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The quaternary glaciation of Chile: a review

La glaciación cuaternaria de Chile: una revisión

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ABSTRACT

A review of literature on the Quaternary glaciations of Chile shows that repeated advances occurred in the central and southern Andes. However, radiocarbon dated sequences have been obtained only for the last glaciation in the Chilean Lakes Region and in the Paine and Magallanes regions of Patagonia. These suggest that glacier lobes from the icefields advanced at least five times during the last glaciation. Reconstruction of palaeo-snowlines indicates that the climatic belts during the glacial interval were basically similar to the modern, but that effective precipitation was greater in the north (arid) of Chile, and that the humid westerlies in temperate latitudes were displaced 5-6° to the north. Snowline descended 800-1000m. While glaciers in the Lakes Region reached their maximum extension at ca.20-21,000 yr BP, those in the south and north of the country may have been more extensive at ca.27,000 yr BP, due to the greater humidity available. Some glacier lobes from the southernmost icefields of Chile were still expanded at ca.12,000 yr BP and may have readvanced during the interval 12,000-9000 yr BP.

Key words: Southern Andes, glacier dynamics, paleo-snowlines, paleolakes.

RESUMEN

Una revisión de la literatura sobre glaciaciones cuaternarias en Chile muestra, que en los Andes del centro y sur, han ocurrido repetidamente avances de glaciares. Sin embargo, secuencias fechadas radiocarbónicamente solamente se han obtenido para la última glaciación en la Región de los Lagos y en las regiones del Paine y Magallanes, en la Patagonia. Ellas sugieren que los lóbulos glaciares de los campos de hielo avanzaron al menos cinco veces durante la última glaciación. La reconstrucción de las paleolíneas de nieves indican que los cinturones climáticos durante la edad glacial fueron básicamente similares a los actuales, pero la precipitación efectiva fue mayor en el norte (árido) de Chile, y que el cinturón de los oestes de las latitudes templadas se desplazó 5-6° al norte. La línea de nieves descendió 800-1000 m. Mientras que los glaciares de la Región de los Lagos alcanzaron su extensión máxima hace 20-21,000 años atrás, aquellos del sur y norte del país pueden haber sido más extensos ca. de 27,000 años, debido a la mayor humedad disponible. Algunos lóbulos glaciares de los campos de hielo del extremo sur de Chile estaban aún expandidos hace 12,000 años A.P. y pueden haber reavanzado entre 12,000 y 9,000 años A.P.

Palabras clave: Andes del sur, dinámica glaciar, paleolíneas de nieve, paleolagos.

INTRODUCTION

Observations on Quaternary glaciation in various parts of Chile have been made since Darwin's visit in the 19th. Century. The Magellan region was commonly visited by European scientists on their way to and from Antarctica and this led to short reports about glacial features in the area (e.g. Nordeņskjld 1898, Quensel 1910). Subsequently, some classic works on Quaternary glaciation and glaciology in southernmost South America laid the foundations for an understanding of the glacial history of the southern Andes (Caldenius1932; Brüggen 1950, Auer1956, Mercer 1976, Rabassa and Clapperton 1990).

This paper reviews the state of knowledge about past glacier fluctuations throughout the Chilean Andes in an attempt to expose problems that should be tackled to give a better understanding of Quaternary glaciation in Chile, and its contribution to studies of global climatic change.

Topography, climate and modern snowline

As in most of the Andes, the large-scale topography of Chile has evolved primarily through late Cenozoic tectonics and volcanic activity (Clapperton 1993a); denudational processes have shaped the smaller-scale relief according to the climatic regime.

Extending approximately north-south across latitudes ca.17°S-56°S, some 4200km, the Chilean Andes contain a number of different tectonic segments with distinctive topography. For example, between latitudes 18°S and 27°S Quaternary-Recent volcanism has created the highest relief, with more than 40 mountains rising above 5500m altitude (Fig.1a); but the mean topographic elevation is ca.4000m. South of Nevado Ojos del Salado (6893m) at latitude 27°S, the Andes are devoid of active volcanoes until latitude 33° 27'S. Nevertheless, underplating of the continental edge by a buoyant part of the Nazca ocean crustal plate has raised this segment of the Andes above a mean altitude of 4000m, culminating in Cerro Aconcagua (6960m).

Volcanic massifs appear again at latitude 33°S, where Volcan Tupungatito (5628m) and Volcan Maipo (5264m) are two of the highest, but a dramatic change in topographic elevation occurs at latitude 37°S, south of which only Cerro Valentin (4058m) at latitude c.46°50'S rises above 4000m, and fewer than ten summits exceed 3000m. Here, thinner crust and the subduction regime have created a segment of highly fractured terrain with abundant volcanism; but the mean altitude of the Andean crest is only ca.1800m. Many volcanic peaks rise above 2000m, as in Volcan Villarica (2940m) and Volcan Osorno (2660m), both of which support small icecaps (Fig.1b). South of latitude 47°S, the volcanic systems are more widely spaced but the mean topographic elevation rises to ca. 2500m and much of this is covered with the Patagonian icefields (Fig.1c).

The climate of the Chilean Andes varies from hyper-arid tropical in the north (lat.17°S-27°S) to hyper-humid temperate at latitude ca.50°S. The precipitation regime clearly controls local and regional snowline altitudes and determines the distribution of modern glaciers. Fig. 2 illustrates the annual precipitation characteristics for stations in different climatic regions of Chile and Fig. 3 shows the dramatic fall in snowline altitude from ca.6000m in the north to ca.250m in the south. This is due to the effect of the three primary climatic systems affecting Chile. In the south (lats.56°S-42°S) the constantly wet westerly system, with only slight changes in precipitation amount seasonally, brings totals in excess of 5000mm to sea level stations (Miller 1976). Such high annual precipitation explains the presence of large icefields in southern Chile, with outlet glaciers descending to sea level (Fig.1c).

Between 42°S-31°S lat., in the so-called 'Mediterranean-type' climatic zone, winter precipitation is brought by the seasonal movement northwards of the Polar Front and associated cyclonic depressions. This nourishes glaciers and snowfields where altitude, topography and exposure provide suitable accumulation sites in these latitudes; but many parts of the mountains even above 4000m altitude lose their snow cover in summer because of high insolation and the relatively low total of mean annual precipitation (250mm).

