PALEOECOLOGY OF THE SOUTHERN CHILEAN LAKE DISTRICT–ISLA GRANDE DE CHILOÉ DURING MIDDLE–LATE LLANQUIHUE GLACIATION AND DEGLACIATION

BY
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ABSTRACT. Subantarctic Parkland and Subantarctic–North Patagonian Evergreen Forest, embracing >40,000 ^{14}C years of middle and late Llanquihue glaciation, are reconstructed from pollen contained in multiple interdrift deposits and cores of lake sediments. The subantarctic plant communities at low elevations have since been replaced by temperate Valdivian Evergreen Forest. Data in support of the vegetation reconstruction derive from close-interval sampling (>1400 pollen analysed stratigraphic levels) and high-resolution chronology (>200 AMS and conventional radiocarbon-dated horizons). Pollen sequences are from 15 sites, eight of which are exposures and seven mires, located in relation to lobes of piedmont glaciers that occupied Lago Llanquihue, Seno Reloncaví, Golfo de Ancud, and the east-central sector of Isla Grande de Chiloé at the northern limit of the Golfo Corcovado lobe.

Recurring episodes of grass maxima representing Subantarctic Parkland, when grass and scrub became widespread among patches of southern beech (*Nothofagus*), bear a relationship to glacial advances. The implication of the maxima, prominent with advances at 22,400 and 14,800 ^{14}C yr BP during late Llanquihue glaciation in marine oxygen-isotope Stage 2, is of successive intervals of cold climate with summer temperatures estimated at 6–8°C below the modern mean. The earliest recorded maximum at >50,000 ^{14}C yr BP is possibly during late Stage 4. At the time of middle Llanquihue glaciation in Stage 3, cool, humid interstades on Isla Grande de Chiloé with Subantarctic Evergreen Forest, which under progressive cooling after 47,000 ^{14}C yr BP was increasingly replaced by parkland. During stepwise deglaciation, when transitional beech woodland communities supplanting parkland became diversified by formation of thermophilous North Patagonian Evergreen Forest, warming in the order of 5–6°C was abrupt after 14,000 ^{14}C yr BP. Closed-canopy North Patagonian Evergreen Forest was established by 12,500 ^{14}C yr BP. Later, after *c*. 12,000 until 10,000 ^{14}C yr BP, depending on location, forest at low elevations became modified by expansion of a cold-tolerant element indicative of ≤2–3°C cooler climate. This stepwise climatic sequence is seen at all late-glacial sites.

Cool, humid interstadial conditions, punctuated by cold stadial climate, are characteristic of the last >40,000 ^{14}C years of the Pleistocene at midlatitude in the Southern Hemisphere. Pollen sequences from southern South America and terrestrial–marine records from the New Zealand–Tasmania sector express a broad measure of synchrony of vegetational/climatic change for marine oxygen-isotope Stages 2–3. The data, combined with the timing of glacial maxima in the Southern Andes, Southern Alps of New Zealand, and in the Northern Hemisphere, are indicative of synchronous, millennial-scale, midlatitude climatic changes in the polar hemispheres.

Introduction

Glaciers in the Andes flowing westward toward the Pacific Ocean during Llanquihue glaciation covered much of southern Chile between the latitudes of 42°30' and 56°00' S. Responding to colder/snowier conditions in the cordillera, glaciers during marine oxygen-isotope Stage 2 were an imposing feature until 14,900–14,700 ^{14}C yr BP, when the latest piedmont lobes to override the lowland began to collapse. Subantarctic Parkland, patches of southern beech (*Nothofagus*) set in open grassland and scrub, bordered the latest glacial maxima at the limit of glaciation on Isla Grande de Chiloé; earlier, vegetation acquired the character of modern Subantarctic Evergreen Forest. While Subantarctic Evergreen Forest today is preserved at 48–55°S, ≥6° of latitude south of Isla Grande de Chiloé where it existed during middle Llanquihue glaciation, Subantarctic Parkland has no modern analog.

Arboreal and non-arboreal plant communities, subject equally as glaciers to the rhythmic forcing of stadial and interstadial climate, expanded and contracted in the course of recurrent cycling of temperature and humidity between >50,000 and 10,000 ^{14}C yr BP. During the early part of the interval, vegetation and climate were near equilibrium for as much as 10,000 years, whereas times of relative climatic stability before and after, by comparison, were of shorter duration. These observations stress the need to regard the climatic sequence, shown by repeated buildup and breakdown of inclusive plant communities, as more complex than has been viewed heretofore.

Our paleoecological studies of the Southern Lake District–Isla Grande de Chiloé were undertaken to develop from high-resolution reconstruction of late Pleistocene vegetation: (1) presence, associations, and migratory movement of plant taxa; (2) climatic parameters that surround stades and interstades of middle and late Llanquihue glaciation; and (3) a standard for demonstrating late Pleistocene intrahemispheric and polar hemispheric relationships and dynamic forcing of climatic events. Pollen assemblages on which our conclusions fundamentally rest are from radiocarbon-dated deposits laid down in conjunction with the formation, maxima, and dissolution of piedmont glacial lobes. Time frames are continuous for protracted cored intervals, unlike glacial chronological records, which represent a series of discontinuous events. In one case from cores taken in a mire at Taiquemó on Isla Grande de Chiloé, the chronology extends uninterruptedly for >50,000 ^{14}C years. Fitted to dated glacial maxima recorded by the stratigraphic and mapping program coordinated with this study, the chronologically controlled pollen data provide an essential measure for the interpretation of climatic conditions that precede, culminate, and follow times of maxima (see also complementary study by Moreno *et al.* 1999).

Sites selected for study (Fig. 1) are on drift deposited by four piedmont lobes that pushed beyond the basins of Lago Llanquihue, Seno Reloncaví, and Golfo de Ancud and west of the islands and waterways at the northern extent of Golfo Corcovado on Isla Grande de Chiloé. The distribution of sites enables comparisons to be made of vegetation response in connection with each lobe. Ultimately, the vegetation is interpreted in relation to the Andean mountain front across the breadth of latitude embraced by the sites. Records uniformly encompass millennia since at least the latest glacial maximum on each of the lobes and include, in addition, segmented earlier intervals. Llanquihue glaciation (Heusser 1974) is correlated with Northern Hemisphere glaciations, the Wisconsinan in North America and Weichselian in Europe.

The Southern Lake District–Isla Grande de Chiloé have been under paleoecological investigation periodically for over 30 years. The current program, carried out annually since 1991, is closely coordinated with study of the regional glacial geology (Andersen *et al.* 1995; Lowell *et al.* 1995, 1996; Heusser *et al.* 1995, 1996a, b, 1998; Zhou and Heusser 1996; Moreno 1997). Prior to 1991, studies explored ground variably tied to the glacial setting (Heusser 1966, 1974, 1981, 1984, 1990a; Godley and Moar 1973; Heusser and Flint 1977; Heusser *et al.* 1992; Villagrán 1980, 1985, 1988a, b, 1991, 1993). In contrast to investigations made during formative years, the present undertaking was designed to produce closely dated pollen stratigraphy of sites strategically located in relation to moraines, outwash, and other glacial features. Most important, the work stands as a counterpart to mapping of the glacial geology and makes a commitment toward unravelling the mutability of ice age climate.

Southern Lake District–Isla Grande de Chiloé (41°00'–42°30'S)

The region (Fig. 1) centers on the broad, elongate Valle Central, a structural trough identified over a distance of >250 km from Lago Llanquihue south to the eastern shores of Isla Grande de Chiloé, where the trough lies drowned by marine waterways. Paralleling the Valle Central, the Cordillera de la Costa west of the Southern Lake District is at elevations of <1000 m and on Isla Grande de Chiloé at <900 m. In the Cordillera de los Andes, bordering the trough to the east, summit elevations are ≤2000 m, except for Monte Tronador (3460 m), Puntiagudo (2490 m), and the active volcanoes, Osorno (2661 m), Michinmávida (2481 m), and Calbuco (2003 m).

The Valle Central throughout the Quaternary has been a repository for glacial drift and volcanic, eolian, alluvial, and colluvial deposits; exposures of bedrock, except along flanks of the valley, are rare. Deposits of volcanic origin, consisting mostly of pyroclastic flows and airfall ash and lapilli, blanket the drift; Volcán Calbuco, intermittently active, is believed to be a primary source of debris and pyroclastic flow deposits to the west and southwest of Lago Llanquihue (Langohr 1974; Moreno and Varela 1985).

Moraines emplaced by the Lago Llanquihue piedmont lobe form arcs between the lake shore and 5–6 km to the west. Morainal arcs of contiguous lobes to the south broaden to 20 km on northeastern Isla Chiloé. Extending beyond to the foot of the Cordillera de la Costa, outwash plains make contact with drift of older glaciations. The cordillera farther west is unglaciated, except for the south-

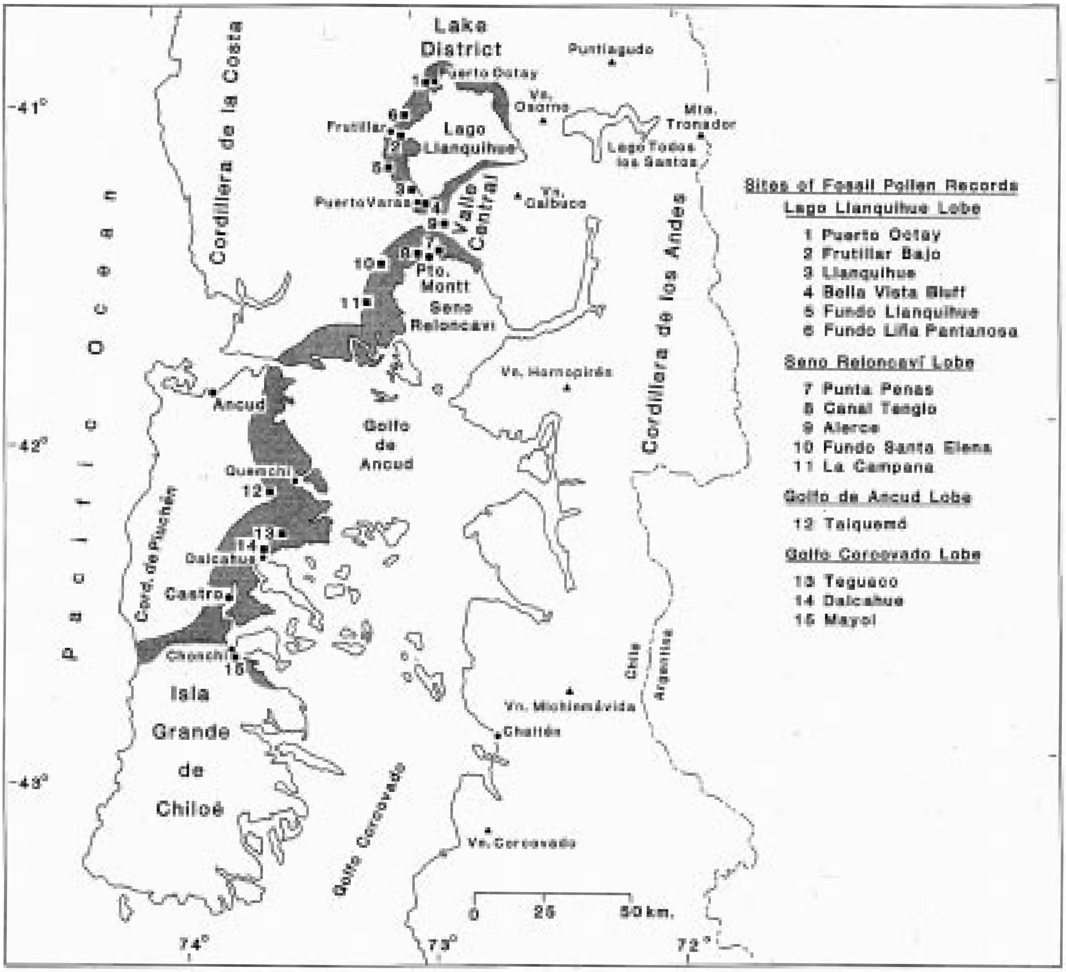

Fig. 1. Distribution of sites of fossil pollen records in relation to piedmont glacial lobes that expanded in the Valle Central in the Southern Lake District and on Isla Grande de Chiloé during late Llanquihue glaciation. Extent of glacial drift at the foreland limit (shown stippled) is taken from Andersen *et al.* (1999).

ern half of Isla Chiloé, which appears to have been covered by ice at the time of Llanquihue Glaciation.

Early studies of regional glacial deposits were made by Brüggen (1950), followed more recently by Olivares (1967), Lauer (1968), Laugenie (1971, 1982), Mercer (1972, 1976, 1982, 1983, 1984), Heusser and Flint (1977), Porter (1981), Lauer and Frankenberg (1984), Moreno and Varela (1985), Andersen *et al.* (1995), Bentley (1995), and Lowell *et al.* (1995, 1996). Glacial maxima during Llanquihue glaciation are recorded at >40,000, 29,400, 26,800, 22,400, and 14,800 ^{14}C yr BP (Denton *et al.* 1999a).

Vegetation

Classification, distribution, and community composition

Valdivian Evergreen Forest. Sites of stratigraphic records (<150 m in elevation) are located within boundaries of what is mapped as Valdivian Evergreen Forest (Schmithüsen 1956; Oberdorfer 1960; Veblen *et al.* 1983; Gajardo 1994). Its extent originally drawn by Schmithüsen (1956) and since modified (Fig. 2), Valdivian Forest makes contact with Lowland Deciduous Beech Forest in the southern part of the Lake District and with North Patagonian Evergreen Forest on southern Isla Grande de Chiloé and the adjacent mainland. Cross-sectional profiles

A–A' and B–B' (Fig. 2), prepared from various sources (Oberdorfer 1960; Villagrán 1980, 1985; Villagrán *et al.* 1993; Freiberg 1985; Donoso 1993; Gajardo 1994), delineate the altitudinal distribution of forest and neighboring vegetation zones.

Classification and distribution of Valdivian Forest, both latitudinally and altitudinally, are matters of interpretation based on community composition and structure, among other factors. Ranges of species frequently overlap contiguous units, making the location of boundaries subject to arbitrary judgement. Inroads made through land clearance, burning, introduction of foreign species, and exploitation for lumber and other resources during the past century have left much of the presettlement forest reduced in area or greatly altered.

In the Southern Lake District at low elevations (<400 m), Valdivian Forest (Fig. 3) adjoins the Valle Central. Decreasing in elevation southward, the forest reaches its limit on southeastern Isla Grande de Chiloé and the facing western slope of the Andes at between 42°30' and 43°S. Communities on the ocean side of the Cordillera de la Costa along drainage courses near tide level, as well as in the Andes just above the valley floor, typically consist of *Aextoxicon punctatum*, 20–35 m in height, growing in association with myrtaceous *Myrceugenia planipes*, *M. ovata*, and *Luma apiculata*. At higher elevations (200–400 m), *Nothofagus dombeyi* and *Eucryphia cordifolia*, 40 m tall, are the main components of the forest, overtopping the canopy species, *Laurelia philippiana*, *Caldcluvia paniculata, Lomatia hirsuta,* and *Gevuina avellana*. Surfaces of ash, lava, and mudflows, the result of recent volcanic activity, feature early successional stands of *N. dombeyi* and *Weinmannia trichosperma,* structured with a secondary stratum of *Lomatia dentata, Pseudopanax laetevirens,* and *Gevuina avellana* above a ground cover of *Gaultheria phillyreaefolia* heath (Villagrán 1980).

Valdivian Forest is rich in lianas (*Hydrangea serratifolia, Cissus striata, Griselinia ruscifolia*), epiphytic ferns (*Polypodium feuillei*, *Hymenophyllum caudiculatum*), and dense bamboo (*Chusquea quila*). Interiors are dark and humid beneath closely knit tree crowns. Species with strong light requirements/tolerances, heliophytic *Fuchsia magellanica, Gunnera chilensis*, and the ferns, *Lophosoria quadripinnata* and *Blechnum chilense,* occupy openings in the canopy or occur at the edge of the forest.

Lowland Deciduous Beech Forest. Lowland Forest of the deciduous beech *Nothofagus obliqua* (Fig. 2) extends south in the Valle Central, terminating in contact with Valdivian Forest some kilometers southwest of Lago Llanquihue (approximately 41°30'S). Associates are evergreen *Laurelia sempervirens* and *Persea lingue*. Throughout the region, Lowland Forest has been converted through settlement to pastures and open stands of *N. obliqua*, which is distinguishable by its 40-m tall, columnar-like growth form. Remnant stands of undisturbed forest are rare.

North Patagonian Evergreen Forest. Lying altitudinally higher than Valdivian Forest in the coastal and Andean cordilleras, North Patagonian Evergreen Forest (Fig. 3) constitutes a distinctive zone dominated for the most part by broad-leaved species. South of the Lake District, the forest descends to sea level along the southern coast of Isla Grande de Chiloé and opposite Chiloé Continental mainland, and spreads farther south to 47–48°S in the vicinity of the Golfo de Penas (Fig. 2). Valdivian structural features and a wealth of lianas, epiphytes, and bamboo also characterize North Patagonian Forest.

Communities with heights of 40–45 m are dominated by *Nothofagus* (*N. dombeyi* in the Andes and *N. nitida* in the Cordillera de la Costa). Associates at low elevations (400–800 m) are *Laurelia philippiana* and *Weinmannia trichosperma* and, less frequently, *Amomyrtus luma, Lomatia ferruginea, Dasyphyllum diacanthoides,* and *Drimys winteri* var. *chilensis*. At higher elevations in the Andes (800–1100 m), *Nothofagus* forms pure stands with an understorey of *Desfontainia spinosa, Maytenus magellanica*, *Myrceugenia chrysocarpa*, and *Drimys winteri* var. *andina*. Forest communities at >600 m generally contrast with the forest below by an abundance of the gymnosperms, *Podocarpus nubigena, Saxe-gothaea conspicua, Pilgerodendron uviferum, and Fitzroya cupressoides*. Species frequent wet places together with the tall myrtaceous shrub, *Tepualia stipularis*.

Near its southern limit, beyond the range of *Saxe-gothaea* and *Fitzroya,* North Patagonian Forest dominated by *Nothofagus nitida* and *N. betuloides* contains an understorey of *Desfontainia spinosa* and *Pseudopanax laetevirens* (Innes 1992). Whereas arboreal Myrtaceae are important in evergreen forest on Isla Grande de Chiloé, they

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Figs 2–3, *see pp. 238–239.*

are virtually absent in the latitude of Golfo de Penas. *Fitzroya,* a tree of great size and age (4 m in diameter, >3600 years; Lara and Villalba 1993) latitudinally restricted between 40° and 42°30'S, is altitudinally widely distributed. During the 19th century, at the time of colonization in southern Chile, stands in the Valle Central were extensive between Lago Llanquihue and Seno Reloncaví.

Subantarctic Evergreen Forest and Magellanic Moorland. Subantarctic Evergreen Forest (Fig. 2) is scattered along the crest of the Cordillera de la Costa and on slopes above North Patagonian Evergreen Forest farther south in the Andes. Communities frequently are not clearly distinguishable because of the occurrence of tension zones containing species, namely, *Drimys winteri* var. *chilensis, Pseudopanax laetevirens, Lomatia ferruginea,* and *Maytenus magellanica*, common to both forests. Subantarctic Evergreen Forest communities, dominated by *Nothofagus betuloides,* are generally relatively open with trees low in stature (≤8 m tall). There are, in addition, limited areas of depauperate woodland formed by *N. antarctica*, which descends to low elevations on the floor of the Valle Central and extends in the south beyond the ranges of *N. nitida* and *N. dombeyi.* Sectors of forest distributed in southernmost Chile (48–55°S) are near sea level on well-drained soil protected from wind. Associated are non-tree species, *Desfontainia spinosa, Lebetanthus myrsinites, Luzuriaga marginata,* and *Pernettya mucronata*, the last-named important in matorral on glacial outwash.

Magellanic Moorland (Godley 1960), or Tundra Magallánica (Pisano 1981), contributes to the complex of communities found in association with Subantarctic Evergreen Forest (Fig. 2). It is localized and discontinuous in the Cordillera de la Costa, both in proximity to the Lake District and on Isla Grande de Chiloé, and in the Chilotan Andes. Southward, Magellanic Moorland is widespread on the islands and outer segments of mainland between Golfo de Penas and Cabo de Hornos (48–56°S). Ombrotrophic (raised) cushion bogs of *Donatia fascicularis* and minerotrophic mires of *Astelia pumila* intersperse with wet upland scrub and patches of *Nothofagus betuloides-N. antarctica* forest. In the cordillera, moorland abounds for the most part at elevations of >600 m on poorly drained, nutrient-deficient ground but also in patches as much as 200 m lower on wet slopes facing the Pacific (Ruthsatz and Villagrán 1991). Moorland is the habitat of the low gymnospermous shrub, *Lepidothamnus fonkii* (Fig. 4), found in the cordillera on Isla Grande de Chiloé (Espinosa 1916) and in the Andes of Chiloé Continental (Heusser *et al.* 1992).

Subantarctic Deciduous Beech Forest. Deciduous *Nothofagus pumilio* and *N. antarctica* represent a high-montane zone to treeline, found exclusively on peaks and ridge tops in the Andes (900–1350 m). The two species, only occasionally mixed in communities, are the dominants of Subantarctic Deciduous Beech Forest, which reaches south in the Andes, occurring to approximately 55˚S (Fig. 2) between the evergreen forests to the west and Patagonian Steppe on the east. Trees, 25 m in height at maturity in the lower part of the zone, diminish in stature and become shrub-like and layered with approach of the treeline (Fig. 4). Shrub cover includes *Drimys winteri* var. *andina, Berberis montana, Maytenus disticha, Escallonia alpina,* and *Ribes cucullatum;* representative herbs are *Rubus geoides, Gunnera magellanica*, and *Valeriana lapathifolia.*

Cordillera de Piuchén, Isla Grande de Chiloé. Illustrative of vegetation zonation as a function of elevation and exposure is the frequency (%) distribution of selected tree/tall shrub species in the Cordillera de Piuchén (Fig. 5). Redrawn from data collected by Villagrán (1985) along transects of the west and east slopes of the cordillera, known also as Piuchué, plant distribution is a result of the combined effect of temperature depression with elevation and rainfall/wind variability. Zonal boundaries, lower in elevation on the western versus interior side of Isla Grande de Chiloé, reflect the prevailing cooler, wetter, and windier conditions on slopes facing the ocean.

