Quaternary pollen records from the Archipiélago de Chiloé in the context of glaciation and climate

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ABSTRACT

Quaternary vegetation, climate and glaciation of the Archipiélago de Chiloé are interpreted from five fossil pollen sequences, chronologically controlled by 35 radiocarbon dates. The earliest one from Punta Tentén, representing open Subantarctic-North Patagonian Rain Forest and Magellanic Moorland during a cold interstade is dated >49,700 yr B.P. The late-glacial and Holocene sequences at Mayol, Estero Huitanque, Dichán, and Puchilco postdate recession of the Castro lobe of the Chiloé piedmont glacier before 14,350 yr B.P. These sites at 14,350-12,000 yr B.P., at first, reflect cold, humid Subantarctic Parkland, followed by warming and forest development; later, at 12,000-10,000 yr B.P. cooling is inferred by changing taxa belonging to North Patagonian Rain Forest communities. Holocene sequences, indicating moderated conditions with Valdivian-type forest and later cooling with North Patagonian-type, are of vegetation considerably disturbed by Paleoindian burning and by European settlement. Holocene sites consistently contain a tephra layer variously dated between 9,760 and 8,820 yr B.P. Data from the late-glacial of this study and from the full-glacial studied previously at Dalcahue show two glacial maxima and final multistep wastage of the Castro lobe. The first step follows a maximum of the ice, dated at close 21,000 yr B.P., during late Llanquihue glaciation; a second step follows another maximum dated at between 14,700 and 14,350 yr B.P., and a third step is implied from pollen data after 12,000 yr B.P. Each step, following long-term cooling on a millennial time scale, is recognized in other geographic regions in the polar hemispheres and may be globally imprinted.

Key words: Quaternary fossil pollen, Vegetation, Climate, Glacial events, Chiloé, Chile.

RESUMEN

Registros de polen cuaternario del Archipiélago de Chiloé en el contexto de glaciación y clima. Basado en cinco secuencias de polen fósil controladas cronológicamente por 35 edades de radiocarbono, se presenta una interpretación de la vegetación, el clima y las glaciaciones cuaternarias del Archipiélago de Chiloé. La más antigua de Punta Tentén, que representa selva pluviosa Subantártica Norpatagónica y tundra Magallánica durante un interestadio frío, fue datada en más de 49.700 a AP. Las secuencias tardiglaciales y holocenas de Mayol, Estero Huitanque, Dichán y Puchilco son posteriores a la recesión del lóbulo Castro del glaciar pedemontano de Chiloé, antes de 14.350 a A.P. Estas localidades de 14.350-12.000 a A.P. reflejan, primero, Parque Subantártico frío y húmedo, seguido por calentamiento y desarrollo de bosque; posteriormente, entre 12.000 y 10.000 a A.P., se infiere un enfriamiento por cambios de taxa pertenecientes a comunidades de selva pluvial norpatagónica. Las secuencias holocénicas, que indican condiciones moderadas con selva de tipo Valdiviano y posterior enfriamiento con selva tipo norpatagónica, están compuestas por vegetación considerablemente perturbada por quemas paleoindias y por la colonización europea. Las localidades holocenas contienen consistentemente una capa de tefra datada entre 9.760 y 8.820 a A.P. Los datos del tardiglacial en este estudio y aquéllos acerca del glacial estudiado anteriormente en Dalcahue muestran dos máximos glaciares y una destrucción en varias etapas del lóbulo de Castro. La primera etapa sigue a un máximo del hielo, datado en cerca de 21.000 a A.P. durante la glaciación Llanquihue tardía; una segunda etapa sigue a otro máximo glaciar datado entre 14.700 y 14.500 a A.P; y una tercera etapa ocurrió depués de los 12.000 a A.P. según se deduce de los datos palinológicos. Cada etapa, que sigue a enfriamientos de largo plazo en una escala de milenios, se reconoce también en otras regiones geográficas de los hemisferios polares, y podrían tener un origen en causas globales.

Palabras claves: Polen fósil, Vegetación, Clima y glaciación, Cuaternario, Chiloé, Chile.

INTRODUCTION

Mid-latitude southern Chile, by virtue of its extensive Quaternary stratigraphic sequences, is recognized as one of the most formidable locations in the Southern Hemisphere for the study of climatic changes related to past ice ages. As part of an ongoing, long-term undertaking to develop a detailed account of Quaternary climatic events in the region, fossil pollen records reported in this paper derive from deposits studied in 1991 during reconnaissance mapping of the glacial geology of the Archipiélago de Chiloé. This work, a continuation of previous studies (Heusser and Flint, 1977; Heusser, 1990), parallels the paleoecological work done on Isla Grande de Chiloé by Godley and Moar (1973) and Villagrán (1985, 1988a, 1988b, 1990, 1991a, 1991b, 1993).

Significant with respect to the current set of fossil pollen data of the last approximately 14,000 years is the need to assess the late-glacial and full-glacial paleoenvironment and examine the nature of regional glaciation and deglaciation. Evidence from geographically-diverse places in the Southern Hemisphere, Antarctica (Lorius *et al.*, 1979; Jouzel *et al.*, 1987a) and New Zealand (Denton and Hendy, 1994), for example, has shown that climate and glaciers underwent broadly-comparable, stepwise fluctuations during the full-glacial and the late-glacial. In the Northern Hemisphere, the latest ice-rafting episodes at 2,000-3,000 year intervals observed in marine sediments of the North Atlantic Ocean (Bond *et al.*, 1993; Bond and Lotti, 1995), which are related to behavior of the Laurentide ice sheet, indicate a measure of correspondence with mountain glacier maxima in New Zealand and southern South America. While the GISP and GRIP ice cores from Greenland have indicated a remarkable degree of rapidly-changing stades and interstades (Dansgaard *et al.*, 1993), similar Dansgaard-Oeschger cycles in ice cores from Antarctica, however, are not clearly expressed (Jouzel *et al.*, 1987b). Our studies in the Southern Andes seek to establish additional sources of evidence that can demonstrate the timing and abruptness of climatic shifts in the polar hemispheres.

The project in 1995 completed its fifth year of field work including mapping of glacial drift deposited in the lowland during the last (Llanquihue) glaciation between Lago Puyehue in the southern part of the lake district and northeastern Isla Grande de Chiloé (40°30'-42°25'S). Maps were drawn at a scale of 1:50,000 from aerial photographs with features checked by ground reconnaissance. Numerous stratigraphic sections of exposures and lake/mire deposits studied, resulting in pollen records with chronologies reaching >50,000 yr B.P., form the basis for interpretation of vegetation sequences and paleoclimate relative to each of four glacial lobes: Llanquihue, Reloncaví, Ancud, and Castro. Chronological data indicate maxima of the lobes at 14,500-14,700, 21,000, 23,100, 26,900, and at or before 35,000 yr B.P. (Lowell *et al.*, in press). It was found that in the case of the Llanquihue lobe, the maximum at 21,000 was greater than the one at 14,500-14,700 yr B.P., whereas for the Castro lobe, the maximum at 14,500-14,700 yr B.P. was most extensive. Latitudinal shifting of storm tracks, differentially affecting the snow accumulation regimes of the lobes at these times of maxima, possibly accounts for this contrast.

ARCHIPIELAGO DE CHILOE

PHYSICAL SETTING AND GLACIATION

The Archipiélago de Chiloé (41°46'-43°28'S, 72°55'-74°23' W) is made up by Isla Grande de Chiloé, 185 km long and as much as 65 km wide, and dozens of smaller islands, the largest of which, Quinchao, Lemuy, Tranqui, and San Pedro, are situated in or about Golfo Corcovado and Golfo de Ancud (Fig. 1). The archipelago is the northernmost of the insular network that extends only with limited interruption to the southern extremity of Chile at Cabo de Hornos (56°S). Altitudes on Isla Grande, mostly <200 m, rise to 700-800 m in the Cordillera de Piuchén, located in the northwestern sector of the island.

