CHILOTAN PIEDMONT GLACIER IN THE SOUTHERN ANDES DURING THE LAST GLACIAL MAXIMUM

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ABSTRACT

The development and timing of events related to the advance of the Chilotan piedmont glacier during the last glacial maximum (25,000-14,000 years Before Present) and during wastage of the ice are outlined from radiocarbon dated stratigraphic sections and the study of fossil pollen and spores of late Llanquihue glacial deposits on Isla Grande de Chiloé and in Chiloé Continental. Advance of the Chilotan glacier followed a climatically moderated interstade that lasted from at least 43,000 to about 30,000 years ago. Cold, wet climate apparently at first was responsible for the buildup and expansion of the ice, whereas after about 26,000 years B.P. and until the greatest extent was reached close to 20,000 years B.P., a colder, drier climate controlled the regimen of the glacier. Recession from this stage was stepwise with a readvance of almost equivalent magnitude at 15,000-14,500 years ago. Climate warmed abrupty beginning before 13,000 years B.P., triggering rapid withdrawal of ice over much of the region in a few hundred years.

The time of the maximum, which coincides with the age of about 20,000-19,000 years B.P. for the event in the Chilean lake district, is attributed to cold climate associated with the intensification of atmospheric circulation in the Southern Hemisphere. Storm systems generated by the southern westerly wind regime were apparently of greater frequency, as well as intensity, bringing greater precipitation to lower latitudes than at present. Climate in summer was colder by an estimated 7°C and annual precipitation heavier by a factor of >2.

Key words: Quaternary Geology, Late Llanquihue Glaciation, Last glacial maximum, Climate and vegetation, Isla Grande de Chiloé, Chile.

RESUMEN

El desarrollo y la datación de los eventos relacionados con el avance del glaciar de piedemonte Chilote, tanto durante el último máximo glacial (25.000-14.000 años Antes del Presente) como en el transcurso del derretimiento del hielo, han sido resumidos mediante dataciones radiocarbón en secciones estratigráficas y el estudio de polen y esporas fósiles en depósitos de la última glaciación, denominada Llanquihue, en Isla Grande de Chiloé y Chiloé Continental.

Al avance del glaciar Chilote siguió un interestadial climáticamente moderado, que duró al menos 43.000 a *ca.* 30.000 años. Un clima frío y aparentemente húmedo fue responsable, en un comienzo, del aporte y expansión del hielo, mientras que, a partir de aproximadamente 26.000 años A.P., un clima más frío y seco, controló el régimen del glaciar. La recesión de esta fase fue muy amplia, con un reavance en la magnitud equivalente de al menos 14.500 años. El clima abruptamente se tornó más caluroso a partir de 13.000 años A.P., condicionando, en pocos cientos de años, un rápido retroceso del hielo desde extensos sectores de la región.

El máximo, coincidente con la edad de 20.000-19.000 años A.P. para el evento en el distrito lacustre chileno, se vincula a clima frío, asociado con la intensificación de la circulación atmosférica en el Hemisferio Austral. Los sistemas de tempestades generados por el régimen de vientos suroccidentales fueron, aparentemente, de mayor frecuencia e intensidad, desarrollando mayores precipitaciones respecto de los actuales en latitudes más bajas. El clima de verano fue más frío, en 7°C por estimación, y la precipitación anual más elevada, por un factor >2.

Palabras claves: Geología del Cuaternario, Ultima glaciación Llanquihue, Ultimo máximo glacial, Clima y vegetación, Isla Grande de Chiloé, Chile.

INTRODUCTION

The Quaternary of Isla Grande de Chiloé (41°45'-43°25'S) was virtually unknown when field work with R.F. Flint was carried out on the northern part of the island in 1976 (Heusser and Flint, 1977). Studies during the field season emphasized reconnaissance mapping of the glacial deposits along some 3,000 km of the highways and backroads of Isla Grande and, northeast of the town of Castro, also on Isla Quinchao. About 80 exposures of drift were examined and mapped with the aid of aerial photographs and topographic maps of the Instituto Geográfico Militar on a scale of 1:50.000. Collections made of biogenic sediments from a number of exposures and sections of mires produced a regional pollen stratigraphy with a total of 25 radiocarbon age determinations. The outcome was a preliminary account of glaciation,

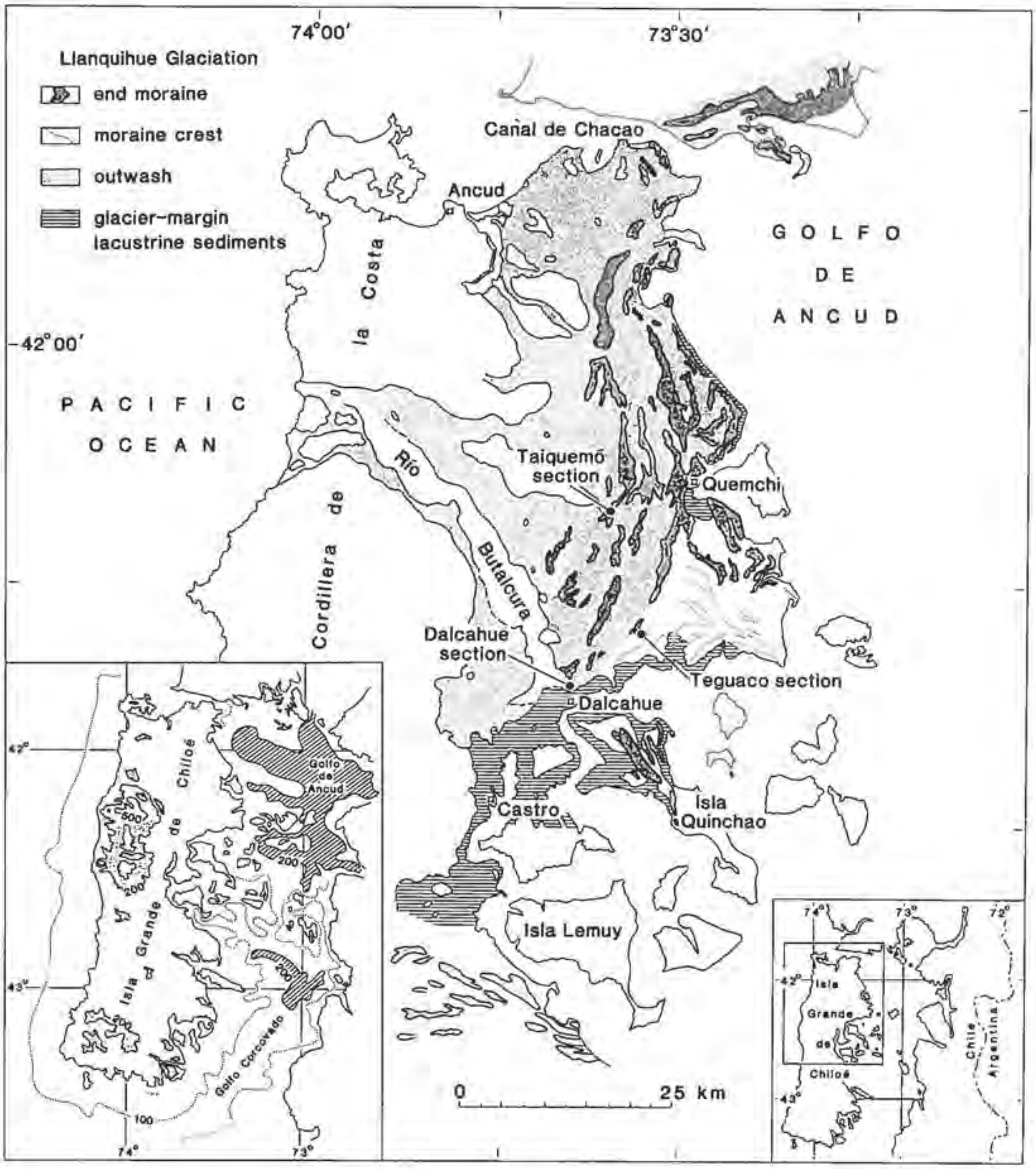

FIG. 1. Map showing physical features, distribution of glacial deposits of Llanquihue Glaciation on northern Isla Grande de Chiloé, and locations of stratigraphic sections of this study. Inset map at lower left shows elevations in the Cordillera de la Costa (contour intervals, 200 and 500 m) and depths offshore of 100 and 200 m (areas >200 m deep shown hatched). Data sources are Heusser and Flint (1977), American Geographical Society (1956), and Instituto Hidrográfico de Chile (1959-1960).

which complemented the studies of Flint and Fidalgo (1964, 1969) on the east side of the Andes, and an uninterrupted record of vegetation and climate over the past 43,000 years.