North of latitude ca.32°S mean annual precipitation falls below 300mm, and comes mainly in the austral winter as occasional outbursts from cyclonic storms extend northwards. Some precipitation may come to this part of the Chilean Andes in the austral summer if convectional storms on the Puno-Altiplano extend westwards (invierno boliviano), but the annual amount from this source is generally insignificant. In this region, dominated by anticyclonic atmospheric circulation, intense radiation and evaporation combined with low precipitation totals cause the permanent snowline to lie above 6000m. Thus even where mountains rise above the mean level of the atmospheric 0°C isotherm, commonly at ca. 4900-4700m in these latitudes (Fox 1993), permanent snow and ice can not survive because of aridity and high insolation. Even the highest massif, which rises to 6893m in Nevado Ojos del Salado, has a patchy distribution of permanent snow, and glaciers no longer exist. Moreover, although the summit of Llullaillaco volcano culminates above 6700m, it has no glaciers and supports only a small permanent snowpatch (Messerli et al. 1993). Not only does the snowline altitude rise from east to west in these

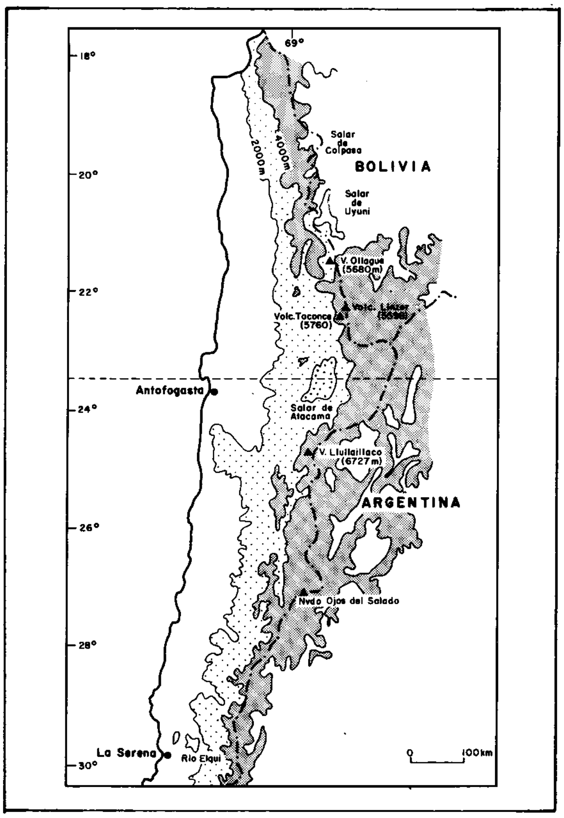

Fig. 1.a

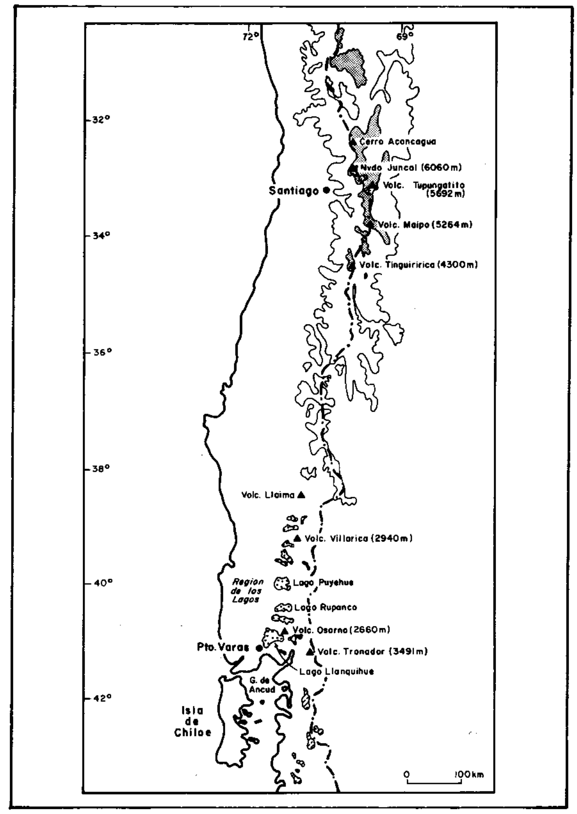

Fig. 1b

Fig. 1.c

Fig. 1: General topography of the Chilean Andes and location of places mentioned in the text.

Topografía general de los Andes de Chile y ubicación de los lugares mencionados en el texto

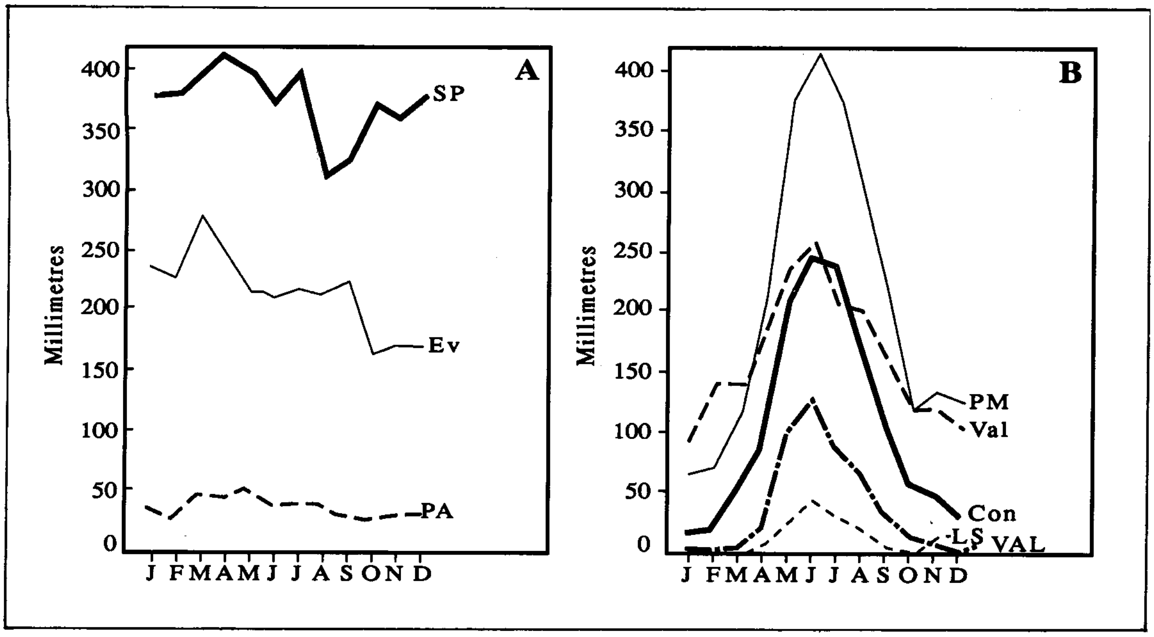

Fig. 2: Mean monthly precipitation for selected stations representing the different climatic regions of Chile (after Miller, 1976).

A. Stations south of 45°S:	SP: San Pedro (47°43'S, 74°55'W)
EV: Evangelistas (52°24'S, 75°06'W)	PA: Punta Arenas (53°10'S, 70°54'W)
B. Stations north of 45°S:	PM: Puerto Montt (41°28'S, 72°57'W)
Val: Valdivia (39°48'S, 73°14'W)	CON: Concepción (36°40'S, 73°03'W)
VAL: Valparaíso (33°01'S, 71°38'W)	LS: La Serena (29°54'S, 71°15'W)

Precipitaciones medias mensuales de estaciones seleccionadas como representativas de diferentes regiones climticas de Chile (de acuerdo a Miller, 1976).

