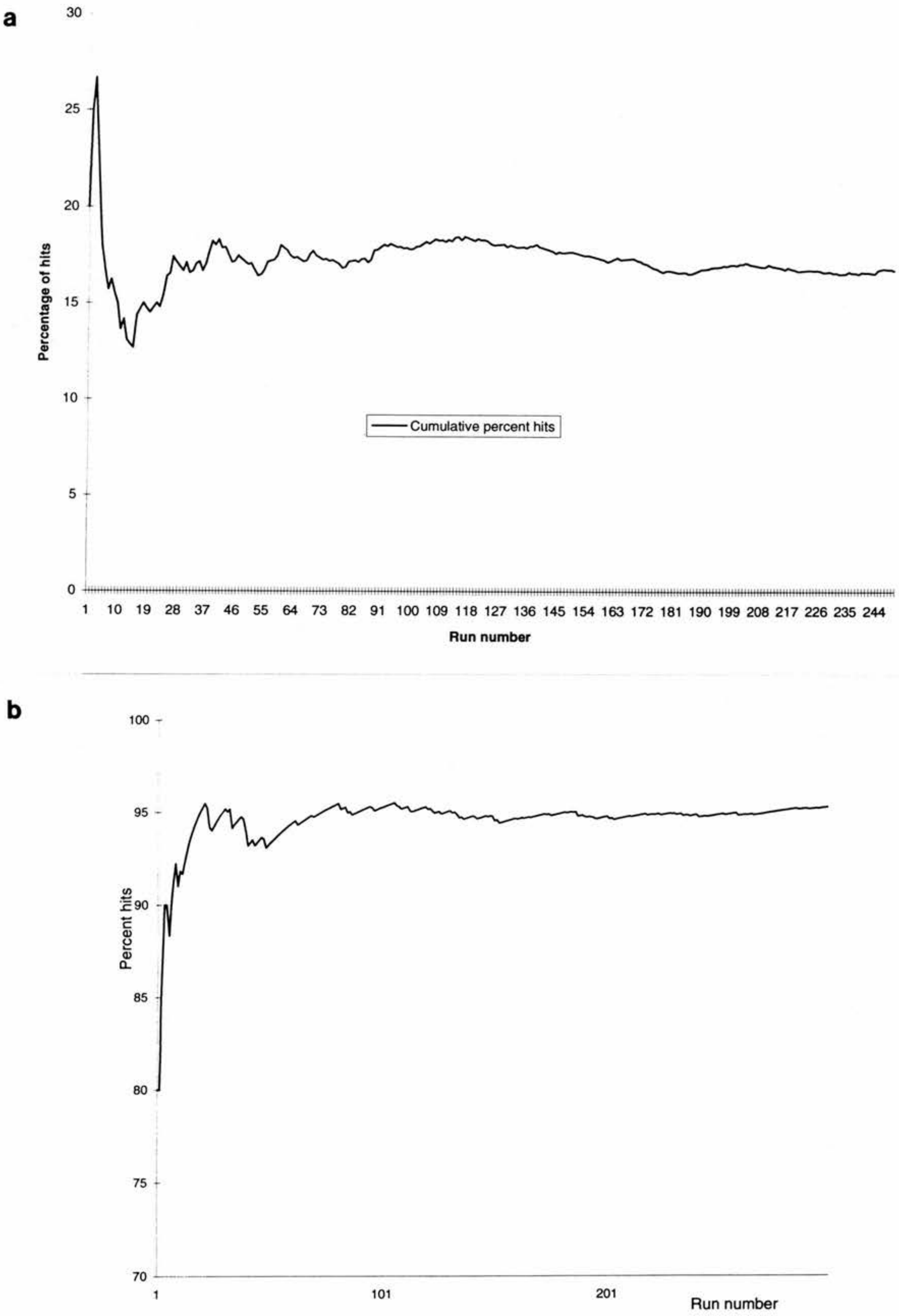


Figure 7.3. Results of correlation program with fixed precision for each event.

(a) Cumulative value of the percentage of hits as a function of number of runs for the scenario with 15 ice-rafting events (precision 100 years) compared to 10 random events (100 year precision). After c.90 runs the average percentage of hits is relatively constant (c. 16-18%).

(b) Scenario with 15 ice-rafting events (300 year precision) and 10 random events (1000 year precision) showing an average match of 94% between the two records. The results from these contrasting scenarios also demonstrate that 100 runs of the program yields a representative average of the percentage of hits obtained.