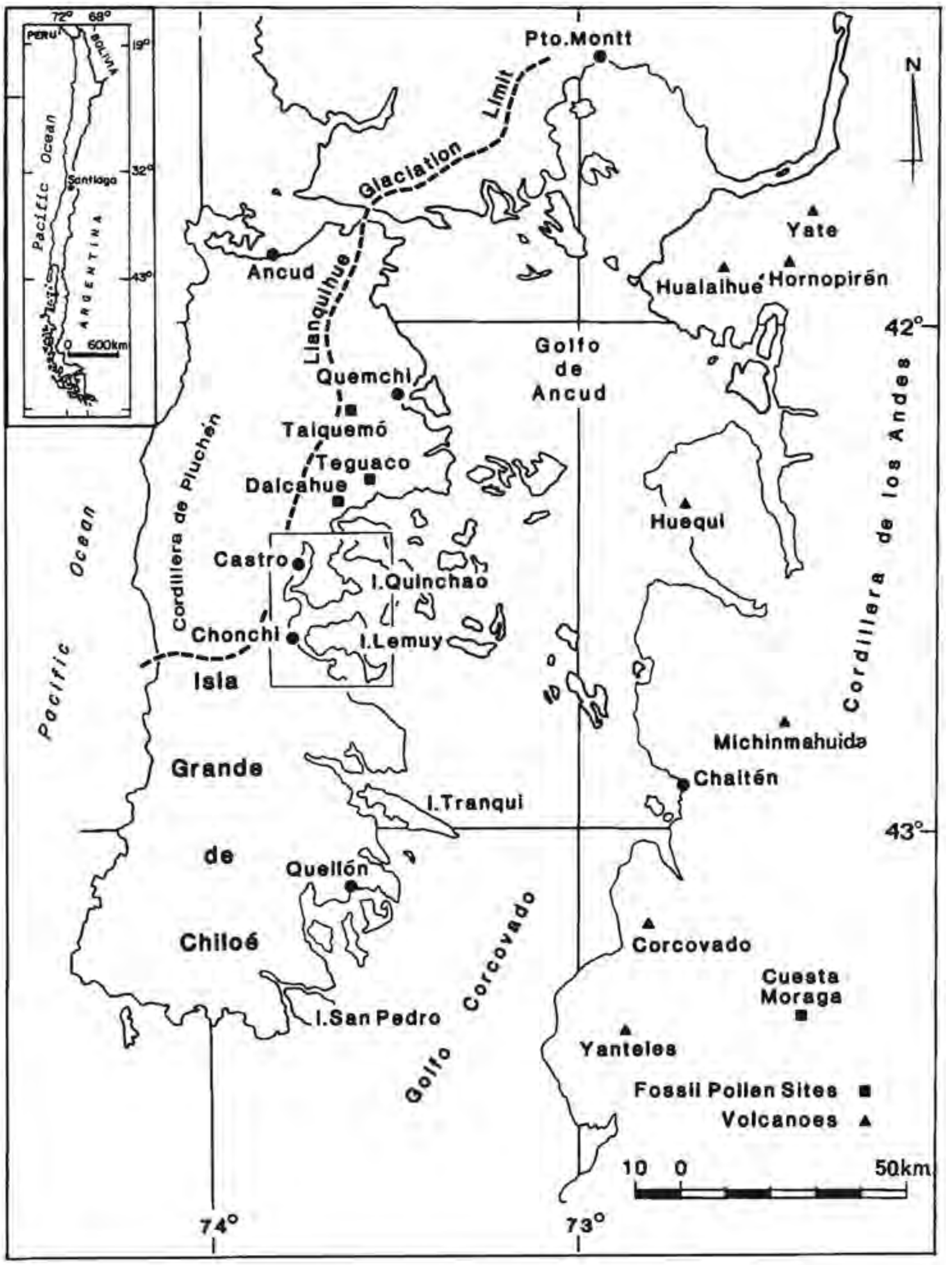

FIG. 1. Map of the Archipiélago de Chiloé emphasizing physical features and locations referred to in the text. Inset delineates the study area (Fig. 4).

Pleistocene glaciers originating in the Cordillera de los Andes on multiple occasions coalesced to form piedmont lobes that pushed onto the northeastern part of Isla Grande (Fig. 1); the southern part, from roughly the latitude of Chonchi, was apparently entirely overridden by ice (Heusser and Flint, 1977; Heusser, 1990). At the time of the late Llanquihue glaciation, ice on Isla Grande reached close to the mountain front (Fig. 1). Arcuate deployment of the moraines and of drift forming island loops offshore delineates lobes of the Chiloé piedmont glacier as it spread westward from the Andes.

During the first of two known advances of the Castro lobe, the Llanquihue ice front at about 22,000 yr B.P. extended to the vicinity of Teguaco (Fig. 1). Later, the lobe continued to advance, reaching a maximum, receded and, subsequently, readvanced beyond Dalcahue at about 14,700 yr B.P. (Lowell *et al.*, in press); Mercer (1984) dated this second advance at 15,000-14,500 yr. Recession of the Castro lobe afterward was accompanied along the eastern border of Isla Grande by the formation at first of ice-front lakes. Wastage of ice later was extensive, taking place at Cuesta Moraga in the glacial source region at 700 m in the Andes (Fig. 1) before 12,300 yr B.P. (Heusser *et al.*, 1992). No subsequent late-glacial readvance of ice has been established.

Glacial geological mapping by B.G. Andersen from aerial photographs in the vicinity of Chonchi (Fig. 1) in the southwestern sector of the Castro lobe shows a dominance of weak morainal features and meltwater channels (Fig. 2). The best developed ice-contact slopes connected with fairly weak marginal moraines occur in a zone near the coast to the north and south of Chonchi. Several of the largest drainage channels start in this zone. The gradient of the marginal moraines and channels is in general low, suggesting that fairly flat glacier lobes occupied the valleys. The lack of well developed end moraines indicates that the glaciers were less active; however, no typical dead-ice topography occurs in the area. Somewhat more distinctive marginal moraines and channels occur on the mountain slopes within the northwest corner of the area mapped.

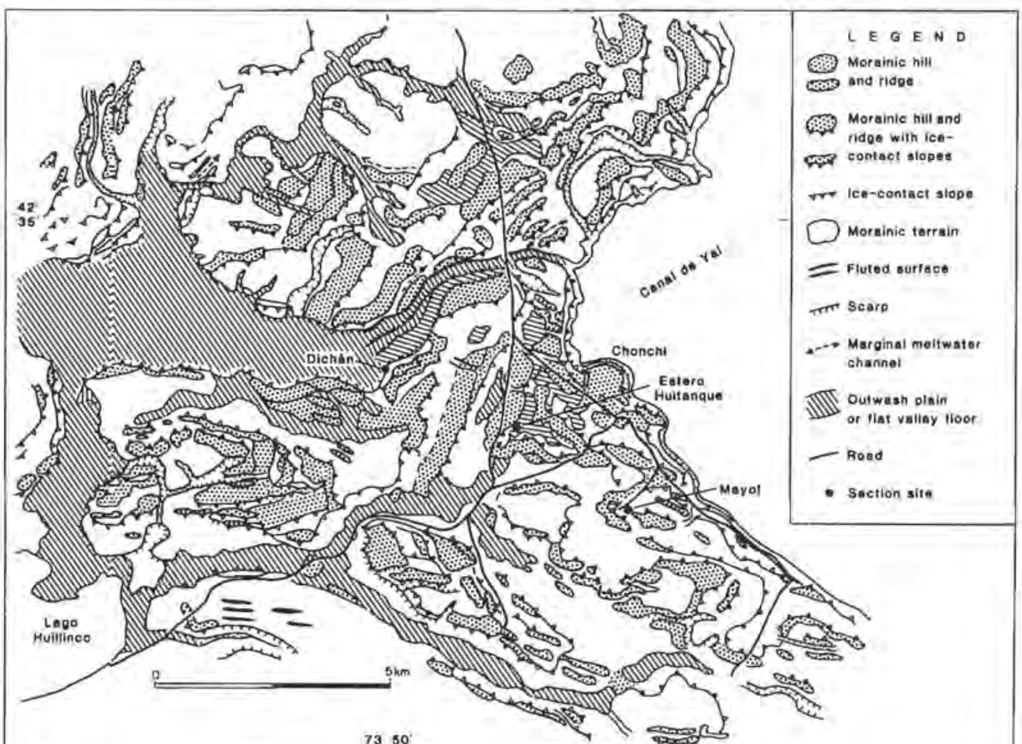

FIG. 2. Glacial geologic map of the vicinity of Chonchi prepared by B. G. Andersen from aerial photographs.

CLIMATE AND VEGETATION

Under the dominant control of the polar maritime air mass over the South Pacific Ocean and of cold Humboldt Current offshore, the southern coast of Chile in the latitude of the Archipiélago de Chiloé is subject to humid, cool-temperate climate throughout the year (Miller, 1976; Prohaska, 1976). Cyclonic depressions associated with the southern westerlies cross the islands from off the ocean with considerable frequency, causing heavy precipitation, strong wind, and cloudiness. Annual precipitation averages between 2,000-3,000 mm with mean temperatures at sea level close to 14°C in January (summer) and 8°C in July (winter). On the Pacific slope of Isla Grande above 600 m altitude, precipitation values are estimated to be >3,000 mm and temperatures as much as 3°C lower. Somewhat drier and warmer conditions are obtained on the inland side of the island, as air crossing the cordillera descends the leeward slope. This contrast influences the abundance and altitudinal distribution of plant species (Villagrán, 1985).

Vegetation, originally described in the works of Skottsberg (1910) and Espinosa (1917), is comprehensively covered by Godley (1968); Godley and Moar (1973); Troncoso and Torres (1974); Veblen *et al.* (1983); Donoso *et al.* (1984, 1985); Villagrán (1985, 1988a, 1988b, 1990, 1991b, 1993); Villagrán *et al.* (1986a, 1986b); Armesto and Figueroa (1987); Armesto and Fuentes (1988) and Ruthsatz and Villagrán (1991). Evergreen rain forest, the prevailing natural vegetation below an altitude of 600-650 m, is classified as Valdivian, North Patagonian, and Subantarctic (Schmithüsen, 1956); Magellanic Moorland (Godley, 1960), mostly at altitudes above 600 m, is constituted by wet, peaty ground, which is covered by cushion bogs and by fens of grass/tussock sedge, among scattered enclaves of woodland of subantarctic species.