Species indicative of Valdivian Evergreen Forest at lowest elevations are *Aextoxicon punctatum, Eucryphia cordifolia,* and *Gevuina avellana.* All three are found together at the southern limit of their ranges (Rodríguez *et al.* 1983) with high frequencies of *Laurelia philippiana* and myrtaceous trees. Above 250 m in elevation in North Patagonian Evergreen Forest, *Laurelia* and the Myrtaceae (myrtle family) are well represented, giving way at and above 350 m to increasing amounts of *Drimys*

Fig. 4, *see p. 242.*

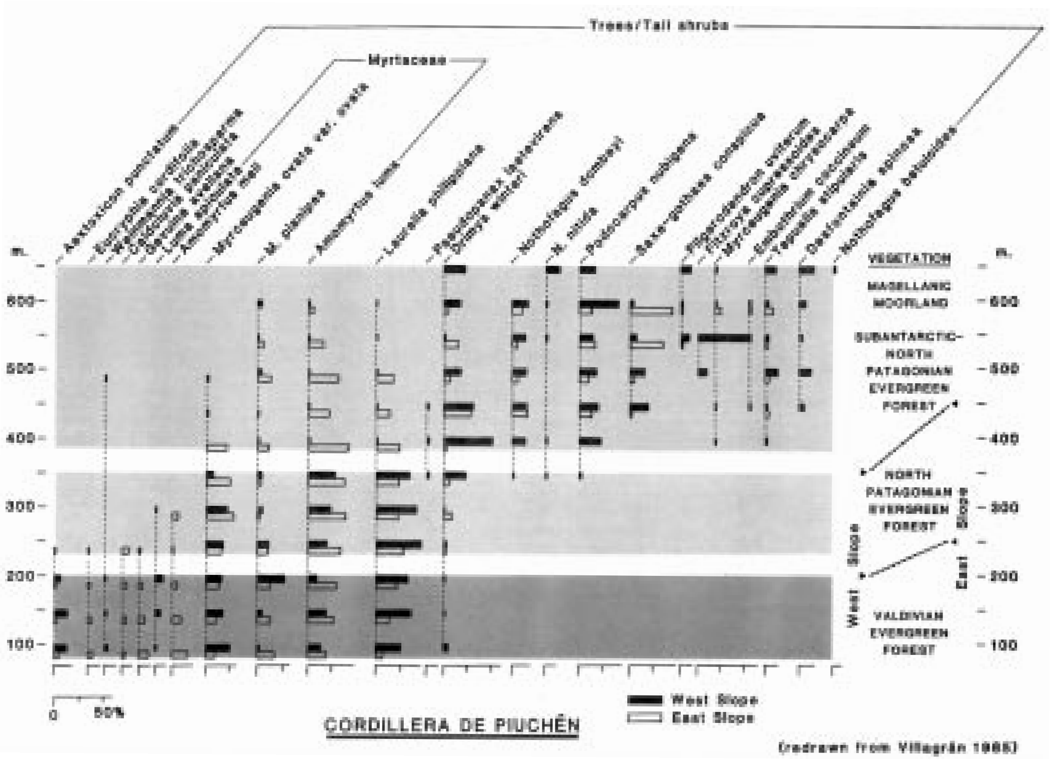


Fig. 5. Relative abundance of trees/tall shrubs along an east–west transect across the Cordillera de Piuchén, Isla Grande de Chiloé.

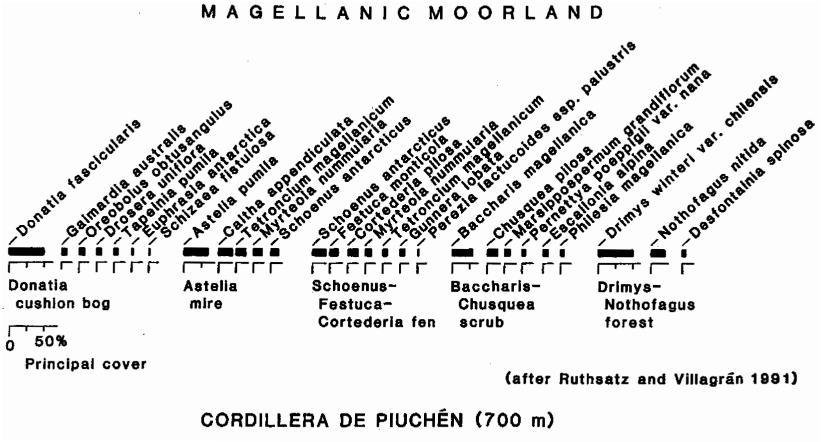
winteri var. *chilensis, Nothofagus dombeyi, Pseudopanax laetevirens, Podocarpus nubigena,* and *Saxe-gothaea conspicua*. At >450 m, increasingly open, arboreal communities are a complex of species of North Patagonian and Subantarctic Evergreen Forest affinity. Important are *Fitzroya cupressoides, Pilgerodendron uviferum*, *Nothofagus betuloides*, and *Embothrium coccineum,* and a tall-shrub constituent represented by *Desfontainia spinosa* and *Tepualia stipularis*.

Magellanic Moorland interrupts the continuity of forest on ocean-facing slopes at about 450 m and is extensive above 600 m. A 130-m-long transect run at an elevation of 700 m records the principal cover (%) of seed plants, shown averaged (Fig. 6) for intercepted communities: *Donatia* cushion bog, *Astelia* mire, *Schoenus–Festuca–Cortaderia* fen, *Baccharis–Chusquea* scrub, and *Drimys–Nothofagus* forest (Ruthsatz and Villagrán 1991). While most species recorded range to subantarctic Tierra del Fuego (Moore 1983), a number are also distributed in moorland northward along the crest of the Cordillera de la Costa (Ramírez 1968).

Community dynamics

Among factors controlling the growth and behavior of trees in forest communities, light plays a role of considerable importance. The ability of species to tolerate low light levels during the generative process is essential to their success as long-lasting community dominants. Even-aged stands of southern beech lacking reproductive size classes, for example, are an indication of poor shade tolerance of seedlings in the understorey. Perpetuation of beech is possible only where gaps in the canopy enable light to reach seedlings at ground level. Alternatively, successive stages are regulated by proximity of competitive species, or by other contributing factors. At treeline, where communities of beech (*N. pumilio* and *N. antarctica*) are not liable to competition, relative stability may be long-term.

Species of beech in the Southern Lake District (*N. dombeyi, N. betuloides, N. pumilio, N. obliqua, N. alpina*) are opportunistic. As invaders on freshly exposed ground, their presence is attributed to disturbance brought on by frequent seismic activity and volcanic eruptions (Veblen and Ashton 1978;



(after Ruthsatz and Villagrán 1991)

Fig. 6. Principal plant cover in five communities (cushion bog, mire, fen, scrub, and forest) in Magellanic Moorland along a 130-m transect at an elevation of 700 m in the Cordillera de Piuchén, Isla Grande de Chiloé.

Veblen *et al.* 1979, 1980, 1981). Equally opportunistic are *Weinmannia trichosperma* and, to a lesser degree, *Eucryphia cordifolia*, both of which, together with beech, are shade intolerant. Regarded as shade tolerant, by contrast, are *Saxe-gothaea conspicua, Laurelia philippiana, Amomyrtus luma, A. meli, Myrceugenia planipes, Podocarpus nubigena, Dasyphyllum diacanthoides, Lomatia ferruginea, Pseudopanax laetevirens,* and *Aextoxicon punctatum.* The success of these species in reaching an advanced steady state is dependent on the extent and frequency of beech-favored disturbance.

Behavior of arboreal species in evergreen forest, both on Isla Grande de Chiloé and at higher latitudes, follows much the same pattern as in the Southern Lake District (Donoso *et al.* 1984, 1985, 1990, 1993; Veblen 1985; Armesto and Figueroa 1987; Armesto and Fuentes 1988; Innes 1992). In Valdivian Forest on Isla Grande de Chiloé, *Nothofagus* and *Weinmannia* are relatively unimportant. Where *Laurelia philippiana* and *Eucryphia cordifolia* are dominant, regeneration in the understorey, if blowdowns and fire are minimized, develops successive stands of *Laurelia, Amomyrtus luma, A. meli, M. planipes,* and subdominants, *Drimys winteri* var. *chilensis* and *Gevuina avellana*. Among species of southern beech in North Patagonian Evergreen Forest near 46°S to the south of Isla Grande de Chiloé, *Nothofagus nitida* displays a greater measure of shade tolerance. Size–frequency distribution of tree species indicates that *N. nitida, Podocarpus nubigena*, and *Laurelia philippiana* are close to a state of equilibrium. Shade tolerance of other noteworthy trees, such as *Fitzroya cupressoides, Pilgerodendron uviferum*, and *Embothrium coccineum*, is comparatively poor.

Climate and vegetation

Wet, temperate, stormy climate of the Southern Lake District –Isla Grande de Chiloé is dictated by cyclonic conditions in the belt of Southern Westerlies coupled with topography and cold offshore Humboldt current (Miller 1976). Oceanic with no dry season, the region lies south of latitudes subject to winter–wet, summer–dry climate (<37°S) and north of the main thrust of the westerlies (50°S). The seasonal control of precipitation by shifting seasonal dominance of polar and subtropical maritime air mass centers that occurs in central Chile does not take place. Except for only brief periods in summer, dry subtropical air does not penetrate southward to the Southern Lake District–Isla Grande de Chiloé. Periods of temperature depression are the result of maritime antarctic air in winter and continental antarctic air both in summer and winter (Taljaard 1972).

The air stream of the westerlies is a constant feature buffeting the vegetation, creating sectors of wind-trained communities and saturated ground. Climate is wettest on ocean-facing slopes in the cordillera, as air moving inland is lifted and cooled to condensation levels (Fig. 7). Leeward, in the rain shadow of the Cordillera de la Costa, precipitation in the Valle Central and on eastern Isla Grande de Chiloé is less, 2000 versus 4000 mm yr^{-1} to the west, and is heavy on the west side of the Andes, reaching 5000 mm yr^{-1} (Almeyda and Sáez 1958). Summer (January) average temperature is 14°C near the coast, and 16°C in the Valle Central; winter (July) temperature, following a reversed trend, is 8°C on the coast and at 6°C, lower in the interior. Seasonal temperature differences are brought about by cold ocean current and cloudiness at the coast, coincident

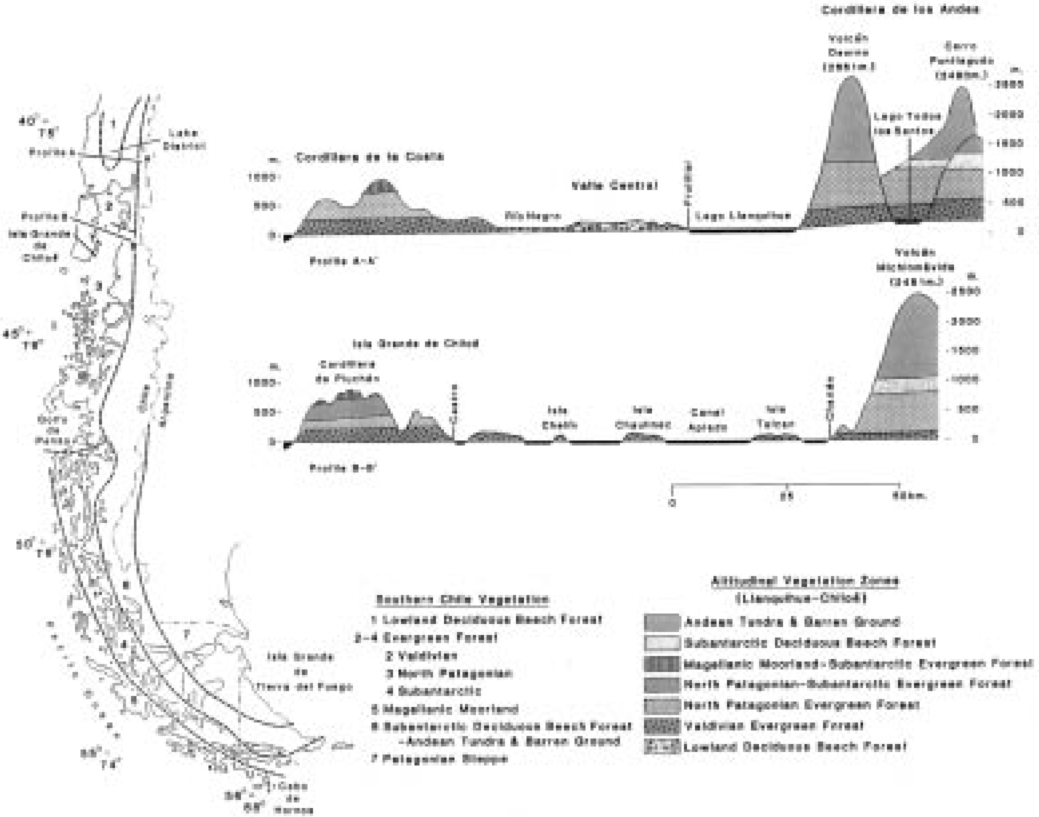


Fig. 2. Vegetation of southern Chile in its latitudinal distribution and altitudinally in cross-section profiles: A–A' in the Southern Lake District and B–B' on Isla Grande de Chiloé (see text for data sources).

with changing summer versus winter levels of insolation in valleys and foothills away from the ocean.

Snowline elevations in Chiloé Continental at 1500 m on west-facing exposures along the Chile–Argentina border decrease to 1200 m in proximity to the Pacific (Mercer 1967). Some 150 m lower in elevation, treeline is subject to a long-lasting snowpack and low temperature, which reduce arboreal reproduction from seeds and cause tree growth to develop and spread vegetatively by layering from the weight of snow. Average summer temperature at treeline (*c*. 600 m) of Subantarctic Deciduous Beech Forest along Canal Beagle in southern Tierra del Fuego (54°56'S) is estimated to be close to 6°C (Puigdefábregas *et al*. 1988; Heusser 1989a). This value probably varies in the order of ± 0.5°C through the forest–tundra ecotone. Elevations of treeline depend on aspect, mountain mass, and precipitation, being higher on equator-facing slopes and under drier conditions in the interior.

Precipitation and temperature parameters for the regional vegetation are approximated from available climatological data (Table 1). Average summer temperatures with an extreme range of 13°C are between 5 and 18°C, while in winter, temperatures extend over 9°C from -1.0° to 8.0°C; average yearly precipitation is between 400 and 8000 mm. Temperature ranges for each vegetation type fall between 1 and 3°C, both in summer and winter, except for Subantarctic Deciduous Beech Forest. In this case, the forest, under continental climate in the Andes, is subject to the highest temperatures, as well as lowest levels of precipitation. Precipitation is highest in Magellanic Moorland at around 50°S, whereas at its southernmost extremity, amounts are considerably less. Subantarctic Evergreen Forest similarly ranges to higher latitudes under decreased precipitation but with extended cloud cover.

Species constituting forest and moorland show

Fig. 3. Top: Valdivian Evergreen Forest east of Volcán Calbuco dominated by *Nothofagus dombeyi*, *Eucryphia cordifolia* (in flower), *Weinmannia trichosperma*, and various Myrtaceae. Bottom: North Patagonian Evergreen Forest of representative *Nothofagus dombeyi, Weinmannia trichosperma, Laurelia philippiana*, and Myrtaceae (*Amomyrtus luma, Myrceugenia planipes*) in Chiloé Continental.

adaptations within limits of precipitation and temperature regimes set by each population (Weinberger 1973, 1974, 1978; Weinberger *et al*. 1973; Steubing *et al*. 1983; Alberdi and Ríos 1983; Alberdi *et al*. 1985). Among regional deciduous species of beech, *Nothofagus obliqua* is relatively thermophilic and drought resistant; *N. alpina*, by comparison, is considered intermediate in thermal requirements; *N. antarctica*, found under a variety of conditions, is comparatively cold resistant and able to thrive with extended dryness; and *N. pumilio*, also cold resistant, generally exhibits higher moisture requirements than *N. antarctica*.

Deciduous species of beech display greater continentality in their distribution, while evergreen species are more oceanic. Registering the broadest ecological setting, *N dombeyi* grows optimally on well-drained but humid ground; *N. nitida*, thermally intermediate, is able, more so than *N. dombeyi,* to grow under wet edaphic conditions; and *N. betuloides* is the most cold-resistant of oceanic species. Arboreal associates regarded as thermophilic are *Eucryphia cordifolia* and *Aextoxicon punctatum*, whereas *Weinmannia trichosperma*, *Laurelia philippiana*, *Amomyrtus luma, Myrceugenia planipes*, and *Luma apiculata* are thermally intermediate; cold-resistant species include *Lomatia ferruginea, Embothrium coccineum, Pseudopanax laetevirens, Drimys winteri* var. *chilensis, Podocarpus nubigena*, and *Pilgerodendron uviferum*.

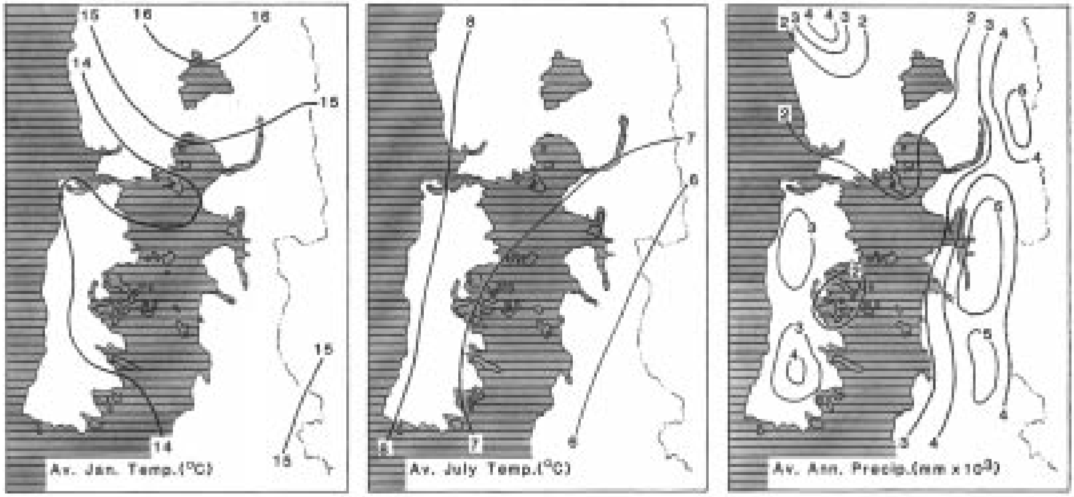


Fig. 7. Average January and July isotherms and annual precipitation isohyets for the Southern Lake District and Isla Grande de Chiloé (from Almeyda and Sáez 1958).

Shrubs possessing cold resistance include *Tepualia stipularis*, *Desfontainia spinosa*, and *Lepidothamnus fonkii*.

Methods

Field

Sites having the potential of producing pollen records with extended or key chronology were located by reconnaissance and through use of topographic sheets and aerial photographs. Several sites of considerable chronostratigraphic value were found in the course of field checking of land forms during glacial geological mapping. Specific attention was given to the location of sites directly related to the formation of the piedmont glacial lobes and their wastage.

Stratigraphic sections are from exposures and mires. Measured sections of exposures, both natural and man-made, are from fresh channel cuts, taking care to avoid modern roots and fractures containing reworked material. Samples were collected for the most part at ≤5-cm intervals, placed in bags and refrigerated before radiocarbon dating and laboratory processing of their content of pollen, spores, and macrofossils.

Coring of mires (logistics and execution, T.V.L.) was by means of a square-rod piston sampler (Wright 1967), employing 1.5-m extension rods. During initial field work, lakes were cored, using a large, specially built collapsible raft. Operation proved time consuming, involving time spent setting up, positioning, and breaking down the platform. Lakes were subsequently abandoned, as mires containing late-glacial–full-glacial lake sediments proved easier to core from a plywood platform set on the mire surface. By means of a 10-cm-diameter auger prior to sampling, overlying Holocene deposits were penetrated and a casing placed in the hole to overcome friction when the sampler and string of extension rods were lowered and raised during coring. A regional tephra layer, dated

Table 1. Temperature and precipitation parameters for vegetation of southern Chile approximated from available climatological data (Almeyda and Sáez 1958).

	Average temperature (°C)		Average annual precipitation (mm)
Vegetation	Summer (January)	Winter (July)	
Lowland Deciduous Beech Forest	15.0–18.0	7.0–8.0	1200–2000
Valdivian Evergreen Forest	14.0–15.0	7.0–8.0	2000–3000
North Patagonian Evergreen Forest	12.0–14.0	4.7–7.0	3000–5000
Subantarctic Evergreen Forest	10.0–12.0	2.5–5.0	1000–5000
Magellanic Moorland	8.0–11.0	3.0–5.0	1500–8000
Subantarctic Deciduous Beech Forest	5.0–15.0	-1.0–2.0	400–5000

at about 9500 ^{14}C yr BP, served as a reference horizon below which cores were taken. A chain hoist, or winch, was used to raise sampler and rods, following each thrust and collection of increment of core.

Cores, 5 cm in diameter with lengths variable according to each sampling thrust, were extruded from a 1-m-long core tube onto clear plastic. Extrusion almost invariably required use of a winch. Lengths were measured and a cursory description recorded before wrapping cores, first in clear plastic and then in aluminum foil, and placing them properly marked in a box for temporary storage in the field. Between each operation, the sampler and core tube were washed with fresh water specifically stored in large barrels for the purpose of cleaning the equipment and minimizing contamination. Multiple cores, at least two and at times three, or more, were taken at each site to ensure continuity of the sedimentary record where breaks occur between increments.

Cores were archived and made available for sampling and study in the Core Laboratory, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY. Archiving involved cataloging, splitting of cores lengthwise to produce archive and working halves, photographing and wrapping in plastic, and storing cores in trays in boxes under refrigeration. Cores were sampled for high resolution at 1-cm and 5-cm intervals, except in the case of a single exploratory core, where the sampling interval was 10-cm.