Further studies made during subsequent field seasons, following the death of R.F. Flint in 1976, and data produced by Mercer (1984; personal commun., 1982, 1984) and Villagrán (1985, 1988a, b, 1990) have added substantially to the glacial record, particularly the setting and chronology of the last glaciation. From this work, it is now possible to outline, in a finite chronological framework and with greater detail, the sequence of events related to the glacial history of Isla Grande de Chiloé and to interpret from the various data sources the mode and timing of advance and retreat of the Chilotan piedmont glacier, as well as the vegetation and climate during the last glacial maximum (25,000-14,000 years B.P.). Focus is on the paleoenvironmental reconstruction from pollen and spore stratigraphy and radiocarbon dating of deposits in terrain occupied by glaciers of the last ice age. Results of this study form a counterpart to the mapping, dating, and paleosetting of deposits in this time frame in the adjoining lake district (approximately 38°-41°S) on the mainland to the north (Weischet, 1958; Heusser, 1966, 1972, 1974, 1981, 1984; Lauer, 1968; Laugenie, 1971; Mercer, 1972, 1976, 1982, 1983, 1984; Mercer and Laugenie, 1973; Porter, 1981).

ISLA GRANDE DE CHILOE

GEOLOGICAL SETTING

The island of Chiloé (Fig. 1) is the largest member (12,000 km²) of the archipelagos lying north of the Península de Taitao (46°-47°S). It lies separated from the mainland by the Canal de Chacao on the north and to the east by Golfo de Ancud and Golfo Corcovado. Much of the eastern part is low-lying, covered by surficial deposits of Quaternary age, whereas to the west in the Cordillera de la Costa, Paleozoic metamorphic basement rock, along with Eocene-Miocene sedimentary marine and Pliocene-Pleistocene volcanic rocks, are exposed (Servicio Nacional de Geología y Minería, 1982). Altitudes in the northern cordillera are locally just above 800 m and in the south, mostly <200 m.

Three recognizable stratigraphic units of drift, Fuerte San Antonio, Intermediate, and Llanquihue, occur on Isla Grande (Heusser and Flint, 1977). The oldest, the Fuerte San Antonio, and the Intermediate (possibly representing more than a single glaciation), both contain clasts with advanced weathering characteristics and are beyond the limit of radiocarbon dating. These drifts may correspond with the Caracol, Río Llico, and Santa María drifts identified in the lake district by Porter (1981). The Fuerte San Antonio and Caracol are considered by Hauser (1986) to be part of the Rodados Multicolores, a highly weathered, oligomictic conglomerate. From tha K-Ar age of obsidian in underlying volcanic bedrock at a site just north of the Fuerte San Antonio drift type locality, the deposit is dated <760,000± 210,000 years (Vergara and Munizaga, 1974), thus limiting the age of Chilotan glaciation.

Whereas Fuerte San Antonio drift is exposed at only a few localities, Intermediate drift is known from at least 20 exposures. Both were found to extend at least 20 km beyond the limit of Llanquihue Glaciation, which overrode the low northeastern border of the island (Fig. 2). West of Castro, the Llanquihue drift reaches an altitude of about 350 m at the edge of the coastal mountains; southward, it appears to continue to the outer coast. This youngest drift consists of much gray, sandy till (Fig. 3), weathered yellowish-brown to a depth of <1 m and containing Andean volcanic clasts with thin weathering rinds (<0.5 mm), and includes ice contact stratified drift (Fig. 4), many meters in thickness and well exposed along the northeastern coast. The drift, bracketed by radiocarbon dates both infinite and finite, was deposited over an interval from >43,000 years B.P. to late-glacial time. It is judged on the basis of stratigraphic and age criteria to be equivalent to the Llanquihue drift observed in moraines bordering Lago Llanquihue. Porter (1981) subdivided Llanquihue drift into three stadial units, informally named Llanquihue I, II and III, which Heusser and Flint (1977) did not recognize on Isla Grande.

Multiple end moraines and outwash of Llanquihue glacial age occupy a belt reaching some 25 km broad in the northeastern part of the island. The moraines (Fig. 5), some of massive proportions (>20 km in length), are well-defined, and appear only moderately changed since emplacement. The outermost

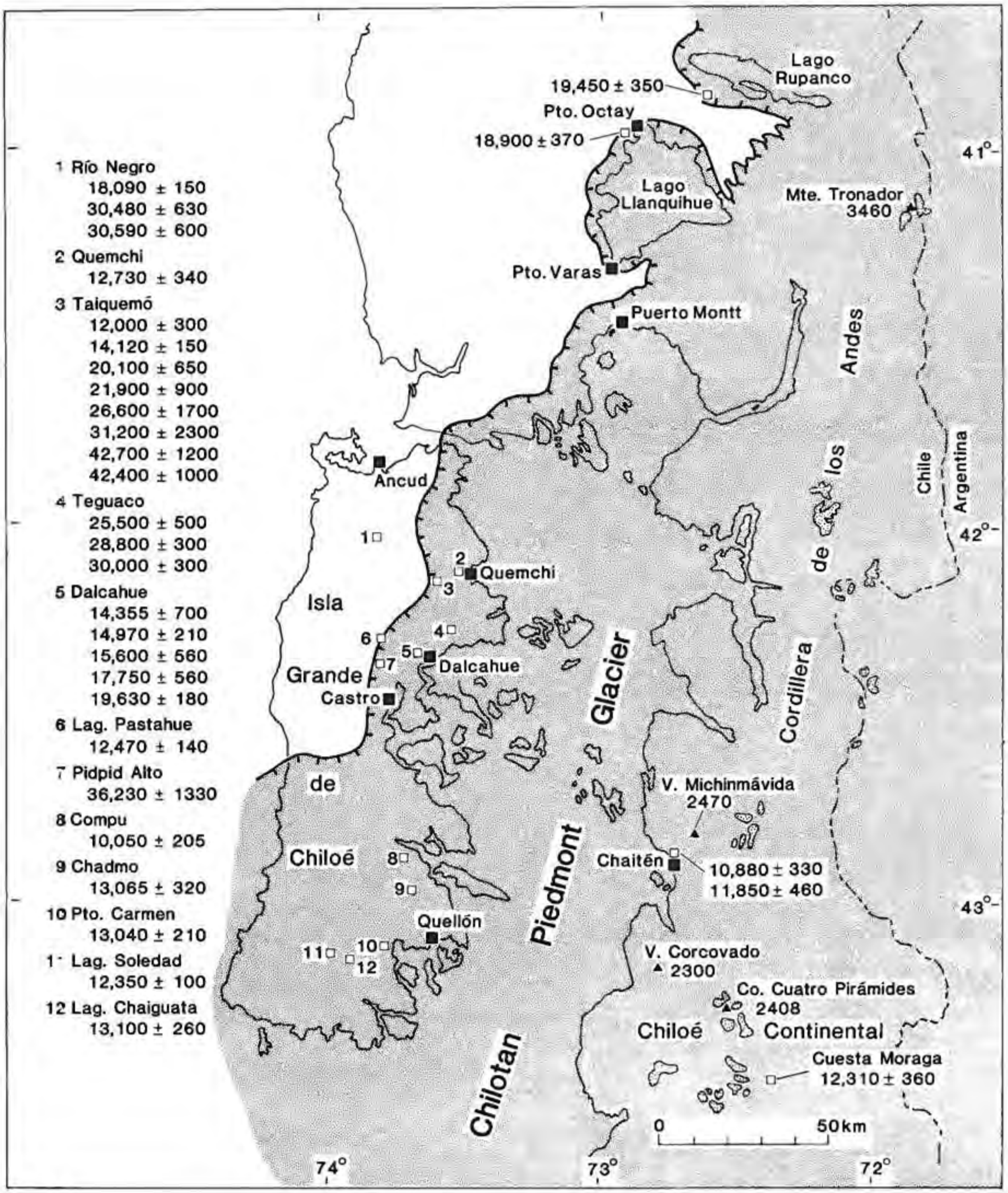

FIG. 2. Extent of Llanquihue Glaciation on Isla Grande de Chiloé, Chiloé Continental, and part of the lake district with dated sites and radiocarbon age determinations relevant to the glacial chronology. Major existing glacier areas in the Cordillera de los Andes are outlined by stippling. Sources are Heusser (1981; unpubl. data), Heusser and Flint (1977), Mercer (1967, 1976, 1984; personal commun., 1982, 1984), Porter (1981), and Villagrán (1985, 1988a, b).