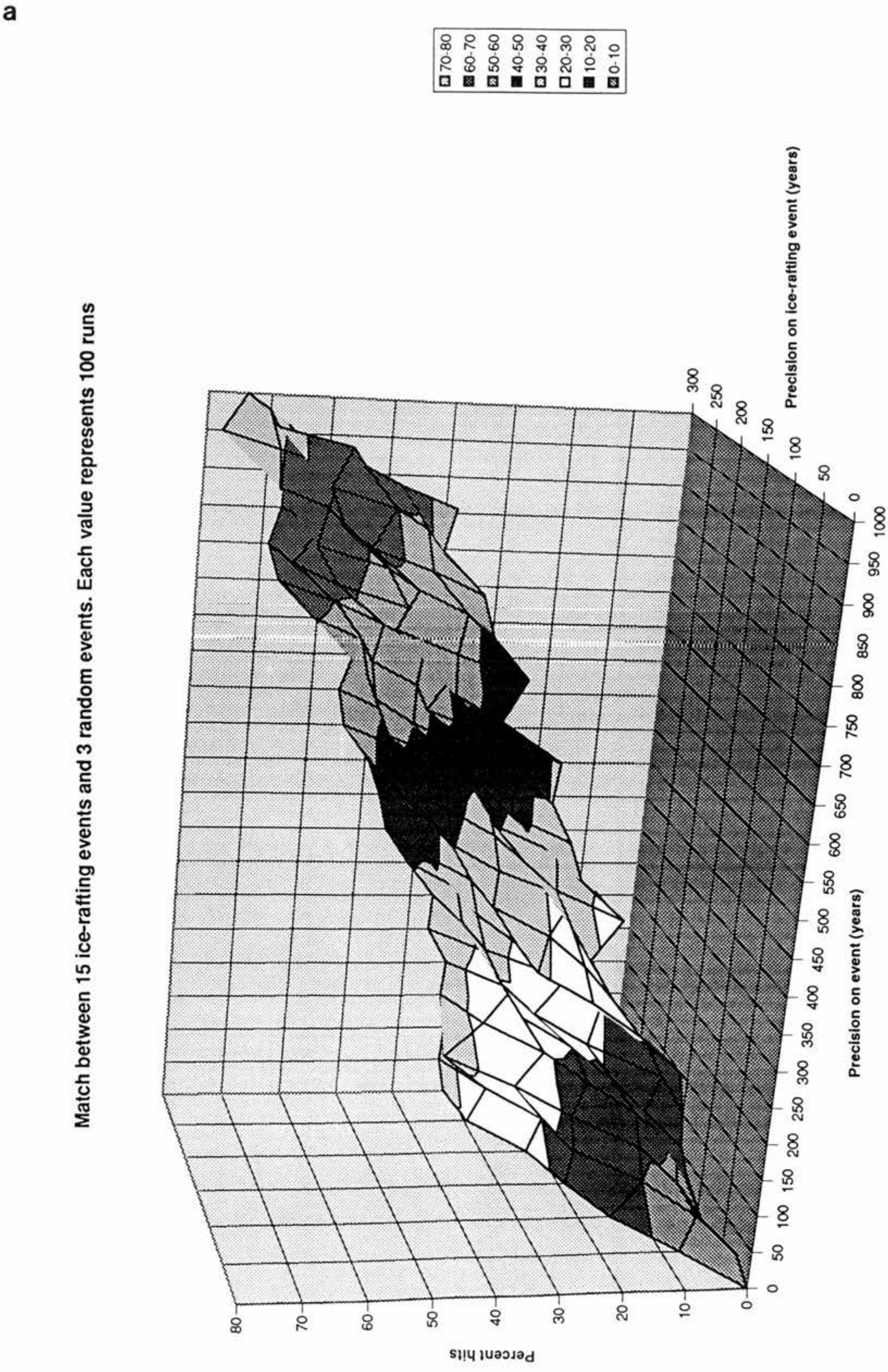
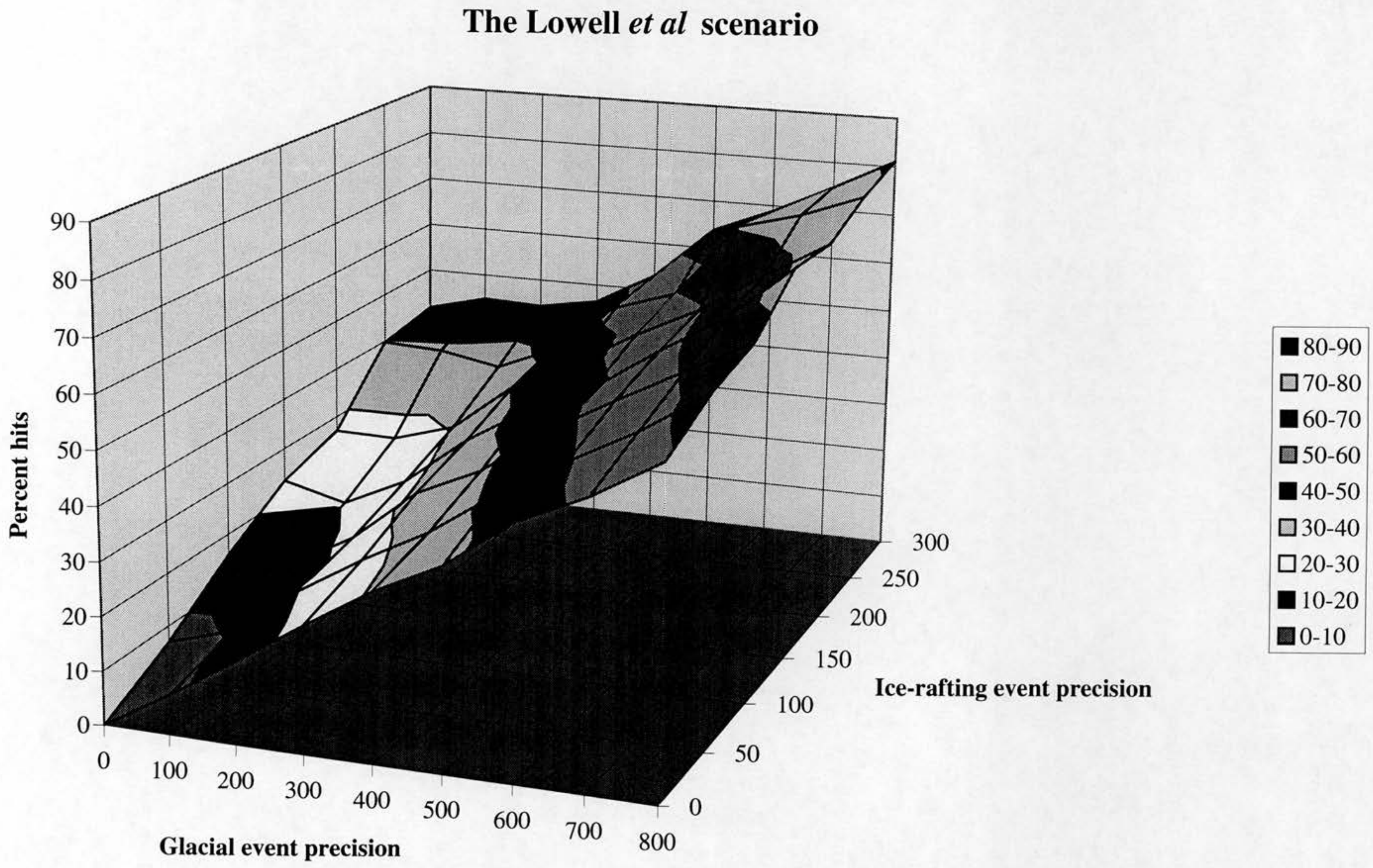