Laboratory

Samples were prepared for analysis of their fossil content (processing, L.E.H.) by standard techniques (Heusser and Stock 1984). An early step in laboratory treatment, separation of pollen and spores from the sediment matrix by use of 7 μm and 150 μm nylon microscreens, ensured the concentration of pollen of small size (*Eucryphia, Caldcluvia*, *Weinmannia*), as well as large size (*Podocarpus, Saxe-gothaea*), and of variably sized spores (*Lophosoria*, *Schizaea, Blechnum, Isoetes*). Pollen grains mounted on slides and identified and counted under the microscope for ascertaining frequency (%) of taxa are sums of upland trees and shrubs/herbs (n=≥300 grains); frequencies of pollen of aquatics and spores of cryptogams, categorized separately, are from additional counts (n=>300 total pollen + spores). Pollen/spores unidentified are on average ≤2%, and sums only on occasion are <300. Slides scanned after counting was complete record taxa not previously identified. Pollen influx (grains cm^{-2} yr^{-1}) was not calculated owing to the diversity of site sediments, which range from coarse sand to fine-grained silt, variably organic in content, and peat. Influx, if reliably of value as an indicator of pollen productivity and vegetation density surrounding sites, requires a measure of uniformity of the sediment matrix over the length of core.

Additional measurements supplement pollen analytical work. Charcoal particulates, where encountered during processing for pollen and spores, are a measure of area in μm^2 cm^{-3} in the 7–150 μm size range. Loss on ignition (%) is based on weight loss after samples oven-dried at 105°C were combusted for 2h in a muffle furnace at 550°C. Magnetic susceptibility was measured on selected cores using a magnetic susceptibility meter model MS2 (Bartington Instruments Ltd, Oxford, UK). Screened plant macrofossils, when encountered, were AMS radiocarbon-dated; otherwise, bulk samples served for dating. Dates were reported by the NSF-Arizona AMS Facility (AA); Center for Applied Isotope Studies, University of Georgia (UGA); Quaternary Isotope Laboratory, University of Washington (QL); and Radiological Dating Laboratory, Trondheim, Norway (T). Dates (uncorrected) and laboratory numbers are included with pollen assemblage data in Tables 3–17 and are included in corresponding diagrams shown in Figs 8–20 and 22–24. For radiocarbon dates, see also Denton *et al.* (1999b).

Frequencies of taxa are diagrammed systematically for each stratigraphic record, grouped as trees and shrubs/herbs of upland provenance and as aquatics/cryptogams. Arrangement within pollen groups, from left to right, is of gymnosperms succeeded by angiosperms, monocotyledons preceding dicotyledons; among vascular cryptogams, ferns precede fern allies with non-vascular *Sphagnum* placed to the far right. Diagrams are subdivided into pollen assemblage zones, according to peak occurrences of key taxa, and show basic stratigraphic and lithological relations. Stratigraphy is with reference to length of core, as recorded by the Core Laboratory at Lamont-Doherty Earth Observatory; core breaks, where indicated, mark extent of penetration by successive thrusts during coring and locate possible hiatuses in the records. Radiocarbon dates included are from samples collected mostly at 1-cm intervals. Amounts of microscopic charcoal particulates encountered at the

Fig. 4. Top: Low shrubby *Lepidothamnus fonkii* backed by short upright *Pilgerodendron uviferum* of Magellanic Moorland at 700 m elevation in Chiloé Continental. Bottom: Treeline of *Nothofagus pumilio* in Subantarctic Deciduous Beech Forest at 1200 m elevation in the Andes near 41°S. Cinder cones in the background are part of the Casablanca volcanic complex.

close of the late-glacial are figured in certain diagrams. Charcoal is attributed to Paleoindian burning and also to volcanism, where sites lie in proximity to volcanic vents (Heusser 1994a).

Lithological units are simply classified by their textural characteristics as clay, silt, sand, gravel, till, and diamicton and by their recognizable organic content as peat, lacustrine sediments, and organic silt. Peat, typically dark brown (7.5YR 3/2) with high loss on ignition (>50%), is usually rich in sedge/wood macroremains. Lacustrine sediments with comparatively low loss on ignition (<25%) are variably gray (7.5YR 5/0), dark gray (7.5YR 4/0), grayish brown (10YR 5/2), and olive (5Y 5/2). Fine grained, by and large, the sediments contain a variety of aquatic forms, including diatoms, sponge spicules, algae (colonial *Pediastrum* and *Botryococcus*, zygospores of *Debarya*, spores of *Spirogyra*), and dinoflagellate cysts.

Organic silt, described as an interdrift deposit with low loss on ignition (≤20%), is in large part pyroclastic flow material. Deposits commonly consist of non-stratified, silt-sized volcanic glass and mineral fragments, including microscopic plant detritus with a substantial complement of pollen and spores. Sites of organic silt containing notable amounts of pyroclastics are Puerto Octay (Fig. 8), Frutillar Bajo (Fig. 9), and Dalcahue (Fig. 23). It is not clear by what mechanism pollen and spores are incorporated in these deposits, which span 10,000–15,000 ^{14}C years and show a variety of pollen assemblages.

Notes on identification and designation of pollen and spores

Identification (analyses, C.J.H.) rests on a reference collection of modern types, used in conjunction with taxonomic descriptions, illustrations, and keys (Heusser 1971; Villagrán 1980). Identity of southern beech is from a complex of regional species, recognized morphologically as *Nothofagus dombeyi* type (*N. dombeyi, N. alpina, N. betuloides, N. nitida, N. antarctica, N. pumilio*) and *N. obliqua* type (*N. obliqua). N. dombeyi* type pollen grains possess annular thickenings associated with the germinal apertures, while those of *N. obliqua* type, lacking thickenings, are simply colpate or appear inaperturate. The aquatic, *Myriophyllum*, resembling *Nothofagus* to some extent, has pore-like, circular to elliptical apertures and psilate–scabrate sculpture, whereas pores of *Nothofagus* are elongate, and exine is microechinate.

Pilgerodendron type applies to inaperturate grains (< 45 μm) of apparent gymnospermous affinity, represented by *P. uviferum*, *Fitzroya cupressoides,* and *Austrocedrus chilensis*. The designation "cf" is used where identity can only be implied, for example, cf *Perezia,* which is not readily distinguished from its allies, *Nassauvia and Leucheria*, of the family Compositae (composite). In cases where two genera or taxa are so much alike as to be indistinguishable, they are hyphenated (*Eucryphia-Caldcluvia*). A special case is *Empetrum*-Ericaceae (heath), where Ericaceae, normally psilate in contrast to densely foveolate *Empetrum*, are at times not clearly identifiable because of apparent differential effects of chemical processing on the exine. A similar problem resides with *Lomatia*, which may include family-related *Gevuina* (Proteaceae).

The multi-member myrtle family, aside from the singular dicolporate species, *Tepualia stipularis*, is undifferentiated. Future differentiation of genera/species in the family seems realistic by means of subtle exine sculpturing patterns. Recent study of genera and species growing in southern Chile recorded morphological differences among *Amomyrtus, Luma, Ugni, Myrteola*, and some species of *Myceugenia* (Zhou and Heusser 1996). Other undifferentiated taxa include Gramineae (grass family), Chenopodiaceae, Caryophyllaceae, Umbelliferae, Ericaceae, Rubiaceae, Liguliflorae-Tubuliflorae (composite tribes), Cyperaceae (sedge family), Ranunculaceae, Hymenophyllaceae, and Filicinae (class of ferns).

Plant nomenclature follows Muñoz (1980), supplemented by Marticorena and Quezada (1985), except for ferns, fern allies, and gymnosperms, where adherence is to Marticorena and Rodríguez (1995).

Vegetation reconstruction and paleoclimate

Multiple fossil pollen records of corresponding time intervals in the Southern Lake District–Isla Grande de Chiloé serve to reconstruct the overall makeup and character of late Pleistocene vegetation. Peak frequencies of taxa, reflecting relative pollen production versus local/regional presence, follow the sequence of developing plant communities. Most trees and shrubs appear to produce small amounts of pollen, are not wind pollinated, and for this reason generally are not well-represented in the records. Adaptation to wind pollination by heightened pollen production accounts for high frequencies of *Nothofagus*, Gramineae, Cyperaceae, *Gunnera, Tetroncium,* and among the gymnosperms, *Lepidothamnus, Podocarpus, Saxegothaea,* and *Pilgerodendron* type. Anemophily underlies the greater representation of these taxa by comparison to plants adapted to pollination by insects. Equipped with sac-like appendages, pollen of *Podocarpus* and *Lepidothamnus* is readily dispersed by regional air currents. Where frequencies of taxa pollinated other than by wind are high, as exemplified by the Myrtaceae, *Drimys*, and *Pseudopanax*, the inference is of species locally in numbers with abundant inflorescences. Local presence also is inferred where there are considerable quantities of species, whose flowers with exerted, or freely disposed stamens, including *Empetrum*, Tubuliflorae, and *Valeriana*, partially disperse pollen by wind.

Frequencies of Gramineae, Tubuliflorae, and Filicinae, taxa adapted to heightened light intensity, reflect a source in open ground, the amount of openness dictated by relative frequencies of the associated arboreal component. From the proportion of Gramineae, *Empetrum*-Ericaceae, and Tubuliflorae relative to *Nothofagus*, vegetation during the full glacial is seen to range from tundra to a variable patchwork of wooded parkland. Conversely, late-glacial prevalence of shade-tolerant, arboreal taxa, *Laurelia,* Myrtaceae *(Amomyrtus, Myrceugenia)*, and *Podocarpus*, infers closely canopied forest stands in existence for extended intervals. Where charcoal is recorded at the close of the late glacial, the indication is of fire creating openings in the forest and providing a pathway for invasion of intolerant, opportunistic taxa, exemplified by *Weinmannia* and *Hydrangea*.

In the case of multiple species under the category of pollen type, certain assumptions can be made regarding species identification. For *Nothofagus dombeyi* type, pollen data during the full glacial imply the presence of *N. betuloides*, a species of cool, humid provenience at higher latitudes; *N. dombeyi* and/or *N. nitida*, less cold tolerant, are implied under the moderated climate of deglaciation. Similar logic applies to the identity of *Pilgerodendron* type, which under full glacial conditions is indicative of *P. uviferum* and during the late glacial equally to *Fitzroya cupressoides*.

Modern analogs of vegetation portrayed by fossil pollen assemblages are recognizable except for Subantarctic Parkland. Although not a distinctive vegetation type of present-day southern Chile, parkland of *Nothofagus* and Gramineae characterized the outwash plains of the Southern Lake District–Isla Grande de Chiloé for millennia during the full glacial. Changing frequencies of *Nothofagus* recorded by the vegetation mosaic serve to reflect treeline fluctuations, as climate favored or restricted arboreal communities. Estimates of temperature changes, implied from data gathered in the vicinity of the modern treeline, apply to the full glacial. Species belonging to Magellanic Moorland–Andean treeline/tundra, such as *Lepidothamnus, Donatia*, *Astelia, Drapetes, Gaimardia, Euphrasia,* and *Huperzia*, suffice as cold climatic indicators.

Climatic parameters for the time of record derive from conditions that at present influence the performance of the same taxa that occur as fossils. This uniformitarian approach toward reconstructing climate is not without uncertainties but provides a measure of insight for explaining conditions of the Pleistocene. Meteorological data with emphasis on precipitation relative to temperature (Almeyda and Sáez 1958; Miller 1976; Prohaska 1976) are generally restricted to station observations at or near sea level, leaving conditions in the cordillera and other remote sectors subject to estimation by interpolation or use of temperature lapse rates.

Pollen and spore records: age and stratigraphy

Pollen and spore stratigraphic records derive from 15 late-glacial–full-glacial deposits of interdrift organic silt and cores of mires penetrating lacustrine sediments that rest on drift of the Lago Llanquihue, Seno Reloncaví, Golfo de Ancud, and Golfo Corcovado piedmont lobes. Table 2 gives location coordinates, elevations, and lobe designations for each site. Records include identification designa-

Table 2. Sites and locations of stratigraphic pollen records in relation to piedmont lobes. (See Fig. 1 for locations).

Lobe	Site	Core	Coordinates	Elevation (m)
Lago Llanquihue lobe	Exposures			
	Puerto Octay		40°58'25"S, 72°53'50"W	100
	Frutillar Bajo		41°08'10"S, 73°01'10"W	100
	Llanquihue		41°16'15"S, 72°59'05"W	55
	Bella Vista Bluff		41°18'55"S, 72°58'40"W	70
	Mires			
	Fundo Llanquihue	HE94-9A	41°13'40"S, 73°03'40"W	110
	Fundo Liña Pantanosa	HE93-6B	41°05'05"S, 73°00'40"W	170
Seno Reloncaví lobe	Exposures			
	Punta Penas		41°29'00"S, 72°53'45"W	10
	Canal Tenglo		41°28'56"S, 72°58'45"W	75
	Mires			
	Alerce	HE93-3B	41°23'38"S, 72°52'45"W	130
	Fundo Santa Elena	HE94-3B	41°30'00"S, 73°06'13"W	110
	La Campana	HE94-4A	41°37'43"S, 73°11'40"W	100
Golfo de Ancud lobe	Mire			
	Taiquemó	HE94-2B	42°10'25"S, 73°35'50"W	170
Golfo Corcovado lobe	Exposures			
	Teguaco		42°17'55"S, 73°35'30"W	100
	Dalcahue		42°20'28"S, 73°39'10"W	135
	Mire			
	Mayol	HE95-2A	42°38'35"S, 73°45'35"W	75

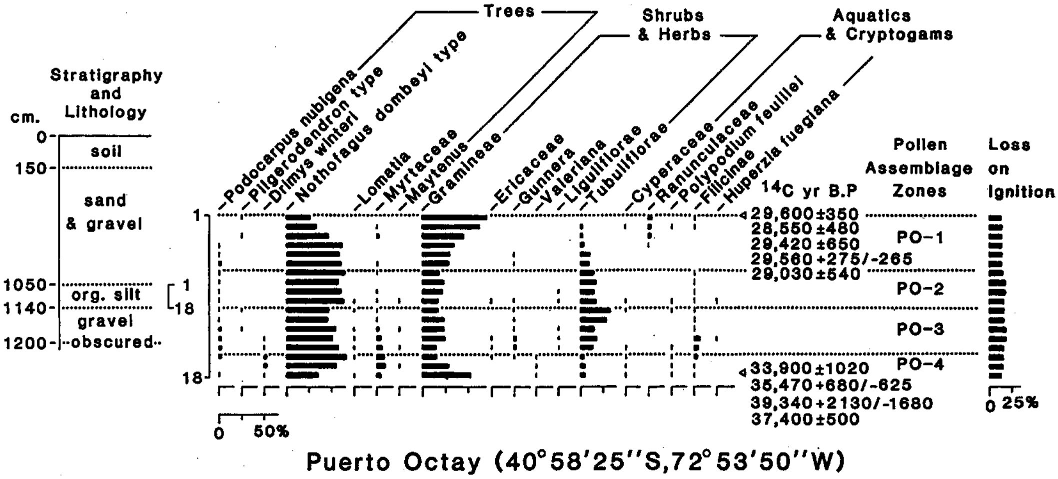


Fig. 8. Pollen and spore diagram of organic silt in road-cut exposure at Puerto Octay, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 3).

tions (HE series) for cores archived and stored in the Core Laboratory at Lamont-Doherty Earth Observatory of Columbia University. See Denton *et al.* (1999b) for lithostratigraphic and chronostratigraphic background on interdrift deposits.

Lago Llanquihue lobe

Puerto Octay. A road cut at Puerto Octay exposes a 90-cm-thick organic silt derived from pyroclastic flow material between units of outwash sand and gravel (Fig. 8). The site, on Route V-55-U about 1 km southwest of Puerto Octay, is just in front of an ice-contact slope, where the Lago Llanquihue lobe rested at times of maxima (Lowell *et al.* 1995). Radiocarbon ages of between 39,340 and 33,900 yr BP from the base of the silt post-date an older glacial maximum, while ages of 29,600–28,550 yr BP at the top closely date the younger maximum. The range of ages implies non-glacial conditions at the site for at least 10,000 ^{14}C years.

Pollen assemblages (Table 3 and Fig. 8) for the organic silt are predominantly of *Nothofagus dombeyi* type (maximum 66%). Gramineae are of greater importance both at the beginning (52%) and end of the record (70%) in zones PO-4 and PO-1; Tubuliflorae are important (33%) midway in the sequence in zones PO-3 and PO-2. Of note, in ad-

Table 3. Pollen assemblage and chronostratigraphic data for Puerto Octay road-cut exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
PO-1 (1055–1080 cm)	Gramineae-*Nothofagus*	29,600±350 (QL-1338) 28,550±480 (UGA-6930) 29,420±650 (UGA-6932) 29,560+275/-265 (A-7667) 29,030±540 (QL-4538)
PO-2 (1080–1100 cm)	*Nothofagus*-Gramineae-Tubuliflorae	
PO-3 (1100–1125 cm)	*Nothofagus*-Tubuliflorae-Gramineae	
PO-4 (1125–1140 cm)	*Nothofagus*-Gramineae-Myrtaceae-*Drimys*	33,900±1020 (QL-4537) 35,470+680/-625 (A-7664) 39,340+2130/-1680 (UGA-6926) 37,400±500 (QL-1339)

dition, are minor but significant percentages of *Drimys winteri* and Myrtaceae (zone PO-4), Filicinae (zone PO-3), and *Podocarpus nubigena* (especially zone PO-3).

The pollen sequence serves as a model of vegetational change associated with shifting stadial–interstadial–stadial climate. Vegetation implied by the data is of Subantarctic Parkland, wherein openness, as shown by higher percentages of grass and Tubuliflorae, is featured at the start, midway, and at the end of the sequence. Interstadial conditions are evident from the many levels with >50% southern beech, which include a primary increase of *Drimys* and myrtle. At the height of the interstade (zone PO-2), parkland west of Lago Llanquihue consisted of beech, broken in its extent by lesser communities of grass and composite. A trend of scaled-down beech at the expense of increasing grass (zone PO-1) closes the record. Beech, falling to 25% of the pollen sum, implies reduction of the tree population and colder/windier climate with proximity of the Lago Llanquihue lobe.

Loss on ignition is at 12–16% for the organic silt. Values only slightly higher in mid section are inclined to conform with trends expressed by the vegetation, indicating only minimal change in organic content over the time of record.

Frutillar Bajo. An exposure on the upper ice-contact slope of the Lago Llanquihue lobe at Frutillar Bajo occurs along a side road off Route V-155, about 1.5 km south of the intersection of Route V-25. A 95-cm-thick organic silt, composed of pyroclastic flow material (Fig. 9), is dated 36,960–34,765 ^{14}C yr BP at the base and 26,940 ^{14}C yr BP at the top. The silt was deposited for at least 10,000 ^{14}C years, as at Puerto Octay, but deposition appears to have started later and continued for nearly 3000 ^{14}C years longer. The date of 26,940 ^{14}C yr BP, the error-weighted mean of 13 dates from the top of the unit, constrains the age of the glacier that subsequently overrode the site and laid down >5 m of overlying till (Lowell *et al.* 1995). Silt at Frutillar Bajo, with a 12–20% loss on ignition, is not unlike the silt deposit at Puerto Octay.

Pollen assemblages (Table 4 and Fig. 9) record diminution of *Nothofagus* and expanse of Gramineae in Subantarctic Parkland. *Nothofagus dombeyi* type averages 50% and Gramineae 41% at lower levels (zones FB-4 and FB-3); at upper levels (zones FB-2 and FB-1), averages, respectively, are 35 and 57%. Interrupting the trend are intervals containing Tubuliflorae (zones FB-4 and FB-2), when communities, altered by episodes of disturbance, were less stable.

Frutillar Bajo lithostratigraphy includes thick till deposited during expansion of the Lago Llanquihue lobe at 26,900 ^{14}C yr BP. Evidence of cold, stadial climate at the time of lobe expansion is seen in the reduction of beech and rise of grass in the uppermost silt (zone FB-1). If evidence for earlier expansion of the lobe is contained in the record at Frutillar Bajo, which at Puerto Octay dates at 29,400 ^{14}C yr BP, it most probably is registered by the fluctuations of grass and composite at midsection (zones FB-3 and FB-2).

A special feature of the organic silt is the presence of zygospores of the alga *Debarya* of the family Zygnemataceae. The spores, originally found to occur in the northern Andes in lake sediments dated between 30,000 and 10,000 ^{14}C yr BP (Van Geel and Van der Hammen 1978), were reported previously from shallow-water lake sediments in the northern part of the Lake District (Heusser 1984). *Debarya* is known also from periodically inundated soil in Europe (Ellis and Van Geel 1978). At Frutillar Bajo, intermittently muddy and poorly drained silty soil, in the absence of aquatic seed plants, likewise apparently afforded a suitable habitat for *Debarya* in cold, humid Subantarctic Parkland.

Llanquihue. A 35-cm-thick lakeside exposure of organic silt (Fig. 10) at the southern edge of the town of Llanquihue rests beneath stratified sand and gravel of an ice-marginal terrace. The silt dates from 15,370 ^{14}C yr BP; an age of 14,890 ^{14}C yr BP for wood at the top of the silt, the error-weighted mean of eight radiocarbon dates, marks the beginning of terrace formation by outwash issued from the proximal Lago Llanquihue lobe (Lowell *et al.* 1995). The silt, containing an abundance of aquatic *Isoetes savatieri* and Cyperaceae, apparently was deposited in a shallow lagoon fronting the lakeshore. Over the time of deposition, organics in the silt, as shown by loss on ignition measurements, increased from a low of 7–9% at depth to 32% at the top.

Gramineae average 39% of the pollen sum and *Nothofagus dombeyi* type 20%, supplemented essentially by *Gunnera, Valeriana*, and Compositae (Tubuliflorae, cf *Perezia*, and Liguliflorae). The record consists of two assemblages (Table 5) in which the principals are bound to *Gunnera* and *Valeriana* at first (zone LL-2) and later to Tubuliflorae (zone LL-1). The assemblages, covering an interval of Subantarctic Parkland of grass and com-

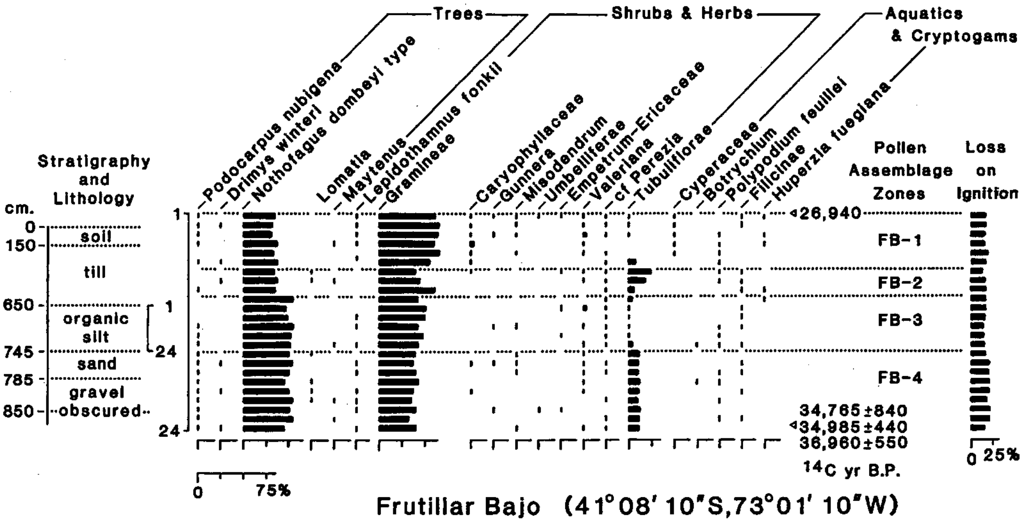


Fig. 9. Pollen and spore diagram of organic silt in road-cut exposure at Frutillar Bajo, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 4).

posite among patches of beech, antedate the proximal position of the Lago Llanquihue lobe at the site.