FIG. 3. Till of the late Llanquihue Glaciation freshly exposed by road construction east of Dalcahue (Fig. 1).

FIG. 4. Ice contact stratified drift of the last glaciation near Quemchi (Fig. 1).

FIG. 5. Morainal topography of late Llanquihue Glaciation on the east side of Isla Grande. Skyline is of Volcán Corcovado (2,300 m) and snow covered Andes to the south.

FIG. 6. Thick lacustrine sediments of the ice-marginal lake formed on wastage of ice of the last glaciation near Castro (Fig. 1).

moraines with relatively long radii of curvature were apparently produced by glaciers crossing terrain of low relief; inner moraines with contrasting shorter radii are thought to have resulted from glaciers that were thin, by comparison, and advanced across subglacial topography of some relief. Fronting these moraines, remarkably large quantities of outwash (>100 m thick) have been dissected into terraces by systems of the westward flowing, meltwater drainage. The Río Butalcura received the bulk of outwash, including the discharge of ice-marginal lakes, formed on wastage of the Llanquihue glacier. The largest lake extended for >50 km from south of Castro to east of Dalcahue (Fig. 1); smaller lakes developed in the vicinity of Quemchi. The lakes, identified by thick sediments of sand, silt, and clay containing dropstones (Fig. 6), in places exceeded altitudes of 100m.

CLIMATE AND VEGETATION

An unrelenting succession of cyclonic storms generated in the belt of westerly winds crosses Isla Grande de Chiloé almost daily, striking the coast with great force (Miller, 1976). Climate, under cool temperate conditions throughout the year, is generally wet and cloudy; only east of the coastal mountains the heavy rainfall is modified in summer. Mean annual precipitation reaches >4,000 mm in the cordillera and around 2,000 mm in the eastern coastal lowland; mean temperature in summer is about 14°C and in winter 7°C (Almeyda and Sáez, 1958).

Evergreen rain forest is the natural vegetation of much of Isla Grande. The forest, consisting of dominant trees attaining 40 m or more in height, is multilayered with humid interiors rich in lianas, parasitic and epiphytic seed plants, ferns, and mosses. During settlement for >300 years, trees were extensively cut and the forest burned and cleared for agriculture. On the lowland, stands are almost all successional with few original tracts showing a minimum of disturbance remaining.

Valdivian Rain Forest is distributed at low altitudes; at higher altitudes in the cordillera are North Patagonian and Subantarctic Rain Forests and communities of limited extent containing elements of Subantarctic Magellanic Moorland (Espinosa, 1917; Schmithüsen, 1960; Oberdorfer, 1960; Godley, 1960; Godley and Moar, 1973; Villagrán, 1985, 1988a, b). Species typical of the Valdivian, North Patagonian, and Subantarctic Rain Forests and Magellanic Moorland are given in Table 1.

TABLE 1. REPRESENTATIVE VASCULAR PLANT SPECIES IN VEGETATION OF ISLA GRANDE DE CHILOE*

Valdivian Rain Forest (0-250 m)
Nothofagus dombeyi (Fagaceae) *Eucryphia cordifolia* (Eucryphiaceae) *Aextoxicon punctatum* (Aextoxicaceae) *Gevuina avellana* (Proteaceae) *Caldcluvia paniculata* (Cunoniaceae) *Amomyrtus meli* (Cunoniaceae) *Myrceugenia planipes* (Myrtaceae)
North Patagonian Rain Forest (250-450 m)
Laurelia philippiana (Monimiaceae) *Amomyrtus luma* (Myrtaceae) *Myrceugenia ovata* var. *ovata* (Myrtaeae) *M. planipes* *Drimys winteri* (Winteraceae)
Subantarctic Rain Forest (>450 m)
Saxe-gothaea conspicua (Podocarpaceae) *Podocarpus nubigena* (Podocarpaceae) *Pilgerodendron uviferum* (Cupressaceae) *Fitzroya cupressoides* (Cupressaceae) *Nothofagus betuloides* (Fagaceae) *N. nitida* (Fagaceae)
Subantarctic Magellanic Moorland (>650 m)
Astelia pumila (Liliaceae) *Donatia fascicularis* (Donatiaceae) *Gaimardia australis* (Centrolepidaceae)

* Nomenclature following Marticorena and Quezada (1985).

METHODS

Samples for the study of fossil pollen and spores and for radiocarbon dating are from freshly exposed measured sections of biogenic interdrift deposits in road cuts at Teguaco and Dalcahue and from a core section of a mire at Taiquemó (Fig. 1). Samples were processed in the laboratory by the method of Heusser and Stock (1984), which follows a schedule of potassium hydroxide deflocculation, washing with sodium pyrophosphate solution, hydrofluoric acid treatment, and acetolysis; nylon microscreens with meshes of 7 and 150 µm are used to concentrate the pollen and spore size fraction from the sediment matrix.

Identifications and counts of the pollen and spores are made under the microscope with the use of modern reference collections and of published taxonomic descriptions and keys (Heusser, 1971; Villagrán, 1980). Identification at the species level is not workable for a number of taxa; for example, *Nothofagus,* which consists entirely of *N. dombeyi* type in samples of this study, represents several inseparable species, and the Myrtaceae cover a number of intractable genera and species. Relative frequencies (%) of pollen at stratigraphic levels in the sections are from sums of leading taxa, including key indicator species = 300; sums used to calculate frequencies of vascular cryptogam/aquatic spores are = >300 pollen and spores.

STRATIGRAPHIC SECTIONS

TEGUACO

The Teguaco section, now obliterated by road building, is a cut located on the west side of the Río Teguaco, 0.3 km east of the settlement of Teguaco, on the road connecting Dalcahue and Quemchi via Tocoihue (Fig. 1). The cut (Figs. 7, 8) exposed thick sand (>3 m) overlain by successive beds of organic silty sand (0.3 m), gyttja (0.3 m), and laminated sandy clay (0.6 m) beneath gravel and soil (1.8 m). The organic silty sand was deposited beginning about 30,000 years ago (Table 2), while the gyttja formed between 28,800 and 25,500 years ago and the laminated sediments later.

FIG. 7. Section at Teguaco (Fig. 1) of interdrift organic sand and gyttja overlain by laminated sandy clay.

TABLE 2. RADIOCARBON AGE DETERMINATIONS OF DEPOSITS ON ISLA GRANDE DE CHILOE AND IN CHILOE CONTINENTAL RELEVANT TO LATE LLANQUIHUE GLACIATION