A. Estaciones al sur de 45°S:	SP: San Pedro (47°43'S, 74°55'W)
EV: Evangelistas (52°24'S. 75°06'W)	PA: Punta Arenas (53°10'S, 70°54'W)
B.Estaciones al norte de 45°S:	PM: Puerto Montt (41°28'S, 72°57'W)
VAL: Valdivia (39°48'S, 73°14'W)	CON: Concepción (36°40'S, 73°03'W)

latitudes, but a clear gradient rises also from north to south between latitudes 30°S and 35°S; a 'snowline' does not exist here since even summits exceeding 6500m are ice-free (Fig.3).

Glaciers are largely absent in the Chilean Andes north of 33°S due to increasing aridity, although some small icefields are present locally as far north as 30°S on massifs exceeding 5000m, as on Cerro Doña Ana and Cerro del Volcan. Farther south, higher seasonal (westerly) precipitation permits substantial icefields and valley glaciers where summits are above ca.4000m, and these were recorded systematically for the first time by Lliboutry (1956). South of lat.37°S, where the Andean crest is almost 2000m lower, glaciers exist only on summits exceeding 2500m until the region of humid westerlies at ca.lat.45°S. South of here, myriads of glaciers are scattered throughout the Chilean cordillera, including the North and South Patagonian Icefields and extensive icefields on Isla Santa Ines and in the Cordillera Darwin of Isla Grande de Tierra del Fuego (Fig.1c).

All of the modern icefields were more extensive during the late Quaternary, while icecaps and valley glaciers formed over wide areas that no longer contain permanent snow.

The quaternary icefields of Chile

There are few published papers reporting detailed morphological and chronological evidence of Quaternary glacier extent in the northern and central Andes of Chile, whereas a considerable literature exists on the glaciation of southern Chile. Thus the following sections review the nature of the published data using a regional approach, dealing in turn with the northern, central and southern parts of the Chilean Andes.

i. *The Northern Andes of Chile:* Brüggen (1950,p.212) referred to glacial features on Volcano Toconce at lat.22°S, and considered that Pleistocene glaciers had descended to 3900m when the snowline dropped to 5000m; this was a remarkable discovery for such a hyper-arid area. Supporting observations were made subsequently by Hollingworth and Guest (1967) in a brief description of moraines on the flanks of Volcano Toconce and adjacent volcanoes between Linzor and Tatio geysers (lats.22°10'-22°21'S). They noted that one of the most extensive moraines terminates at about 4280m and considered it to be of Quaternary age. The most recent work on Quaternary glaciation in northern Chile has been by Grosjean et al. (1991), Messerli et al.,(1993) and Fox (1993).

Fox (1993) estimated the modern and late Pleistocene snowline altitudes of the Central Andes (5-28°S) on the basis of glacial features (cirques and moraines) interpreted from satellite imagery. This study concluded that in the latitude of northernmost Chile (17-20°S), the modern snowline rises from ca.5200m in the eastern cordillera of Bolivia to 5600m in the Chilean Andes. At latitudes 23-27°S, snowline rises steeply east to west across the Andes from 5200-6000m (Fig.4) in the

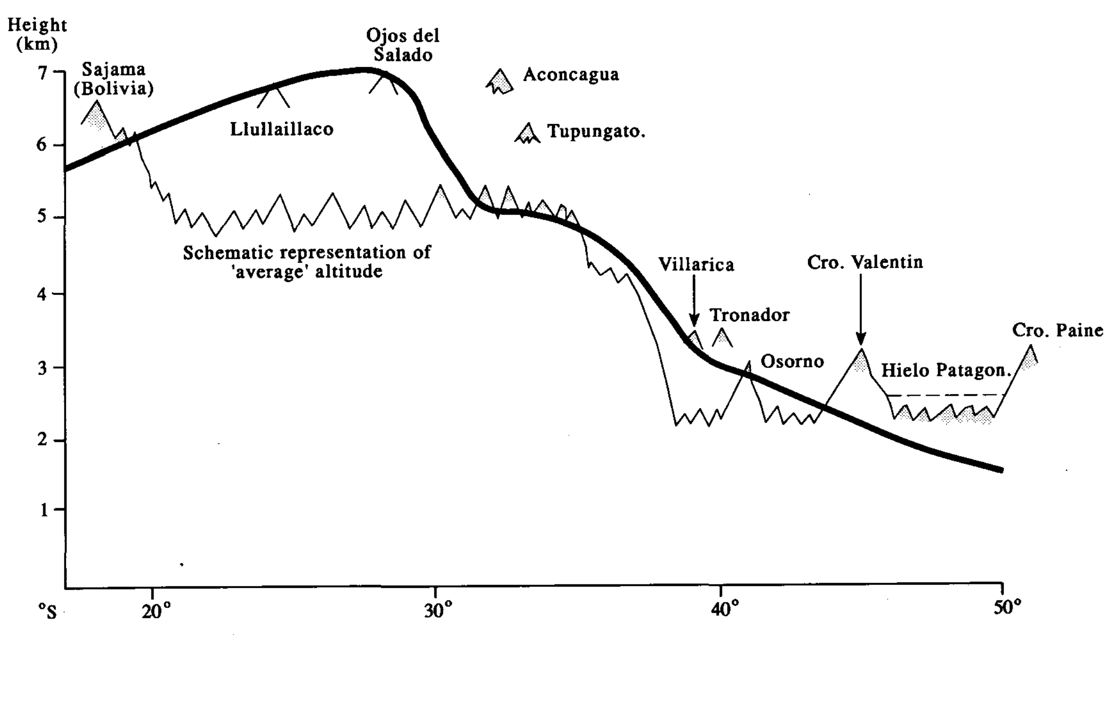

Fig. 3: Schematic representation of the average topography along the Chilean Andes from 18°-51°S, and an estimate of the modern glacial Equilibrium Line Altitude (thick line). Based on Fox (1993), Messerli et al.(1993) and Lliboutry (1956).

Representación esquemtica de la topografía media a lo largo de los Andes chilenos de 18x a 51xS, y una estimación de la Altitud de la Línea de Equilibrio de los glaciares en la actualidad (línea gruesa). Basado en Fox (1993), Messerli et al. (1993) y Lliboutry (1956).

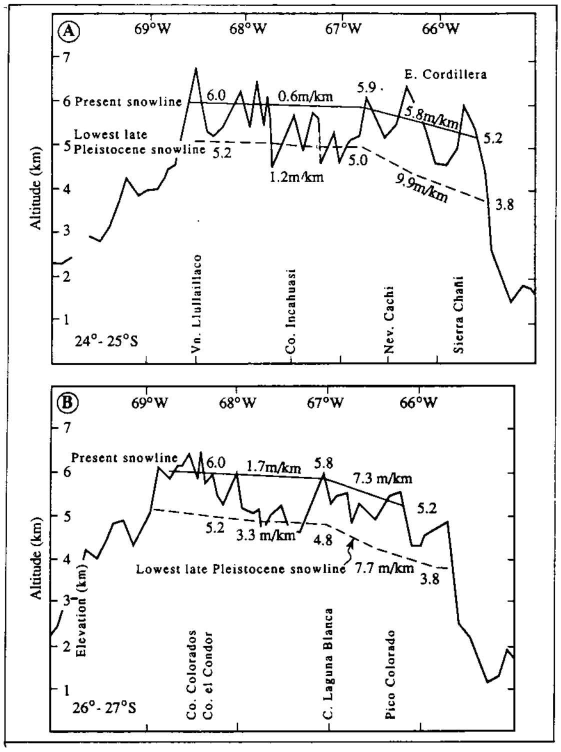

Fig. 4A & B: Estimates of modern and late Pleistocene snowline gradients across W-E transects in the Central Andes at latitudes 24-25°S and 26-27°S (after Fox1993).