Bella Vista Bluff. Organic silt 15 cm thick occurs interbedded with laminated silt and clay at Bella Vista Bluff in Puerto Varas (Fig. 11). The silt, as in the case of the lacustrine sediments at Llanquihue, is similarly attributed to the presence nearby of the Lago Llanquihue lobe. The deposit, exposed along the cliff at Calle Maipo, forms part of an ice-contact terrace subsequently covered by debris flows of volcanic material. The flows, which are believed to have originated on the slopes of Volcán Calbuco (Fig. 1), 30 km east of Puerto Varas, buried the terrace as they spread, confined at the edge of the Lago Llanquihue lobe, to the lake outlet at Río Maullín (Porter 1981). A weighted mean age of 14,620 ^{14}C yr BP at the top of the organic silt layer and ages of 15,635 and 15,730 ^{14}C yr BP in the basal portion date an interval when glaciolacustrine sedimentation from the nearby ice front was interrupted. An unusually small loss on ignition, averaging 7%, characterizes the organic silt.

Average 15% *Nothofagus dombeyi* type and >50% Gramineae at Bella Vista Bluff, compared with 20% and 39%, respectively, at Llanquihue, are indicative of arboreally restrictive, cold climate, by

Table 4. Pollen assemblage and chronostratigraphic data for Frutillar Bajo road-cut exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
FB-1 (650–674 cm)	*Gramineae-Nothofagus*	26,940[1]
FB-2 (674–686 cm)	Gramineae-Tubuliflorae-*Nothofagus*	
FB-3 (686–710 cm)	*Nothofagus*-Gramineae	
FB-5 (710–745 cm)	*Nothofagus*-Gramineae-Tubuliflorae	34,765±840 (UGA-6945) 34,985±440 (UGA-6919) 36,960±550 (UGA-6724)

[1] Error-weighted mean of 13 radiocarbon dates on grass and litter (see Lowell *et al.* 1995).

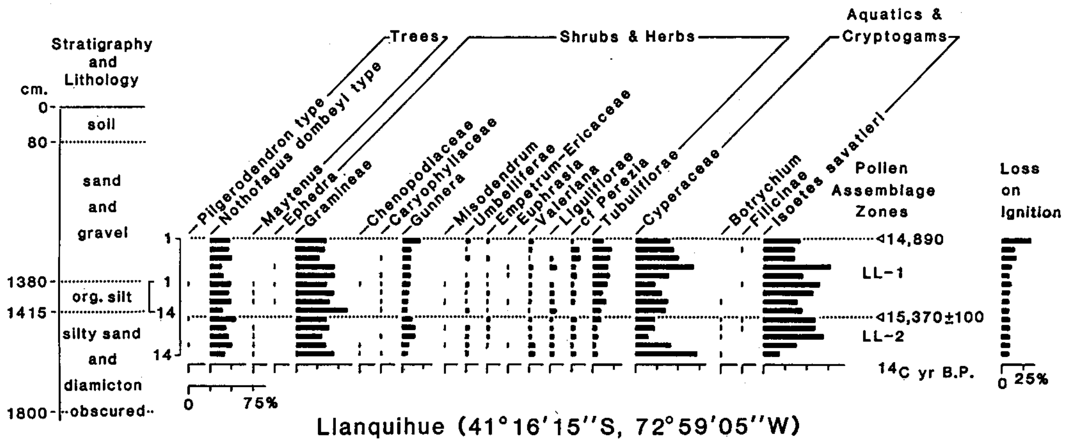


Fig. 10. Pollen and spore diagram of organic silt in lakeside exposure at Llanquihue, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 5).

which the forward position of the Lago Llanquihue lobe apparently was maintained. Pollen assemblages (Table 6), in addition to *N. dombeyi* type and the consistent pre-eminence of Gramineae, feature Tubuliflorae with *Gunnera* and *Valeriana* early in the record (zone BVB-1) and Tubuliflorae with *Valeriana* during the remainder (zone BVB-2). Vegetation on the surrounding terrain is seen as grass-dominated Subantarctic Parkland dotted with small tracts of beech.

Fundo Llanquihue (HE-93-9A). The mire at Fundo Llanquihue with an area estimated at 1.5 ha is the source of a pair of pollen records spanning >10,000 ^{14}C years of the full glacial, late glacial, and early Holocene. The first record (Fig. 12), obtained from a core studied at 5-cm sampling intervals, is initially reported; the second record at 1-cm intervals (Fig. 13) emphasizes the value of high-resolution sampling.

The mire is located 5 km west of Lago Llanquihue along a backroad originating on Route V-500, just inside the moraine formed during maximum extension of the Lago Llanquihue lobe at 22,400 ^{14}C yr BP. The >700-cm core, radiocarbon-dated at 23 levels, consists mostly of lacustrine sediments, which above a depth of 245 cm become peaty (Fig. 12). Vascular aquatics in the sediments are predominantly *Isoetes savatieri* with minor amounts of *Myriophyllum* and *Littorella*; among the algae, *Pediastrum, Botryococcus,* and *Debarya* show wide distribution.

The uppermost 60 cm of core are early Holocene in age on the basis of three dates, 9195, 9155, and 9400 ^{14}C yr BP (UGA-6891, 6893, and 6894, respectively), which bracket a 10-cm-thick, regionally distributed tephra layer. The oldest pollen-bearing sediments, resting on sand, range in age between 20,890 and 20,455 ^{14}C yr BP. These sediments derive from a pyroclastic flow that apparently occurred during a brief interval at the time of deglaciation. Measurements of loss on ignition below a depth of 245 cm are 2–17%; higher in the core, values jump to ≥44% and reach close to 100% at

Table 5. Pollen assemblage and chronostratigraphic data for Llanquihue lakeside exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
LL-1 (1380–1403 cm)	Gramineae-Tubuliflorae–*Nothofagus*	14,890[1]
LL-2 (1403–1415 cm)	Gramineae-*Nothofagus-Gunnera-Valeriana*	15,370±100 (15 cm, AA-20379R)

[1] Error-weighted mean of eight radiocarbon dates on wood (see Lowell et al. 1995).

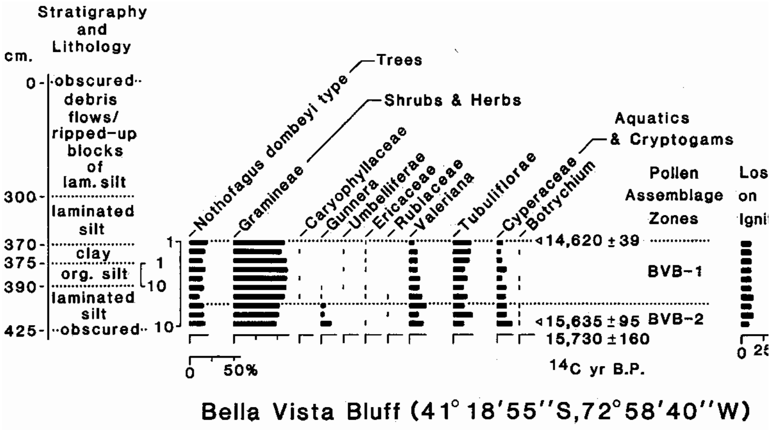


Fig. 11. Pollen and spore diagram of organic silt in lakeside exposure at Bella Vista Bluff, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 6).

the upper three levels. The sharp rise in values at 245 cm corresponds with depositional and apparent successional changes in aquatic communities occupying the basin. *Isoetes*, characteristic of open water, is virtually replaced by Cyperaceae at about 16,575 ^{14}C yr BP during incipient mire formation; later, at 13,545–12,955 ^{14}C yr BP, there is further transition from Cyperaceae to *Empetrum*-Ericaceae (heath). Charcoal contained in the upper 100 cm of core, a registry of the first recorded fires, dates no earlier than 10,810 ^{14}C yr BP.

The pollen record (Fig. 12), exclusive of the Holocene, is divided into eight assemblage zones (Table 7). Nearly identical radiocarbon dates (within statistics) for six levels make the earliest interval of short duration, lasting no more than a few centuries and probably less. The interval traces deglacial herb-shrub communities and a variable component (average 17%) of *Nothofagus dombeyi* type. Herb-shrub taxa are initially Gramineae (average 43%) mixed with lesser amounts of *Gunnera, Empetrum*-Ericaceae, Tubuliflorae, *Lepidothamnus fonkii,* Caryophyllaceae, and *Valeriana* (zone FL-8); subsequently (zone FL-7), as a result of increase of *Nothofagus* (56%), all taxa decline except *Empetrum*-Ericaceae, which remain the chief associate of Gramineae (25%).

Rapidly moderating climate, indicated by the short-term build-up of *Nothofagus*, followed the maximum of the Lago Llanquihue lobe. Frequencies of *Nothofagus* reach 82% and endure at levels >50% for four millennia, supplemented by Gramineae (zone FL-6). High frequencies associated with Subantarctic Parkland suggest patchy, open-grown *Nothofagus* with pollen productivity higher than in closed stands. While climate continued to be moderated but cool during this interval, no known glacial maxima were registered. Except for a pulse in Gramineae of 53–58% at 16,575–16,070 ^{14}C yr BP and another of 39–42% at 14,470–14,055 ^{14}C yr BP (zones FL-5 and FL-4), *Nothofagus* was dominant from >20,000 until 13,545 ^{14}C yr BP (zone FL-3). The pulses, as episodes of transitory diminution of *Nothofagus*, are together with subantarctic *Euphrasia* and *Huperzia fuegiana* (zone FL-4) apparent responses to colder climate. Conditions prevailing at these times conceivably underlie the change in regimen that preceded a

Table 6. Pollen assemblage and chronostratigraphic data for Bella Vista Bluff lakeside exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
BVB-1 (375-386 cm)	Gramineae-Tubuliflorae-*Valeriana-Nothofagus*	14,620±39[1]
BVB-2 (386–390 cm)	Gramineae-Tubuliflorae-*Valeriana-Gunnera-Nothofagus*	15,635±95 (A-8550) 15,730±160 (A-9190)

[1] Error-weighted mean of six radiocarbon dates (Denton *et al.* 1999b).

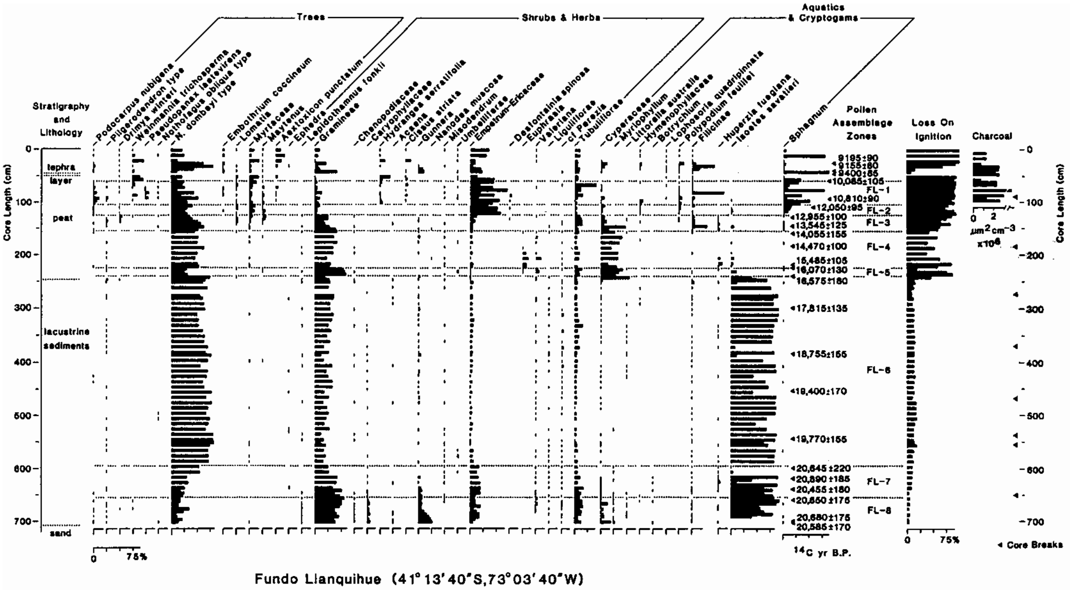


Fig. 12. Pollen and spore diagram of core taken in mire at Fundo Llanquihue sampled at 5-cm intervals and subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 7).

known advance and maximum of the Lago Llanquihue lobe at 14,800 ^{14}C yr BP. The pulse in Gramineae represented by zone FL-5, together with peak Cyperaceae, is possibly a manifestation, at least in part, of mire formation and peat deposition, following lacustrine sedimentation.

At about 14,000 ^{14}C yr BP, *Nothofagus* reexpanded in the course of late-glacial woodland transition, followed at 13,000 ^{14}C yr BP by an influx and rise of thermophilous North Patagonian Evergreen Forest taxa, Myrtaceae, *Drimys winteri, Lomatia*, and *Maytenus* (zone FL-3), which, heretofore, were only occasionally recorded in trace amounts. Under an unprecedented warming trend, peak Myrtaceae are registered at 12,000 ^{14}C yr BP (zone FL-2). *Empetrum*-Ericaceae form what is presumed to have been site-restricted heathland that remained in place until the end of the late glacial.

After 12,000 ^{14}C yr BP, a reversal of the trend is implied by expansion of cold-tolerant *Podocarpus nubigena* and *Pseudopanax laetevirens* (zone FL-1). These indicators of subantarctic affinity are at Fundo Llanquihue not far from the northern extent of their present-day ranges (Rodríguez *et al.* 1983; Marticorena and Rodríguez 1995). Consequently, their representation is comparatively poor. But as will be seen in records from sites to the south at Alerce (Fig. 17), Fundo Santa Elena (Fig. 18), and Mayol (Fig. 24), for example, frequencies are much higher. Changes in the pollen record at 10,085 ^{14}C yr BP and thereafter are identified by irregular amounts of *Weinmannia trichosperma, N. dombeyi* type, *Myrtaceae, Aextoxicon punctatum,* and *Hydrangea serratifolia,* an apparent response to fire disturbance indicated by an abundance of charcoal.

The record generated at 1-cm intervals (Fig. 13) gives a resolution of <100 ^{14}C years between levels, offering in comparison with the 5-cm pollen record far greater detail. Peaks of taxa, for example, become more pronounced when displayed through 1-cm-spaced levels versus only a few, affording a comprehensive measure of insight regarding the significance of an event. Where peaks relative to the 5-cm stratigraphy have shifted, the changes necessitated alteration of pollen zone boundaries. The added detail in the record has also required some subdividing of established zones. By subdividing zones FL-8 and FL-1 at Fundo Llanquihue, renumbering of the zones has been avoided.

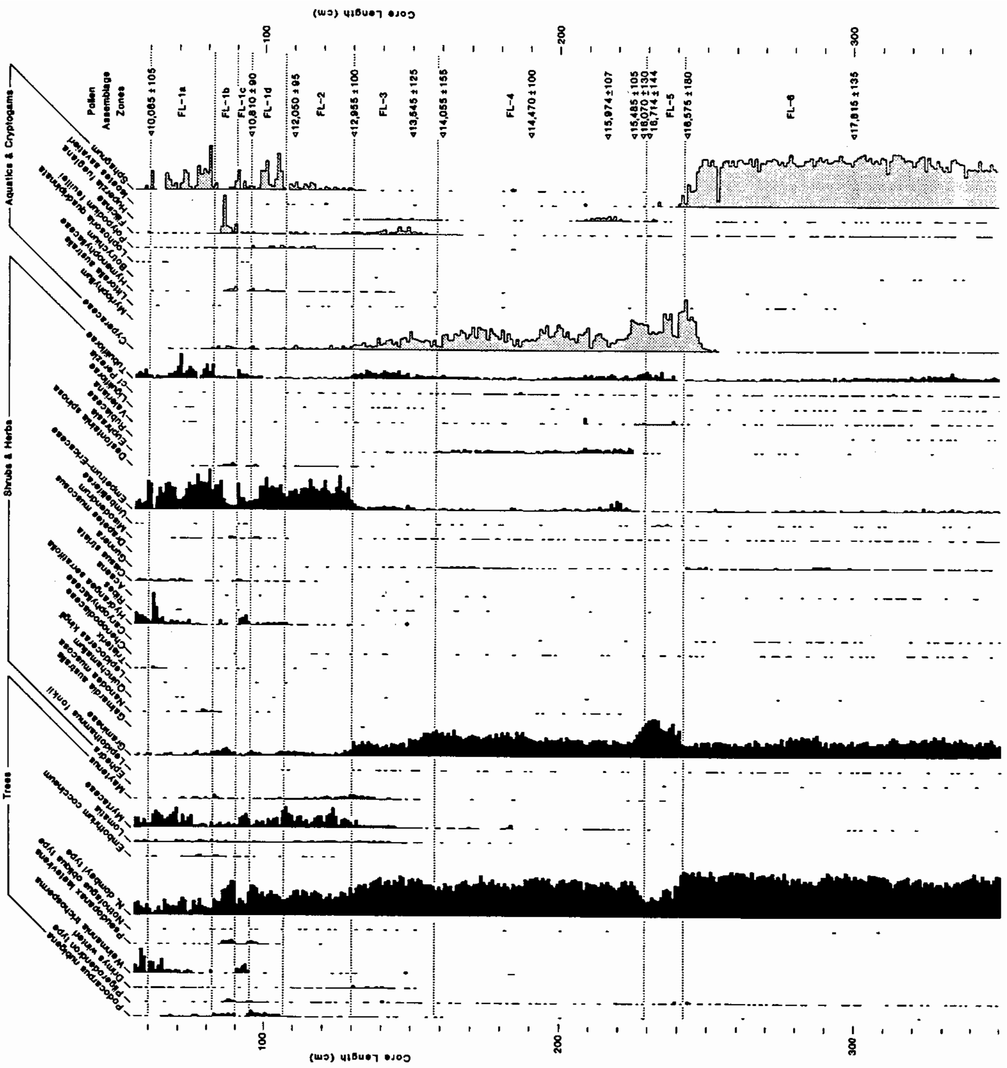
Zone FL-8 and subdivisions 8d–8a clearly display short-term pulses of *Nothofagus* that interrupt most noticeably the integrity of *Gunnera* and *Empetrum*-Ericaceae. The pulses likewise appear to bear on the performance of *Isoetes*, creating the im-

Table 7. Pollen assemblage and chronostratigraphic data for core from Fundo Llanquihue mire.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
FL-1a (60–82 cm)	*Empetrum*-Ericaceae-Tubuliflorae-Myrtaceae-*Nothofagus*-*Weinmannia*	10,085±105 (60 cm, UGA-6895)
FL-1b (82–90 cm)	*Nothofagus*-*Pseudopanax*-*Podocarpus*-Gramineae-*Empetrum*-Ericaceae	
FL-1c (90–95 cm)	*Weinmannia*-*Nothofagus*-Myrtaceae-*Hydrangea*-*Empetrum*-Ericaceae-Tubuliflorae	
FL-1d (95–107 cm)	*Nothofagus*-*Podocarpus*-*Pseudopanax*-Myrtaceae-*Empetrum*-Ericaceae	10,810±90 (95 cm, UGA-6896)
FL-2 (107–130 cm)	Myrtaceae-*Nothofagus*-*Lomatia*-*Maytenus*-*Empetrum*-Ericaceae	12,050±95 (110 cm, UGA-6897)
FL-3 (130–158 cm)	*Nothofagus*-Gramineae-Tubuliflorae-*Lomatia*-*Maytenus*	12,955±100 (130 cm, UGA-6898) 13,545±125 (150 cm, UGA-6899)
FL-4 (158–229 cm)	*Nothofagus*-Gramineae-*Euphrasia*-*Empetrum*-Ericaceae-Tubuliflorae	14,055±155 (160 cm, UGA-6900) 14,470±100 (190 cm, AA-15892) 15,974±107 (216 cm, AA-19444R) 15,485±105 (225 cm, AA-15893)
FL-5 (229–242 cm)	Gramineae-Tubuliflorae-*Nothofagus*	16,070±130 (228 cm, UGA-6901) 16,714±144 (230 cm, AA-19447)
FL-6 (242–600 cm)	*Nothofagus*-Gramineae-Tubuliflorae	16,575±180 (243 cm, UGA-6902) 17,815±135 (300 cm, AA-15894) 18,755±155 (384 cm, UGA-6904) 19,400±170 (460 cm, UGA-6905) 19,770±155 (542 cm, UGA-6906)
FL-7 (600–676 cm)	Gramineae-*Nothofagus*-*Gunnera*-*Empetrum*-Ericaceae-Tubuliflorae	20,645±220 (600 cm, UGA-6907) 20,890±185 (620 cm, UGA-6908) 20,455±180 (640 cm, UGA-6909) 20,650±175 (660 cm, UGA-6910)
FL-8a (676–686 cm)	*Nothofagus*-Gramineae-Tubuliflorae	
FL-8b (686–693 cm)	Gramineae-*Gunnera*-*Empetrum*-Ericaceae-Tubuliflorae-*Nothofagus*	
FL-8c (693–696 cm)	Gramineae-*Nothofagus*-*Gunnera*-Tubuliflorae	
FL-8d (696–707 cm)	Gramineae-*Gunnera*-*Empetrum*-Ericaceae-Tubuliflorae-*Nothofagus*	20,680±175 (700 cm, UGA-6912) 20,585±170 (701 cm, UGA-6913)

pression that there may be a tie-in with hydrological changes taking place on the unstable, newly deglaciated ground. Readily apparent is the fact that climatic/edaphic conditions early in the record were not restrictive to *Nothofagus*, which at times was able to gain ≥50% of the pollen sum soon after withdrawal of the Lago Llanquihue lobe. Periodically impeded at the beginning (zone FL-8), *Nothofagus* in Subantarctic Parkland ultimately increased steadily to dominance (zone FL-7), which continued without interruption until Gramineae, producing brief, conspicuously high frequencies (maximum of 60%), became prominent at 16,714–16,575 ^{14}C yr BP (zone FL-5).