Sample Location and Stratigraphic Relations	Age (years B.P.)	Laboratory Number	References
Isla Grande de Chiloé			
Compu, peat in mire over drift	10,050 ± 205	GX-3806	Heusser and Flint, 1977
Lago Soledad, near-basal peat over drift	12,350 ± 100	Beta-10484	Villagrán, 1988
Laguna Pastahue, sandy gyttja over drift	12,470 ± 140	Beta-4720	Villagrán, 1985
Quemchi, peat in mire over drift	12,730 ± 340	RL-605	Heusser and Flint, 1977
Laguna Chaiguata, near-basal peat over drift	13,100 ± 260	Beta-10485	Villagrán, 1988a
Puerto Carmen, sandy peat over drift	13,040 ± 210	Beta-10481	Villagrán, 1988a
Chadmo, peat in mire over drift	13,065 ± 320	GX-3809	Heusser and Flint, 1977
Dalcahue, intertill wood in peat	14,355 ± 700	GX-8686	Mercer, 1984
Dalcahue, intertill wood in peat	14,970 ± 210	I-12996	Mercer, 1984
Dalcahue, intertill wood in peat	15,600 ± 560	GX-9978	Mercer, 1984
Dalcahue, intertill peat	17,750 ± 560	Beta-33820	C.J. Heusser, unpublished
Dalcahue, intertill peat	19,630 ± 180	QL-4324	C.J. Heusser, unpublished
Teguaco, peat interbedded in drift	25,500 ± 500	QL-1017	C.J. Heusser, unpublished
Teguaco, peat interbedded in drift	28,800 ± 300	QL-1018	C.J. Heusser, unpublished
Teguaco, peat interbedded in drift	30,000 ± 300	QL-1019	C.J. Heusser, unpublished
Taiquemó, peat in mire	12,000 ± 300	QL-1003	Heusser and Flint, 1977
Taiquemó, peat in mire	14,120 ± 150	QL-1004	Heusser and Flint, 1977
Taiquemó, peat in mire	20,100 ± 650	QL-1055	Heusser and Flint, 1977
Taiquemó, peat in mire	21,900 ± 900	QL-1006	Heusser and Flint, 1977
Taiquemó, peat in mire	26,600 ±1,700	QL-1008	Heusser and Flint, 1977
Taiquemó, peat in mire	31,200 ±2,300	QL-1009	Heusser and Flint, 1977
Taiquemó, peat in mire	42,700 ±1,200	QL-1011	Heusser and Flint, 1977
Taiquemó, peat in mire	42,400 ±1,000	QL-1012	Heusser and Flint, 1977
Río Negro, peaty clay in mire	18,090 ± 150	Beta-21812	Villagrán, 1988b
Río Negro, peat with clay in mire	30,480 ± 630	Beta-20895	Villagrán, 1988b
Río Negro, peat with clay in mire	30,590 ± 600	Beta-4728	Villagrán, 1988b
Pidpid Alto, peat in stream cut	36,230 ±1,330	Beta-7419	Villagrán, 1985
Chiloé Continental			
Chaitén peat over till	10,880 ± 330	RL-1891	C.J. Heusser, unpublished
Chaitén wood in peat over till	11,850 ± 460	GX-9982	J.H. Mercer, personal commun., 1984
Cuesta Moraga, peat over drift	12,310 ± 360	RL-1892	C.J. Heusser, unpublished

Pollen and spore stratigraphy follows the changing trends of the primary components, *Nothofagus* (beech) and Gramineae (grass), representing varying degrees of open vegetation. In pollen assemblage zone 5 (Gramineae-Umbelliferae-*Nothofagus)*, consisting of no more than 25% *Nothofagus*, tree species are especially restricted, apparently by cold and/or dryness. Above, in zone 4 *(Nothofagus*-Gramineae-Tubuliflorae-*Isoetes savatieri)* and in zone 3 *(Nothofagus-Dacrydium fonckii*-Gramineae-Tubuliflorae-*Isoetes savatieri)*, the increase of *Nothofagus* and the rich diversity of elements of the modern subantarctic vegetation, including Magellanic Moorland *(Dacrydium fonckii, Astelia pumila, Gaimardia australis, Drapetes muscosus, Donatia fascicularis,* and *Huperzia selago)*, are indicative of cold, wet climate. Abundance of the aquatic *Isoetes savatieri*, especially in zone 4, implies the presence of a freshwater lake of some depth in existence for >3,000 years; organic deposition terminated abruptly about 25,500 years ago when laminated sandy clay was laid down in the basin.

Pollen assemblages in zone 2 (Gramineae-*Nothofagus)* and in zone 1 *(Nothofagus*-Gramineae), representing the laminated unit, suggest marked alteration of plant communities surrounding the site. From the increase in Gramineae and decrease of species of Magellanic Moorland affinity in zone 2, a

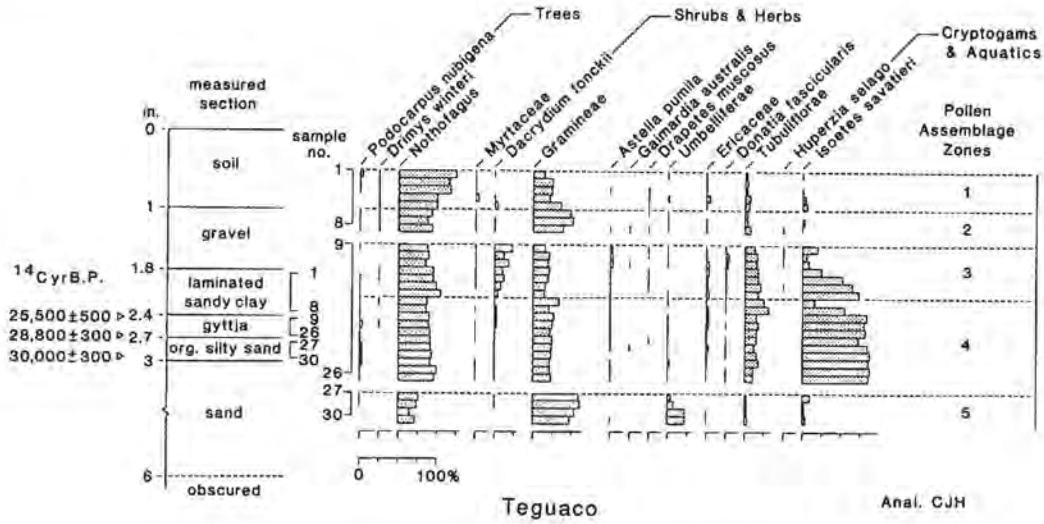

FIG. 8. Pollen and spore diagram of measured section at Teguaco.

cold, less humid episode is implied, followed by moderating climate, which in zone 1 favored the increase of *Nothofagus*. These latest changes at Teguaco, in progress while laminated silt was being deposited, possibly reflect the proximity of a fluctuating ice margin. Apparent corresponding stratigraphic aspects of the record are found at Río Negro (Fig. 2), located outside the border of Llanquihue Glaciation, in northern Isla Grande (Villagrán, 1988b).

DALCAHUE

On the Dalcahue-Quemchi road, along which the Teguaco section was located, intertill peat containing wood is exposed about 1 km northeast of the T-junction at Route W-45, which is 1.6 km north of Dalcahue (Fig. 1). A measured section at the site (Fig. 9; J.H. Mercer, personal commun., 1982) exhibits a layer of peat containing wood in the uppermost part (0.6 m), overlain, in turn, by layers of sand (0.2 m), sand and gravel(4.2 m), and till (0.2 m), and underlain by gravel (0.1 m) and till (>2.4 m). From radiocarbon dates of 14,355, 14,970, and 15,600 years B.P. of the wood in the section (Table 2), Mercer (1984) pointed to a date of 15,000-14,500 years ago for a final, full-glacial readvance of the Llanquihue

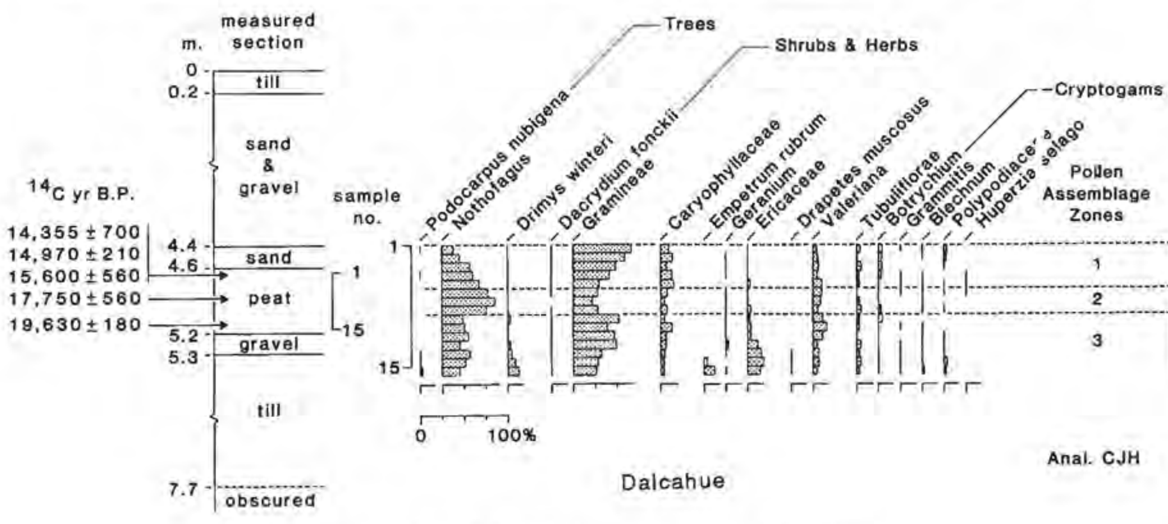

FIG. 9. Pollen and spore diagram of measured section at Dalcahue.

glacier at Dalcahue.