Figure 7.4. Results of program with stepped changes in precision of the two sequences of events. Average percentage hits are a function of both the precision on the ice-rafting events and the precision on the random events so results are plotted as a contoured 3-dimensional surface.
(a) 15 ice-rafting events, 3 random events.
(b) A simulation of the Lowell *et al* scenario: eight random (glacial) events correlated to eight specific Heinrich events.

b


The Lowell et al scenario
Percent hits
90
80
70
60
50
40
30
20
10
0
Glacial event precision
0
100
200
300
400
500
600
700
800
Ice-rafting event precision
0
50
100
150
200
250
300
■ 80-90
▨ 70-80
■ 60-70
▨ 50-60
■ 40-50
▨ 30-40
□ 20-30
■ 10-20
▨ 0-10

Chapter 8: Summary and further work

8.1. Summary of conclusions

The primary aim of this research was to investigate the relative importance of local and climatic factors on the fluctuations of two closely adjacent outlet glaciers in the southern Lake District. This study is part of a wider effort to correlate glacial records from the Northern and Southern Hemispheres in order to investigate the climatic links between the two hemispheres. Such information will aid understanding of the mechanisms of climate change. The area studied has been used as a representative proxy for the climate of much of southern South America.

The research has two main conclusions; one relating to the glacier chronologies and one on glacier processes. Firstly, the chronologies for the Puyehue and Rupanco glaciers are broadly similar to each other and to the Llanquihue 'type' chronology. The c.21 ka and 14.5 ka advances previously reported in the Lake District were probably major fluctuations which affected all the glaciers and were almost certainly related to substantial climatic deterioration. Other advances postulated by Lowell *et al* (*in press*), for example at c.23 ka, 26 ka, and 29 ka, are less securely tied down and these latter events have not yet been identified in other proxies such as the palynological record.

There is evidence for significant discordant behaviour of individual glacier lobes on a short timescale of c. 1000 years or less. Asynchronous behaviour of the Puyehue and Rupanco lobes has been demonstrated by empirical evidence and by modelling studies carried-out in parallel with this research. There is a good match between the model and the field evidence which shows that the differential behaviour can be explained largely in terms of differences in the geometry of the two glacier basins.

The Puyehue glacier may have led the Rupanco glacier by as much as 1000 years. During initial glacier build-up the lag was likely to have been greater, but in response to subsequent climatic fluctuations Rupanco would have had a shorter lag in response time. Estimates of the lag which may have been introduced by the Rupanco glacier calving into substantially deeper water also suggest a *maximum* lag of c. 1000 years during advance. However, the difference may have been only of the order of a few years if ice velocities were large. During retreat the lag between Rupanco and Puyehue was smaller than during advance, probably amounting to a few decades. From these considerations it seems likely that during most of the last glaciation there were lags of at least decades, or possibly centuries between individual glaciers. During advance, however, the difference may have been of the order of 1000 years or more. Comparison of the radiocarbon chronologies of the study area to the Llanquihue chronology has also highlighted consistent timing of some advances but also some intervals of discordant behaviour, during which the different glaciers may have reached the culmination of their advances as much as 1500 years apart. This is particularly important for the c. 21 ka advance of Llanquihue which occurred after 19.5 ka in the Puyehue and Rupanco basins.