After 16,000 ^{14}C yr BP, during lengthy tenure of the cold indicator *Euphrasia* (zone FL-4), Gramineae-*Nothofagus* ratios are highest at 14,470–14,055 ^{14}C yr BP (zone FL-4), coincident with the final maximum of the Lago Llanquihue lobe. Subsequently, Gramineae lost their position of prominence, while *Nothofagus* increased for a time before being modified by quantities of *Drimys, Lomatia*, Myrtaceae, and *Maytenus* (zone FL-3). Taking place for just over a millennium, dating until 12,955 ^{14}C yr BP, the invasion of taxa of the developing North Patagonian Evergreen Forest coincided with collapse of the lobe. Under continued warming until about 12,000 ^{14}C yr BP (zone FL-2), Myrtaceae gain frequencies



as high as 35–37%, before giving way during a cooling trend to increased *Nothofagus, Podocarpus,* and *Pseudopanax* (zones FL-1d and FL-1b). Diverse assemblages interrupting and following the course of cooling (zones FL-1c and FL-1a) appear chiefly to be the result of burning (charcoal recorded in FL-1, Fig. 12). Note is taken of epiphytic *Polypodium feuillei* and Hymenophyllaceae, which substantiate high levels of humidity in the late-glacial forest at Fundo Llanquihue and other sites.

Fundo Liña Pantanosa (HE-93-6B). Because of its location in the outer part of the moraine belt, Fundo Liña Pantanosa, 17 km north-northeast of Fundo Llanquihue, was cored with a view toward further substantiating the full-glacial–late-glacial pollen stratigraphy and chronology related to wastage of the Lago Llanquihue lobe. Approximately 1 ha in area, the locality is ≤ 1 km south on a backroad that runs off of Route V-55U, 5 km northeast of Frutillar Alto. Lacustrine sediments contain much *Isoetes* and occasionally *Debarya* before undergoing succession, in turn, by Cyperaceae and *Empetrum*-Ericaceae during conversion

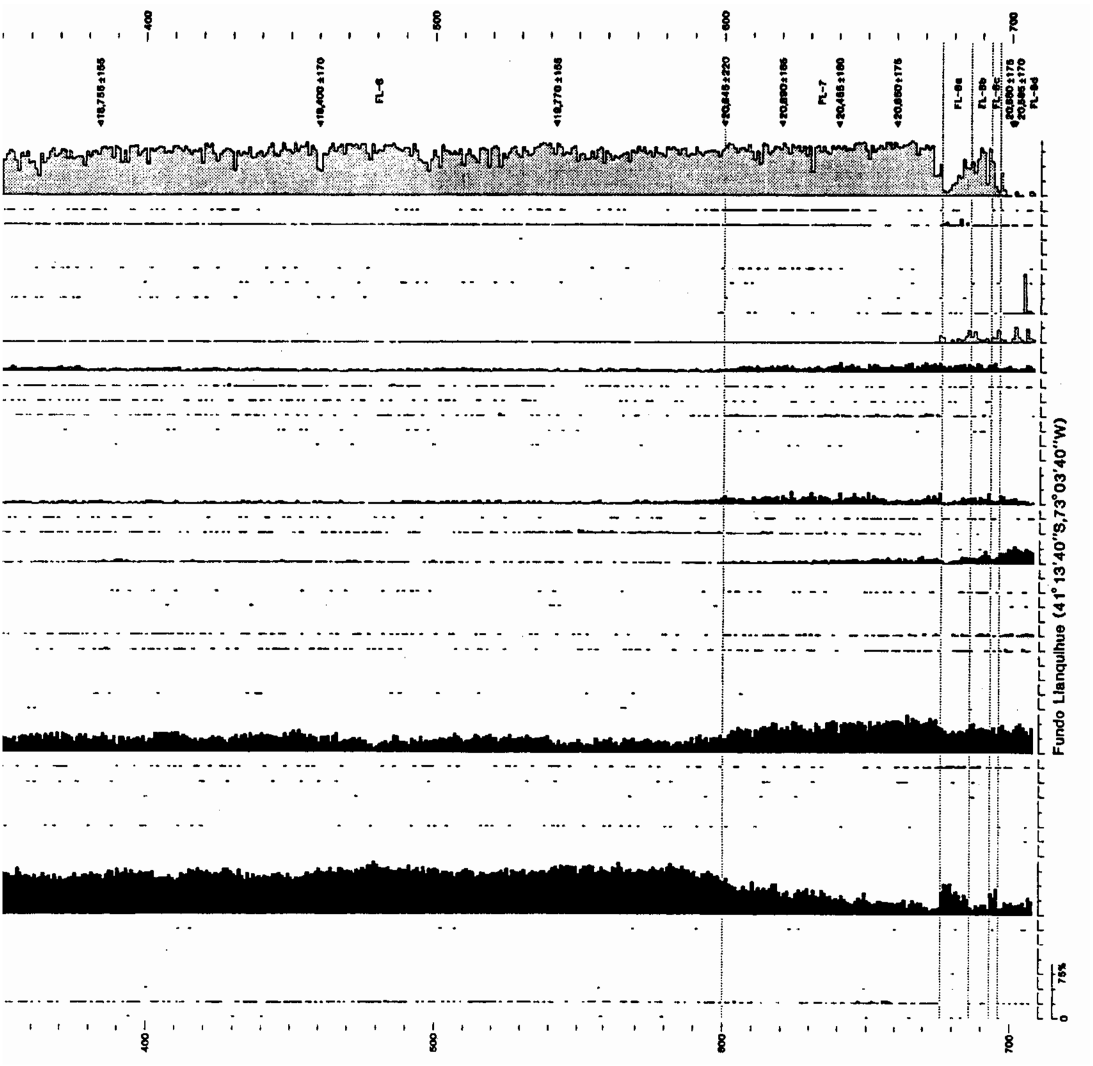


Fig. 13. Pollen and spore diagram of core taken in mire at Fundo Llanquihue sampled at 1-cm intervals and subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 7).

of open water to mire. The age of 19,993 ^{14}C yr BP for the base of the core at Fundo Liña Pantanosa is close to the age of just over 20,000 ^{14}C yr BP for Fundo Llanquihue.

The pollen record at 10-cm sampling intervals from the 350-cm-length of core (Fig. 14) contains the basic features observed in the refined record at Fundo Llanquihue (Fig. 13). Pollen assemblages (Table 8) and trends are, fundamentally, a match throughout, while abundances of taxa vary. A similar initial grouping of Gramineae with *Gunnera* (zone FLP-6) and with *Empetrum*-Ericaceae and Tubuliflorae later (zone FLP-5) is apparent, as well as the shift to *Nothofagus* dominance after 19,768 and before 18,471 ^{14}C yr BP (zone FLP-4). Strong domination of *Nothofagus* (maxima of >75%) in association with Gramineae (maxima of >20%) conveys the importance of arboreal communities in the surrounding Subantarctic Parkland. Transition of parkland to North Patagonian Evergreen Forest (zone FLP-3), beginning at 14,215 ^{14}C yr BP and coincident with the decline of the Gramineae, coincides with the appearance of *Drimys, Lomatia*, Myrtaceae, and *Maytenus*.

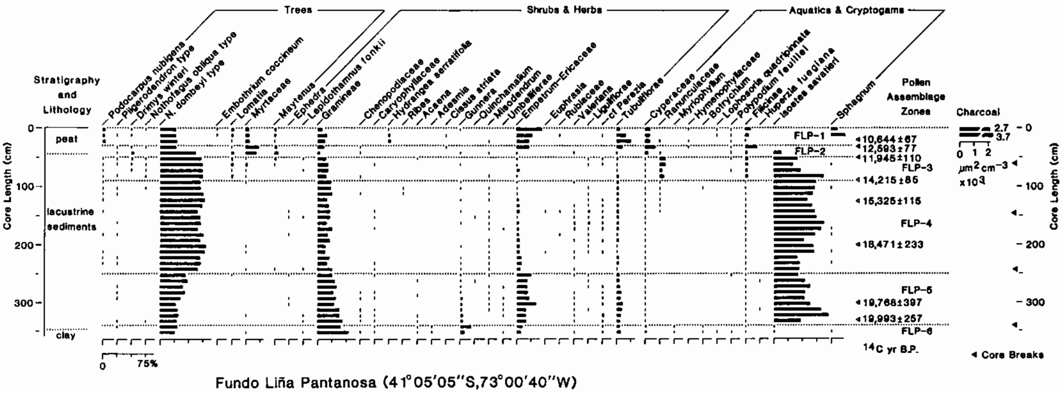


Fig. 14. Pollen and spore diagram of core taken in artificially drained mire at Fundo Liña Pantanosa, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 8).

Data imply an unprecedented warming trend (zone FLP-3), culminating with the short episode of peak Myrtaceae at 12,593–11,945 ^{14}C yr BP (zone FLP-2), and later, a reversal of trend suggested by the presence of *Podocarpus* (zone FLP-1). After 10,644 ^{14}C yr BP, while fire is evident from the quantity of charcoal deposition, there is no clear indication of resulting community change.

Noteworthy in the low-resolution data at Fundo Liña Pantanosa is the absence of significant, short-term changes that with greater resolution are shown to occur at Fundo Llanquihue. Not evident, for example, is the increase in Gramineae, lasting no more than centuries, at 16,714–16,575 ^{14}C yr BP (zone FL-5; Fig. 13).

Seno Reloncaví lobe

Punta Penas. The seacliff facing Seno Reloncaví along Route V-65 at Punta Penas, about 2 km east of Puerto Montt, exposes a prominent organic silt layer, among beds of laminated silt, overlain by till (Fig. 15). The 15-cm-thick, compact organic silt, exhibiting loss on ignition of 9–12% and a limiting age of 16,275–15,940 ^{14}C yr BP, was deposited during a low-water stage that interrupted the deposition of the laminated unit. In the virtual absence of aquatics in the pollen record, the organic silt appears to be of non-lacustrine origin.

Throughout (Table 9 and Fig. 15), *Nothofagus dombeyi* type with relatively few associates has the highest frequencies (≥75%). Gramineae, its major associate, are at first 33–35% (zone PP-2), and in

Table 8. Pollen assemblage and chronostratigraphic data for core from Fundo Liña Pantanosa mire.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
FLP-1 (0–30 cm)	N*othofagus-Podocarpus*-Gramineae-*Empetrum*-Ericaceae-Tubuliflorae	10,644±67 (20 cm, AA-19441)
FLP-2 (30–50 cm)	Myrtaceae-*Maytenus-Nothofagus*	12,593±77 (31 cm, AA-19442)
FLP-3 (50–90 cm)	*Nothofagus-Lomatia*-Gramineae	11,945±110 (50 cm, AA-15896) 14,215±85 (89 cm, AA-19443)
FLP-4 (90–250 cm)	*Nothofagus*-Gramineae	15,325±115 (120 cm, AA-15897) 18,471±233 (200 cm, AA-15898)
FLP-5 (250–340 cm)	Gramineae-*Nothofagus-Empetrum*-Ericaceae-Tubuliflorae	19,768±397 (300 cm, AA-14774) 19,993±257 (330 cm, AA-15900)
FLP-6 (340–350 cm)	Gramineae-*Gunnera-Nothofagus*	

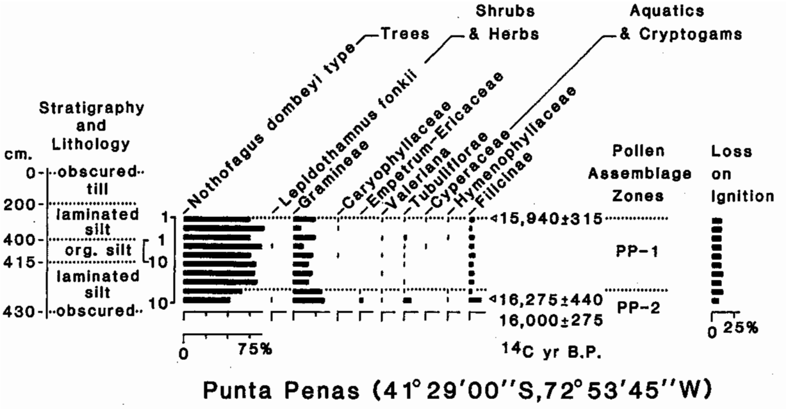


Fig. 15. Pollen and spore diagram of seacliff exposure at Punta Penas, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 9).

the remainder of the sampled section, the average amount is only 18% (zone PP-1). The taxa-poor assemblage records depauperate Subantarctic Parkland during a short-term interstade when conditions were sufficiently moderated for southern beech to become dominant.

The setting indicated by the stratigraphy and age of the deposit is of a nearby active front of the Seno Reloncaví lobe that ultimately overrode Punta Penas. Activation of the lobe, following deposition of the organic layer, is inferred by the overlying laminated silt unit. Dated after 15,940 ^{14}C yr BP, activation was possibly effected during an interval of cold climate implied at Fundo Llanquihue after 16,714–16,575 ^{14}C yr BP (Fig. 13). Some fluctuation of glaciolacustrine sedimentation is indicated by the presence above the 15-cm-thick organic silt of additional thin organic layers, the uppermost of which has a weighted mean date of 14,900 ^{14}C yr BP. Maximum of the Seno Reloncaví lobe to the north beyond Punta Penas occurred shortly thereafter.

Canal Tenglo. Road construction on the ice contact slope along Route V-805 on the north side of Canal Tenglo, 2 km west of Puerto Montt, exposed layers of peat interbedded with sand and silt in the lower part of the slope and a single peat layer between two glaciofluvial units of coarse Andean gravel in the upper part (Fig. 16). Nine peat layers, ranging from 8 to 30 cm in thickness in a measured section of 49.9 m, are identified beginning with the uppermost as Units 1, 2, 6, 7, 10, 14, 15, 16, and 17; the base of Unit 17 is 38 m above sea level. Twenty dates between 39,660 and 23,005 ^{14}C yr BP apply to the deposit.

The Canal Tenglo site is considered to be a segment of a major drainage channel that received sediments transported fluvially from the slopes of Volcán Calbuco, about 40 km to the northeast. Each pyroclastic sand/silt layer interbedded between peat layers in the lower part of the deposit is thought to represent an interval of volcanic activity. The abandoned drainage channel, following each pulse of activity, became an avenue for plant invasion and peat accumulation. The layers of peat with their content of Cyperaceae (formidable in Unit 10) and *Botrychium* (Unit 7) are mostly terrestric but also lacustrine in origin, as indicated by distribution of aquatic *Isoetes*. The source of glaciofluvial sediments in the upper deposit apparently reflects proximity of the Seno Reloncaví lobe, but its location with reference to Canal Tenglo is unknown.

Table 9. Pollen assemblage and chronostratigraphic data for Punta Penas seacliff exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
PP-1 (400–412 cm)	*Nothofagus*-Gramineae	15,940±315 (T-10296A)
PP-2 (412–415 cm)	Gramineae-*Nothofagus*	16,275±440 (T-10297A) 16,000±275 (T-10298A)

Fig. 16. Pollen and spore diagram of exposure of ice contact slope at Canal Tenglo, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 10).

In the succession of pollen assemblages at Canal Tenglo (Table 10), *Nothofagus dombeyi* type, Gramineae, and Tubuliflorae are throughout expressive of the intricately changing scene taking place both locally and in adjacent Subantarctic Parkland (Fig. 16). At 39,660 ^{14}C yr BP (zone CT-5), *Nothofagus* frequencies reach 64%, a value that is not repeated until higher in the section in basal zone CT-3d. Intervening zones with ≥50% Gramineae (zones CT-4c to CT-4a) are distinctive by their content of *Valeriana, Gunnera*, and *Euphrasia*, together with variable Tubuliflorae and *Nothofagus*. The date of 31,405 ^{14}C yr BP (upper zone CT-4a) for the horizon nearest the level where *Nothofagus* increases (zone CT-3d) places the tenure of Gramineae superiority in the parkland after 39,660 ^{14}C yr BP at >8000 ^{14}C years.

Chronological assignments are remarkably good with a minimum of inverted dates at 34,000–30,000 ^{14}C yr BP. Dates covering the time range, which encompasses most of the section (Units 16 to 2), disclose the high frequency of community changes at Puerto Montt. The ascendency of *Nothofagus* to a maximum under a climate most favorable for arboreal expansion in the entire record (zones CT-3d through CT-3a), for example, possibly occurred during an interval lasting no more than 100 years. Registered through much of the sequence is *Lebetanthus myrsinites*, a low subantarctic shrub found growing today as far north as 44°S (Moore 1983). Included also are short intervals (zone CT-3c and CT-3b) of *Pilgerodendron* type and Myrtaceae (cf *Myrteola*), followed by *Lepidothamnus fonkii, Astelia pumila,* and *Donatia fascicularis*, all of which typify cushion bog in present-day, cold and wet Magellanic Moorland. Minor but significant percentages of *Nothofagus obliqua* type are out of place in the ecological context of cushion bog and are ascribed to wind transport from lower latitudes.

Uppermost Units 6, 2, and 1 record a sharp decline of *Nothofagus* from 78% at 31,505 ^{14}C yr BP (zone CT-3a) to 11% by 24,055 ^{14}C yr BP (zone CT-1), coincident with expanded Gramineae at first and, subsequently, expanded Tubuliflorae. The shift to non-arboreal dominance is indicative not only of increasingly cold climate but also of disturbance, as implied by lithological changes and the unprecedented high level of Tubuliflorae contained in Unit 1 (zone CT-1). Coarsening in lithology of

Table 10. Pollen asscmblage and chronostratigraphic data for Canal Tenglo scaclilff exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
CT-1 (Unit 1)	Tubuliflorae-Gramineae-*Nothofagus*	23,005±120 (T-11330A) 23,120+130/-125 (T-7626) 24,055±150 (A-7912)
CT-2 (Units 2 and 6)	Gramineae-Tubuliflorae-*Nothofagus*	29,680+270/-260 (A-8170) 28,465+225/-245 (A-8171) 30,610+290/-280 (A-8172) 29,255+210/-200 (A-7701) 29,655+230/-225 (A-7705) 29,210+210/-205 (A-7913) 31,975+265/-255 (A-7703) 31,230+210/-205 (A-7914)
CT-3a (Unit 7)	*Nothofagus*-Gramineae	31,505+300/-290 (A-7625) 31,985+280/-270 (A-7915)
CT-3b (Unit 7)	*Nothofagus-Lepidothamnus*-Gramineae-*Empetrum*-Ericaceae-Tubuliflorae	
CT-3c (Unit 7)	*Nothofagus-Pilgerodendron* type-Myrtaceae	
CT-3d (Unit 7)	*Nothofagus*-Gramineae-Tubuliflorae	
CT-4a (Units 7, 10, and 14)	Gramineae-*Nothofagus-Valeriana*-Tubuliflorae	31,405+250/-245 (A-7734) 33,165+300/-285 (A-7696) 31,690+295/-275 (A-7700)
CT-4b (Unit 15)	Gramineae-*Nothofagus-Gunnera-Valeriana*	31,905+265/-260 (A-7721)
CT-4c (Unit 16)	Gramineae-*Nothofagus-Valeriana*-Tubuliflorae	33,950+355/-340 (A-7694) 34,450+335/-320 (A-7695)
CT-5 (Unit 17)	*Nothofagus*-Gramineae-Tubuliflorae	39,660+640/-595 (A-7699)

the upper glaciofluvial deposits reflects proximity of the Seno Reloncaví lobe. Unit 2, given a mean age of 29,600 ^{14}C yr BP, rests beneath a bed of boulder gravel, 14.5 m thick, apparently deposited by an advance of the lobe. Unit 1, with a mean age of 23,060 ^{14}C yr BP, is overlain by a 9-m-thick bed of coarse gravel of the latest advance revealed at the top of the section (Lowell *et al.* 1995).

Alerce (HE-93-3B). At a distance 3 km east of the settlement of Alerce and <1 km south of Route V-615, a hill known locally as "La Pulga" forms a segment of moraine emplaced at the maximum of the Seno Reloncaví lobe. The moraine at this locality is separated by a broad outwash plain from the moraine formed to the north at the maximum of the Lago Llanquihue lobe. On the proximal side of "La Pulga" is a wetland complex of mires, irregular in outline and broken by eyes of open water, some 15 ha in area. Of several cores collected at different places at the site, the core chosen for study and containing the pollen record reported here is from an extended area of mire at the extreme southeastern part of the complex.

Lacustrine sediments, resting on sand and overlain by peat, make up the greater part of the core between 625 and 955 cm (Fig. 17). Measurements of loss on ignition on samples taken at 5-cm intervals are 5–9% in the sand, rise to 42% in the lacustrine sediments, and reach a maximum of 67% in the peat. *Isoetes savatieri*, the principal aquatic in a succession of pulses, declines upward through the lower portion of the peat. The pulses bear no relationship to loss on ignition, which changes gradually, steadily increasing upward in the core samples.

Of 13 dates at Alerce, the oldest at 16,621 ^{14}C yr BP is from a depth of 870 cm, 85 cm above the sandy base of the core. Below this level, the projected age for the base using two possible age models is around 20,000 ^{14}C yr BP in one, where dates of 14,389 and 15,284 ^{14}C yr BP, out of line in the series, are excluded; the other model, taking into account a change in sedimentation rate at depth, follows the rate provided by the three lowest dates and comes close to 21,000 ^{14}C yr BP. Either of these ages seems reasonable, when compared with bottom dates at Fundo Llanquihue (Fig. 13) and Fundo Liña Pantanosa (Fig. 14) for early deglaciation following the maximum of the Lago Llanquihue lobe.