Vegetation of Isla Grande is taken into account by a transect (Fig. 3) at altitudes >100 m across the Cordillera de Piuchén in the north-central part of the island (Villagrán, 1985, 1988a, 1988b). Valdivian Rain Forest, increasingly reduced in extent since the arrival and settlement by Europeans >400 yr ago, is distributed at <200-250 m. Communities contain the trees, *Eucryphia cordifolia, Gevuina avellana, Caldcluvia paniculata, Laurelia philippiana*, and several myrtaceous species, *Amomyrtus luma, A. meli, Myrceugenia planipes, M. ovata* var. *ovata* and *Luma apiculata.*

North Patagonian Rain Forest above 200-250 m in altitude is first dominated by *Laurelia philippiana, Amomyrtus luma*, and *M. ovata* var. *ovata.* Above 350-450 m, communities are a manifestation of forest at lower altitudes in the southern part of Isla Grande. Tree species include broad-leafed *Nothofagus dombeyi, N. nitida, Weinmannia trichosperma*, and *Pseudopanax laetevirens*, together with the gymnosperms, *Podocarpus nubigena, Saxe-gothaea conspicua*, and *Fitzroya cupressoides*; tall shrub/small tree species are *Desfontainia spinosa, Myrceugenia chrysocarpa*, and *Tepualia stipularis.*

Ocean-facing slopes and platforms higher than 600 m are a patchwork of Subantarctic Rain Forest communities, identified principally by *Nothofagus betuloides, Pilgerodendron uviferum*, and *Drimys winteri*, interspersed with Magellanic Moorland. Moorland on Isla Grande is the discontinuous, mountainous counterpart to widespread distribution of the wetland complex at low altitudes on coastal islands to the south. Species present have adapted to the prevailing conditions of heavy rainfall, poor drainage, and a relatively low temperature regime. Ombrotrophic cushion bogs of *Donatia fascicularis* contrast minerotrophic fens characterized by distinct communities of *Astelia pumila* and *Schoenus antarcticus* (Ruthsatz and Villagrán, 1991).

It should be noted that tree species that characterize each type of rain forest often exhibit wide ecological amplitudes and are, thus, present over a range of altitudes/latitudes in a variety of communities. For example, *Nothofagus dombeyi, Weinmannia trichosperma*, and *Pseudopanax laetevirens* of the North Patagonian Rain Forest may also be important in Valdivian-type forest. The status of species in each community, as pointed out by Villagrán (1988a), is dictated, largely, according to a combination of temperature and moisture adaptations, shade tolerance levels, and topography.

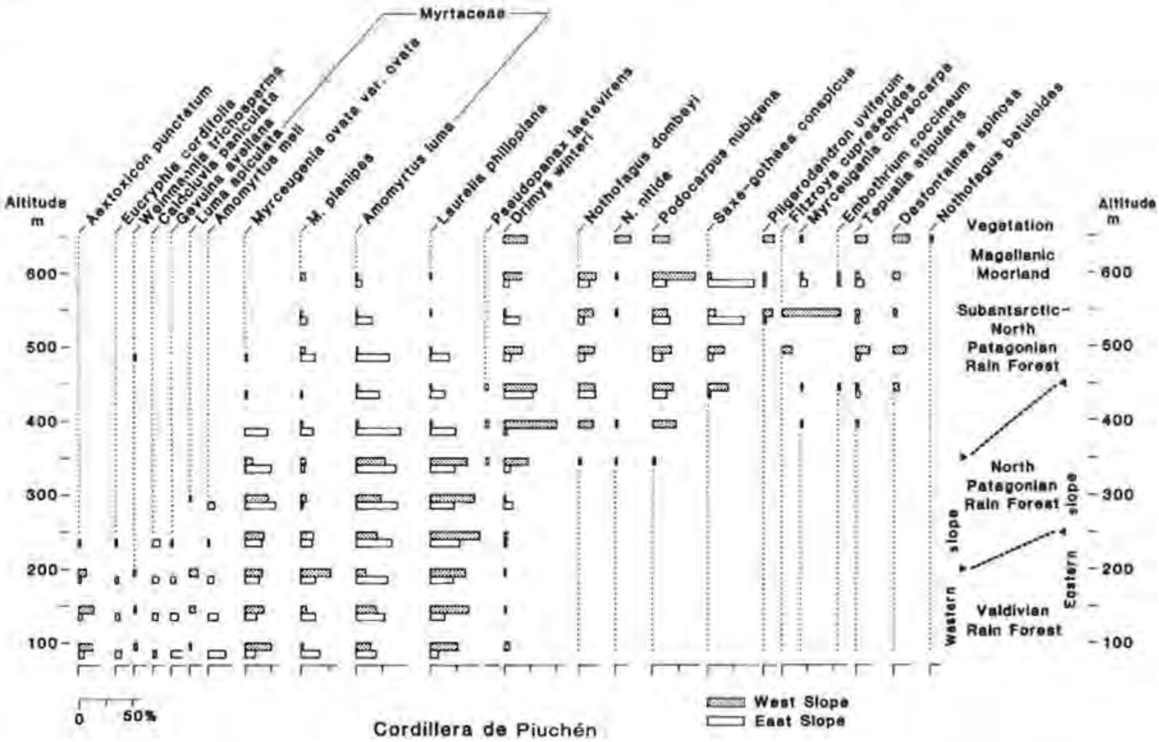

FIG. 3. Frequency distribution of arboreal/subarboreal species on west and east slopes along a transect across the Cordillera de Piuchén, shown in relation to rain forest and moorland vegetation (redrawn from Villagrán, 1985).

METHODS

Stratigraphic samples from a measured section at Punta Tentén and from cores taken at four mire sites at Mayol, Estero Huitanque, Dichán, and Puchilco, all located in relation to drift of the Castro lobe in or about the east-central part of Isla Grande (Fig. 4), were processed for pollen and spores (Heusser and Stock, 1984), charcoal particulates (total area in microns^2 cm^{-3} in the 7-150 micron size range), percentage loss on ignition (Aaby, 1986), and radiocarbon ages.

Fossil pollen and spores were identified and counted under the microscope (analyses C.J.H.) and taxa grouped in frequency (%) diagrams (Fig. 5-9), as upland trees and shrubs/herbs (n = 300 pollen grains) and as aquatics/cryptogams (n =>300 total pollen and spores). Specimens were also scanned to include the presence of any taxon not found in the sums counted. Unidentifiable grains usually constituted 1-2%.

Most pollen and spores are morphologically distinct (Heusser, 1971; Villagrán, 1980) at generic or familial levels. Types are designated for certain intractable genera, as in the case of *Nothofagus,* which is distinguishable only as *N. dombeyi* and *N. obliqua* types, and *Pilgerodendron* type, which in the Archipiélago de Chiloé is represented by both *Pilgerodendron uviferum* and *Fitzroya cupressoides.* Frequency diagrams are divided stratigraphically into pollen assemblage zones, based on peak amounts of key taxa.

Plant nomenclature follows Marticorena and Quezada (1985), except in the instance of the gymnosperm, *Lepidothamnus fonckii* Phil. [=*Dacrydium fonckii* (Phil.) Florin].

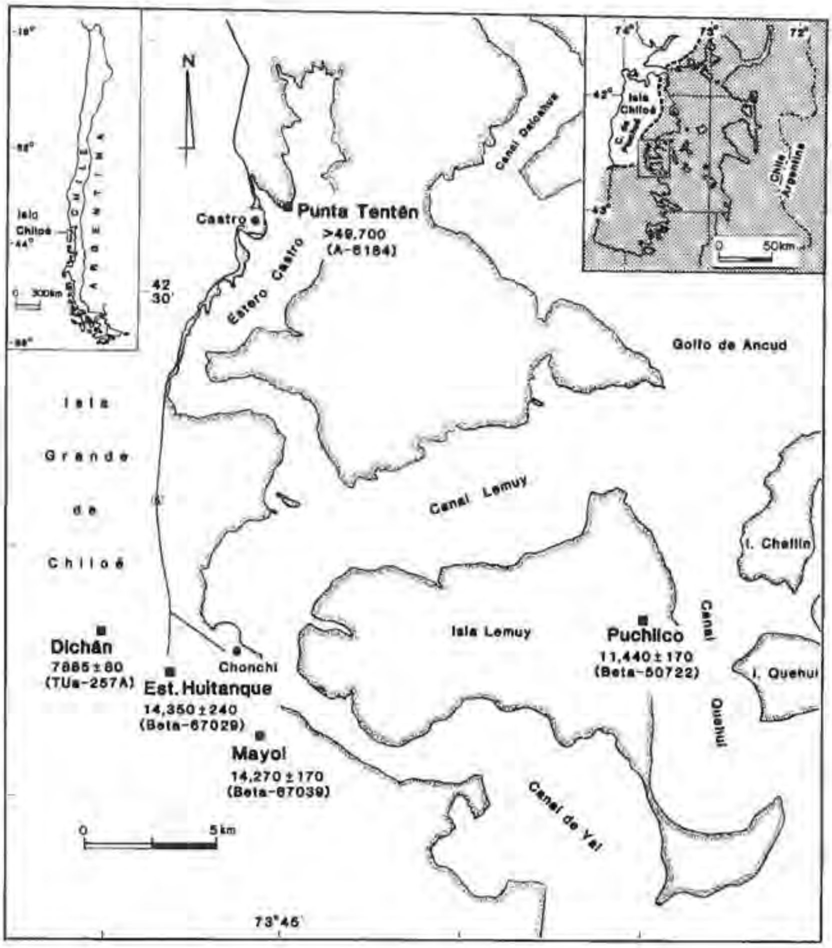

FIG. 4. Map of the study area where sites with their respective radiocarbon ages are at Mayol, Estero Huitanque, Dichán, Puchilco and Punta Tentén.

SITES, STRATIGRAPHY, PALYNOLOGY, AND RADIOCARBON CHRONOLOGY

MAYOL, ISLA GRANDE DE CHILOE

The *Sphagnum-Empetrum rubrum* mire at Mayol (42°38'35"S, 73°45'35"W; 75 m altitude) is situated approximately 2.5 km south of Chonchi (Fig. 4). A 5.7-m section of the mire (Fig. 5) shows a sequence from top to bottom of unhumified *Sphagnum* moss, detritus peat, and gyttja overlying coarse sand. The detritus peat contains pieces of wood in the lower part, indicative of past arboreal plant cover, and contains a thin tephra layer at 2.5-2.6 m depth. Thirteen radiocarbon-dated levels provide chronological control for the section. Maximum ages at two levels from the base of the section, 14,270 and 13,935 yr B.P., although stratigraphically inverted, are within the limits of error of each other; the tephra layer is dated between 9,500 and 9,380 yr B.P.