The second conclusion is that there is a characteristic landform association and pattern around both Lago Puyehue and Rupanco. Analysis of the moraines and sediments has demonstrated that this is the result of a distinctive style of glacier behaviour where lakes and feedback controls play a strong role in the location and formation of moraine limits (Bentley, 1996). The extent of the glacial advances in the Puyehue and Rupanco basins is controlled by the distribution of sediment; a direct result of the topography and the presence of the lake. The termini were stable at the western ends of the lakes at the transition between fine-grained, low strength lacustrine sediment and coarse-grained, high strength outwash. A model for the moraine-forming process shows that the glaciers may have advanced to closely similar limits at the downglacier end of the lake for a wide range of mass balance conditions. Once at the western ends of the lakes the glaciers were unlikely to advance further in response to further climatic deterioration and thus were partly decoupled from climate. In contrast to this, climatic amelioration was likely to initiate substantial retreat fairly rapidly. As a result, successive glacier advances constructed stacked moraine loops in the same locations around the lakeshores. The buttressing effect of pre-existing moraines exerted a progressively stronger feedback control on subsequent advances as the topographic barrier to advance increased. The moraine pattern and morphologies around Lago Llanquihue are similar and imply that this process was also important there.

Another specific aim which has been addressed by this research is the question of a Younger Dryas equivalent advance in the region. There is no glacial geological evidence of such an event in the study area or elsewhere in the Lake District but glaciological considerations suggest that glaciers would have been very small or perhaps have totally melted by that time, so that any evidence would only be present high in the main cordillera, or absent altogether (Clapperton, 1993a). Thus the absence of moraines of this age does not necessarily preclude the possibility that a climatic event affected the region at this time so this is not a critical site for testing the global synchroneity of the Younger Dryas. The palynological record in the Lake District and evidence for glacier advances elsewhere in southern South America suggest that such an event probably did occur (McCulloch, Bentley and Sugden, *in prep.*; Clapperton, 1993a).

These conclusions highlight how important it is to establish the relative importance of climatic and local factors on glacier response. Two points emerge from this work which are relevant to studies which attempt to derive glacial chronologies as proxies for climate. First, the short-term asynchronous behaviour illustrates there is a clear potential for non-climatic modulation of the glacier response, particularly by valley geometry and calving dynamics. The effect can be as much as 1000 years in the

Chilean Lake District and so the effects of topography should be distinguished from climate before seeking wider comparisons. A second implication, also linked to the moraine-forming model, is that morphostratigraphic, lithostratigraphic and dating techniques need to be applied together in order to recognise all glacial advances in areas such as the Chilean Lake District. Moraine morphology alone is inadequate.

The importance of geometrical effects has been shown before (e.g. Firbush and Andrews, 1984; Oerlemans, 1989) and the potential of climatic decoupling of calving termini is well known (e.g. Mercer, 1961; Warren, 1992; Warren and Rivera, 1994). The contribution of this thesis is to have used a field-based approach to show asynchrony, independent of any dating technique, and that differential behaviour of glaciers can be an inherent feature, controlled by basin topography. It has also shown the value of glaciological modelling on a single glacier scale and testing results against the field evidence when trying to unravel the palaeoclimatic significance of the geologic record. The good match of empirical and model results has provided a powerful tool for interpreting former glacier behaviour.

8.2. Further work and some alternative approaches

Comparison of field evidence and modelling results on a single glacier scale has given insights into the behaviour of the Puyehue and Rupanco glaciers. The empirical evidence has provided a test of the glaciological model and so a logical extension of the modelling would be to apply it to the Llanquihue, Seno Reloncavi and Castro basins. This could assess the potential for differential response of the three lobes to climate. The glacial geology of each lobe is relatively well known and so the model could be well-constrained and tested. The possibility that topography has changed, particularly in the Llanquihue basin, is a problem but this might be partly overcome by carrying out sensitivity tests. The size of Volcan Osorno could be varied from near-zero to its present-size and the effect on glacier behaviour could be determined. In this way the possible range of glacier behaviour could be assessed. If the Llanquihue lobe proves very sensitive to this factor then this also could be explored further to increase the understanding of how topography influences glacier behaviour.

The moraine-forming model could be investigated further at other sites where temperate glaciers discharged into lakes. For example, the moraine loops around the southern ends of the North American Great Lakes and around the Italian Lakes may have been formed by this process. If there are additional examples of the process in the Pleistocene record then these will have implications for glacial chronologies established for those sites.

There is an alternative approach to the problem of a 'type' glacial chronology for the Lake District of southern Chile. In order to attempt to reduce the uncertainty of a broad spread of dating control for each advance derived from a large number of dates, each with errors commonly up to 500 years, and sometimes of ambiguous origin it might be profitable to take a *smaller* number of samples and date them using the AMS technique. Each sample could be of organic material with undoubted origin (e.g. wood rather than 'organic sediment') and from the best constrained stratigraphic situations where the possibility of entrainment, reworking and contamination is minimal (e.g. the 'leaf litter horizon' below a till described by Lowell et al (*in press*)). The dating procedure could include long counting times so that the standard errors are minimised to a few decades. As discussed above, the mean of the few oldest minima, or youngest maxima, could be used to try to remove the effect of different generations of organic material, or a large spread of dates within a single generation. In this way it should be possible to refine some glacial chronologies and allow a more confident comparison to other glaciers. This would have the dual benefit of establishing the magnitude of leads and lags, so improving our knowledge of the glacial system, and also allow more confident regional and global comparisons. This approach is possible with existing methods and many appropriate samples exist. At present the well-constrained samples tend to be treated fairly equally with samples which do not yield such firm results and so the potential for distinguishing 'secure' results from those less reliable is often lost. Lowell's (1995) recommendation of averaging 15 or more dates from a single unit can be useful but it still emphasises the quantity of dates rather than the 'quality' and stratigraphic certainty of each date. Without such a new approach there is a risk that more and more dates which are often averaged will 'smear' the timing of glacial advances to such an extent that correlations may not be meaningful. This is particularly evident in the light of the computer program discussed above which has shown how easily a good correlation may be obtained if the timing of events is not closely constrained.