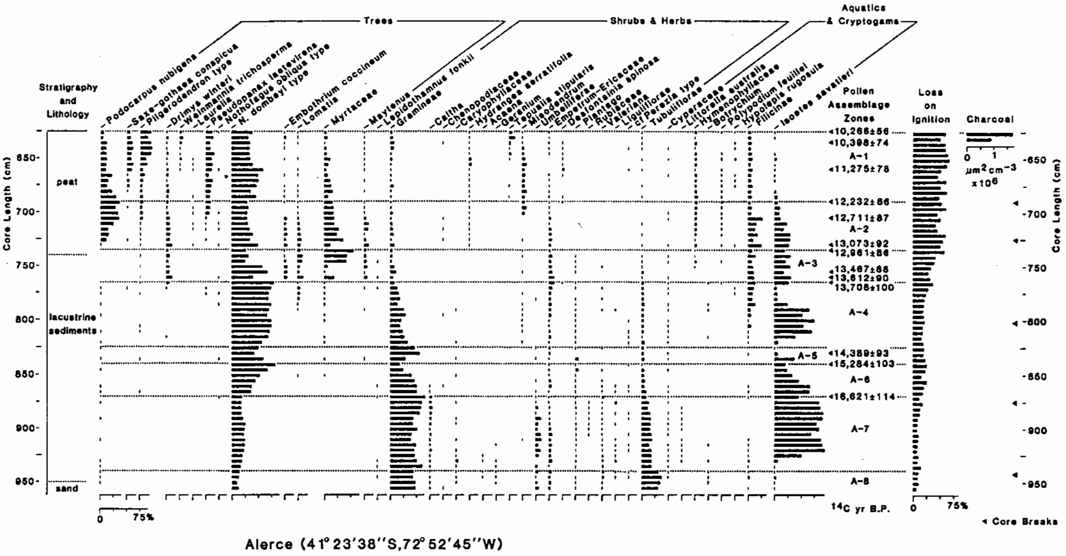


Fig. 17. Pollen and spore diagram of core taken in mire at Alerce, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 11).

Gramineae, the principal component among pollen assemblages of Subantarctic Parkland early in the Alerce record (Table 11), average just under 50% of the pollen sum (Fig. 17). Their initial peak at 66% late in zone A-7 at 16,621 ^{14}C yr BP may correlate with the peak registered at Fundo Llanquihue in zone FL-5 (Fig. 12). Tubuliflorae with a mean value of 33% are a primary associate at the beginning (zone A-8) but later (zone A-7) decline, mixed with minor amounts of assorted taxa (*Caltha*, Caryophyllaceae, *Acaena, Geranium*, Umbelliferae, *Empetrum*-Ericaceae, *Plantago*, Rubiaceae,

Table 11. Pollen assemblage zone and chronostratigraphic data for core from Alerce mire.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
A-1 (625–690 cm)	*Nothofagus-Pseudopanax-Podocarpus–Saxe-gothaea-Pilgerodendron* type	10,266±56 (625 cm, AA-13524) 10,398±74 (635 cm, AA-13525) 11,275±78 (660 cm, AA-13526)
A-2 (690–735 cm)	*Podocarpus-Nothofagus-Drimys-Embothrium-Lomatia*-Myrtaceae-*Maytenus*	12,232±86 (690 cm, AA-13527) 12,711±87 (705 cm, AA-13528) 13,073±92 (730 cm, AA-13529)
A-3 (735–765 cm)	Myrtaceae-*Nothofagus-Drimys-Embothrium-Lomatia-Maytenus*	12,961±86 (735 cm, AA-13530) 13,467±88 (755 cm, AA-13531) 13,612±90 (760 cm, AA-13532)
A-4 (765–825 cm)	*Nothofagus*-Gramineae	13,708±100 (765 cm, AA-13533)
A-5 (825–840 cm)	Gramineae-*Nothofagus*	14,389±93 (830 cm, AA-13534)
A-6 (840–870 cm)	*Nothofagus*-Gramineae	15,284±103 (840 cm, AA-13535)
A-7 (870–940 cm)	Gramineae-*Nothofagus-Caltha*-Umbelliferae-*Empetrum*-Ericaceae-Tubuliflorae	16,621±114 (870 cm, AA-13536)
A-8 (940–955 cm)	Gramineae-Tubuliflorae-*Nothofagus*	

Valeriana, Liguliflorae, and cf *Perezia*). Paralleling the decline is an increase of *Nothofagus dombeyi* type from a low of 9% to a high of 26%. Except for a maximum of Gramineae (46–55%) at 14,389 ^{14}C yr BP (zone A-5), *Nothofagus* is dominant in zones A-6 and A-4, reaching 82% and 80%, respectively, at 15,284 and 13,708 ^{14}C yr BP.

In opposition to a decline of Gramineae in zone A-4, *Nothofagus* increases during initial warming in the course of a transitional woodland phase, which begins after 14,389 ^{14}C yr BP and lasts for >600 ^{14}C years. The increase is marked by the developing presence of *Drimys winteri, Lomatia,* and the heliophilic Filicinae. By 12,961 ^{14}C yr BP (zone A-3), the Myrtaceae at 54% under optimum conditions reach their highest frequency, mixed with *Drimys, Nothofagus, Embothrium coccineum, Lomatia*, and *Maytenus*. The Myrtaceae and their arboreal associates making up North Patagonian Evergreen Forest continued in effect for some 700 ^{14}C years, as *Podocarpus nubigena*, reaching peak 27–33% at 12,232 yr ^{14}C BP (zone A-2), gained prominence later among forest communities. The drop in Filicinae frequency during the interval is, by inference, an indication of canopy closure; earlier, forest stands were sufficiently open to support high-level light requirements of Filicinae. Besides *Podocarpus*, other cold-tolerant species in zone A-1, *Pilgerodendron uviferum, Saxe-gothaea conspicua,* and *Pseudopanax laetevirens,* record the influence of colder climate. Compared with Fundo Llanquihue, late-glacial warming appears to have ended several hundred radiocarbon years earlier at Alerce.

The response threshhold and increase of *Podocarpus,* reached after 13,073 and before 12,711 ^{14}C yr BP, are taken as an indication of cooling. In their exploratory study of the Myrtaceae at Alerce, Zhou and Heusser (1996) identified pollen of *Myrceugenia chrysocarpa*, a high-montane species in the Myrtaceae, coincidental with *Podocarpus*, thus providing additional evidence for the implication of relatively early onset of a cooling trend. Alerce lies just west of the Andean front, where the mass of Volcán Calbuco (2003 m), only 25 km distant, is possibly a factor related to relatively early cooling in the surrounding region.

Fundo Santa Elena (HE-94-3B). The core taken at Fundo Santa Elena is from a mire, 0.3 ha in area, resting in the moraine belt of the Seno Reloncaví lobe. The site is <1 km off Route V-720, 7 km south of Aeropuerto Tepual, and about 13 km west of Puerto Montt. The age of the site is approximately 14,000 ^{14}C yr BP on the basis of a date of 13,870 ^{14}C yr BP for lacustrine sediments just above sand in the lower part of the core (Fig. 18). The core was sampled at 5-cm intervals and consists of 85 cm of lacustrine sediments, which contain numerous microspores of *Isoetes*; 195 cm of overlying peat/peaty sediments complete the section.

Nothofagus dombeyi type is the primary pollen among taxa making up the assemblages (Table 12). Early in the record (Fig. 18), associates are Gramineae, *Empetrum rubrum*, and Tubuliflorae (zone FSE-7) and, subsequently, essentially Gramineae (zone FSE-6). While frequencies of *Nothofagus* amount to as much as 74%, Gramineae are at a maximum of only 25%. The assemblages parallel the warming trend during transition from Subantarctic Parkland to open beech woodland at the beginning of the first millennium. With continued warming (zone FSE-5), *Drimys winteri, Lomatia,* Myrtaceae, and *Maytenus* appear, providing evidence of diversification of the arboreal taxa. Among members of the assemblage, Myrtaceae (33–37%) are most abundant at the start of the second millennium of record at 12,620 ^{14}C yr BP (zone FSE-4). Communities of incipient North Patagonian Evergreen Forest had not at this time undergone closure, their openness inferred by the significant amounts of light-dependent Filicinae.

Subsequent phasing out of Myrtaceae by cold-tolerant *Pseudopanax laetevirens* at 24–25% frequency accompanies an apparent reversal in the early warming trend (zone FSE-3). Cooler climate is equally substantiated after 11,865 ^{14}C yr BP by *Podocarpus nubigena* in amounts as high as 30% (zone FSE-2). Fire, shown by charcoal in the core at and somewhat earlier than 10,806 ^{14}C yr BP, ultimately created openings permitting Gramineae, *Hydrangea serratifolia,* and *Tepualia stipularis* to increase, among mixed arboreal communities of *Weinmannia trichosperma* and *Saxe-gothaea conspicua* (zone FSE-1).

Pollen assemblages at Fundo Santa Elena are limited to the interval of deglaciation at 14,000–10,000 ^{14}C years ago. A longer record of extended full-glacial coverage was expected because of the location of the coring site well within the outer belt of moraines formed by the Seno Reloncaví lobe. The fact that the site is younger than anticipated may be attributed to remnant ice from the lobe occupying the basin at Fundo Santa Elena until about 14,000 ^{14}C yr BP.

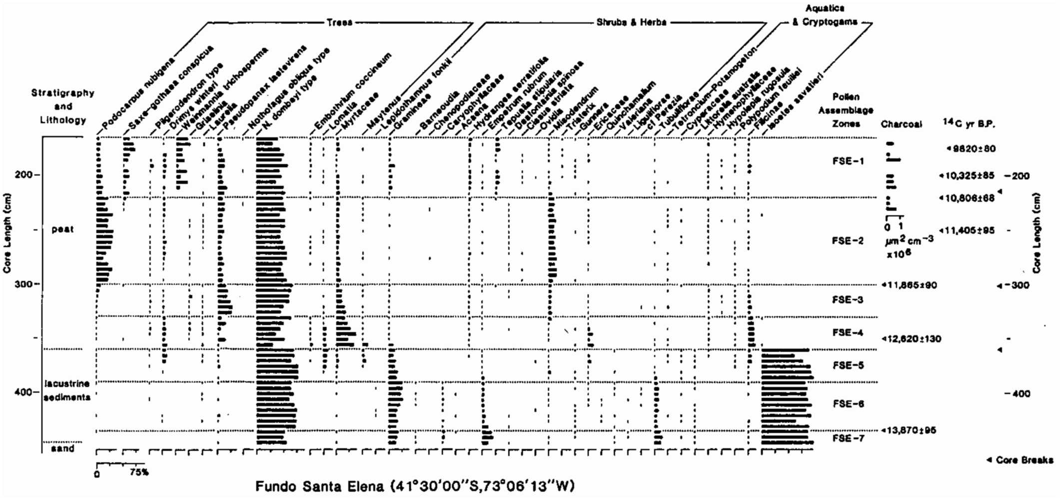


Fig. 18. Pollen and spore diagram of core taken in mire at Fundo Santa Elena, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 12).

La Campana (HE-94-4A). The mire at La Campana, approximately 1 ha in area, is located <0.5 km east of Route V-85, 5.5 km south of the junction with Route 5. The site lies 9 km south of Fundo Santa Elena, well within the area covered by the Seno Reloncaví lobe. The 335-cm length of core was sampled at 5 cm intervals between 50 and 385 cm and consists of 55 cm of peat and 280 cm of lacustrine sediments, which bottom in sand (Fig. 19). *Isoetes savatieri* is the featured aquatic with values mostly at >75%. Dates of 18,235, 18,156, and 17,821 ^{14}C yr BP over the lower 30 cm of the core give a mean age of about 18,000 ^{14}C yr BP for the deposit.

The initial assemblage of Gramineae at 64–69% (Table 13, Fig. 19) and a variety of herbs and shrubs (all with frequencies of <15%), including *Empetrum rubrum*, Tubuliflorae, *Gunnera, Lepidothamnus fonkii*, Caryophyllaceae, and *Acaena*, typifies grass-dominated Subantarctic Parkland (zone LC-9). From the similarity of radiocarbon dates bracketing the zone, the time frame of the assem-

Table 12. Pollen assemblage and chronostratigraphic data for core from Fundo Santa Elena mire.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
FSE-1 (165–220 cm)	*Nothofagus-Saxe-gothaea-Weinmannia-* Gramineae-*Tepualia*	9820±80 (175 cm, AA-15901) 10,325±85 (200 cm, AA-15902)
FSE-2 (220–300 cm)	*Podocarpus-Nothofagus-Misodendrum*	10,806±68 (220 cm, AA-19447) 11,405±95 (250 cm, AA-15903)
FSE-3 (300–330 cm)	*Nothofagus-Pseudopanax*-Myrtaceae	11,865±90 (300 cm, AA-15904)
FSE-4 (330–360 cm)	Myrtaceae-*Nothofagus-Drimys-Lomatia-Maytenus*	12,620±130 (350 cm, AA-15905)
FSE-5 (360–390 cm)	*Nothofagus-Drimys-Lomatia-Maytenus*-Gramineae	
FSE-6 (390–435 cm)	*Nothofagus*-Gramineae-Tubuliflorae	
FSE-7 (435–445 cm)	*Nothofagus*-Gramineae-*Empetrum*-Tubuliflorae	13,870±95 (435 cm, AA-15907)

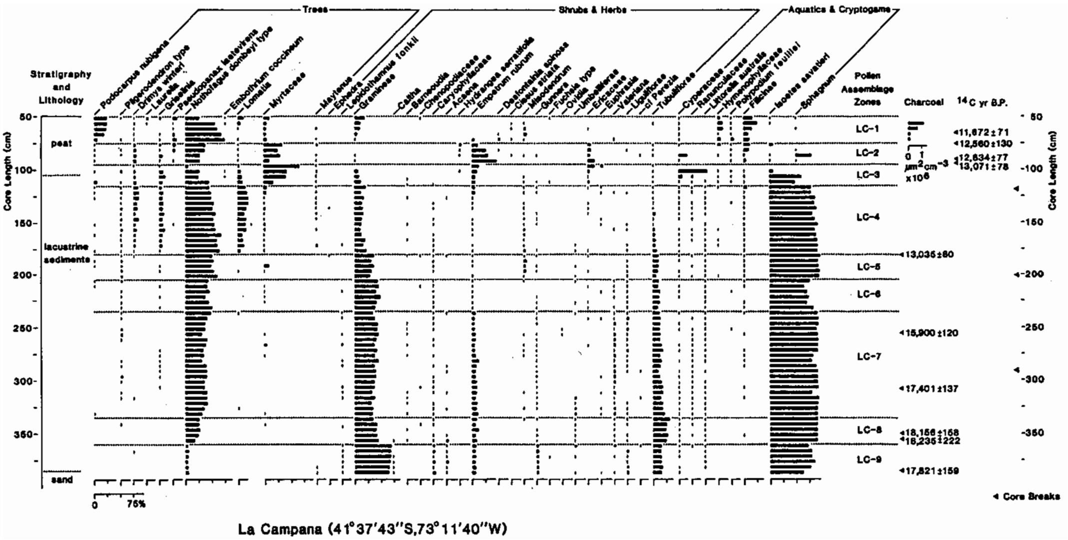


Fig. 19. Pollen and spore diagram of core taken in mire at La Campana, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 13).

blage may amount to several hundreds of years or less. An outstanding feature is the superior position of Gramineae (30–45%), maintained together with *Gunnera* (zones LC-8 and LC-7) and Tubuliflorae (peaking in zone LC-8) until 13,035 ^{14}C yr BP (zone LC-5), its last rise estimated at 15,000–14,000 ^{14}C yr BP (zone LC-6). Frequencies of *Nothofagus dombeyi* type at 5–7% are unusually low but rise (zone LC-8) to a high of 49% at around 15,000 ^{14}C yr BP (zone LC-7), before varying close to a mean of 42% until about 14,000 ^{14}C yr BP (zone LC-6).

After 14,000 ^{14}C yr BP (zone LC-5), sequential late-glacial pollen assemblages at La Campana, exhibiting limited variation, are essentially conform-

Table 13. Pollen assemblage and chronostratigraphic data for core from La Campana mire.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
LC-1 (50–75 cm)	*Podocarpus-Nothofagus-Pseudopanax*-Gramineae	11,672±71 (62 cm, AA-19450)
LC-2 (75–95 cm)	*Nothofagus*-Myrtaceae-*Drimys-Pseudopanax-Empetrum*-Ericaceae	12,560±130 (75 cm, AA-15908) 12,834±77 (87 cm, AA-19451) 13,071±78 (92 cm, AA-19452)
LC-3 (95–115 cm)	Myrtaceae-*Nothofagus-Griselinia*	
LC-4 (115–180 cm)	*Nothofagus-Lomatia-Drimys-Griselinia*-Gramineae	
LC-5 (180–205 cm)	*Nothofagus*-Gramineae-Tubuliflorae	13,035±80 (180 cm, AA-15910)
LC-6 (205–235 cm)	Gramineae-Tubuliflorae-*Nothofagus*	
LC-7 (235–335 cm)	Gramineae-*Empetrum-Valeriana*-Tubuliflorae-*Nothofagus*	15,900±120 (255 cm, AA-15911) 17,401±137 (305 cm, AA-15912)
LC-8 (335–360 cm)	Gramineae-*Empetrum-Nothofagus*	18,156±158 (355 cm, AA-15913) 18,235±222 (357 cm, AA-19453)
LC-9 (360–385 cm)	Gramineae-Tubuliflorae-*Empetrum*-Caryophyllaceae-*Gunnera*	17,821±159 (385 cm, AA-15916)

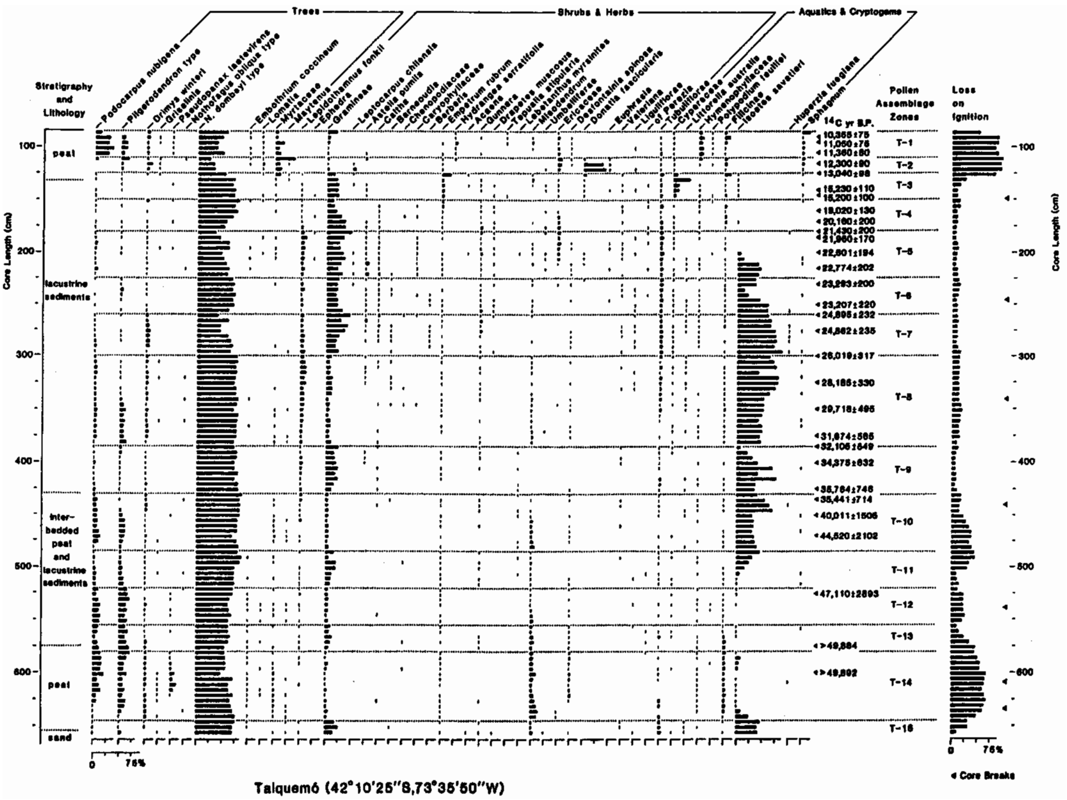


Fig. 20. Pollen and spore diagram of core taken in mire at Taiquemó, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 14).

able with the pattern recorded under conditions of climatic warming at Fundo Santa Elena. Developing as open woodland transition during climatic warming, *Nothofagus* advanced to replace parkland. In the 500 years between 13,035 and 12,560 ^{14}C yr BP (zones LC-4–LC-2), woodland consisting principally of *Nothofagus* at maxima of 63–67% was at first subject to influx by *Drimys winteri, Griselinia, Lomatia,* and Myrtaceae during rapid transformation to North Patagonian Evergreen Forest. From the continuing presence of Gramineae, communities remained relatively open until the maximum reached by the Myrtaceae (67%). Apparently local is the expansion of *Empetrum rubrum*-Ericaceae heath (zone LC-2). Increased frequencies of *Podocarpus nubigena* and *Pseudopanax laetevirens* (zone LC-1) register a response to climatic cooling that commenced after 12,560 ^{14}C yr BP (zone LC-1). Fire (by charcoal presence) is the evident cause of reopening of the vegetation, as recorded by increases of Filicinae, Gramineae, and *Nothofagus.*

Golfo de Ancud lobe

Taiquemó (HE-94-2B). Morainal arcs west of Quemchi on Isla Grande de Chiloé are, by their curvature and orientation, conformable to the extent of both the Golfo de Ancud and Golfo Corcovado lobes. The sector where Taiquemó is located takes in the contact area of the lobes, which along its outermost distal edge is difficult to apportion without detailed study of the drift morphology to one lobe or the other. Taiquemó is arbitrarily placed in relation to the Golfo de Ancud lobe.