The basin at Mayol was originally a small freshwater lake that became converted to mire. Aquatics in the gyttja include considerable amounts of the vascular cryptogam *Isoetes savatieri* and the green alga *Pediastrum*, while overlying deposits are principally of *Sphagnum*, Cyperaceae, Ericaceae, and *Empetrum rubrum*. The percentage loss on ignition curve follows the change in residual organic matter over the course of deposition and clearly marks the location of the tephra layer at 2.5-2.6 m.

Pollen assemblage zones M-8 through M-5 approximate the late-glacial; the Holocene is covered by the zones M-4 through M-1 (Table 1). Chronostra-

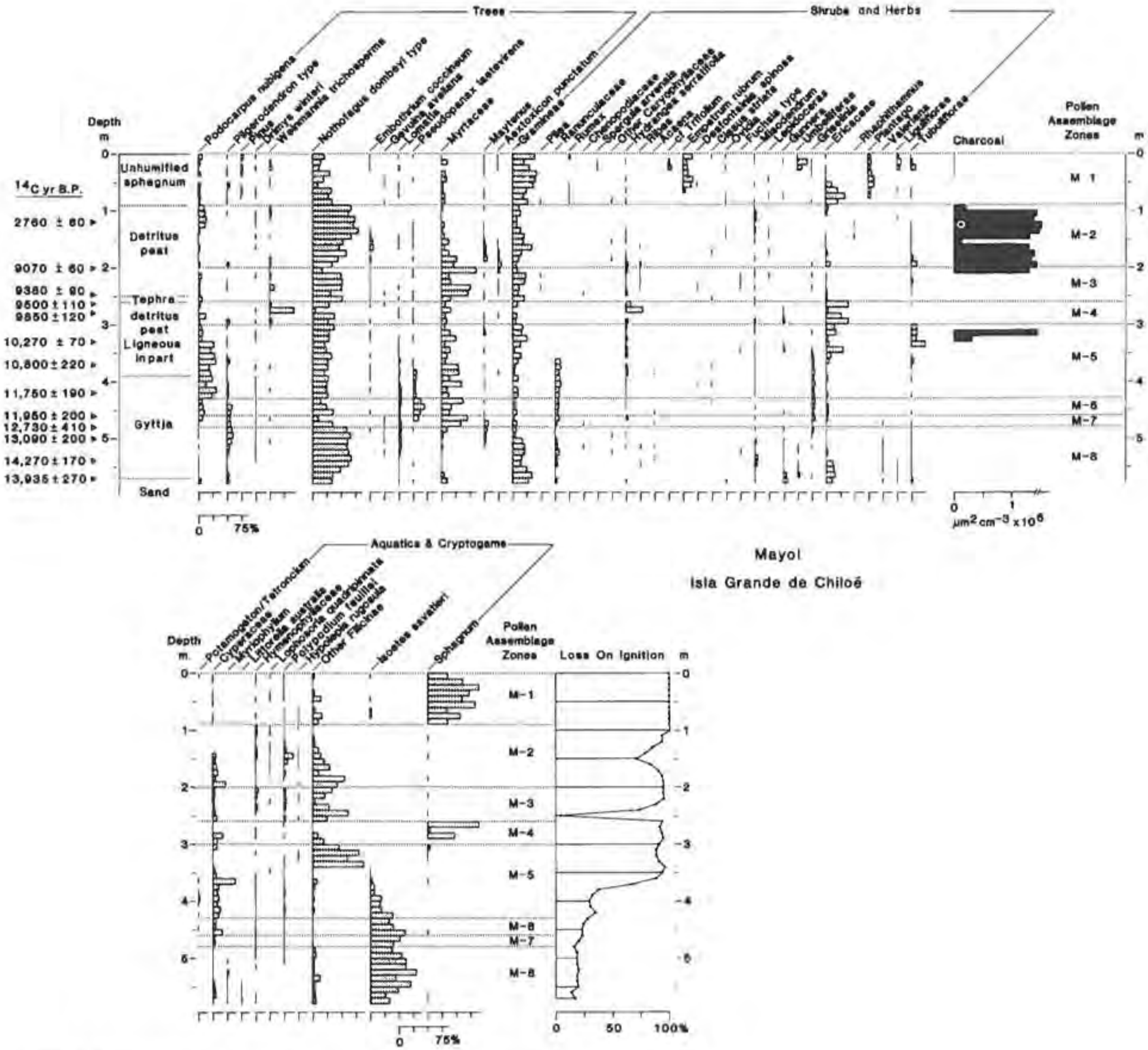

FIG. 5. Pollen and spore diagram of the core from Mayol, Isla Grande de Chiloé.

tigraphy (Fig. 5) is emphasized for the late-glacial and early Holocene between 14,270 and 9,070 yr B.P. (zones M-8 - M-3), where the sedimentation rate averages 14 yr cm^{-1}. Later, until 2,760 yr B.P. (zone M–2), the rate at 79 yr cm^{-1} is exceedingly low, while afterward the rate increases to 23 yr cm^{-1}. The low rate between 9,070 and 2,760 yr B.P. appears related to a continuous succession of fires, as revealed by the charcoal record over the 6,300 year interval.

TABLE 1. POLLEN ASSEMBLAGE AND CHRONOSTRATIGRAPHIC DATA FOR MAYOL, ISLA GRANDE DE CHILOE.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr B.P.)
		0
M-1 (0-0.9 m)	Gramineae - *Empetrum*-Ericaceae - *Plantago*-*Pinus* - *Nothofagus*	
		>400
M-2 (0.9-2.0 m)	*Nothofagus* - *Podocarpus*-Gramineae	2760±60 (1.2 m, Beta -67034)
		9000
M-3 (2.0-2.6 m)	*Nothofagus* - Myrtaceae-Gramineae	9070±60 (2.0 m, Beta-61865) 9380±90 (2.5 m, Beta-61866)
		9500
M-4 (2.6-3.0 m)	*Weinmannia* - *Nothofagus*-*Hydrangea* - Ericaceae	9500±110 (2.6 m, Beta -67035) 9850±120 (2.8 m, Beta-67036)
		10,000
M-5 (3.0-4.3 m)	*Podocarpus* - *Nothofagus*-Myrtaceae - Gramineae-Tubuliflorae	10,270±70 (3.3 m, Beta-61867) 10,800±220 (3.7 m, Beta-67037) 11,750±190 (4.2 m, Beta-61869)
		11,500
M-6 (4.3-4.6 m)	*Pseudopanax* - Myrtaceae-*Nothofagus*	
		12,000
M-7 (4.6-4.8 m)	Myrtaceae - *Maytenus*-*Nothofagus*	11,950±200 (4.6 m, Beta-61868)
		12,750
M-8 (4.8-5.7 m)	*Nothofagus* - *Lomatia*-*Pilgerodendron* type-Gramineae - Ericaceae	12,730±410 (4.8 m, Beta-67038) 13,090±200 (5.0 m, Beta-62440) 14,270±170 (5.4 m, Beta-67039) 13,935±270 (5.7 m, T-9660A)

Late-glacial vegetation (14,270-10,000 yr B.P.), indicated by the pollen and spore record during approximately the first millennium of deposition, is essentially Subantarctic Parkland of *Nothofagus dombeyi* type. Frequency of *Nothofagus* at the beginning (34%) reaches a maximum (66%) late in zone M-8, following displacement of nonarboreal communities, which consisted of Gramineae and Ericaceae together with *Gunnera* and a few other minor, but distinctive taxa. While arboreal components other than *Nothofagus* are present initially (*Pilgerodendron* type, *Lomatia*, Myrtaceae, *Maytenus*), their frequencies only begin to rise shortly before 13,000 yr B.P., indicating incipient diversificat on of species in the flora under moderated conditions suitable for plant invasion. By approximately 12,000 yr B.P. (zone M-7), frequency of *Nothofagus dombeyi* type (10%) is greatly reduced largely by Myrtaceae (46%) of the developing North Patagonian Rain Forest. Subsequently, *Pseudopanax laetevirens* (zone M-6) is prominent for an estimated 200 yr, followed for some 1,500 yr by *Podocarpus nubigena* (22-31%), which under a cooler climate against a backdrop of *Nothofagus* and Myrtaceae is manifest until 10,270 yr B.P.

Vegetation during the first millennium of the Holocene at Mayol (10,000-0 yr B.P.) is given over for the most part to *Nothofagus dombeyi* type and Myrtaceae (zones M-4 and M-3). Burning at around 10,000 yr B.P., evident from the presence of charcoal and ascribable to Paleoindians, may account for the short episode of *Weinmannia trichosperma/Hydrangea serratifolia* (zone M-4) between 9,850 and 9,500 yr B.P. The pollen record after 9,000 yr B.P. shows no clear evidence of Valdivian Rain Forest, which has been described for the Holocene elsewhere on Isla Grande (Villagrán, 1985, 1988a). The noticeably high incidence of fire, shown by charcoal (zone M-2) may explain the apparent exclusion of Valdivian-forest indicator species. Late in the Holocene at around 2,760 yr B.P., North Patagonian Rain Forest is expressed by the high proportion of *Nothofagus* (80%) coupled with *Podocarpus nubigena* (zone M-2).