The computer program discussed in Chapter 7 provides a useful tool for discussing the correlation of sequences of events and illustrating some pitfalls of correlation. However, it has a number of limitations which might be removed by a more complex algorithm. The program does not at present provide a measure of cyclicity, which may be appropriate to the correlation of some glacial sequences where cyclicity is an important feature. In addition, a future extension might be to attempt to explore in more detail the correlation of continuous records (such as the ice-rafting data) to discontinuous records (such as the glacial geologic record). At present, only the 'events' recognised in the ice-rafting record by Bond and Lotti (1995) are isolated for use in the program. These events could be defined more rigorously and the entire record incorporated. This would then enable a more robust measure of the strength of match as it could not only measure 'hits' but also identify periods when the records are out of phase.

There is evidence of earlier glaciation recorded in the field area. Specifically, a number of sites along the south-east shore of Lago Puyehue show lava flows interbedded with probable glacial sediments. The interbedded sequences have been eroded during subsequent glaciation(s) such that they now make up some of the areally-scoured topography south of Lago Puyehue. One of these sites is described in Appendix B. Further study could investigate in detail the sedimentology of the interbedded sediments to establish their origin, and date the sequences by potassium-argon dating of the lava flows. Another example is the lava flow directly underlying the Puyehue IIB moraine at the Pilmaiquen site. Dating of the lava flows would provide the first means of dating directly the earlier glaciation of the Lake District, since at present the moraines in the Central Valley are undated and their chronology depends upon relative weathering criteria.

Appendix A: A computer program for correlation of glacial events.

The program *Compare* is written in QBasic, which is a relatively unsophisticated programming language included with the MS-DOS operating system on most IBM-compatible PCs. The program measures the match between two sequences of dates, such as glacial events or ice-rafting episodes. Although the program is simple and relatively short, it provides an interesting illustration of some of the problems associated with correlation of glacial events between hemispheres. A listing of the program is given below. The program can be divided into four main sections.

The first section concerns setting up the conditions for the comparison of the sequences. First, the computer reads in a pre-existing file (*Heinrich*) which contains the dates of glacial events as taken from Figure 3 of Bond and Lotti (1995). The user is asked in turn for each of the dates whether it is to be used in the correlation or not. The chosen ice-rafting events are written to the *Heintemp* file. Next, the user inputs the Number of runs and the Number of random events to be generated. The former is a device for smoothing the results; 100 runs usually provides a relatively stable final result. The latter input is then taken to the second section of the program where that number of random events are generated using the computer's random number facility. No dates outside the range of 9200 BP to 30600 BP are used since no ice-rafting events have yet been dated outside this interval. The random events are also non-overlapping. That is, even with the worst-case precision of 1000 years for the glacial events, adjacent glacial events do not overlap. The rationale behind this stems from the treatment of radiocarbon dates. Where the errors for clusters of radiocarbon dates overlap, the dates are often taken to relate to the same advance, and thus advances with overlapping dates are difficult to distinguish. The final sequence of random glacial events is written to a file called *Random*.

The third section compares the first value in *Random* to each of the values in the *Heintemp* file. Any match (where the compared dates overlap) is counted as a 'hit'. The same procedure is applied to each of the values in *Random*. The number of hits is totalled after each of the random events have been compared to each of the ice-rafting events. If a glacial event matches with more than one ice-rafting event then this is only counted as one hit. Two nested loops then increment the precision associated with each sequence of events in turn, and the process of comparison is repeated. Numbers of hits for each set of precision values are recorded. When the least favourable precision values are reached (1000 years for the glacial events and 300 years for the ice-rafting events), a new set of dates are generated and written to *Random*. The whole comparison procedure is repeated and a *running mean* is calculated for the percentage hits for each set of precision values. This is repeated as many times as the user requested.