Estimación de gradientes de líneas de nieves actuales y del Pleistoceno tardío a travs de transectos W-E en los Andes Centrales a las latitudes 24-25xS y 26-27xS (de acuerdo a Fox 1993).

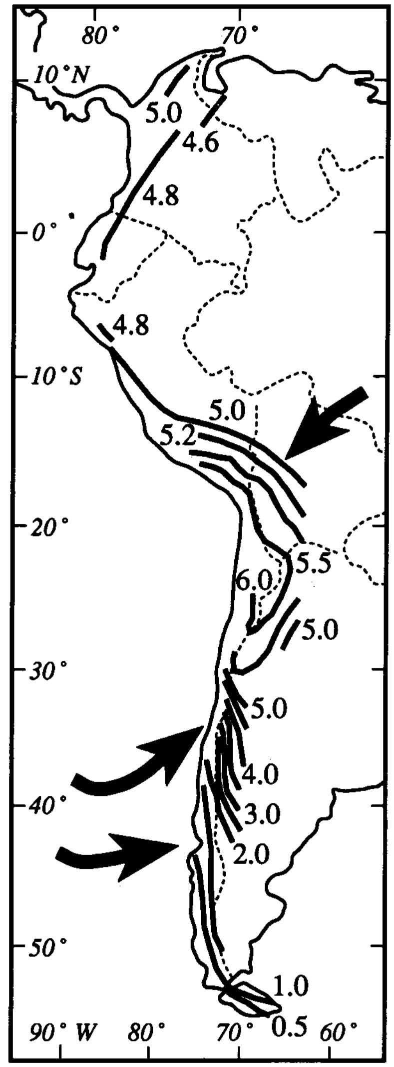

Fig. 4C: Estimate of snowline altitude along the Andes (after Fox1993). The thick arrows indicate precipitation-bearing winds which affect the Chilean Andes.

Estimación de las altitudes de la línea de nieves a lo largo de los Andes (de acuerdo a Fox 1993). Las flechas gruesas indican los vientos que traen las precipitaciones que afectan los Andes chilenos.

region of maximum aridity. Since the altitude of the mean annual 0°C isotherm is at ca.4400m over the southern Altiplano-Puna, the snowline lies 1000-1500m higher. This means that although the topography is high enough to support glaciers, there is inadequate precipitation.

From the mean altitude of 5665 reconstructed glaciers on the southern Altiplano and Puna region, Fox (1993) estimated late Pleistocene snowline altitudes of ca.3800m in the east and 4400-4600m in the west at latitudes 17-20°S; at latitudes 23-27°S, the snowline gradient was much steeper, rising east-west from 3800-5200m (Fig.4). These data indicate that the tropical easterly atmospheric circulation dominated the climate of these latitudes during the late Quaternary, as now. This contradicts the conclusion of Hastenrath (1971) that the late Pleistocene snowline was depressed more in the west than in the east, from which he inferred a northward migration of the moist westerlies from 29°S (modern limit) to 25°S.

Fox's results imply a late Quaternary snowline depression in the arid Andes of northern Chile of ca.800m and he inferred that glaciers reached their maximal extent in this region when precipitation was 75%

less than now. This conclusion is remarkable since it implies the development of large glaciers with a mean annual precipitation of only ca.70mm, and in view of strong insolation and evaporation at such latitudes, the validity of such a view is doubtful. This amount of precipitation decrease may well have occurred at the height of the last global glaciation maximum when arid conditions prevailed in many parts of tropical and sub-tropical South America (Clapperton 1993b), but is unlikely to have coincided with the maximal extent of glaciation in the Altiplano-Puna region.

Grosjean et al. (1991) and Messerli et al.(1993) mapped glacial and periglacial (geocryogenic) features and palaeolake shorelines in the Chilean Andes immediately northeast and east of Salar de Atacama (Fig.1). Here, even the highest mountain, Volcan Llullaillaco (6739m), has only a permanent firn patch under the present climate. This region appears to have been too dry during the last global glaciation maximum for extensive glaciers and palaeolakes, but may have been affected by extreme geocryogenic conditions. It appears that late Quaternary glaciers nourished by westerly precipitation developed only as far north as the latitude of La Serena (30°S).

Radiocarbon and thermoluminescence dating of palaeolake sediments suggests that precipitation increased during the late-glacial interval 17.000-15.000 yr BP when a shallow lake 5-10m higher than the modern one developed in the Laguna Leija basin (23°47'S; 4300m alt.). Although temperatures were still low, these higher

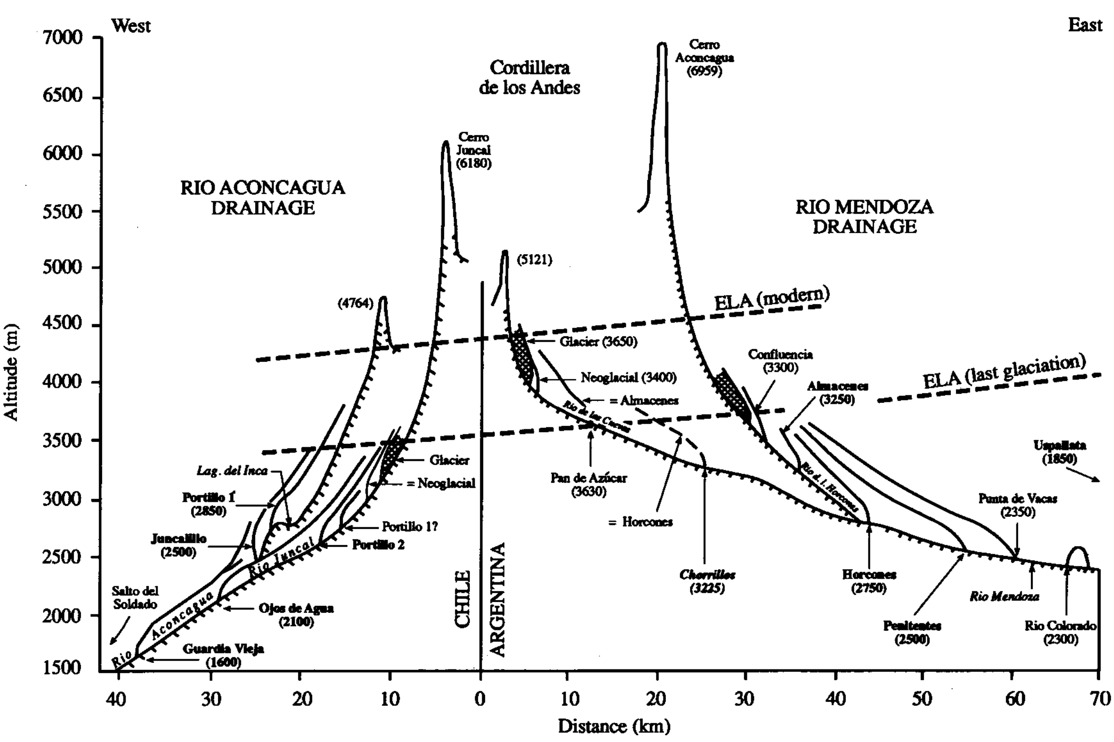

Fig. 5: Transect across the Andes around latitude 33°S showing the glacial limits mapped along the Rio Mendoza in Argentina and the Rio Aconcagua in Chile (after Caviedes1972 and Espizúa1993).