Pollen and spore stratigraphy at 4 cm intervals and additional radiocarbon ages of 19,630 years B.P. at the base of the peat and 17,750 years B.P. at midsection (Fig. 9; Table 2) provide detail of the zonation and timing of vegetation changes over some 5,000 years. Zone 3 (Gramineae-*Nothofagus)*, zone 2 *(Nothofagus*-Gramineae), and zone 1 (Gramineae-*Nothofagus)* trace the development and gradual replacement of arboreal communities in open vegetation on the landscape. The abundance of Ericaceae mixed with *Empetrum rubrum* early in zone 3 is reflective of initial heath communities that invaded in the course of early deglaciation; the Gramineae, containing throughout quantities of Caryophyllaceae, *Geranium, Valeriana,* and Tubuliflorae, are indicative of succeding grassland, today developed at higher latitudes in the region of the Fuegian Andes of southern Chile (Moore, 1983).

Peak *Nothofagus* at 60% in zone 2, dated 17,750 years B.P. and reached following its succession with *Drimys winteri* in zone 3, identifies the mildest climatic interval over the time of record. Later, cold conditions during the approximately three millennia of zone 1, when percentages of the Gramineae progressively outnumber *Nothofagus,* apparently account for the readvance of the Llanquihue glacier that overrode the site 15,000-14,500 years B.P. Climate appears to have been drier during the late-glacial at Dalcahue, unlike the interval 28,800-25,500 years ago at Teguaco (Fig. 8), when greater humidity was consistent with a strong representation of Magellanic Moorland plants.

TAIQUEMO

About 10 km west of Quemchi, Route W-35 intersects a short spur road, where 0.5 km distant from the turnoff is the location of the Taiquemó mire (Fig. 1). Situated close to the limit of Llanquihue drift, the mire

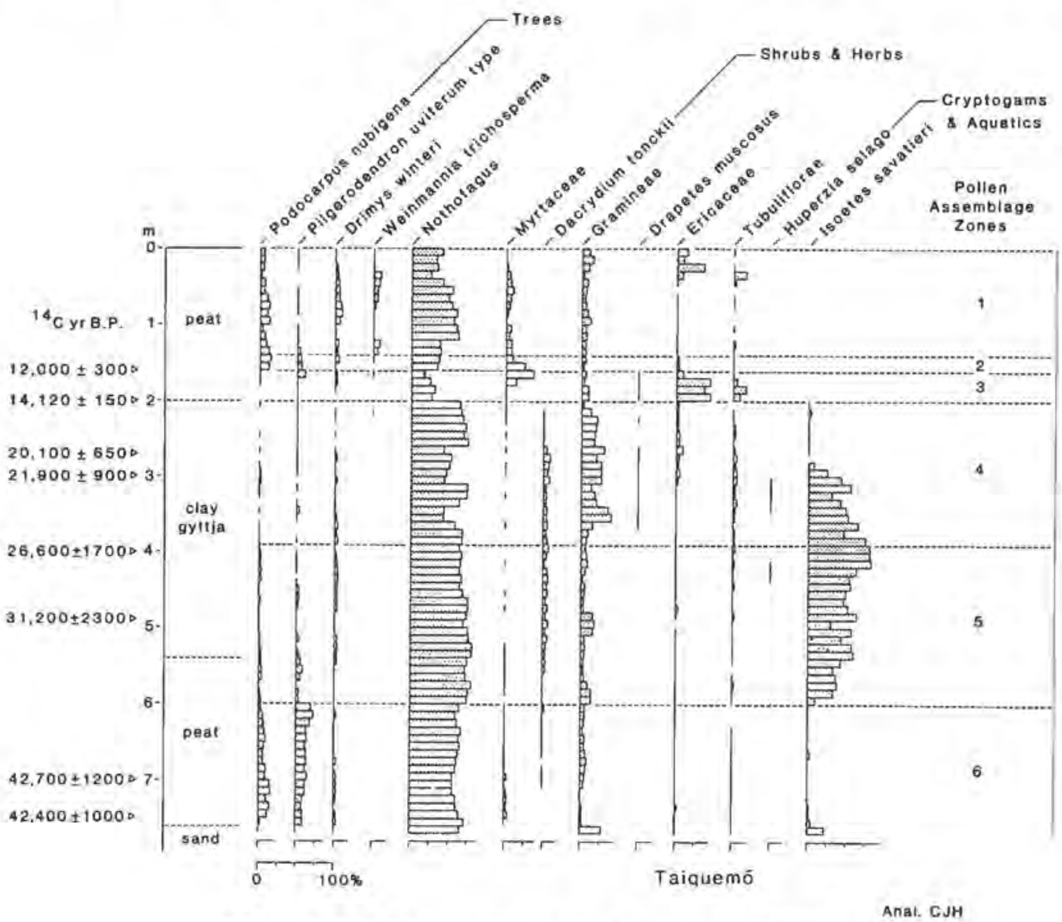

FIG. 10. Pollen and spore diagram of mire section at Taiquemó.

rests in a basin held within an early Llanquihue moraine. The 7.6 m section of the deposit (Fig. 10) penetrates clay gyttja (3.4 m) interbedded between layers of peat (each about 2 m thick). Eight radiocarbon dates (Table 2) establish the approximate chronostratigraphic relations: the underlying peat at 43,000-33,000 years B.P. represents a pre-late Llanquihue interstade, the clay gyttja at 33,000-14,000 years B.P. includes the last glacial maximum, and the overlying peat at 14,000-0 years B.P. is late-glacial and Holocene in age.

Pollen and spore stratigraphy (Fig. 10) is divided into six assemblage zones. Zone 6 *(Nothofagus-Pilgerodendron uviferum* type-*Podocarpus nubigena*-Myrtaceae) spans the early interstade (43,000-37,000 years B.P.), during which arboreal communities, including quantities of *Drimys winteri*, occupied the landscape under a cool, humid climate; comparable conditions seem to be reflected by zone 2 *(Nothofagus-Podocarpus nubigena-Pilgerodendron uviferum* type-Myrtaceae) during the late glacial (12,000-10,000 years B.P.), when, however, the Myrtaceae were of greater importance in the generating forest.

Zone 5 *(Nothofagus-Dacrydium fonckii*-Gramineae-*Isoetes savatieri)* records differentiation in the vegetation (37,000-26,000 years B.P.), whereby *Nothofagus* became increasingly dominant and *Dacrydium fonckii* of the Subantarctic Magellanic Moorland more abundant [Note that *D. fonckii* at Taiquemó was misidentified as *Podocarpus andina (= Prumnopitys andina)* in Heusser and Flint (1977)]. Cooler, wetter climate indicated by these vegetation changes is also evident from the accompanying lacustrine conditions, shown by the striking increase of the aquatic *Isoetes savatieri* and the changeover from peat to clay gyttja.

Zone 4 *(Nothofagus*-Gramineae-*Dacrydium fonckii-Isoetes savatieri)* is characterized by the distinctive profile of the Gramineae with percentages reaching 41% of the pollen sum (26,000-14,000 years B.P.). Arboreal communities on Isla Grande de Chiloé, which were more extensive during earlier millennia, became reduced by the expansion of grassland/tundra, apparently as climate grew colder and less humid. Decrease of *Isoetes savatieri* in the lower part of the zone is thought to result from shoaling of the lake that formed during the earlier lacustrine phase. Correspondence of maximum values of this aquatic close to the boundaries of zone 5-4 at Taiquemó and zone 4-3 at Teguaco (Fig. 8), which appears to be chronostratigraphic, implies a shift from increasing to decreasing precipitation about 26,000 years ago.

Zone 3 *(Nothofagus*-Myrtaceae-Ericaceae-Tubuliflorae) covers the late-glacial successional trend in vegetation, whereby initially under a moderating climate, shrub heath communities became established, followed by the Myrtaceae (14,000-12,000 years B.P.) and later, during the two millennia of zone 2 by arboreal taxa, for example, *Podocarpus nubigena*, of cooler climatic affinity (Table 1). The general warming of the Holocene is characterized by the singular presence of arboreal *Weinmannia trichosperma* in Zone 1 (10,000-0 years B.P.).