Once completed, the fourth section writes all the running means to *Excelhit*. This is a file which can be imported into the charting program, Microsoft *Excel* and the results plotted. Some of the plotted results are shown in Chapter 7 on 3-dimensional graphs showing the dependence of the match on the precision of the dates in each sequence. The *Excelhit* file also contains a record of the number of the ice-rafting events used in the comparison, the dates of the ice-rafting events, and the number of runs of the program.

```
' Compare          v.16 (30/7/95)

'compares two sequences of dates, each with associated precision, and calculates the match.

'initial setup
CLS
DEFDBL A-Z

' setup file of Heinrich events to be used

OPEN "heinrich" FOR INPUT AS #5
OPEN "heintemp" FOR OUTPUT AS #6
DIM h(15) AS DOUBLE

FOR b = 1 TO 15
     INPUT #5, h(b)
     WRITE "Use ", h(b), " Heinrich event in correlation (N for No, any other key for Yes)"
     INPUT ; a$
     IF UCASE$(a$) <> "N" THEN
     WRITE #6, h(b)
     chosenhein = chosenhein + 1
     END IF

NEXT b
WRITE ""
CLOSE #6

INPUT "How many runs ?", runnumber
INPUT "How many random events", eventnumber

WRITE
WRITE "RUNNING.........."

OPEN "hit2" FOR OUTPUT AS #9
WRITE #9, "No. of runs=", runnumber
WRITE #9, "No. of random events=", eventnumber
WRITE #9, "No of Heinrich events=", chosenhein
WRITE #9, "Heinrich error", "Event error", "Average Percent hits"

'sets up features which cannot be repeated in runs loop
DIM x(eventnumber + 1) AS DOUBLE
OPEN "excelhit" FOR OUTPUT AS #4
OPEN "record" FOR OUTPUT AS #10
FOR heinerror = 0 TO 100 STEP 50
FOR eventerror = 0 TO 100 STEP 50

'sets up for multiple runs of random sequences to compare against ice rafting record

cumulativepercenthits = 0
percenthits = 0

FOR runs = 1 TO runnumber
hits = 0
```

```
'creates a file of user-defined number of non-overlapping random number events called RANDOM
OPEN "RANDOM" FOR OUTPUT AS #1
RANDOMIZE TIMER
a = 1
DO UNTIL a = eventnumber
    x(a) = INT(RND * 50000) + 1
    eventmax = x(a) + eventerror
    eventmin = x(a) - eventerror
    testcount = 0
    IF a <> 0 THEN
        DO UNTIL overlaptrue = 1 OR endofcompare = 1
            eventtestmax = x(testcount) + eventerror
            eventtestmin = x(testcount) - eventerror
            IF eventmax > eventtestmax AND eventmin < eventtestmax OR
              eventtestmin > eventmin AND eventtestmin < eventmax THEN a = a - 1
            : overlaptrue = 1
            IF testcount = a - 1 THEN endofcompare = 1
            testcount = testcount + 1
        LOOP
        IF overlaptrue <> 1 THEN WRITE #1, x(a)
    END IF
IF x(a) > 9000 AND x(a) < 31000 THEN
    IF overlaptrue <> 1 THEN WRITE #1, x(a)
    a = a + 1
    END IF
LOOP
CLOSE #1

'comparison to record of ice-rafting events

OPEN "RANDOM" FOR INPUT AS #8
DO UNTIL EOF(8)
    INPUT #8, rand
    OPEN "heintemp" FOR INPUT AS #7
    DO UNTIL EOF(7) OR hittrue = 1
        INPUT #7, hein
        randmax = rand + eventerror
        randmin = rand - eventerror
        heinmax = hein + heinerror
        heinmin = hein - heinerror
        IF heinmax > randmax AND heinmin < randmax THEN hits = hits + 1
        IF heinmin < randmin AND heinmax > randmin THEN hits = hits + 1
        IF randmax > heinmax AND randmin < heinmin THEN hits = hits + 1
    LOOP
    CLOSE #7
LOOP
CLOSE #8
IF hits > eventnumber THEN percenthits = 100 ELSE percenthits = (hits / eventnumber) * 100
cumulativepercenthits = cumulativepercenthits + percenthits
WRITE #4, percenthits, (cumulativepercenthits / runs)
NEXT runs
WRITE #9, heinerror, eventerror, (cumulativepercenthits / runnumber)
WRITE heinerror, eventerror, cumulativepercenthits / runnumber
NEXT eventerror
NEXT heinerror
CLOSE
END
```

Appendix B: Evidence of pre-Llanquihue glaciation.

There are a small number of sites within the field area which demonstrate evidence of glaciation pre-dating the last (Llanquihue) glaciation.

Chonleufu Pescadero

Along the south shore of Lago Puyehue the road has been blasted through part of the areally scoured bedrock inside the Puyehue IV limit but outside the Puyehue V moraine. Several cliff exposures show interbedded sequences of lava flows and fluvial or fluvioglacial sediments (Fig. B.1). A lower lava flow with columnar jointing has been erosionally overlain by a thick unit of interbedded gravels and sand lenses. This unit completely covers the irregular lava surface. The clasts in the lower part of the unit are almost exclusively angular to sub-angular blocks of lava up to 30cm across. These have identical characteristics to the lava below. The lower gravels grade upwards into a lens of cross-bedded yellow sand which is 30m wide and up to 1.5m thick. Above this are more sandy gravel beds with less lava clasts, interdigitated with coarse sand lenses. A faceted bullet-shaped boulder 2.5m across is horizontally aligned within the gravels but no striated clasts are seen. The whole clastic unit is extremely hard and does not disaggregate when hammered and is partly lithified. The unit is erosionally overlain by another columnar-jointed lava flow. At its base this flow has entrained sub-rounded clasts of other lithologies as well as large amounts of sand.

Interpretation

This section shows two eruptive events separated by a period of fluvial sedimentation. A key interpretation here is whether the clastic sediments were laid down in a glacial environment, as this would have important implications for early glaciation of the area. The large boulder is faceted and bullet-shaped but this may be a clast inherited from a much earlier glacial event. The presence of the broad sand lenses and the thick gravels both suggest substantial fluvial accumulation which is in contrast to the small, low bedload, incised streams in this part of the field area at present. On balance a glacial origin is possible but there are insufficient data to prove it at present. If it can be shown to be glacial then a K-Ar date on each of the lava flows would bracket the age of an early glaciation in the Puyehue basin.