Transecto a través de los Andes cerca de la latitud 33°S mostrando los límites de los glaciares mapeados a lo largo de los cursos de los ríos Mendoza en Argentina y Aconcagua en Chile (de acuerdo a Caviedes 1972 y Espizúa 1993).

lake levels imply mean annual precipitation of ca.300-400mm, which is 60-70% higher than the modern value. A further increase in precipitation occurred after ca.15.000 yr BP, and warmer conditions prevailed. The level of Laguna Leija rose 25m above its modern surface, implying an increase in effective precipitation of ca.120% (Messerli et al. 1993,p.122).

In the adjacent cordillera glacial moraines extend to 4200m near Tatio geysers, but have not been dated. Nevertheless, Messerli et al. (1993) assigned them to the late-glacial interval of increased precipitation and inferred that the snowline had descended to ca.4650m, indicating a depression of approximately 1350m below the modern value. The validity of this conclusion depends on the age of the moraines, however, and they could be much older. An alternative interpretation is that they formed during a cold but humid interval prior to the last global glaciation maximum.

A key observation by Messerli et al.(1993) is that the moraine limit rises from 4300m at 22°S to 4900m at 25°S and that moraines are absent from Ojos del Salado at 28°S. This pattern suggests that late Quaternary precipitation was brought to the Andes of northern Chile by the southward shift of an intensified tropical summer rainfall pattern from a northerly to northeasterly source, probably with double the modern annual cloud cover.

ii. *The Central Andes of Chile:* This section of the Andes corresponds to the volcanically inactive segment characterised by wide areas above 4000m altitude. It lies between latitudes 30°-33°S and contains many summits above 5000m; Cerro Aconcagua (6960m) is the highest. Precipitation totals rise north to south from ca.200-300mm to over 1000mm in the Aconcagua area as the influence of winter cyclonic circulation increases. Glacial features in the area are widespread

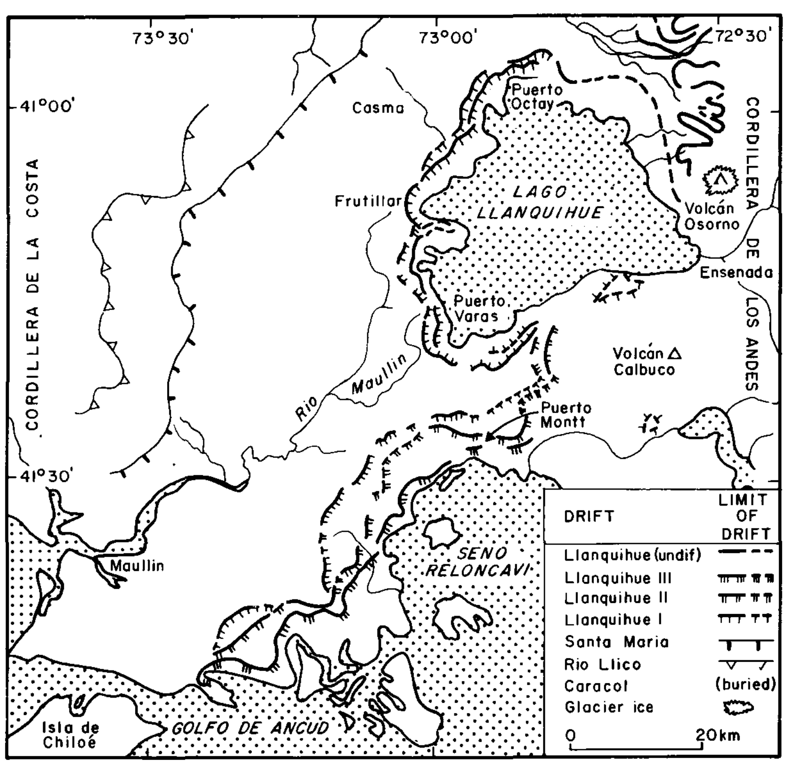

Fig. 6: Limit of Quaternary glacial deposits around Lago Llanquihue in the Chilean lakes region, according to Porter (1981).

Límite de los depósitos glaciales del Cuaternario alrededor del Lago Llanquihue en la Región de los Lagos de Chile, de acuerdo a Porter (1981).

Fig. 7: Glacial deposits of late Quaternary advances to the west of Lago Llanquihue (near Puerto Varas).
Depósitos glaciales de avances del Cuaternario tardío en el oeste del Lago Lanquihue (cerca de Puerto Varas).

compared to the region immediately north, and have been described by Brüggen (1950), Borde (1966), Santana (1967), Paskoff (1970), Caviedes (1972) and Caviedes and Paskoff (1975). The latter study combined observations made along two transects into the mountains, in the Rio Elqui basin (ca.30°S) and in the Rio Aconcagua basin (ca.33°S), and is the most informative.

The only modern glacier in the Rio Elqui basin is on the summit of Cerro El Tapado (5124m), where the modern snowline is estimated to lie at ca.5000-5500m. Greater precipitation in the Rio Aconcagua basin nourishes glaciers that descend in places to 3400m where the snowline lies at ca. 4300m (Lliboutry,1956).

In the Elqui basin (Fig.1), the limits of two distinct glacial stages were identified at 3100m and 2500m altitude, the lower being more weathered than the upper. In the Rio Aconcagua basin, at least three major moraine stages exist, at 2800m, 1600m and 1300m altitude, each lower one showing a greater degree of weathering. Table 1 illustrates the correlation and inferrred ages for moraines in the central Andes of Chile. These data suggest that glacier expansions in this part of the Andes were associated with a marked increase in precipitation, possibly caused by an equatorward shift by 5-6°lat. of the austral polar front.