The mire at Taiquemó, about 2 ha in area, sits 0.5 km south along a side-road intersecting Route W-35, 10 km west of Quemchi. The site is a basin formed within the southern segment of a 7-km-long moraine. A 655-cm core, consisting of peat

Table 14. Pollen assemblage and chronostratigraphic data for core from Taiquemó mire.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
T-1 (85–110 cm)	*Podocarpus-Pilgerodendron* type-*Drimys-Pseudopanax-Nothofagus*-Myrtaceae-Gramineae	10,355±75 (90 cm, AA-17974) 11,050±75 (95 cm, AA-17975) 11,360±80 (105 cm, AA-17976)
T-2 (110–125 cm)	Myrtaceae-*Nothofagus-Drimys-Donatia*-Ericaceae	12,300±90 (115 cm, AA-17977)
T-3 (125–150 cm)	*Nothofagus*-Gramineae-*Empetrum*	13,040±98 (125 cm, AA-14751) 15,230±110 (140 cm, AA-17979) 15,200±100 (145 cm, AA-17980)
T-4 (150–180 cm)	*Nothofagus*-Gramineae	19,020±130 (160 cm, AA-17982) 20,160±200 (170 cm, AA-17984)
T-5 (180–225 cm)	Gramineae-*Nothofagus-Lepidothamnus*-Tubuliflorae	21,430±200 (180 cm, AA-17985) 21,960±170 (190 cm, AA-17986) 22,601±194 (200 cm, AA-14754) 22,774±202 (215 cm, AA-17989)
T-6 (225–260 cm)	*Nothofagus-Pilgerodendron* type-Gramineae-Tubuliflorae	23,293±200 (230 cm, AA-17990) 23,207±220 (250 cm, AA-14756)
T-7 (260–300 cm)	*Gramineae-Nothofagus-Drimys-Lepidothamus*-Tubuliflorae	24,895±232 (260 cm, AA-17991) 24,862±235 (275 cm, AA-14757)
T-8 (300–385 cm)	*Nothofagus-Podocarpus-Pilgerodendron* type-*Drimys-Lepidothamus*-Gramineae	26,019±317 (300 cm, AA-14758) 28,185±330 (325 cm, AA-14759) 29,718±495 (350 cm, AA-14760) 31,674±565 (375 cm, AA-14761)
T-9 (385–430 cm)	*Nothofagus*-Gramineae	32,105±549 (385 cm, AA-17992) 34,375±632 (400 cm, AA-14762) 35,764±746 (425 cm, AA-14763)
T-10 (430–485 cm)	*Nothofagus-Podocarpus-Pilgerodendron* type-*Misodendrum*	35,441±714 (435 cm, AA-17993) 40,011±1505 (450 cm, AA-14764) 44,520±2102 (470 cm, AA-17994)
T-11 (485–520 cm)	*Nothofagus*-Gramineae	
T-12 (520–555 cm)	*Nothofagus-Podocarpus-Pilgerodendron* type	47,110±2893 (525 cm, AA-14767)
T-13 (555–580 cm)	*Nothofagus-Podocarpus-Pilgerodendron* type-*Gramineae-Misodendrum*	>49,884 (575 cm, AA-14769)
T-14 (580–645 cm)	*Nothofagus-Podocarpus-Pilgerodendron* type-*Drimys-Pseudopanax*-Myrtaceae-*Desfontainia-Misodendrum*	>49,892 (600 cm, AA-14770)
T-15 (645–655 cm)	*Nothofagus*-Gramineae-Tubuliflorae	

and associated sediments, is from above basal sand in the 760-cm deep, central part of the basin. The Pleistocene part of the core (Fig. 20) consists of peat at 85–135 cm, followed successively by 295 cm of lacustrine sediments, 145 cm of interbedded peat and lacustrine sediments, and lowermost, 80 cm of highly compacted peat. Loss on ignition measurements, at 90–100% in the upper peat, fall to 4–18% in the lacustrine sediments. Thereafter, values are mostly >25% and as much as 67% in the lower peat and lacustrine sedimentary units. *Isoetes savatieri,* in numbers at the base and in the middle half of the core, is the principal vascular aquatic. Its distribution and maxima, in opposition to intervals of peat deposition, are an indication of times of open water. Water levels no doubt varied and may have been excessively high, prohibiting persistence of the species at times, when its presence is poorly or intermittently recorded.

Situated at the outer limit of Llanquihue glaciation, Taiquemó is the oldest and most complex of sites among the lobes mapped. A total of 30 dates, ranging from >49,892 to 10,355 ^{14}C yr BP, provide age assignments for 15 pollen assemblage zones of stadial/interstadial significance (Table 14). The outstanding feature of the pollen record, displayed by assemblages from samples collected at 5-cm intervals, is the lengthy dominance of *Nothofagus dombeyi* type, coupled with the recurrence of Gramineae maxima.

The first maximum of Gramineae at 25% of the pollen sum, reached with *Nothofagus* at 71–75% during the very onset of deposition (zone T-15), is of infinite radiocarbon age (Fig. 20). Later maxima are: 9–12% (zone T-13), also infinite in age; 10–18% (zone T-11) with limiting dates of 47,110 and 44,520 ^{14}C yr BP; 14–23% (zone T-9) at 35,764–32,105 ^{14}C yr BP; 10–45% (zone T-7) at 26,019–24,895 ^{14}C yr BP; 19–48% (zone T-5) at 22,774–21,430 ^{14}C yr BP; and 19–21% (zone T-3) at 15,200–13,040 ^{14}C yr BP. Frequencies of *Nothofagus* of ≥65% are little altered during Gramineae maxima, except in zones T-7, T-5, and T-3. Each rise of Gramineae during these latter instances, effecting a reduction in *Nothofagus* frequency, can be explained as a response to low stadial temperatures.

Early in the Taiquemó pollen record, for several millennia before 47,110 ^{14}C yr BP when frequencies of Gramineae are low (zones T-14 through T-12), *Nothofagus* occurs in association with *Podocarpus nubigena, Pilgerodendron* type, and *Pseudopanax laetevirens* at maxima, respectively, of 21, 19, and 11%. The striking presence of these arboreal taxa, in addition to *Drimys winteri, Griselinia, Embothrium coccineum, Lomatia,* Myrtaceae, *Maytenus*, *Desfontainia spinosa, Misodendrum,* and Filicinae, implies immediate tracts of interstadial forest. In the absence of a substantial frequency of Myrtaceae, among other taxa, the assemblage is evocative of Subantarctic Evergreen Forest, as a modern analog, under a cool, humid climatic regime. During a successive interstade with dates of 44,520 and 35,441 ^{14}C yr BP (zone T-10), remnants of the forest are seen in a related pollen assemblage, but taxa noted earlier have either decreased in value or have failed to be recorded. While Subantarctic Parkland increased afterward, as noted by successive, developing Gramineae maxima, a late vestige of Subantarctic Forest is evident from the assemblage at between 32,105 and 26,019 ^{14}C yr BP (zone T-8). Over the remaining record at Taiquemó until about 13,000 ^{14}C yr BP, parkland appears to be the main contributor to the regional vegetation setting.

The trend evident overall is of increasingly cold climate beginning after 47,110 and extending until 21,430 ^{14}C yr BP. Climate during this interval appears to have been not only cold but wet for most of the time. Peat deposited in the basin at first became increasingly overlain by lacustrine sediments, as the original mire with standing water was converted to a lake. Supporting evidence for cold climate is the steady presence of the subantarctic shrub, *Lepidothamnus fonkii,* and variable occurrences of the cold indicators, *Astelia pumila, Drapetes muscosus, Donatia fascicularis, Euphrasia,* and *Huperzia fuegiana.*

The ultimate maximum of Gramineae (zone T-3) covers the final, full-glacial cold stade, after which climate moderated for a millennium or more. By 13,040 ^{14}C yr BP, increasing numbers of thermophilous Myrtaceae and associated arboreal taxa of North Patagonian Evergreen Forest affinity (zone T-2) were introduced. *Donatia* at 36–42% (zone T-2), indicative of locally developed but transient cushion bog, appears to exert a masking effect on the Myrtaceae. Its occurrence is reminiscent of modern-day cushion bogs scattered in forest in the coastal and Andean cordillera (Heusser 1982; Heusser *et al.* 1992). After 12,300 ^{14}C yr BP, North Patagonian Forest communities became modified by influx of *Podocarpus* (24–35%) and *Pilgerodendron* type (10–13%) during episodic cooling lasting until 10,355 ^{14}C yr BP. In the absence of charcoal, fire is not implicated as a possible cause for late-glacial vegetational changes.

Magnetic susceptibility measured at 4-cm intervals in the core at Taiquemó is diagrammed in comparison with loss on ignition and core stratigraphy/lithology (Fig. 21). Applicable for correlating core data (Dearing 1986), magnetic susceptibility of the lithologically variable sedimentary sequence supplies additional data of interpretive value in a vegetation/climatic/glacial context. The cause of magnetization in lacustrine sediments stems from magnetic minerals eroded from the peripheral upland and transported to the lake basin. Strength of erosion, both physical and chemical, and vegetation type, structure, and distribution are factors contributing to the variability of the magnetic signal (Almquist-Jacobson *et al.* 1992; Rosenbaum *et al.* 1994).

Aside from a basal peak in sand, two episodes with high magnetic susceptibility values are registered at Taiquemó. Beginning with an initial build-up after 30,000 ^{14}C yr BP, most robust is the episode reached in lacustrine sediments between 23,000 and 21,000 ^{14}C yr BP; a secondary episode after about 50,000 ends in an abrupt peak dated at

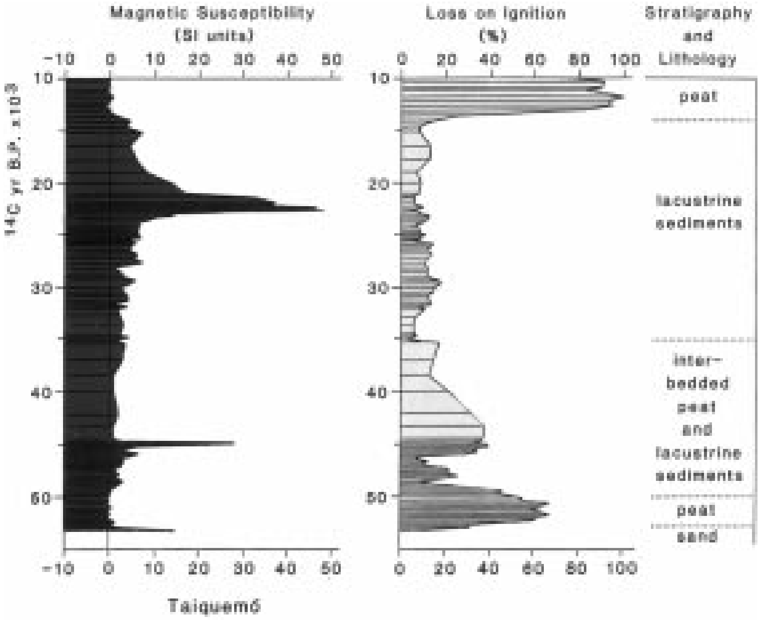


Fig. 21. Magnetic susceptibility and loss on ignition measurements on core from Taiquemó diagrammed in relation to core stratigraphy and lithology.

45,000 ^{14}C yr BP during deposition of interbedded lacustrine sediments and peat. Loss on ignition shows a general decrease during the first episode; in the second, considerable decrease at first is followed by a series of fluctuating values. Where peat occurs in the core, magnetic susceptibility appears to be inversely related to loss on ignition, as illustrated by the zero and negative values with ignition losses of >65% in the upper and near-basal peats.

The episode of peak magnetic susceptibility from 30,000 to 14,000 ^{14}C yr BP occurs coincident with glacier maxima that fall between 29,400 and 14,800 ^{14}C yr BP. Eolian input, thought to be from wind stress over outwash, is presumed to be the major process contributing the magnetized mineral fraction. Open Subantarctic Parkland, the prevailing vegetation, offered minimal obstruction to impede wind transport. The episode after 50,000 until 45,000 ^{14}C yr BP may identify an earlier glacier maximum.

Golfo Corcovado lobe

Teguaco. The Golfo Corcovado lobe at the time of its advance onto Isla Grande de Chiloé in the vicinity of Teguaco blocked drainage and created lakes in stream valleys heading north from Canal Dalcahue. The event is recorded in a 320-cm-thick measured section of basal sand, which is overlain by compact gyttja/organic sand and beds of sand and laminated silt (Fig. 22). The locality, 1.5 km northeast of the settlement of Teguaco, is a road cut at Puente Quillaico on the west side of Río San Juan Poniente. The organic silt in place prior to glacial advance is directly covered by woody debris and laminated silt deposited when the lake was impounded. The age of the lobe-impounded lake from an error-weighted mean of 12 dates of the woody debris is 22,300 ^{14}C yr BP (Lowell *et al.* 1995).

Pollen occurs in the gyttja/organic sand and in two of three successively higher beds of laminated silt. The gyttja/organic sand contains assemblages (Table 15, Fig. 22) of Gramineae at ≥75% and of *Nothofagus dombeyi* type at <25% (zones T-2c and T-2a), interrupted by increases of *Nothofagus* and Tubuliflorae to maxima, respectively, of 37% and 28% (zone T-2b). Pollen data are explicit in indicating Subantarctic Parkland, including an episode during which *Nothofagus* apparently expanded (zone T-2b). Time control for zone T-2c is provided by a basal date of 30,000 and another of 28,800 ^{14}C yr BP from higher in the zone; zones T-2b and T-2a are limited by dates of between 28,800 and 22,300 ^{14}C yr BP.

The pollen assemblage depicted by the beds of laminated silt (zone T-1) contrasts assemblages in the underlying gyttja/organic sand. Frequencies of

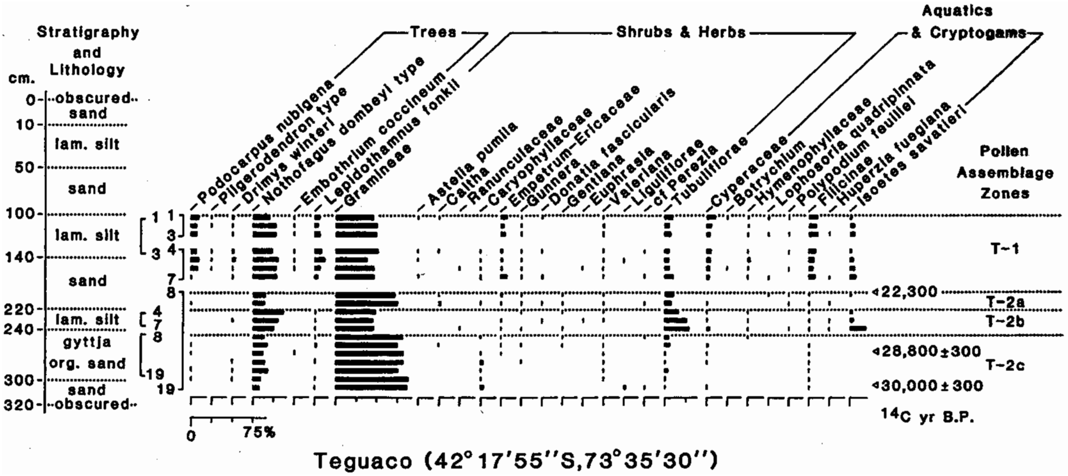


Fig. 22. Pollen and spore diagram of gyttja–organic sand and laminated silt in stream-cut exposure at Teguaco, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 15).

Nothofagus and Gramineae are at levels comparable to those in zone T-2b; however, the assemblage exhibits greater richness of *Podocarpus nubigena, Lepidothamnus fonkii*, *Empetrum*-Ericaceae, and Filicinae, among other taxa. Indicative is an apparent episode of cold but moderated climate, possibly dating or post-dating an advance of the Golfo Corcovado lobe. The units of laminated silt continued to be deposited in the valley of the Río San Juan Poniente as long as the lake existed. Not until the lobe damming the lake retreated, or other downstream blockage was breached, did the lake drain.

Dalcahue. A 152-cm-thick organic silt, originating from pyroclastic flow material (Fig. 23) and exposed between beds of till in a road cut at Dalcahue, provides key data for unraveling the glacial history of Isla Grande de Chiloé. The site, 1.6 km north of Dalcahue, is on the Dalcahue–Quemchi road, about 1 km east of the junction with Route W-45. Discovered by Mercer (1984), who placed the latest glacial advance to cross the site at 15,000–14,500 ^{14}C yr BP, the organic silt was redated in the course of the present study.

Thirty-five samples of wood and fibrous material from the top of the silt, predating overriding of the glacier, have an error-weighted, mean age of 14,810 ^{14}C yr BP (Lowell *et al.* 1995). The implication of the age and stratigraphy is that Dalcahue was not overridden by the lobe during the advance recorded at Teguaco, but later at 14,810 ^{14}C yr BP, when the lobe passed over the Dalcahue site, which lies 11.5 km beyond Teguaco to the southwest. This situation contrasts with the relationship regarding

Table 15. Pollen assemblage and chronostratigraphic data for Teguaco stream-cut exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
T-1 (100–140, 220–240 cm)	Gramineae-*Nothofagus-Podocarpus-Drimys-Lepidothamnus-Empetrum*-Ericaceae-Tubuliflorae	
T-2a (240–250 cm)	Gramineae-Tubuliflorae-*Nothofagus*	22,300[1]
T-2b (250–265 cm)	*Nothofagus*-Gramineae-Tubuliflorae	
T-2c (265–300 cm)	Gramineae-*Nothofagus*	28,800±300 (QL-1018) 30,000±300 (QL-1019)

[1] Error-weighted mean of 12 radiocarbon dates on organic trash/wood samples (see Lowell et al. 1995).

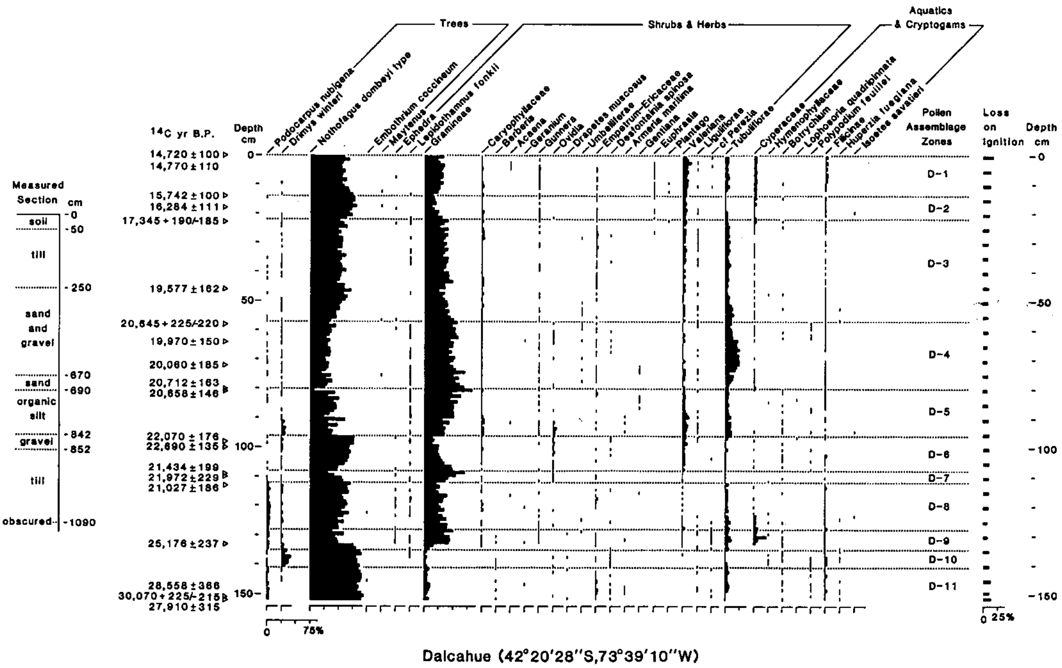


Fig. 23. Pollen and spore diagram of organic silt in road-cut exposure at Dalcahue, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 16).

the Seno Reloncaví and Lago Llanquihue lobes, each of which reached outermost positions during the earlier of two latest maxima.

The organic silt at Dalcahue, despite loss on ignition of mostly <10%, proved to contain abundant, unusually well-preserved pollen (4800–25,000 grains cm^{-3}). The silt, on the basis of color and textural changes, appears to consist of three lithostratigraphic units measuring on average 0–106, 106–139, and 139–152 cm. Pollen stratigraphy of the silt (Fig. 23), divided into 11 pollen assemblage zones (Table 16), is detailed from analyses made at 1-cm intervals and a chronology of 20 radiocarbon dates.

At as much as 30,070 ^{14}C yr BP at the base of the exposure and for some time thereafter, *Nothofagus dombeyi* type at 80–94% of the pollen sum is superior to Gramineae and Tubuliflorae, which are both at <10% (zone D-11). Attributed to a nearby source of Subantarctic Evergreen Forest, *Nothofagus* occurs together with *Drimys winteri* at 17% (zone D-10), fluctuating against a steady background of minimal *Podocarpus nubigena* (<5%). Later in the record after 25,176 ^{14}C yr BP, Gramineae increase sharply to 51% (zone D-9), and at 21,972–21,434 ^{14}C yr BP at a maximum of 71% (zone D-7) become codominant with *Nothofagus* under apparently colder conditions of developing Subantarctic Parkland. Gramineae, briefly reduced by short-term *Nothofagus* (zone D-6), in turn, are at maximum frequency of 84% at 20,712 ^{14}C yr BP (zone D-5) and continue to be dominant (>50%) until about 20,645 ^{14}C yr BP (zone D-4) in association with Tubuliflorae (20–24%). At peak frequency in zones D-7–D-4, Gramineae are coincident with a glacial maximum 22,400 ^{14}C yr BP.

Successively after 20,645 ^{14}C yr BP (zone D-3), amounts of *Nothofagus* increase, at 16,284–15,742 ^{14}C yr BP to as much as 77–81% (zone D-2), followed by the latest rise of Gramineae (zone D-1) from 13 to 34% together with an increase in *Valeriana* of 3 to 13%. Both develop in the singular presence of *Euphrasia* until the end of the record, dated at 14,770 and 14,720 ^{14}C yr BP.