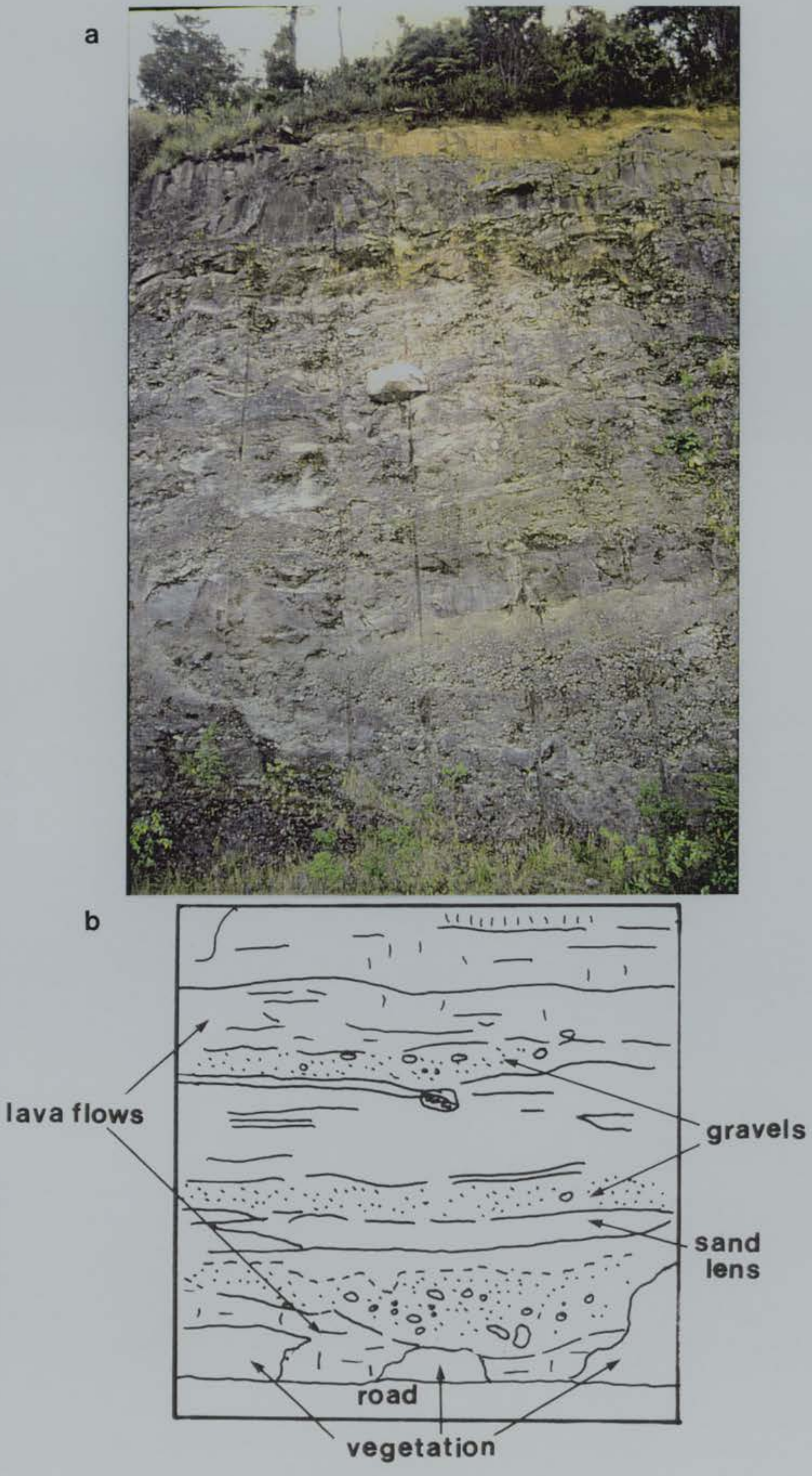


Figure B.1. Chonleufu Pescadero site

(a) Photograph of interbedded lava flows and possible fluvioglacial sediment.

(b) Sketch of section showing the irregular sub-horizontal contacts between the lava flows and clastic sediments.

Pilmaiquen

The section into the Puyehue IIB moraine at Pilmaiquen is underlain by a columnar-jointed lava flow. Further downstream from this site the lava flow is underlain by fluvioglacial sediments, in turn underlain by another lava flow. As with the Chonleufu Pescadero site, a potassium-argon age determination on the lavas would provide constraints on the timing of previous glaciation. Interestingly, the Pilmaiquen site is close to the west end of Lago Puyehue, and so if the lavas were dated they may also indicate a maximum date for when the lake basin was eroded. The date of lake formation has implications for when the model of moraine formation described in Chapter 6 may have become operative in the Puyehue basin.