Villagrán (1985), working with a core with minimal disturbance taken near Castro (Fig. 1), interpreted Holocene paleoenvironments from pollen data. She found a major early Holocene prominence of Valdivian-type *Eucryphia/Caldcluvia*, which was preceded and followed by North Patagonian Myrtaceae (cf. *Myrceugenia* and *Amomyrtus*) and *Drimys*, among other taxa. The broad implication of data from the core is of relatively cool/wet climate at the late-glacial-Holocene boundary and during the late Holocene, interrupted by the warmer/drier early Holocene. Onset of the warm/dry interval is dated at about 9,580 yr B.P., which at Mayol, Estero Huitanque, and Puchilco (Figs. 5, 6, 8) falls close to the age of a tephra layer bracketed by dates of between 9,760 and 8,820 yr B.P.

Settlement by Europeans during the past >400 yr resulted in the loss of forest cover on Isla Grande and brought about the introduction of exotic taxa. These centuries of change created an increase in open space shown by the conspicuous increase in Gramineae and decrease of *Nothofagus dombeyi* type (zone M-1). Openness made possible the spread of light-demanding plants, including exotics (*Pinus*, *Rumex*, *Spergula arvensis*, cf. *Trifolium*, Umbelliferae, *Plantago*, Liguliflorae, Tubuliflorae). Low incidence of charcoal during the period of settlement, following high frequency/intensity of Paleoindian burning, infers that clearing was predominantly through tree cutting, probably because of the need of lumber for construction.

ESTERO HUITANQUE, ISLA GRANDE DE CHILOE

The site of the freshwater mire at the head of Estero Huitanque (43°37'30"S, 73°48'00"W; 52 m altitude) is on the east side of Route 5, less than 3 km southwest of Chonchi (Fig. 4). A 4.8 m section of the mire, taken below mounds of *Sphagnum* overrun by *Empetrum rubrum*, covers a sequence of unhumified *Sphagnum*, detritus peat, gyttja, and sand (Fig. 6). A tephra layer at 1.57-1.73 m, limited in age by radiocarbon dates of 9,200 and 8,820 yr B.P. and marked by a distinct decrease in percentage loss on ignition, is interbedded in the upper detritus peat. Values for loss on ignition show a sharp rise in organic content at 3.9-3.8 m, just above the gyttja, marking the beginning of shoaling at the core site, coincident with reduction in extent of open water. Peat higher in the section is contributed chiefly by *Sphagnum*, Cyperaceae, Ericaceae, and *Empetrum rubrum*.

Aquatics present in the gyttja and lower part of the detritus peat (*Myriophyllum*, *Azolla filiculoides*, *Isoetes savatieri*) were deposited during a lake stage prior to replacement by mire. The presence of massulae containing microspores of *Azolla* at Estero Huitanque, and also at Puchilco (Fig. 8), is unusual and is the first report of this plant in the Quaternary deposits of southern Chile. According to Gunckel (1984), the species ranges from Arica to Magallanes, and Looser (1961) recorded it from Isla Lemuy, the location of Puchilco, one of two modern collections recorded in the Province of Chiloé.

The section at Estero Huitanque is divided into four pollen assemblage zones, their time spans ascertained by nine radiocarbon dates and, in the case of the uppermost zone (EH-1), by the centuries of European settlement (Table 2). Late-glacial vegetation (14,350-10,000 yr B.P.) commenced as Subantarctic Parkland of *Nothofagus dombeyi* type and

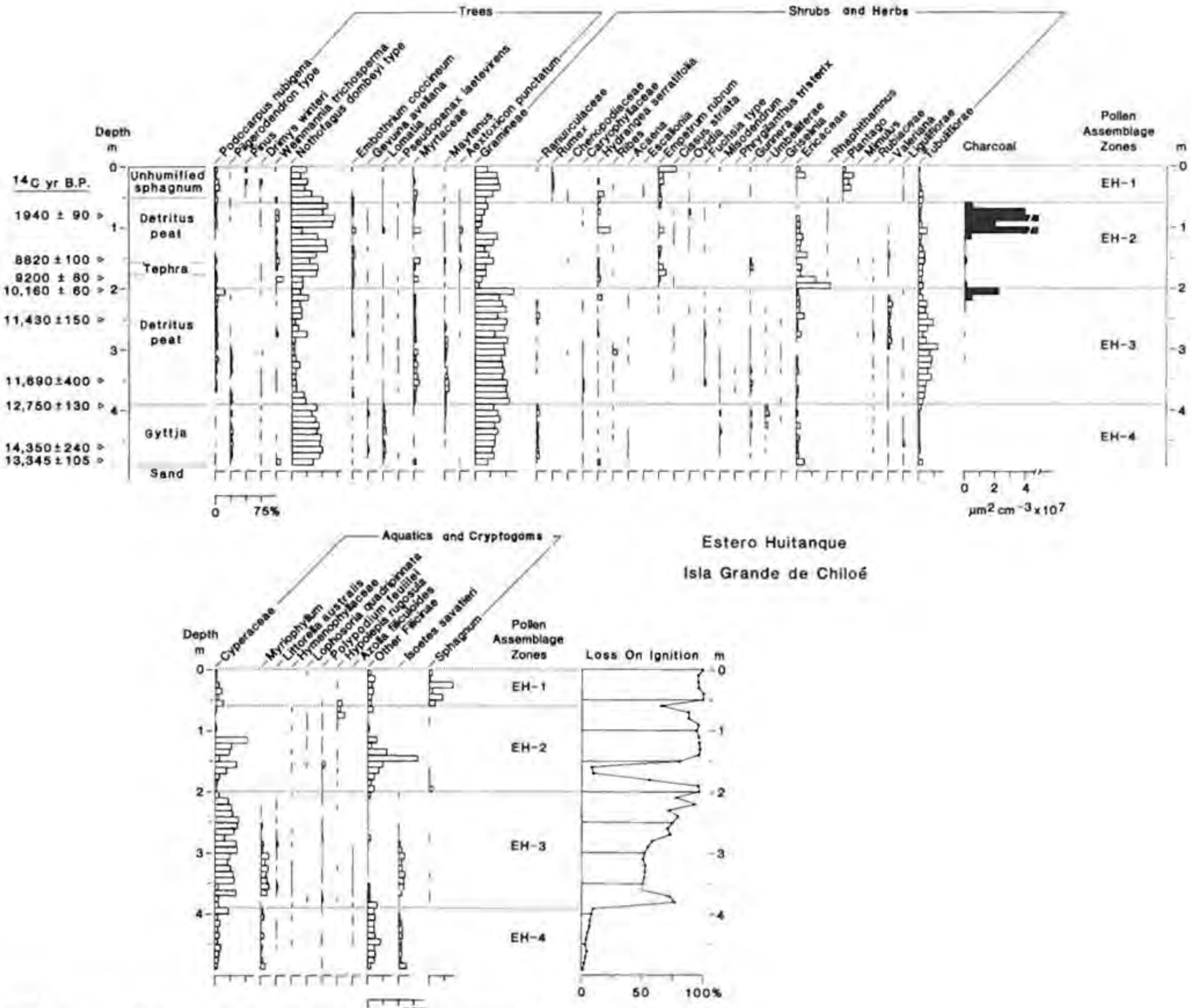

FIG. 6. Pollen and spore diagram of the core from Estero Huitanque, Isla Grande de Chiloé.

Gramineae (zone EH-4). The episode covers the time of deposition before 12,750 yr B.P. There follows an interval of Gramineae-Tubuliflorae, averaging 62% of the pollen sum (zone EH-3), extending for *ca.* 2,700 yr until about 10,000 yr B.P. Over this time span, North Patagonian Rain Forest elements, except for *Nothofagus*, are comparatively minor. The Gramineae-Tubuliflorae assemblage infers principally grassland, containing small, scattered stands of trees. Dominance of Gramineae at this site compared with arboreally-dominated Mayol suggests a local late-glacial vegetation mosaic. Charcoal in uppermost late-glacial levels is from the earliest major fires at Estero Huitanque.

Holocene vegetation (10,000-0 yr B.P.) is characterized by the increase of *Nothofagus dombeyi* type (79%), despite incidences of fire indicated by abundances of charcoal (zone EH-2). Growth of the mire stagnated at this time, possibly as a result of burning; rates of sedimentation before 8,820 and after 1,940 yr B.P. average respectively, 17 and 24 yr cm^{-1}, while during intervening millennia the rate at 98 yr cm^{-1} is conspicuously low. Later arrival by Europeans and clearing of the land with settlement of Chonchi (zone EH-l) coincide with the decrease of *Nothofagus*, rise of Gramineae, introduction of foreign adventives, including *Pinus*, *Rumex*, and *Plantago*, and cessation of Paleoindian burning.