A more recent study of moraines in the Rio Mendoza valley (Argentina) on the eastern side of Cerro Aconcagua has provided an interesting correlation with the Caviedes-Paskoff scheme (Espizua 1993). Five Quaternary moraine limits were identified (Fig.5), the oldest of which formed before the deposition of a tephra dated to ca.360.000 yr BP. This, the Uspallata glaciation, shows that a trunk glacier flowed 80km from Cerro Aconcagua to terminate at 1850m altitude. Assuming the mountains have not risen or lowered substantially (tectonically) since this glacial stage, a snowline lowering of ca.1430m is implied. The other three stages, the Horcones (2750m), the Penitentes (2500m) and the Punta de Vacas (2350m) were estimated to indicate snowline lowering of ca.1000, 1200 and 1250m respectively (Espizúa 1993; p.161).

Comparing the moraine stages either side of the divide in the central Andes, it is clear that the snowline gradients in the second half of the Quaternary have always sloped upwards from west to east, reflecting precipitation supply from the westerlies. Age determinations on the Penitentes drift using $^{230}Th/^{232}Th$ and U-series techniques suggest that this glaciation occurred sometime before 40.000 yr BP, but it is not closely dated. The Horcones drift was assigned a latest Pleistocene age because it is composed of relatively unweathered till and has fresh morphology, while the Almacenes moraine farther upvalley is believed to date from the late-glacial interval 14.000-10.000 yr BP.

iii. *The Southern Andes* From 33-37°S much of the Andean crest lies above 4.000m and was glaciated extensively during the Quaternary, judging from the erosional forms evident on topographical maps. Even where the mean altitude of the Andean cordillera drops dramatically to ca.2000m south of ca.37°S, much of the range was glaciated during Quaternary cold intervals since it lies in a zone of comparatively high precipitation. However, very little information is available on the glacial sequence of this region, possibly due to the effect of very active Quaternary-Holocene volcanism. Thus it is not until the Region de los Lagos (Lakes Region) is reached at latitude 39°S that published studies of Quaternary glacial sequences are available.

The abrupt beginning of a remarkable series of glacially-deepened lake basins on either side of the Andes at this latitude is striking and demands an explanation (Fig.1); yet no one has addressed the issue. Presumably they relate in some way to a zone of high glacial-age precipitation periodically nourishing Quaternary icecaps with erosive outlet glaciers descending to the softer sedimentary strata of the Central Valley.

The most informative papers published on the Quaternary glacial sequence of the Chilean Lakes region are those by Brüggen (1950), Weischet (1958,1964), Olivares (1967), Lauer (1968), Laugenie (1971), Mercer (1976), Porter (1981) and Heusser (1990). Rabassa and Clapperton (1990) and Clapperton (1993a) have provided comprehensive overviews.

The climate of this region is currently dominated by the seasonal migration northwards in winter of the austral Polar Front, which largely accounts for mean annual precipitation totals of ca.3000-4000mm in the mountains. Despite abundant precipitation, the low terrain and generally mild temperatures inhibit the development of ice caps and modern glaciers are confined to mountains rising above 2500m (commonly Quaternary volcanoes). It has been estimated that the snowline in this region lies at ca.2200m in the north and possibly as low as 1800m in the south (Rabassa et al. 1980). The largest icefields cap the summits of volcanic massifs such as Lonquimay (2822m), Llaima (3214m), Villarica (2840m), Lanin (3776m), Osorno (2661m) and Tronador (3554m), but there may be as many as 1000 small glaciers scattered along the Andean

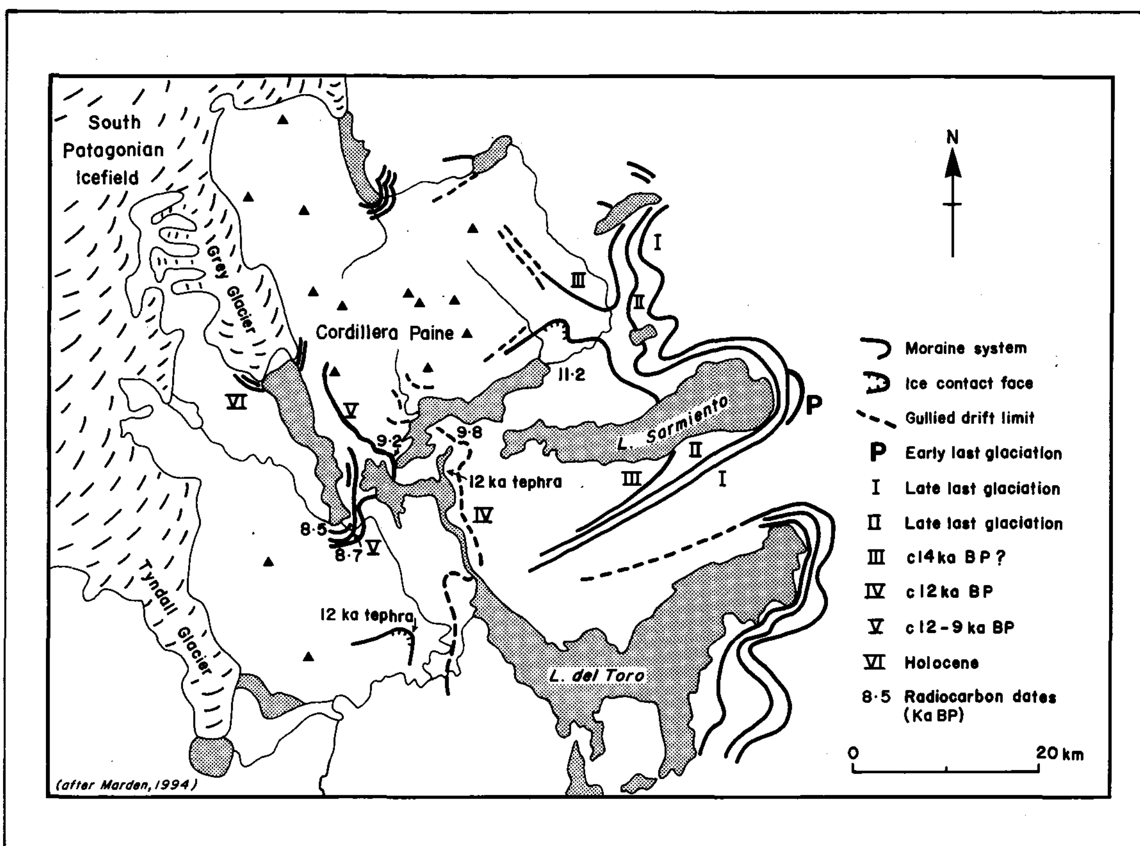

Fig. 8: Schematic map showing the distribution of last glaciation moraine limits in the Cordillera del Paine area at the southeast margin of the Hielo Patagonico Sur (South Patagonian Icefield), according to Marden (1994).

Mapa esquemático mostrando la distribución de los límites de las morrenas de la última glaciación en al área de Cordillera del Paine en el márgen sureste del Hielo Patagónico Sur (de acuerdo a Marden 1994).