CHILOTAN PIEDMONT GLACIER DURING THE LAST GLACIAL MAXIMUM

At different times during the Llanquihue Glaciation, glaciers from the Cordillera de los Andes overrode much of the island of Chiloé (Heusser and Flint, 1977). Coalescing piedmont lobes crossed the intervening trough that separares the island from Chiloé Continental. The trough, at present marine and >300 m deep (Instituto Hidrográfico de Chile, 1959-1960), is formed by adjoining waterways of Golfo de Ancud and Golfo Corcovado (Fig. 1). This connection with the open sea may be relatively recent, however, since the glacial deposits do not appear to contain marine sediments or fossils. Ice fronts on Isla Grande (Fig. 2), having moved forward >100 km from the central Andes, rested across the northeastern lowland and in the central part of the island butted against the eastern edge of the Cordillera de la Costa; south of 42°40'S, glaciers advanced >200 km to the present Pacific coast and possibly onto the continental shelf, where canyon cutting is believed to be the result of ice scour (Mordojovich, 1981). Thicknesses of ice, estimated in the lake district at the time of the last glacial maximum and probably applicable to the latitude of Chiloé, range from 800-1,000 m on the flanks of the Andes to nearly 1,300 m at the ice divide (Porter, 1981).

A chronology of the buildup of ice in the Andes during late Llanquihue Glaciation, which resulted in the formation of the Chilotan piedmont glacier and its encroachment on Isla Grande during the last glacial maximum, derives from the dated sections discussed in this study. The advance of the glacier (Fig. 11) followed interstadial conditions, which are indicated by stratigraphic records at Teguaco and Taiquemó (Figs. 8, 10), where the interval is known to have lasted from at least 43,000 until around 30,000 years B.P. (Heusser *et al.*, 1981). Although climate at Teguaco was apparently cold by about 30,000 years B.P., it was also relatively non-humid, and the major impetus for glacier advance to occur in the Andes probably did not develop until climate later became increasingly humid. This rise in humidity is inferred by the onset of lacustrine conditions at Teguaco at about 29,000 years B.P., followed by the increase of hygrophilous indicators of the Subantarctic Magellanic Moorland (for example, *Dacrydium fonckii)*, and also at Taiquemó, where the chronology is less precise, and Río Negro (Villagrán, 1988b) to the north (Fig. 2).

One may speculate that the cold, humid conditions at first brought about the snow accumulation in the Andes required to expand the Chilotan piedmont glacier. Intensification of storm frequency associated with the southern westerlies could account for greater snowfall at this time. When the Chilotan piedmont glacier advanced to its outermost position at close to 20,000 years ago (Fig. 11), as implied by the date of 19,650 years B.P. for peat directly postdating the till at Dalcahue (Fig. 9), positive mass balance of the glacier seems to have been maintained, even though climate, perhaps colder, had by then become less humid. This climatic change is best illustrated by shoaling of the lake at Taiquemó after about 26,000 to apparent low levels at 22,000 years B.P. and by spread of treeless vegetation, especially of grasses and composites, which are indicative of the drier and colder climate.

Although not evident from the high proportion of grass at Taiquemó, an interval of cold, humid climate is inferred by the increase close to 18,000 years B.P. of Magellanic Moorland elements at Río Negro. Villagrán (1988b) attributes this difference to the proximity of Taiquemó to the glacial border, where moraines and outwash presented contrasting edaphic conditions for vegetation; Río Negro, by comparison, is located beyond the ice margin. Unfortunately, the dating control at both Taiquemó and Río Negro is not at close intervals, which makes comparison of the records and climatic interpretation difficult.

Recession of the Chilotan glacier that followed its

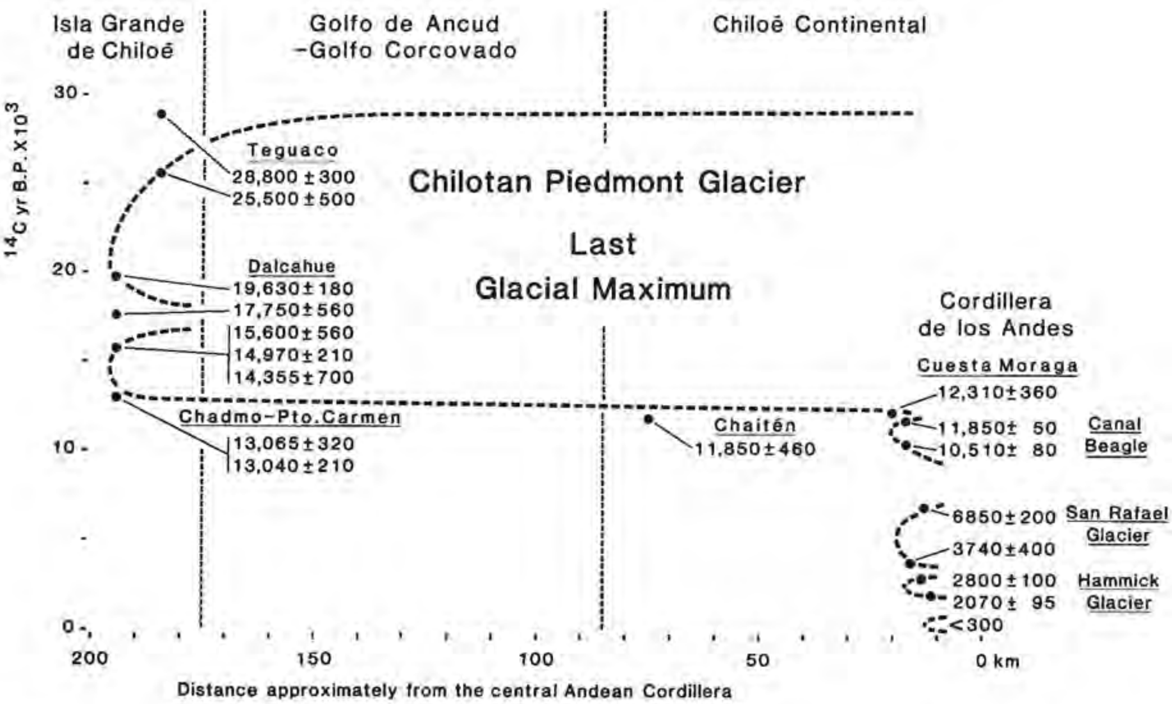

FIG. 11. Reconstructed chronology of advance and retreat of the Chilotan piedmont glacier during the last glacial maximum. Data sources are given in the text.

maximum appears to have been stepwise, involving a major readvance of the ice front (Fig. 11). The readvance was dated at Dalcahue (Fig. 2) at 15,000-14,500 years B.P. by Mercer (1984), who noted: "The site is close to a subdued ridge, with abundant boulders, that is thought to mark the limit of the readvance". This 'subdued ridge' is evidently the end moraine mapped to the north and west, extending about 2 km beyond the location of the Dalcahue section (Fig. 1). The full extent of the readvance and of the preceding recession have not been determined; however, from the amplitude of climatic fluctuation inferred by the pollen stratigraphy, variations of the ice front were considerable.

Following this readvance, wastage of the ice on Isla Grande was under way by 13,000 years B.P. (Fig. 11), as shown by basal dates of sediments in basins formed on Llanquihue drift at Chadmo, Puerto Carmen, and Laguna Chaiguata (Table 2; Fig. 2). While recession was widespread before 12,000 years B.P., indicated by dates at Quemchi, Laguna Pastahue, and Laguna Soledad, remnant ice as at Compu, may have remained in place until about 10,000 years ago. In Chiloé Continental, wastage was apparently equally rapid, taking place at Cuesta Moraga at 700 m in the Andes before 12,300 years B.P., only several hundred years after the glacier had begun to withdraw on Isla Grande; however, from dates near sealevel at Chaitén, withdrawal of ice locally may have occurred several hundred years later (Table 2; Fig. 2).

DISCUSSION AND CONCLUSIONS

The Chilotan piedmont glacier at the time of the last glaciation formed part of the glacier complex that spread in the lake district and across the archipelagos of southern Chile from the Cordillera de los Andes. Whereas south of the island of Chiloé, the amount of ice cover and chronology of advance and retreat are poorly known, fluctuations of the late Llanquihue glacial lobes in the lake district can be more readily tied in with the record from Isla Grande, as a result of the mapping by Porter (1981) and studies by Mercer (1972, 1976, 1983, 1984) and Heusser (1966, 1974, 1981) about lagos Llanquihue and Rupanco (Fig. 2).