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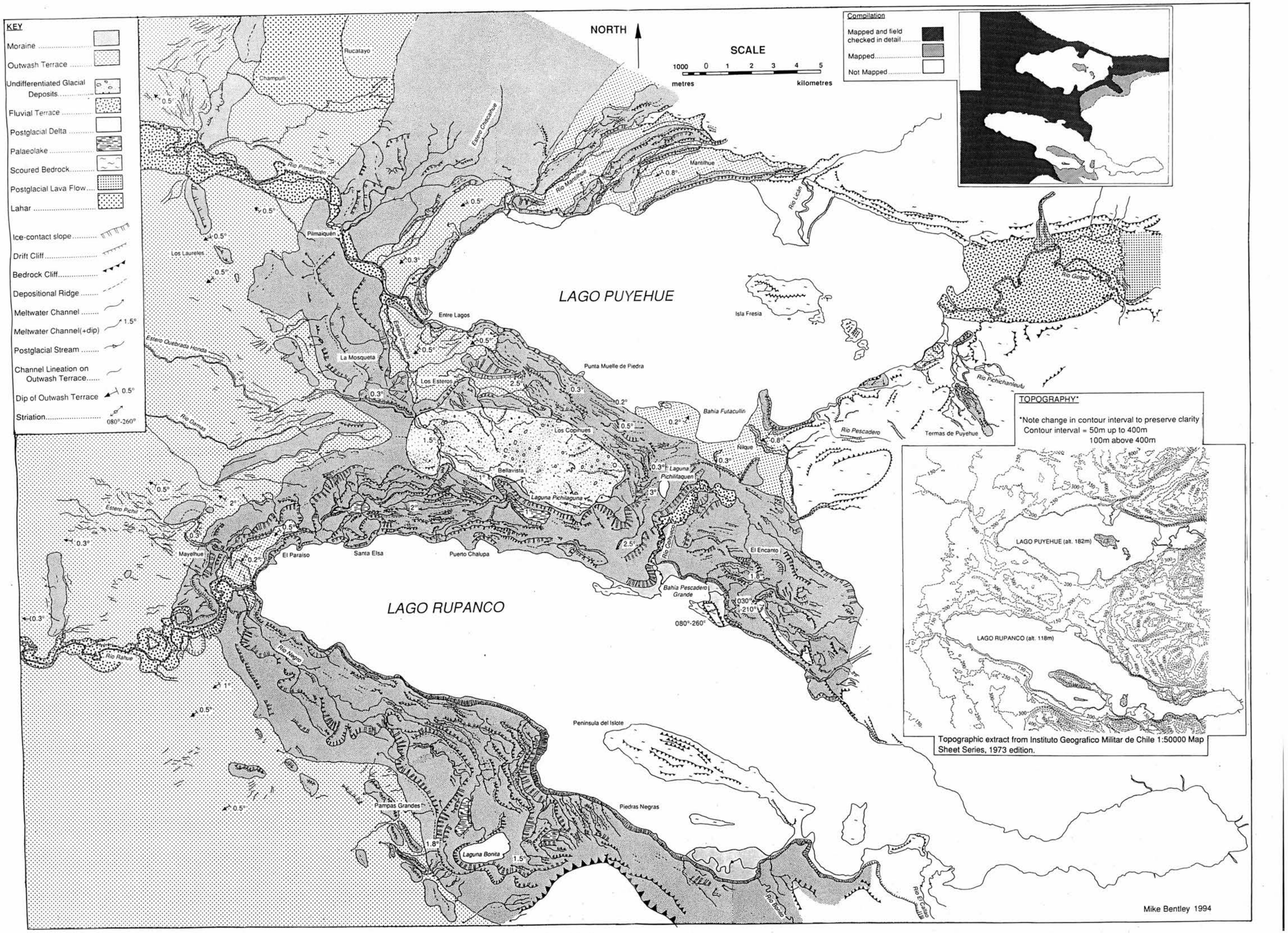
Figure 2.1. Geomorphological Map of area around Lago Puyehue and Lago Rupanco. A nested sequence of amalgamated rampart moraines and single ridge moraines occurs around each lake. The mapping is based on 1:50000 scale aerial photographs backed-up by field study of landform morphology and relations.


KEY
Moraine
Outwash Terrace
Undifferentiated Glacial Deposits
Fluvial Terrace
Postglacial Delta
Palaeolake
Scoured Bedrock
Postglacial Lava Flow
Lahar
Ice-contact slope
Drift Cliff
Bedrock Cliff
Depositional Ridge
Meltwater Channel
Meltwater Channel(+dip)
1.5°
Postglacial Stream
Channel Lineation on Outwash Terrace
Dip of Outwash Terrace
0.5°
Striation
080°-260°
NORTH
SCALE
1000 0 1 2 3 4 5
metres
kilometres
Compilation
Mapped and field checked in detail
Mapped
Not Mapped
LAGO PUYEHUE
LAGO RUPANCO
Rucatayo
Champulli
Estero Chacaihue
Rio Pilmaiquen
Rio Mantilhue
Mantilhue
Rio Licán
Rio Golgol
Pilmaiquén
Los Laureles
Entre Lagos
Estero Chirrihue
La Mosqueta
Estero Quebrada Honda
Los Esteros
Punta Muelle de Piedra
Isla Fresia
Bahía Futacullin
Rio Pichichanleufu
Rio Pescadero
Termas de Puyehue
Nilque
Los Copihues
Bellavista
Laguna Pichilaguna
Laguna Pichilafquen
Rio Damas
Estero Pichil
Mayelhue
El Paraiso
Santa Elsa
Puerto Chalupa
Rio Coihueco
El Encanto
Bahía Pescadero Grande
030°-210°
080°-260°
Rio Rahue
Rio Negro
Peninsula del Islote
Pampas Grandes
Piedras Negras
Laguna Bonita
Rio Bonito
Rio El Callao
0.5°
0.3°
0.8°
0.2°
2.5°
1.5°
2°
3°
1°
1.8°
TOPOGRAPHY*
*Note change in contour interval to preserve clarity
Contour interval = 50m up to 400m
100m above 400m
LAGO PUYEHUE (alt. 182m)
LAGO RUPANCO (alt. 118m)
Topographic extract from Instituto Geografico Militar de Chile 1:50000 Map Sheet Series, 1973 edition.
Mike Bentley 1994