TABLE 2. POLLEN ASSEMBLAGE AND CHRONOSTRATIGRAPHIC DATA FOR ESTERO HUITANQUE, ISLA GRANDE DE CHILOE.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr B.P.)	
			0
EH-1 (0-0.6 m)	Gramineae - *Empetrum*- *Plantago* - *Rumex* - *Pinus* - *Podocarpus* - *Nothofagus*		
			>400
EH-2 (0.6-2.0 m)	*Nothofagus* - Gramineae-Ericaceae	1940±90 (0.8 m, Beta -67025) 8820±100 (1.5 m, Beta-61948) 9200±80 (1.8 m, Beta-61947)	
			10,000
EH-3 (2.0-3.9 m)	Gramineae - Tubuliflorae-*Valeriana* - *Podocarpus* - Myrtaceae - *Maytenus*-*Nothofagus*	10,160±60 (2.0 m, Beta-61861) 11,430±150 (2.5 m, Beta-67026) 11,690±400 (3.5 m, Beta-67028)	
			12,750
EH-4 (3.9-4.8 m)	*Nothofagus* - *Lomatia*-Gramineae	12,750±130 (3.9 m, Beta-61862) 14,350±240 (4.6 m, Beta-67029) 13,345±105 (4.8 m, TUa-259a)	

DICHAN, ISLA GRANDE DE CHILOE

The mire at Dichán (42°37'00"S, 73°49'40"W; 50 m altitude), located 4.5 km west of Chonchi (Fig. 4), is developed on a recent meander scar in the floodplain of Estero Huenué, which accounts for its Holocene age of 7,885 yr B.P. The deposit at the site consists for the most part of detritus peat underlain by interbedded peat and sand and overlain by unhumified *Sphagnum*. Mounds of *Sphagnum* at the surface are covered in part by *Empetrum rubrum* (Fig. 7).

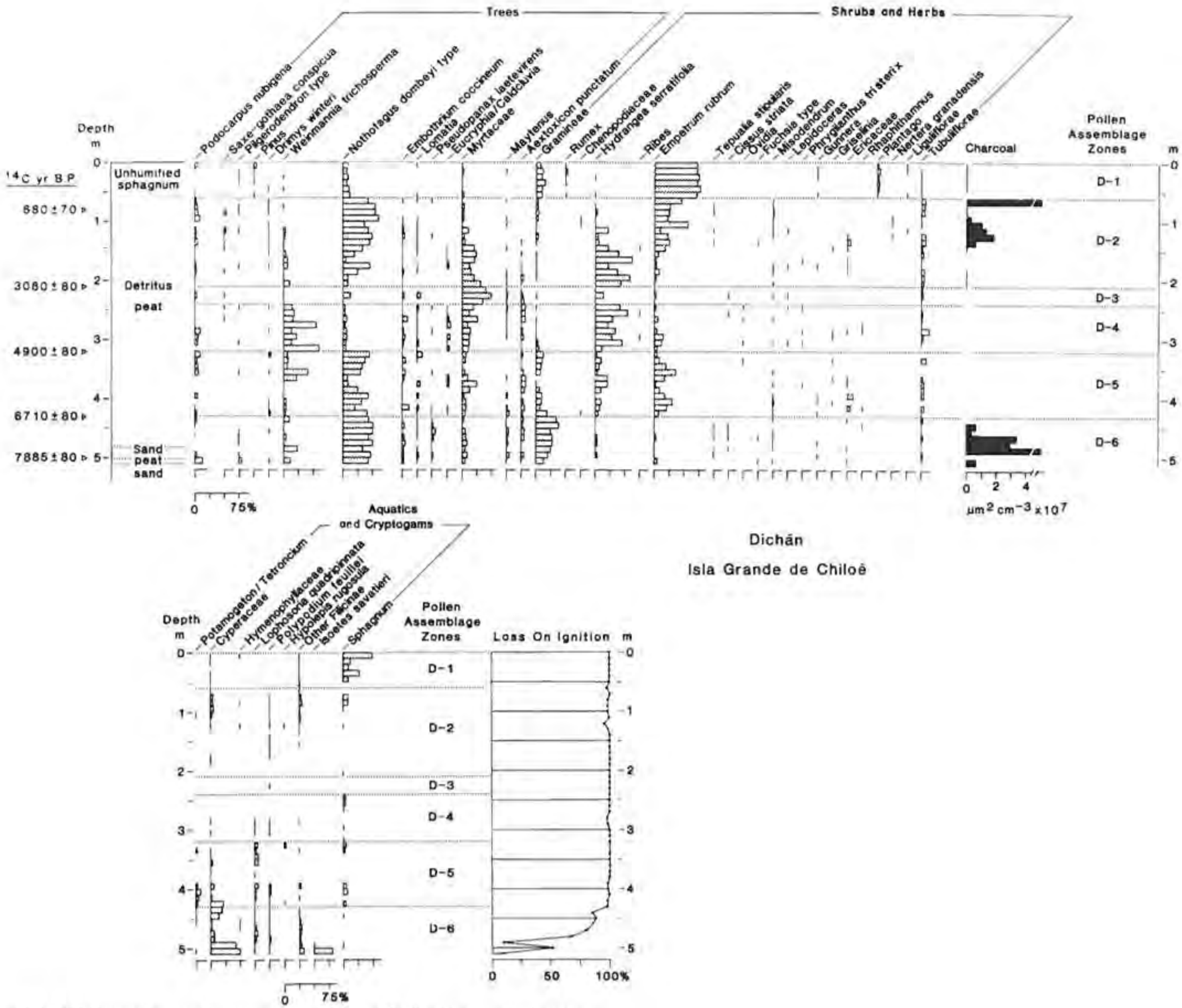

FIG. 7. Pollen and spore diagram of the core from Dichán, Isla Grande de Chiloé

Sedimentation began in a backwater of the meander in what was apparently a sluggish drainage course occupied by Cyperaceae with *Isoetes savatieri*. Following initially-interrupted, organic deposition, percentage loss on ignition records a steady sequence of values close to 100% over the remainder of the 5.0-m section of the deposit. Sedimentation during the time of record, averaging 9-16 yr cm^{-1} between five radiocarbon-dated levels and the surface, reveals no striking irregularities that reflect protracted, low-water stages of the river.

Six pollen assemblage zones are recognized for the nearly 8,000-year account of vegetational change at Dichán (Fig. 7; Table 3). Rain forest dominated by *Nothofagus*, inferred by *N. dombeyi* type assemblages (zones D-6, D-5, and D-2), was subject to fire both at the start and later, which created openness and may be the cause initially for the high frequency of Gramineae (38%). Vegetation, otherwise, contained variable quantities of taxa associated with Valdivian forest: *Weinmannia trichosperma* (zones D-5 and D-4), Myrtaceae (centered on zone D-3), and *Hydrangea serratifolia* (zones D-4 and D-2). The occurrence of peak Myrtaceae, typically an inhabitant of low ground along rivers, may derive from disturbance during periods of flooding. Disturbance may also be a factor related to the variable frequency of *Weinmannia* and *Hydrangea*, both of which are light dependent and require open communities in order to endure.

Land clearance during European settlement is substantiated in the uppermost part of the section by the reduction in *Nothofagus* frequencies (zone D-1) and presence of alien *Pinus*, *Rumex*, and *Plantago*.

TABLE 3. POLLEN ASSEMBLAGE AND CHRONOSTRATIGRAPHIC DATA FOR DICHAN, ISLA GRANDE DE CHILOE.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C years B.P.)	
			0
D-1 (0-0.6 m)	*Empetrum* - Gramineae- *Rumex* - *Plantago* - *Pinus*		
			>400
D-2 (0.6-2.1 m)	*Nothofagus* - Myrtaceae- *Hydrangea* - *Empetrum*	680±70 (0.8 m, Beta -67030)	
			3100
D-3 (2.1-2.4 m)	Myrtaceae	3080±80 (2.1 m, Beta-67031)	
			3500
D-4 (2.4-3.2 m)	*Weinmannia* - *Hydrangea*		
			4900
D-5 (3.2-4.3 m)	*Nothofagus* - Myrtaceae- *Empetrum*	4900±80 (3.2 m, Beta-67032)	
			6700
D-6 (4.3-5.0 m)	*Nothofagus* - Gramineae	6710±80 (4.3 m, Beta-67033) 7885+80 (5.0 m, TUa257A)	

PUCHILCO, ISLA LEMUY

The site of the *Sphagnum* mire at Puchilco (42°36'45"S, 73°36'15"W; 110 m altitude) is in the northeastern sector of Isla Lemuy, *ca.* 2 km inland from the shore of Canal Quehui (Fig. 4). The mire rests in a drainageway connecting the basins of Lagunas de Puchilco. A 4.1-m section of the 11,440-yr B.P. deposit (Fig. 8) shows detritus peat, which includes some wood, resting on sand, overlain, in turn, by layers of humified and unhumified *Sphagnum*. Aquatic *Isoetes savatieri* attests to the presence of open water at the start of detritus peat deposition; later, detritus contributed in the main by other aquatics is from Cyperaceae and *Sphagnum*, along with *Potamogeton*/*Tetroncium*, *Myriophyllum*, and Azolla filiculoides. A tephra layer, emplaced in the peat at 3.10-3.15 m and dated between 9,760 and 8,880 yr B.P., is clearly registered by the percentage loss on ignition curve.