An older limiting age for the lobe advancing in the basin of Lago Rupanco is implied by the date of 19,450 years B.P. of the topmost peat in a bog overridden by ice that formed an end moraine a short distance beyond the bog on the south side of the lake (Mercer, 1972). A younger limiting age is the date of 18,900 years B.P. of basal peat deposited in a spillway abandoned along the western shore of Lago Llanquihue near Puerto Octay, as the lobe in the lake basin receded eastward and lake level lowered (Heusser, 1981; Porter, 1981). The age of the maximum advance of the Chilotan piedmont glacier close to 19,630 years B.P. is not, within limits of the dating errors, incompatible with bracketing ages of between about 20,000 and 19,000 years B.P. for outermost stands of ice lobes in the lake district.

The uniformity in the behavior of the glaciers in these two sectors of the southern Andes is remarkable, given the contrasting terrain and the distances over which the lobes advanced. Forcing by a climatic regime that uniformly controlled both regions was apparently strong enough to overcome these differences. Glaciers on entering the lakes became partially afloat; in Chiloé Continental, even with eustatic lowering of sea level of >100 m, much of the ice from the Andes on reaching Golfo Corcovado and Golfo de Ancud, where bathymetry shows water >300 m deep (Fig. 1), also became afloat. While Golfo Corcovado remained tidal, Golfo de Ancud may have developed as a freshwater or brackish lake, if the islands now in place along its southern edge were extended and blocked entry of the sea, and Canal de Chacao to the northwest was emerged and above tide level. Ice fronts were differentially subject to erosion by calving, and by tidal action in the case of the Chilotan glacier, which was apparently also in large part aground, as it passed over the island area separating the two gulfs.

Recognition in the lake district of a correlative episode of late-glacial readvance, dated on Isla Grande at 15,000-14,500 years B.P. (Mercer, 1984), is problematical. From dated lake level fluctuations of Lago Llanquihue, Porter (1981) inferred that the episode "had begun by about 15,000 years ago and culminated shortly after 13,000 years ago". Although the date of about 15,000 years ago approximates the time of the readvance on Isla Grande, from dates placing the beginning of deglaciation there before 13,000 years B.P., it seems unlikely that culmination of the readvance in the lake district occurred soon after 13,000 years ago. The rise of lake level, from which the readvance is interpreted, may be accounted for by an alternative factor, involving, perhaps, volcanism or tectonic activity.

Glaciers that had begun to recede before 13,000 years ago on the island of Chiloé apparently continued to be in a state of recession during the early Holocene thermal maximum, which peaked between about 9,400-8,600 years B.P. (Heusser and Streeter, 1980). That a second late-glacial readvance took place in the latitude of Isla Grande before the thermal maximum, as implied by atmospheric cooling interpreted from pollen data (Heusser, 1966, 1984) with dates between 11,850 and 10,510 years B.P. at Beagle Channel, Tierra del Fuego (Heusser and Rabassa, 1987), has not been demonstrated. With the return of a series of cold and wet climatic intervals during the Neoglaciation in late Holocene time, small valley glaciers were generated anew from icefields fed by the net accumulation of snow, a number of which remain today at higher altitudes in the Andes (Fig. 2). According to Mercer (1982), three episodes of glacier expansion are dated at about 4,500-4,000 and 2,700-2,000 years B.P. and during recent centuries.

The Neoglacial history of San Rafael Glacier with its source in the North Patagonian Icefield (46°40'S), located about 270 km south of the island of Chiloé, exemplifies the episodic response pattern of Andean glaciers (Lawrence and Lawrence, 1959; Muller, 1959; Heusser, 1960, 1964). San Rafael Glacier during the first episode came forward as a piedmont lobe an estimated 10-15 km. Peat dated 6, 850 years B.P. in an exposure near the 1959 ice front predates the time of the advance; recession that followed took place from the outermost moraine before 3,740 years B.P., the near-basal date for peat in a kettle lake, and from the innermost moraine before 3,720 years B.P., the oldest dates for peat resting on outwash. The second episode is apparent from a remnant moraine, making up a point of land and small islands along the north shore of Laguna de San Rafael. This episode, undated, is inferred from Mercer's (1970, 1982) dates of 2,800 and 2,070 years B.P., which apply, respectively, to the advance and recession of Hammick Glacier (48°52'S) on the west side of the South Patagonian Icefield. During the third and final episode, dated <300 years, San Rafael Glacier was smaller in size than in preceding episodes. From historical accounts, the ice front, after being in a state of recession in 1675, was forward in 1766, and later receded by 1882. Recession that was rapid between 1910 and 1935 slowed after 1940 until 1958, when the ice again came forward over ground ice-free for at least 30 years. According to Aniya (1988), withdrawal of San Rafael Glacier from its mid-century position has been considerable, amounting to 2,800 m between 1944 and 1986.

These performances of late Quaternary glaciers in the Southern Andes have been tempered by the climatic mold that overall influenced the Southern Hemisphere (Heusser, 1989a, b, c). The growth of the antarctic ice sheet and its peripheral border of sea ice during the last glacial maximum refrigerated the polar latitudes, forcibly directing cold ocean currents northward along the Chilean coast. The timing of events in Antarctica, where, for example, the ice sheet in West Antarctica reached its maximum between 22,000 and 17,000 years ago (Stuiver *et al.*, 1981), broadly parallels the glacial chronology and episodes of cold climate in the Southern Andes.

General atmospheric circulation in the Southern Hemisphere is regulated by the strong temperature gradient created between the pole and the equator by the extreme cold of the antarctic continent. The southern westerly wind system, which effects the storms and heavy precipitation experienced in southern Chile, gains its unusual power as a result of this gradient. Strengthening and weakening of the system in the past has been a key factor influencing both the growth and recession of glaciers and ice sheets and the distribution of vegetation. Villagrán (1988b) has pointed out the northward migration of elements of the Magellanic Moorland during the last glaciation. This shift corresponds to the northward movement of *Nothofagus* of the Valdivian Rain Forest and descent of podocarp *Prumnopitys andina* from the Andes onto the ice age lowland of subtropical Chile (Heusser, 1990). The cold and humid paleoclimate characterized by the reconstructed vegetation, with summer temperature lower than today by about 7°C and annual precipitation greater by a factor of >2 at this latitude, is possibly an expression of the magnitude of change that prevailed when the Chilotan piedmont glacier came forward during the last glacial maximum.

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REFERENCES

Almeyda, E.; Sáez, F. 1958. Recopilación de datos climáticos de Chile y mapas sinópticos respectivos. *Ministerio de Agricultura,* 195 p. Santiago.

American Geographical Society. 1956. Map of Hispanic America on a Scale of 1:1,000,000, Puerto Montt-Río Chubut. *Hoen and Co.,* 1 sheet. Baltimore.

Aniya, M. 1988. Glacier inventory for the Northern Patagonian Icefield, Chile, and variations 1944/45 to 1985/86. *Arctic and Alpine Research,* Vol. 20, p. 179-187.

Espinosa, M.R. 1917. Los alerzales de Piuchue. *Museo Nacional de Historia Natural, Boletín,* Vol. 10, p. 36-93.

Flint, R.F.; Fidalgo, F. 1964. Glacial geology of the east flank of the Argentine Andes between latitude 39°10'S and latitude 41°20'S. *Geological Society of America, Bulletin,* Vol. 75, p. 335-352.

Flint, R.F.; Fidalgo, F. 1969. Glacial drift in the eastern Argentine Andes between latitude 41°10'S and latitude 43°10'S. *Geological Society of America, Bulletin,* Vol. 80, p. 1043-1052.

Godley, E.J. 1960. The botany of southern Chile in relation to New Zealand and the Subantarctic. *Royal Society, Proceedings,* Vol. 152, p. 457-475.

Godley, E.J.; Moar, N.T. 1973. Vegetation and pollen analysis of two bogs on Chiloé. *New Zealand Journal of Botany,* Vol. 11, p. 255-268.

Hauser, A. 1986. Rodados multicolores; su distribución y características en el sur de Chile. *Revista Geológica de Chile,* No. 27, p. 69-83.

Heusser, C.J. 1960. Late-Pleistocene environments of the Laguna San Rafael area, Chile. *Geographical Review,* Vol. 50, p. 555-577.