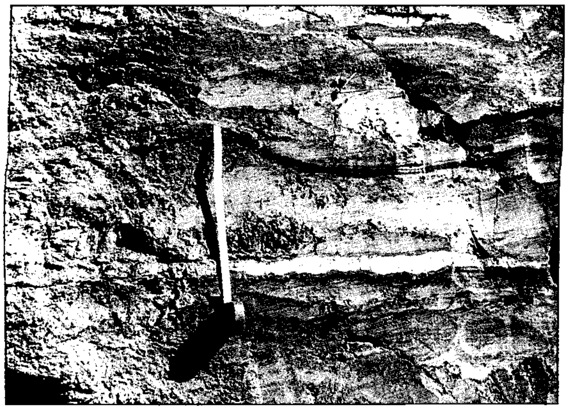

Fig. 9: Tephra from Volcan Reclus (white bed) dated to ca.12.000 yr BP. It overlies a thin bed of peat which covers glaciolacustrine sediments deposited in a lake formed by a lateglacial readvance of ice in Magellan Strait.

Tefra del V. Reclus (capa blanca) datada en ca. de 12.000 años A.P.. Sobreyace a una delgada capa de turba y está cubierta por sedimentos glacio-lacustres depositados en un lago originado por un reavance tardiglacial del hielo en el Estrecho de Magallanes.

crest of Chile and Argentina (Rabassa 1981).

The large morainal arcs surrounding the Chilean lakes have been described in papers referred to above, but the most detailed study of their chronology is still that by Porter (1981). Working around and to the west of Lago Llanquihue, Porter separated the glacial deposits into mappable 'drift units' which were described at type sections and assigned a local nomenclature. On the basis of relative weathering studies, four separate drift sheets were distinguished, each representing a full glaciation. The youngest drift, known as the 'Llanquihue drift', forms morainal arcs around the margin of Lago Llanquihue and components of it have been radiocarbon dated to the last glaciation. The other three drifts, extending up to 40km farther west, have no age control but are presumed to represent glacier expansions since the early-mid Quaternary (Fig.6).

The Llanquihue drift was subdivided into three components of different age (Mercer1976, Porter1981) and named Llanquihue I,II and III, oldest to youngest. Since the Llanquihue I drift is older than the range of conventional radiocarbon dating, but is relatively fresh in appearance, Mercer (1983) considered it could have been deposited during marine isotope stage 4 (MIS4); Porter (1981) was more cautious and did not rule out a penultimate glaciation age for this unit.

Llanquihue II drift is better constrained with radiocarbon dates. Outwash gravels overlain by Llanquihue II till contains peat clasts as young as 20,100 +/-500 yr BP (Mercer 1976) and this indicates the advance culminated after ca.20.000 yr ago. Recession of the Llanquihue II glacier is believed to have occurred just before 18,900 +/-370 yr ago, since this is the age of basal peat in a meltwater spillway that functioned when the glacier lay at its drift limit. Thus Porter (1981) concluded the Llanquihue II glaciation occurred at 20.000-19.000 yr ago, corresponding closely to the global glaciation maximum, a view supported by Heusser (1991) based on evidence from Isla de Chiloe farther south.

Llanquihue III drift seems to have been deposited by a readvance of the Llanquihue glacier following an interval of recession (the "Varas interstade" of Mercer 1976) when it withdrew almost to the eastern end of the Lago Llanquihue basin. There is no end moraine, but interpretation of glacio-lacustrine deposits and radiocarbon dating led Porter (1981) to infer that readvances had culminated about 15.000-14,500 yr ago and after ca.13,145 yr ago. Support for a readvance during this late-glacial interval came from Dalcahue on Isla de Chiloe, where an organic bed buried by till inside the limit of a subdued Llanquihue III (equivalent) moraine yielded radiocarbon ages in the range 15,600-14,300 yr BP (Mercer 1984); this suggests a readvance culminated just before ca.14.000 yr BP.

At the time of writing, detailed investigations of the drift sequences around Lago Llanquihue, Lago Rupanco and Lago Puyehue are yielding new results (Denton 1993). It is clear that the moraine sequence is much more complex than originally believed and that it may indicate repeated advances of outlet glaciers from the Lakes Region icecap to similar limits during the last glaciation (Fig.7).

Porter (1981) estimated that a snowline depression of ca.1000m must have occurred for an outlet glacier to reach the western side of the Llanquihue lake basin. Recent modelling experiments have suggested that the conterminous icecap over this part of the Andes could not be generated by temperature depression alone and that a substantial increase in mean annual precipitation must also have occurred (Hulton et al. 1994).

iv. *The Chilean Channels and Fuego-Patagonia*: South of latitude 46°S the climate is dominated by wet maritime westerly air chilled in its passage across the Humboldt Current. Although there is seasonal movement north and south of the zone of intense precipitation, much of the west coast of Chile south of latitude 46°S is wet and windy all year round. This explains the presence of two substantial icefields centred on relatively low (ca.2000m) topography in temperate latitudes, the Hielo Patagonico Norte (HPN) and Hielo Patagonico Sur (HPS). Moreover, a multitude of smaller icecaps and glacier systems are scattered throughout this zone wherever the topography is high enough, as on Isla Santa Ines and Cordillera Darwin, where glaciers descend to sea level. The Equilibrium Line Altitudes of glaciers in this region range between 500m in the west and 1350m in the east (Kerr and Sugden in press).

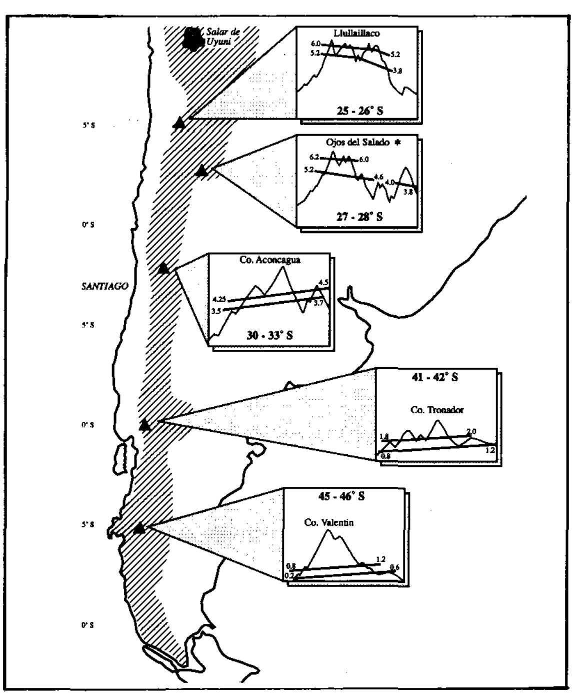

Fig. 10: Schematic diagram showing the present and last glaciation snowline altitudes throughout various latitudes of the Andes.

Diagrama esquemático mostrando las alturas de la línea de nieves en la actualidad y durante la última glaciación a través de los Andes a varias latitudes.

Very little is known about the extent of Quaternary glaciation in the Chilean Channels region and it has commonly been assumed that the expanded Patagonian icefields terminated on the continental shelf west of the land masses (Caldenius 1932, Denton and Hughes 1981). However, recent palaeoecological studies in the area suggest that land refugia for some plants and flightless beetles possibly existed on Isla Wellington during the last glaciation (Ashworth et al.1991). This has important implications for reconstructions of glacial-age climate in the region as it suggests a rather restricted ice extent when the global ice volume was at its highest.