Divisible in the section are seven pollen assem-

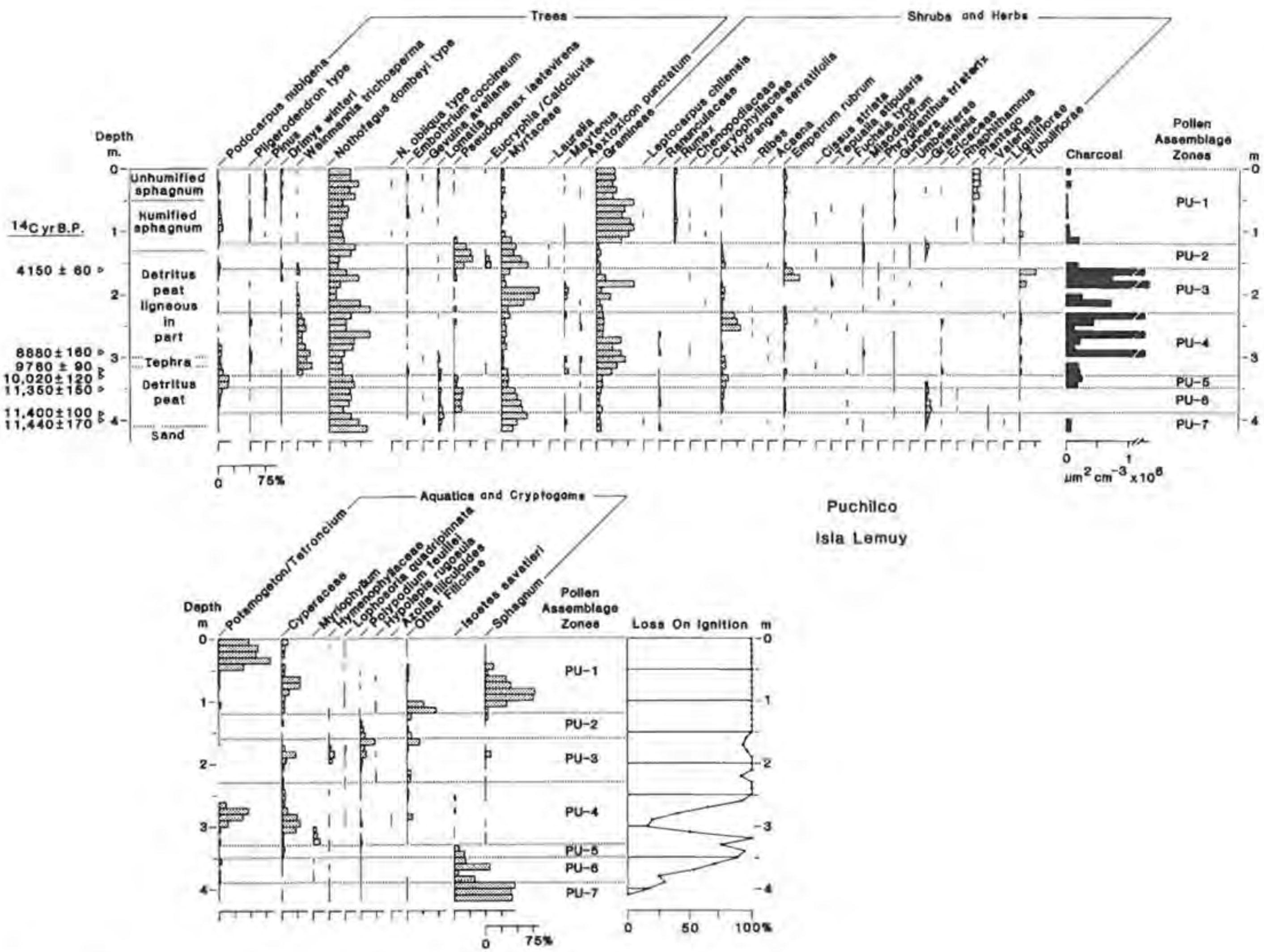

FIG. 8. Pollen and spore diagram of the core from Puchilco, Isla Lemuy.

blage zones, the chronostratigraphy of which is established from seven radiocarbon dates and from exotic pollen incicators related to the presence of European man in recent centuries (Table 4). Late-glacial zones (PU-7-PU-5) trace the initial rise of Myrtaceae and *Lomatia* at the expense of *Nothofagus dombeyi* type in North Patagonian Rain Forest (zone PU-7, >11,440-11,400 yr B.P.), followed by peaks of *Pseudopanax laetevirens* (zone PU-6, 11,400-11,350 yr B.P.) and of *Podocarpus nubigena* (zone PU-5, 11,350-10,020 yr B.P.). Holocene communities contain varying amounts of *Nothofagus* in association with *Weinmannia trichosperma* until an estimated 6,500 yr B.P. (zone PU-4), Myrtaceae afterward until 4,150 yr B.P. (zone PU-3), and later, both Myrtaceae and *Pseudopanax laetevirens* (zone PU-2), extending to the beginning of the European era. Openness, inferred by quantities of Gramineae and by intolerant Valdivian-type *Hydrangea serratifolia* and *Weinmannia* (zone PU-4), probably resulted from fire disturbance, which is seen in the amounts of charcoal deposited during the interval. As recorded elsewhere on Isla Grande, Gramineae are noticeably abundant (60%) following the arrival of Europeans (zone PU-1), and occur with the adventives, *Pinus*, *Rumex*, and *Plantago*.

TABLE 4. POLLEN ASSEMBLAGE AND CHRONOSTRATIGRAPHIC DATA FOR PUCHILCO, ISLA LEMUY.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr B.P.)	
PU-1 (0-1.2 m)	Gramineae - *Plantago*- *Rumex* - *Nothofagus*- *Podocarpus* - *Pinus*		0
PU-2 (1.2-1.6 m)	*Pseudopanax* - Myrtaceae- Eucryphia/Caldcluvia- *Nothofagus*		>400
PU-3 (1.6-2.3 m)	*Nothofagus* - Myrtaceae- Gramineae - *Empetrum*- Tubuliflorae	4150±60 (1.6 m, Beta-61863)	4150
PU-4 (2.3-3.3 m)	*Nothofagus* - *Weinmannia*- Gramineae - *Hydrangea*-	8880±160 (2.9 m, Beta -61864) 9760±90 (3.2 m, Beta-50718)	6500
PU-5 (3.3-3.5 m)	*Nothofagus* - *Podocarpus*	10,020±120 (3.3 m, Beta-50719)	10,000
PU-6 (3.5-3.9 m)	*Nothofagus* - Myrtaceae- *Pseudopanax* - Griselinia	11,350±150 (3.5 m, Beta-50721)	11,350
PU-7 (3.9-4.1 m)	Myrtaceae - *Lomatia*- *Nothofagus*	11,400±100 (3.9 m, Beta-50720) 11,440±170 (4.0 m, Beta 50722)	11,400

PUNTA TENTEN, ISLA GRANDE DE CHILOE

A measured section >163 cm thick at Punta Tentén (42°28'20"S,73°44'45"W), an intertidal site along upper Estero Castro approximately 1 km east of the town of Castro (Fig. 4), consists of beds of sand, peat, silty peat, and tephra, which are underlain by a diamicton and overlain by colluvium (Fig. 9). Both beds of silty peat are increasingly organic from bottom to top; the peat bed higher in the section is much compacted and contains, at upper levels, remains of tree trunks as much as 10 cm thick. An age of >49,700 yr B.P. on the wood predates the age of the last glacial maximum. The site has been subject to tectonism, whereby the upper of the two silty peat beds is tilted and dips 5-10° to the north.

Pollen and spore stratigraphy, divided into four pollen assemblage-zones (Fig. 9; Table 5), shows *Nothofagus dombeyi* type (>50%) dominant and Gramineae subdominant. The implication of the data is of openness within or beyond mostly tree-covered upland. In the sequence of beds, a successional component is inferred by the early abundance of *Lycopodium* (PT-1). Subsequent quantities of Cyperaceae and *Myriophyllum* are, in turn, indicative of progressive paludification with increasingly aquatic conditions (PT-2 and PT-3) and, ultimately, change toward a subaerial type site (PT-4). Present-day intertidal relations at Punta Tentén were apparently established at some time following deposition of the uppermost peat, as there is no indication of marine submergence earlier in the measured section.

From its stratigraphic position and its content predominantly of *Nothofagus* pollen, the deposit is considered to be interstadial and most probably of Pleistocene age, but may be older. Kinds and quantities of taxa in the record are largely indicative of cold-temperate Subantarctic-North Patagonian Rain Forest (*Nothofagus, Embothrium coccineum, Drimys winteri, Podocarpus nubigena, Saxe-gothaea conspicua*) with restricted presence of Magellanic Moorland (*Lepidothamnus fonckii, Donatia fascicularis*, Gramineae). Taxa indicative of relatively moderated climatic regimes (Myrtaceae, *Hydrangea, Gevuina, Eucryphia, Aextoxicon*) are not in evidence. General relationships can be seen in the modern distribution of species in the Cordillera de Piuchén (Fig. 3).

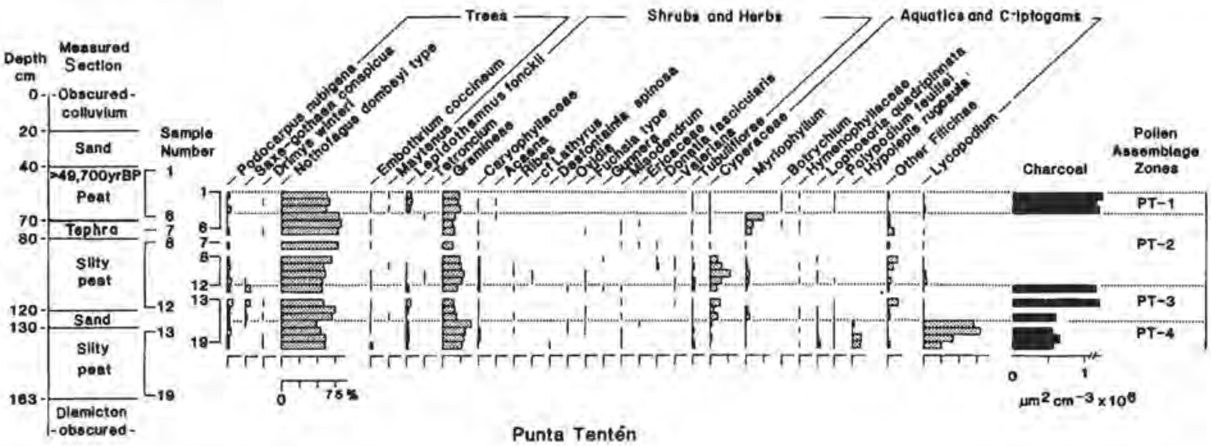

FIG. 9. Pollen and spore diagram of the measured section at Punta Tentén, Isla Grande de Chiloé.