Heusser, C.J. 1964. Some pollen profiles from the Laguna de San Rafael area, Chile. *In* Ancient Pacific Floras (Cranwell, L.M.; editor). *University of Hawaii Press,* p. 95-114. Honolulu.

Heusser, C.J. 1966. Late-Pleistocene pollen diagrams from the Provice of Llanquihue, southern Chile. *American Philosophical Society, Proceedings,* Vol. 110, p. 269-305.

Heusser, C.J. 1971. Pollen and spores of Chile. *The University of Arizona Press,* 167 p. Tucson.

Heusser, C.J. 1972. On the occurrence of *Lycopodium fuegianum* during late-Pleistocene interstades in the Province of Osorno, Chile. *Torrey Botanical Club, Bulletin,* Vol. 99, p. 178-184.

Heusser, C.J. 1974. Vegetation and climate of the southern Chilean Lake District during and since the last interglaciation. *Quaternary Research,* Vol. 4, p. 290-315.

Heusser, C.J. 1981. Palynology of the last interglacial-glacial cycle in midlatitudes of southern Chile. *Quaternary Research,* Vol. 16, p. 293-321.

Heusser, C.J. 1984. Late-glacial-Holocene climate of the Lake District of Chile. *Quaternary Research,* Vol. 22, p. 77-90.

Heusser, C.J. 1989a. Late Quaternary vegetation and climate of southern Tierra del Fuego. *Quaternary Research,* Vol. 31, p. 396-406.

Heusser, C.J. 1989b. Polar perspective of late-Quaternary climates in the Southern Hemisphere. *Quaternary Research,* Vol. 32, p. 60-71.

Heusser, C.J. 1989c. Climate and chronology of Antarctica and adjacent South America over the past 30,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology,* Vol. 76, p. 31-37.

Heusser, C.J. (in press). Ice age vegetation and climate of subtropical Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology.*

Heusser, C.J.; Flint, R.F. 1977. Quaternary glaciations and environments of northern Isla Chiloé, Chile. *Geology,* Vol. 5, p. 305-308.

Heusser, C.J.; Rabassa, J. 1987. Cold climatic episode of Younger Dryas age in Tierra del Fuego. *Nature,* Vol. 328, p. 609-611.

Heusser, C.J.; Streeter, S.S. 1980. A temperature and precipitation record of the past 16,000 years in southern Chile. *Science,* Vol. 210, p. 1345-1347.

Heusser, C.J.; Streeter, S.S.; Stuiver, M. 1981. Temperature and precipitation record in southern Chile extended to 43,000 years ago. *Nature,* Vol. 294, p. 65-67.

Heusser, L.E.; Stock, C. 1984. Preparation technique for concentrating pollen from marine sediments and other sediments with low pollen density. *Palynology,* Vol. 8, p. 225-227.

Instituto Hidrográfico de Chile. 1959-1960. Corral a Isla Guafo. Carta 700. *Armada de Chile,* 1 hoja. Valparaíso.

Lauer, W. 1968. Die Glaziallandschaft des südchilenischen Seengebietes. *Acta Geographica,* Vol. 20, p. 215-236.

Laugenie, C. 1971. Elementos de la cronología glaciar en los Andes chilenos meridionales. *Cuadernos Geo-*

gráficos del Sur, Vol. 1, p. 7-20.
Lawrence, D.B.; Lawrence, E.G. 1959. Recent glacier variations in southern South America. *American Geographical Society, Technical Report, Office of Naval Research Contract Nonr-641(04)*, 39 p. New York.
Marticorena, C.; Quezada, M.; 1985. Catálogo de la flora vascular de Chile. *Gayana*, Vol. 42, p. 1-157.
Mercer, J.H. 1967. Southern Hemisphere Glacier Atlas. *US Army Natick Laboratories, Technical Report, 67-76-ES*, 325 p. Natick, U.S.A.
Mercer, J.H. 1970. Variations of some Patagonian glaciers since the late-glacial: II. *American Journal of Science*, Vol. 269, p. 1-25.
Mercer, J.H. 1972. Chilean glacial chronology 20,000-11,000 carbon-14 years ago: some global comparisons. *Science*, Vol. 176, p. 1118-1120.
Mercer, J.H. 1976. Glacial history of southernmost South America. *Quaternary Research*, Vol. 6, p. 125-166.
Mercer, J.H. 1982. Holocene glacier variations in southern South America. *Striae*, Vol. 18, p. 35-40.
Mercer, J.H. 1983. Cenozoic glaciation in the Southern Hemisphere. *Earth and Planetary Sciences , Annual Review*. Vol. 11, p. 99-132.
Mercer, J.H. 1984. Late Cainozoic glacial variations in South America south of the equator. *In* Late Cainozoic Palaeoclimates of the Southern Hemisphere (Vogel, J.C.; editor). *A.A. Balkema*, p. 45-58. Rotterdam.
Mercer, J.H.; Laugenie, C.A. 1973. Glacier in Chile ended a major readvance 36,000 years ago: some global comparisons. *Science*, Vol. 183, p. 1017-1019.
Miller, A. 1976. The climate of Chile. *In* World Survey of Climatology. Vol. 12. Climate of Central and South America (Schwerdtfeger, W.; editor). *Elsevier*, p. 113-145. Amsterdam.
Moore, D.M. 1983. Flora of Tierra del Fuego. *Anthony Nelson*, 396 p. Oswestry, U.K.
Mordojovich, C. 1981. Sedimentary basins of Chilean Pacific offshore. *In* Energy Resources of the Pacific Region (Halbouty, M.T.; editor). *American Association of Petroleum Geologists*, p. 63-82. Tulsa.
Muller, E.H. 1959. Glacial history of the Laguna San Rafael area. *American Geographical Society, Technical Report, Office of Naval Research Contract Nonr-641(04)*, 23 p. New York.
Oberdorfer, E. 1960. Pflanzensoziologische Studien in Chile. *J. Cramer*, 208 p. Weinheim, West Germany.
Porter, S.C. 1981. Pleistocene glaciation in the southern lake district of Chile. *Quaternary Research*, Vol. 16, 263-292.
Schmithüsen, J. 1960. Die Nadelhölzer in den Waldgesellschaften der südlichen Anden. *Vegetatio*, Vol. 9, p. 313-327.
Servicio Nacional de Geología y Minería. 1982. Mapa Geológico de Chile. Escala 1:1.000.000, Hoja No. 4, 37°10'-43°30'S (Escobar, F.; editor). *Instituto Geográfico Militar*, 6 hojas. Santiago.
Stuiver, M.; Denton, G.H.; Hughes, T.J.; Fastook, J.L. 1981. History of the marine ice sheet in West Antarctica during the last glaciation. *In* The Last Great Ice Sheets (Denton, G.H.; Hughes, T.J.; editors). *Wiley-Interscience*, p. 319-346. New York.
Vergara, M.; Munizaga, F. 1974. Age and evolution of the Upper Cenozoic andesitic volcanism in central-south Chile. *Geological Society of America, Bulletin*, Vol. 85, p. 603-606.
Villagrán, C. 1980. Vegetationsgeschichte und pflanzensoziologische Untersuchung in Vicente Pérez Rosales Nationalpark (Chile). *Dissertationes Botanicae*, Vol. 54, p. 1-165.
Villagrán, C. 1985. Análisis palinológico de los cambios vegetacionales durante el Tardiglacial y Postglacial en Chiloé, Chile. *Revista Chilena de Historia Natural*, Vol. 58, p. 57-69.
Villagrán, C. 1988a. Late Quaternary vegetation of southern Isla Grande de Chiloé, Chile. *Quaternary Research*, Vol. 29, p. 294-306.
Villagrán, C. 1988b. Expansion of Magellanic Moorland during the late Pleistocene: palynological evidence from northern Isla de Chiloé, Chile. *Quaternary Research*, Vol. 30, p. 304-314.
Villagrán, C. (in press). Glacial climates and their effects on the history of the vegetation of Chile: a synthesis based on palynological evidences from Isla de Chiloé. *Review of Palaeobotany and Palynology*.
Weischet, W. 1958. Studien über den glazial bedingten Formenschatz der südchilenischen Längssenke im West-Ost Profil beiderseits Osorno. *Petermanns Geographische Mitteilungen*, Vol. 102, p. 161-172.

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