Farther south, large moraine systems extend eastwards from the southern margin of the HPS and from the former icecap centred on Isla Desolacion, Isla Santa Ines and Cordillera Darwin. The moraines were mapped by Caldenius (1932) who believed that most of them represent late stages of the last glaciation. Studies of glacial deposits in Argentina by Mercer (1976) demonstrated that the most extensive Patagonian glaciation occurred about one million years ago. Meanwhile, paleo-magnetic data from glacial sediments around Lago Buenos Aires (Lago General Carrera) have shown that the system of five complex moraine belts represent Pliocene and Quaternary glaciations (Clapperton 1983; Mörner and Sylwan 1989). Similarly, the stacked drifts composing the peninsulas in Magellan Strait, viz. Segunda Angostura, Primera Angostura and Punta Dungeness (Fig.1), may represent a long history of late Cenozoic glaciation.

The sequence of glacial advances during the last glaciation in this region of Chile has now been mapped in detail in two places, around Torres del Paine and in

Magellan Strait. In the Lago Sarmiento basin adjacent to the Paine massif (Fig.8) four major moraines may be associated with advances of the last glaciation (Marden 1994). The easternmost (Stage P, Fig.8) is composed of deformed lacustrine sediments and could represent the initial 'clear-out' of the lake basin during an early stage of the last glaciation. The next two are similar in form and weathering characteristics and may mark limits reached during a later stage of the last glaciation, prior to the global glaciation maximum, but there is no dating control. The fourth moraine is older than a tephra dated to 12.000 yr BP and is morphological very fresh. While it would 'fit' with the Llanquihue III stage of the Lakes Region in terms of relative position, its precise age is not known.

Younger moraines and drift limits (lV and V on Fig.8) are late-glacial in age. The easternmost, situated some 20km from the modern icefront, indicates a stillstand during deglaciation and must have occurred just before ca.12.000 yr BP. This is known from the reworked pumice clasts forming uppermost layers of the outwash, the pumice having travelled through the glacier system from the accumulation zone close to Reclus volcano (Fig.1c). Geochemical analyses and radiocarbon dating have established that this volcano had a large eruption at ca.12.000 yr BP (R.McCulloch, personal communication1993). Recession from this stillstand limit was followed by a readvances to form a moraine complex sometime before 8.700 yr BP, the minimal radiocarbon age of basal peat in a kettle basin immediately inside the end moraine.

The palaeoclimatic significance of these data is that deglaciation after the last glacial maximum in this area was not rapid. Moreover, moraine complex V (Fig.8) may well have been deposited by an readvance of Grey glacier responding to a climatic perturbation induced by the Younger Dryas stadial event of the North Atlantic (Clapperton 1993c) particularly if the icefield was already in a relatively expanded position. Marden (1994) has explained these differences between Paine and sites farther north in terms of migrations of the belt of high precipitation.

Preliminary data on the late Quaternary glacial sequence in Magellan Stait suggests that Magellan glacier advanced along the strait at least five times during the last glaciation, the last occasion occuring after 12.000 yr BP. Following the last glaciation maximum, Magellan glacier probably withdrew rapidly southwards due to rapid ablation through calving in a proglacial lake 200-500m deep (Porter et al.1992). The glacier possibly remained at topographic pinning points in the southern part of Magellan Strait (as at Paso del Hambre) between ca.14.000-12.000 yr BP before advancing into deposits containing Reclus tephra (Fig.9) dated to ca.12.000 yr BP (R.McCulloch, personal communication 1993). This advance may have produced a renewed rise in proglacial lake level that cut impressive shorelines near Porvenir and on the northern tip of Isla Dawson (Fig.1c).

In conjunction with evidence emerging from the Chilean Lakes region for repeated advances of these climatically-sensitive glacier systems during the last glaciation, the Paine and Magellan sequences suggest responses to the global climatic fluctuations during MIS3 and MIS2 implied by the ice core records

DISCUSSION

Knowledge of the succession of Quaternary glacier fluctuations in Chile is important for understanding the nature of climatic changes throughout almost 40 degrees of latitude in the Southern Hemisphere. This review of existing data about such fluctuations raises the following conclusions

1. The overall pattern of climatic belts affecting Chile remained essentially similar to the modern one, as indicated by the palaeo-snowline gradients (Fig.10). These imply that precipitation decreased from east to west in northern Chile and from west to east in central and southern Chile, as now.

2. Although the climatic pattern was similar, there were substantial changes in temperature and effective precipitation, and in the location of westerly rain belts. For example, in the semi-arid northern Andes,

the presumed lowering of mean annual temperature during Quaternary glacial intervals must have been accompanied by an increase in effective mean annual moisture, otherwise glaciers clould not have formed. Similarly, extensive icefields could not have built up in the Chilean lakes region without a significant rise in precipitation. Moreover, Quaternary icefields would probably have been more extensive in southern Chile if precipitation had been as high as the modern total.

3. Increased effective precipitation in northern Chile during glacial intervals may have resulted from greater cloudiness and lower evaporation induced by a cooler atmosphere. Higher precipitation in the lakes region may have resulted from a northerly migration of the zone of greatest westerly humidity, due to a weaker Pacific anticyclonic system and an expanded sub-Antarctic cover of sea ice.

4. The estimated snowline depression of 800-1000m for late Quaternary glacial intervals in Chile may not indicate that the atmosphere cooled by as much as 5-6.5°C (assuming a 0.65°C/100m lapse rate), since higher precipitation in some regions would have had a significant effect in lowering the snowline. An overall cooling by at least 4°C seems likely, but could have been more or less at different sites, where local influences such as exposure to katabatic winds were probably important.

5. The apparent rise in the glacial snowline towards latitude 28-30°S from both northern and southern directions suggests that this currently hyper-arid region remained as dry during glacial intervals, despite the (assumed) lowering of atmospheric temperature. This implies that the seasonal westerlies failed to penetrate or migrate more than about 2 degrees of latitude farther north than their modern limit, and that the humid (tropical) easterlies did not expand much farther south than their current (seasonal) extent.

Wider Implications

Evidence emerging from radiocarbon-dated glacial sequences in the Llanquihue and Magellan areas suggests that icefield outlet glaciers advanced to similar limits several times during the last glaciation. As new ice core data from Greenland and marine core data from the North Atlantic imply atmospheric fluctuations of a quasi-cyclical nature throughout the last glaciation (Bond et al.,1993), the Chilean icefields may also have responded in a similar fashion, assuming high sensitivity to variations in temperature and precipitation. The validity of such correlation awaits detailed glacial chronologies from the various glaciated regions of Chile.

The nature and age of glacier fluctuations in northern and north-central parts of Chile remain poorly known and require detailed investigation. This is an important task to undertake since it is vital to compare palaeoclimatic records between subtropical arid and temperate humid regions to understand the precise nature of global climatic changes during the late Quaternary.

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