TABLE 5. POLLEN ASSEMBLAGE AND CHRONOSTRATIGRAPHIC DATA FOR PUNTA TENTEN, ISLA GRANDE DE CHILOE.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr B.P.)
PT-1 (40-55 cm)	*Nothofagus* - *Lepidothamnus*-Gramineae	>49,700 (40 cm, A-6184)
PT-2 (55-120 cm)	*Nothofagus* - Gramineae	
PT-3 (120-145 cm)	*Nothofagus* - Saxe-gothaea-Gramineae	
PT-4 (145-163 cm)	*Nothofagus* - Gramineae	

Fires are possibly the cause of openness in the vegetation, as charcoal occurs virtually throughout the deposit, except where frequency of *Nothofagus dombeyi* type (83%) is highest and wet conditions maximal (zone PT-2). Fires on Isla Grande are attributable to Paleoincians, as the island is not subject to lightning strikes, and is isolated, distantly removed from volcanoes, which may serve as other vectors of burning (Heusser, 1994). The charcoal sequence thus, may imply antiquity of human presence in Chile at > 49,700 yr B.P., considerably beyond the oldest-known, Paleoindian age of 13,000 yr B.P. (Dillehay, 1989).

DISCUSSION AND CONCLUSIONS

The sequence of events surrounding late Llanquihue fluctuations of the Castro lobe in a paleoenvironmental context are summarized in figure 10. Following the glacial maximum near Teguaco (close to 21,690±120 yr B P., A-7729), the full-glacial reported in this paper derives from the intertill site at Dalcahue (Fig. 1; Heusser, 1990; Lowell *et al.*, in press), shown bracketed by radiocarbon dates of 19,630±180 and 14,720±100 yr B.P. (QL-4324 and A-6189, respectively); the mires at Mayol and Estero Huitanque (Fig. 4) are sources of data for the late-glacial dated between 14,350 and approximately 10,000 yr B.P. Mean summer temperature during the full-glacial is estimated at ≥4°C (Villagrán, 1988b) and as much as 6-6.5°C (Heusser, 1991) below the present; an estimate of 2-3°C of temperature depression compared with today at the close of the late-glacial, when *Podocarpus nubigena* was important in the pollen record, results from the application of a lapse rate of -0.55°C 100 m^{-1} to the inferred 300-500 m lower altitudinal zone of *P. nubigena* in the Cordillera de Piuchén (Fig. 3).

Uncovering sites of this study, the Castro lobe pulled back from its latest maximum before approximately 14,350 yr B.P., which at Estero Huitanque (Fig. 4) is the earliest deglacial age on Isla Grande. Earlier after 14.720 yr B.P., the Castro lobe had advanced at Dalcahue (Fig. 1), *ca.* 40 km to the northeast, making duration of the maximum on the order of several hundred years. While increase of Gramineae and decrease of *Nothofagus* at Dalcahue after an estimated 16,500 yr B.P. infers progressive cooling for two millennia prior to overriding of the site by the ice (Fig. 10), the duration of the glacier at its outermost stand was comparatively short. The onset of cooling is estimated based on AMS radiocarbon dates of 17,000±145 and 15,975±145 yr B.P. (UGA-7056 and UGA-7053, respectively).

Termination of the maximum occurred abruptly when climate grew warmer, enabling *Nothofagus* to expand both at Mayol (zone M-8; Fig. 5) and Estero Huitanque (zone EH-4; Fig. 6). The interval of milder climate that followed was marked by arboreal diversification beginning before 13,000 yr B.P., including peak Myrtaceae at Mayol close to 12,000 yr B.P. (zone M-7; Fig. 5). Afterward at Mayol (zones M-6 and M-5), and also at Puchilco (zones PU-6 - PU-5; Fig. 8), peak percentages of *Pseudopanax laetevirens* and *Podocarpus nubigena* imply colder conditions and reversal of the warming trend. A colder setting is apparent from the modern altitudinal distribution of these species with reference to species of Myrtaceae in the Cordillera de Piuchén (Fig. 3). At Estero Huitanque (zone EH-3; Fig. 6), the colder interval dated later than 12,750 yr B.P. is reflected by the high proportion of Gramineae and Tubuliflorae and by the comparatively poor display of arboreal species.

Initial late-glacial expansion and subsequent diminution of *Nothofagus* on Isla Grande, as climate at first became milder and later colder, can be seen in other data from the Southern Andes. The fluctuation from >50 to <30% *Nothofagus* occurs on the Península de Taitao at 46°25'S after 14,335±145 yr B.P., and includes peak *Podocarpus nubigena* (>35%) between 11,000 and 10,000 yr B.P. (Lumley and Switsur, 1993); in Tierra del Fuego at 54°52' S after 14,640 ± 260 yr B.P., values of >75% *Nothofagus* decrease to <2% between 11,160 and 10,200 yr B.P. (Heusser, 1989, 1993).

Repetition of a sudden reversal of trend with subsequently milder climate is best shown at the late-glacial-Holocene boundary at Puchilco (zone PU-4; Fig. 8), where the profile of *Weinmannia trichosperma*, unimportant in the late-glacial, follows *Podocarpus nubigena* in <300 yr. The shift during similar short periods is also noted at Mayol (zones M-5 - M-4; Fig. 5) and Estero Huitanque (zones EH-3 - EH-2; Fig. 6), but has been subdued in each case, apparently, by fire.

Late-glacial Chiloé vegetation over the roughly 4,000 yr of record underwent transition from open Subantarctic Parkland (probably containing *Nothofagus betuloides*) to mostly closed North Patagonian Rain Forest. Internal changes in the North Patagonian communities during the latest two millennia, the shift from Myrtaceae to *Podocarpus nubigena* in the pollen assemblages, for example, suggests concordant altitudinal lowering of vegetation belts in the cordillera. Open grassland at Estero Huitanque (zone EH-3; Fig. 6) possibly reflects the spread of high-cordilleran/high-latitude communities. No clear modern analogue, however, exists for either Subantarctic Parkland or grassland in Pacific coastal southern Chile.

FIG. 10. Summary of vegetational, glacial, and climatic events related to fluctuations of the Castro lobe during late Llanquihue glaciation. Late-glacial at Mayol (Fig. 6) is combined with the full-glacial at Dalcahue (Heusser, 1990; Lowell *et al.*, in press).

Magellanic Moorland elements are not evident in these or in other lowland, late-glacial records (Villagrán, 1985, 1988a). Elements appear to have migrated to the cordillera, following the glacial advance of 14,700 yr B.P., and have become isolated both on Isla Grande (Villagrán, 1991b) and in Chiloé Continental (Heusser *et al.*, 1992). Earlier, during the full-glacial under colder conditions, moorland communities were widely distributed at low altitudes beyond the ice front on northeastern Isla Grande (Villagrán, 1988b, 1990, 1993). Their presence at Taiquemó (Fig. 1) extends to approximately 43,000 yr B.P. (Heusser, 1990).

In conclusion, stepwise deglaciation, following a maximum stand of the late Llanquihue Castro lobe on Isla Grande at close to 21,000 yr B.P., included a second maximum at approximately 14,700 yr B.P. Climatic interpretation of the radiocarbon-dated pollen records covering the full-glacial and late-glacial suggests cycles of long-term cooling and comparatively rapid warming, respectively, leading up to and succeeding times of maxima. This order of events centers on the 14,700-yr B.P. maximum, but is also implied by evidence for cooler climate at the time of the Younger Dryas Chron (11,000-10,000 yr B.P.). Cooling preceding maxima appears to have been millennial in extent, whereas successive warming was of shorter duration, apparently, accountable in centuries.

Paleoenvironments and times of maxima of the Castro lobe bear a close relationship to other records on a global scale (Lowell *et al.*, in press). The emerging pattern is recognizable in marine sediments that are tied to oxygen isotope stratigraphy in both polar hemispheres. In the Southwest Pacific at oxygen iso tope stage 2, pollen of grasses and other herbs reflects the mostly treeless vegetation that dominated South Island, New Zealand under subantarctic conditions during the last glacial maximum (Heusser and van de Geer, 1994); in the Northern Hemisphere, ice-rafting events (YD, H1, and H2) that punctuate the behavior of the Laurentide ice sheet (Bond *et al.*, 1993; Bond and Lotti, 1995) follow the cycling of glacial advances/cooling discernible in the Southern Hemisphere.

Cooling related to the Younger Dryas Chron seen in the Chiloé records, despite a source of controversy in southern South America (Heusser, 1993), is reported from northern South America (Kuhry *et al.*, 1993), northwestern North America (Mathewes, 1993), Atlantic Canada (Mott *et al.*, 1986) and Scandinavia (Paus, 1989), among other geographic regions. Although Chiloé pollen zones show shifts with an inferred drop of temperature at the time of the Younger Dryas, the Southern Andes have yet to yield evidence of corresponding glacial activity. The converse of this situation exists in New Zealand, where pollen data (McGlone, 1988) provide no clear indication of climatic change during glacial advance of Younger Dryas age, which most recently has been demonstrated for the Franz Josef Glacier in the Southern Alps of South Island (Denton and Hendy, 1994). The variable nature of the evidence, or lack of it, for colder climate of Younger Dryas age is possibly caused by low intensity/short duration forcing factors, linked to the irregular ecophysiological responses of different plant species.

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