Exploratory pollen stratigraphy, produced previously from an exposure about 10 m to the south of the location reported here, shows grass increasing to as much as 67% at the top of a measured section (Heusser 1990a). This larger quantity of grass is more in keeping with colder/windier surround-

Table 16. Pollcn assemblage and chronostratigraphic data for Dalcahue road-cut exposure.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
D-1 (0–14 cm)	*Nothofagus*-Gramineae-*Valeriana*-Tubuliflorae	14,720±100 (0 cm, A-6189) 14,770±110 (0 cm, A-6190)
D-2 (14–22 cm)	*Nothofagus*-Gramineae-*Valeriana*	15,742±100 (14 cm, AA-19423) 16,284±111 (18 cm, AA-19424)
D-3 (22–57 cm)	*Nothofagus*-Gramineae-*Valeriana*-Tubuliflorae	17,345+190/-185 (23 cm, A-7689) 19,577±162 (46 cm, AA-19425)
D-4 (57–80 cm)	Gramineae-Tubuliflorae-*Nothofagu*s	20,645+225/-220 (58 cm, A-7690) 19,970±150 (64 cm, AA-19427R) 20,060±185 (72 cm, AA-19428R)
D-5 (80–96 cm)	Gramineae-*Nothofagus*-*Drimys*- Caryophyllaceae-*Valeriana*-Tubuliflorae	20,712±163 (80 cm, AA-19429) 20,658±146 (81 cm, AA-19430)
D-6 (96–108 cm)	*Nothofagus*-Gramineae-*Valeriana*	22,070±176 (98 cm, AA-19432) 22,690±135 (100 cm, A-7683)
D-7 (108–112 cm)	Gramineae-*Nothofagus*	21,434±199 (109 cm, AA-19433) 21,972±229 (110 cm, AA-19434)
D-8 (112–128 cm)	*Nothofagus*-*Podocarpus*-Gramineae-Tubuliflorae	21,027±186 (113 cm, AA-19435)
D-9 (128–135 cm)	Gramineae-Tubuliflorae-*Nothofagus*-*Podocarpus*	25,176±237 (133 cm, AA-19436R)
D-10 (135–141 cm)	*Nothofagus*-*Drimys*	
D-11 (141–152 cm)	*Nothofagus*-*Podocarpus*-Gramineae-Tubuliflorae	28,558±366 (151 cm, AA-19438) 30,070+225/-215 (151 cm, A-7685) 27,910±315 (152 cm, AA-19439)

ings to be expected with advance of the Golfo Corcovado lobe during the long tenure of Subantarctic Parkland.

Mayol (HE-95-2A). Mayol (Fig. 24) covers five late-glacial millennia following collapse of the Golfo Corcovado lobe, thus contributing continuity to the full glacial taken into account at Dalcahue. The glacier that terminated the record at Dalcahue, when ice overrode the site, reached west of Mayol, leaving the basin in which the mire at Mayol rests to accumulate pollen after the glacier retreated. The advance of ice dated 14,810 ^{14}C yr BP at Dalcahue, closely matched by the date of 14,941 ^{14}C yr BP for deglaciation at Mayol, suggests a maximum of short duration.

The mire, an estimated 2 ha in area, is located 2 km south of Chonchi, about 1 km distant along a side road that leads southwest from Mayol off the main southeast-bearing Chonchi–Queilén road. A 285-cm length of core taken at the site consists of 65 cm of peat underlain by 220 cm of lacustrine sediments terminating in sand. During early lake occupancy, *Isoetes savatieri* grew in the basin, together in the beginning with algae, *Pediastrum, Botryococcus*, and *Debarya*, and vascular plants, *Myriophyllum* and Cyperaceae. After an interval lasting about 2000 ^{14}C years, *Isoetes* underwent decline, as late-glacial deposition of peat proceeded, contributed in the main by Cyperaceae with some *Sphagnum*.

Pollen stratigraphy at Mayol (Fig. 24), set at 5-cm intervals, offers further confirmation of an established late-glacial pattern of vegetation change observed previously in other chronostratigraphic lobe records. Chronology is provided by 15 radiocarbon dates, offering an average resolution of <100 ^{14}C yr between sampled intervals. The earliest pollen assemblage (Table 17), dated between 14,941 and an estimated 14,000 ^{14}C yr BP, is made up by Gramineae (31–49%) and *Empetrum*-Ericaceae (10–25%). The assemblage includes distinctive *Gunnera* and *Plantago,* with *Nothofagus dombeyi* type expanding from a low of 20% at the beginning to 49% at the close (zone M-7). Rising to dominance, *Nothofagus* in the form of transitional woodland was comparatively open, a feature shown by significant quantities of *Misodendrum* and Filicinae.

Under ameliorating conditions partial to its

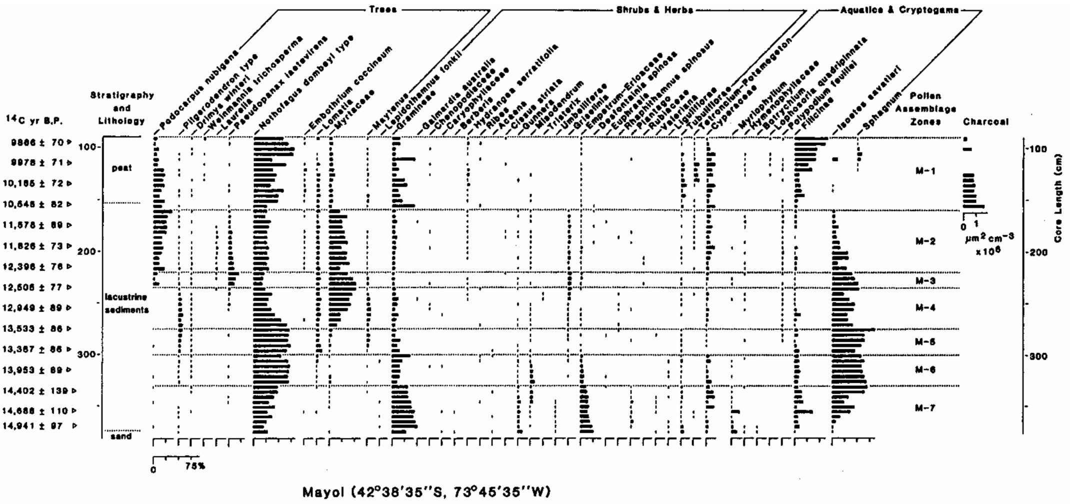


Fig. 24. Pollen and spore diagram of core taken in mire at Mayol, subdivided into pollen assemblage zones (for pollen assemblage and radiocarbon age data see Table 17).

growth and reproduction, *Nothofagus* by 13,533 ^{14}C yr BP displaced much Gramineae (zone M-6) to supply 65–73% of the pollen sum (zone M-5). Remaining quantities (≤15%) of Gramineae apparently are from tracts of residual woodland that under warmer climate by 13,387 ^{14}C yr BP (zone M-5) were infiltrated by *Pilgerodendron* type, *Lomatia,* Myrtaceae, and *Maytenus*. Continuing moderating climate supported communities of North Patagonian Evergreen Forest, which by 12,505 ^{14}C yr BP were dominated by Myrtaceae (zones M-4 and M-3) at peak frequency (52–53%). Later, as a result of a reversal in the warming trend, suppression by *Pseudopanax laetevirens* (21%) and by *Podocarpus nubigena* (36%) after 12,396 ^{14}C yr BP in the presence of *Laurelia* reduced Myrtaceae to values averaging 29% (zone M-2). At Mayol, following 2500 years of progressive warming, cooler conditions and lastly disturbance by fire were in effect during the remaining 2500 years of record. After

Table 17. Pollen assemblage and chronostratigraphic data for core from Mayol mire.

Pollen assemblage zone	Pollen assemblage	Age (^{14}C yr BP)
M-1 (90–155 cm)	*Nothofagus-Podocarpus-Lomatia*-Myrtaceae-Gramineae-Tubuliflorae	9,866±70 (95 cm, AA-20356) 9,978±71 (115 cm, AA-20357) 10,165±72 (135 cm, AA-20358)
M-2 (155–220 cm)	*Podocarpus-Nothofagus-Laurelia-Pseudopanax-Lomatia*-Myrtaceae	10,545±82 (155 cm, AA-20359) 11,578±89 (175 cm, AA-20360) 11,862±73 (195 cm, AA-20361) 12,396±76 (215 cm, AA-20362)
M-3 (220–235 cm)	*Pseudopanax*-Myrtaceae-*Nothofagus-Lomatia*	
M-4 (235–275 cm)	Myrtaceae-*Nothofagus-Pilgerodendron* type-*Lomatia-Maytenus*	12,505±77 (235 cm, AA-20363) 12,949±89 (255 cm, AA-20364)
M-5 (275–300 cm)	*Nothofagus-Pilgerodendron* type-*Lomatia-Maytenus*-Gramineae	13,387±86 (275 cm, AA-20365) 13,533±86 (295 cm, AA-20366)
M-6 (300–330 cm)	*Nothofagus*-Gramineae-*Misodendrum*	13,953±89 (315 cm, AA-20367)
M-7 (330–375 cm)	Gramineae-*Nothofagus-Gunnera-Empetrum*-Ericaceae-*Plantago*	14,402±139 (335 cm, AA-20368) 14,688±110 (355 cm, AA-20369) 14,941±97 (370 cm, AA-20370)

10,545 ^{14}C yr BP, expansion of light-dependent *Nothofagus*, Gramineae, Tubuliflorae, and Filicinae, coeval with charcoal contained in the upper part of the deposit (zone M-1), is accountable by fire.

Discussion

Vegetation reconstruction

Regional Pleistocene vegetation between >50,000 and 10,000 ^{14}C yr BP is shown in Fig. 25. Age plots for each locality (reconstructed from pollen records seen in Figs 8, 9, 12–14, 16–20, 22–24) show the timing of the development of Subantarctic Parkland, Subantarctic Evergreen Forest, and North Patagonian Evergreen Forest in southern Chile. That vegetation sequences from the chronostratigraphic standpoint are not entirely uniform throughout can be attributed to: (1) time-transgressive migration of species; (2) local edaphic control, a factor contributing to the establishment of parkland, for example, in the case of the Lago Llanquihue lobe interdrift sites, Puerto Octay and Frutillar Bajo; (3) differential climate in effect at respective geographic locations; and (4) radiocarbon dating error.

Subantarctic Evergreen Forest, indicated at Taiquemó during middle Llanquihue glaciation, is distinctive only of the Golfo de Ancud and Golfo Corcovado lobes on Isla Grande de Chiloé. The island apparently was a refugium for a number of tree species under conditions that match the present forest environment at 48–54°S in southern Chile. Forest stands were evidently discontinuous, where present at low elevation, possibly in relation to positions of ice fronts. This is illustrated by the presence of Subantarctic Parkland at Teguaco after 30,000 ^{14}C yr BP, which dates earlier than at Taiquemó or Dalcahue. Vegetation closely ordered on the relatively narrow east side of the Cordillera de la Costa on Isla Grande de Chiloé was apparently in a tension zone and more sensitive to shifting climatic conditions than in the broad, topographically open Valle Central where Subantarctic Parkland is continuously in evidence. Subantarctic Evergreen Forest is recognized (Fig. 20; zone T-14) by dominance of southern beech (cf *N. betuloides*) and amounts of *Podocarpus nubigena, Pilgerodendron* type, *Pseudopanax laetevirens,* and *Drimys winteri*; less numerous but significant are *Embothrium coccineum, Lomatia, Maytenus, Desfontainia spinosa,* and myrtle. While *Pilgerodendron* type is almost certainly with reference to *P. uviferum*, other species implied are *Lomatia ferruginea*, *Maytenus magellanica,* and *Myrteola nummularia* (myrtle). These taxa likewise contribute to the makeup of southernmost North Patagonian Evergreen Forest; however, appreciable amounts of myrtle (other than *Myrteola*) and the presence of *Laurelia* and *Weinmannia trichosperma*, which reside in North Patagonian Forest, are not in evidence.

Pervading the vegetation, where chronologies overlap, is a general uniformity of Subantarctic Parkland, followed at about 14,000 ^{14}C yr BP by transition to North Patagonian Evergreen Forest. Subantarctic Parkland is exclusively the vegetation on drift of the Lago Llanquihue and Seno Reloncaví lobes during middle and late Llanquihue glaciation. Periodically spread over drift of the Golfo de Ancud and Golfo Corcovado lobes, parkland also became featured on Isla Grande de Chiloé during late Llanquihue glacial maxima. Where impeded drainage existed, as at Canal Tenglo (Fig. 16; zones CT-3c and CT-3b), parkland included communities of Magellanic Moorland containing *Astelia pumila, Donatia fascicularis, Lepidothamnus fonkii, Pilgerodendron uviferum*, and myrtle (cf *Myrteola*). Moorland is especially apparent at Taiquemó (Fig. 20) during late Llanquihue glaciation and locally in the late glacial. This evidence corroborates reports by Villagrán (1988b, 1990) of Magellanic Moorland at low elevations on northern Isla Grande de Chiloé during the Pleistocene.

Subantarctic Parkland formed a vegetation mosaic, in which the principals, southern beech and grass, interacted. Oscillating mostly in opposition to the other, each reached maximum frequencies of >75%. Beech–grass communities possess no clear modern analog because of the distinctive setting unmatched to a comparable degree by present-day vegetation in southern Chile. Lowell *et al.* (1995) point out that extensive outwash plains of glaciofluvial sediments, formed during times of glacial maxima, provided an unusual surface for the principals to thrive. The open landscape offered little or no protection against strong katabatic wind coming off the piedmont lobes, thus favoring expansion of grass and localization of beech. Increased frequencies of beech represent a response to withdrawal of ice fronts and greater interstadial warmth and landscape stability.

North Patagonian Evergreen Forest rapidly developed late-glacial floristic and structural integrity stepwise after 14,000 ^{14}C yr BP. In the course of glacier recession, transitional communities of beech first expanded, representing the final phase of beech–grass cycling at the close of the parkland

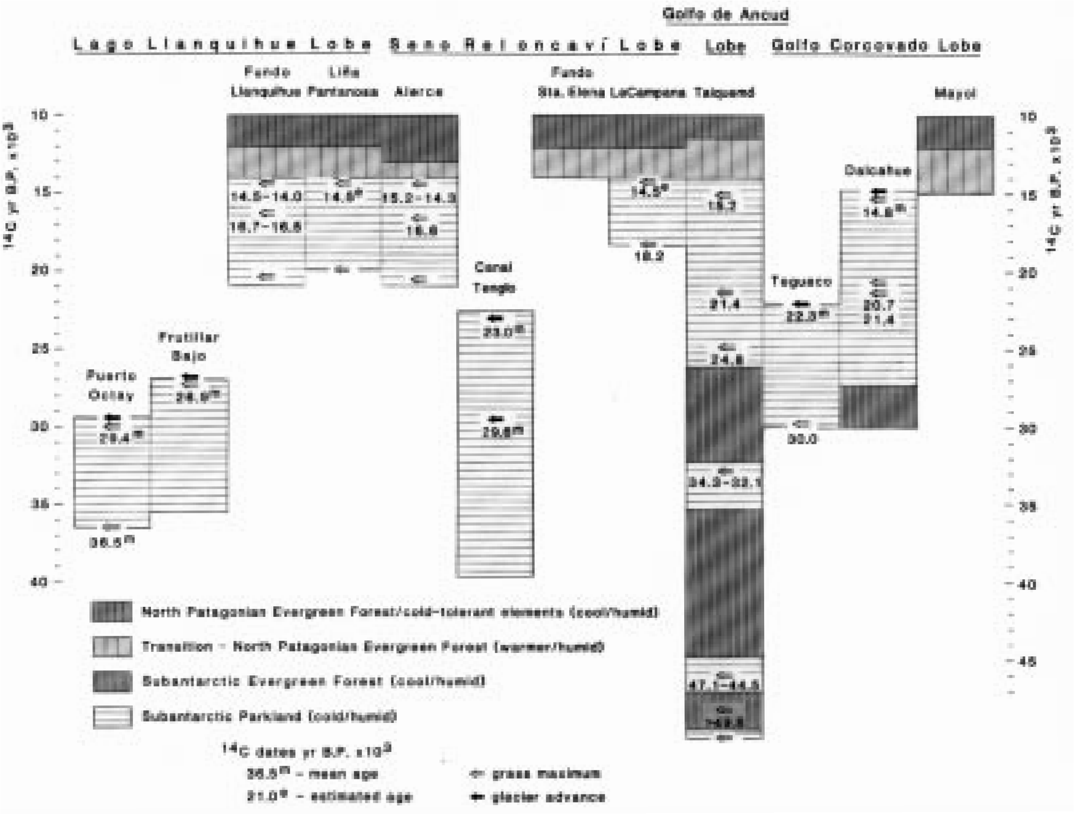


Fig. 25. Vegetation expressed by long-term pollen records at sites in relation to piedmont lobes in the Southern Lake District and on Isla Grande de Chiloé during middle and late Llanquihue glaciation and deglaciation. Sites with short-term data (<1000 ^{14}C years) at Llanquihue, Bella Vista Bluff, and Punta Penas are not shown. Singular occurrence early in the record of Subantarctic Evergreen Forest in relation to the Golfo de Ancud and Golfo Corcovado lobes apparently reflects the presence of a tension zone sensitive to shifting climate, which at times favored expansion of Subantarctic Parkland. In contrast, Subantarctic Parkland, not similarly influenced, dominated with reference to the Lago Llanquihue and Seno Reloncaví lobes. Subantarctic Parkland was uniformly prevalent at the peripheries of the four lobes after 26,000 until 14,000 ^{14}C yr BP. Thereafter, all late-glacial records show stepwise transitional woodland and advance of thermophilous North Patagonian Evergreen Forest until about 12,000 ^{14}C yr BP, followed by cooling until 10,000 ^{14}C yr BP.

era. The forest in a later step reached an advanced state in some 1500 ^{14}C years, dominated by thermophilous myrtle and beech (cf *Nothofagus dombeyi* and/or *N. nitida*). Communities included *Embothrium, Lomatia, Maytenus, Drimys, Laurelia,* and *Weinmannia*, which regionally also had been suppressed, or excluded, during parkland residency. In the final step, forest composition and dominance began to shift at around 12,000 ^{14}C yr BP, changing somewhat earlier at some sites and later at others, when *Podocarpus* and *Pseudopanax* expanded and variously continued in effect, together with *Pilgerodendron* type and *Saxe-gothaea*, until about 10,000 ^{14}C yr BP.

A schematic account of vegetation during the last >10,000 ^{14}C years of the Pleistocene (Fig. 26) is drawn from the detailed pollen stratigraphy at Fundo Llanquihue. The layout is couched in the performance of ecologically significant southern beech, grass, composite, and vegetation types: Subantarctic Parkland shrubs and herbs (other than grass, composite, and heath), *Ephedra, Lepidothamnus, Nanodea,* Chenopodiaceae, Caryophyllaceae*, Ribes, Acaena, Gunnera, Drapetes,* Umbelliferae*, Euphrasia,* Rubiaceae*, Valeriana,* and *Huperzia*; North Patagonian Evergreen Forest thermophilic trees, myrtle, *Embothrium, Lomatia*, *Maytenus, Drimys*, and *Weinmannia*; North Patagonian Evergreen Forest cold-tolerant elements, *Podocarpus*, *Pilgerodendron* type, and *Pseudo-*

panax, and heath, *Empetrum*-Ericaceae. The assignment of certain taxa to groups is somewhat arbitrary, as regards, for example, *Drimys, Weinmannia*, and *Embothrium*, each of which is wide-ranging, tolerant of broad temperature regimes.

Following the 22,400 ^{14}C yr BP glacial maximum, Subantarctic Parkland primarily of grass prevailed with southern beech as the pre-eminent vegetation west of Lago Llanquihue for >6000 ^{14}C years until the final maximum of grass at about 14,000 ^{14}C yr BP. Open parkland became progressively phased out mainly by beech with the result that by 13,000 ^{14}C yr BP, grass, composite, and other parkland shrubs and herbs were minimal. The short-term peak of grass, lasting no more than two or possibly three radiocarbon centuries just prior to 16,000 ^{14}C yr BP, is the only apparent noteworthy event recorded earlier than 14,000 ^{14}C yr BP. Peak composite at around 16,000 and before 14,000 ^{14}C yr BP implies the presence of ecotones that identify transition to beech woodland. The ecotones are reminiscent of openings and edges of present-day beech forest in southernmost Chile containing an abundance of the shrubby composite, *Chiliotrichum diffusum* (Moore 1983).

Closed North Patagonian Evergreen Forest, structured by thermophilic elements, was in place at Fundo Llanquihue before 12,000 ^{14}C yr BP (warming phase); increased frequencies of southern beech and declining grass during transition to North Patagonian Forest after 14,000 ^{14}C yr BP signal the beginning of the warming trend. After 12,000 ^{14}C yr BP, expansion of cold-tolerant forest elements (cooling phase) reflects a shift in community dominance; one element, *Podocarpus nubigena*, growing at present mostly above an elevation of 400 m in the neighboring cordillera (Villagrán *et al.* 1993), is significant at the Fundo Llanquihue site. Heath, locally present, formed on the open acidic surface of the Fundo Llanquihue mire. After 10,800 ^{14}C yr BP, ravages of fire are held accountable for reduction of beech, as well as the cold-tolerant elements, and for expansion of successional composite.

For millennia between 15,000 and 10,000 ^{14}C yr BP, Mayol (Fig. 27) summarizes deglacial vegetation change for comparison with Fundo Llanquihue. At Mayol, heath is not abundant after 13,000 ^{14}C yr BP, as at Fundo Llanquihue, thus providing an opportunity for greater expression of tree frequencies. The opening rise of southern beech and peaks of thermophilic and cold-tolerant elements, respective warming and cooling phases of the ensuing North Patagonian Evergreen Forest, are comparatively robust prior to the disturbance of vegetation by fire. Although sequentially similar, vegetational changes at the sites in their chronological settings differ by two or more centuries, a feature possibly created by local conditions and the responses of taxa to forcing at each site. Mayol on Isla Grande de Chiloé lies about 170 km south of Fundo Llanquihue.

Long-term vegetational episodes for >50,000–10,000 ^{14}C yr BP are recapitulated at Taiquemó (Fig. 28). Illustrated for the most part are Subantarctic Evergreen Forest in the early part of the record and subsequent attenuation of forest by periodic pulses of grass, which ultimately dominate Subantarctic Parkland by 21,000 ^{14}C yr BP. Southern beech is consistently at high frequency, as a parkland/forest component. The final pulse of grass at 14,000 ^{14}C yr BP precedes the changeover from parkland to North Patagonian Evergreen Forest.

Recurrent cycling of grass, giving rise to peaks throughout Taiquemó, begins with the opening pulse at >50,000 ^{14}C yr BP, which possibly is during late oxygen-isotope Stage 4, dated at 59,000 ^{14}C yr BP (Martinson *et al.* 1987). Stage 4 covers comparatively cold millennia and logically is associated with middle-Llanquihue moraine emplacement and early deposition at Taiquemó. The pulses of grass, ranging over cycles from a few thousand to as much as 10,000 ^{14}C years, suggest a relationship with the timing of iceberg discharges on millennial scales in the North Atlantic (Bond and Lotti 1995).

Fire is not evident during late-glacial forest development at Taiquemó, as it is at Fundo Llanquihue and Mayol, thus allowing undisturbed succession of thermophilic and cold-tolerant elements until 10,000 ^{14}C yr BP.

Paleoclimate and maxima of regional piedmont lobes

Pollen records imply the presence of Subantarctic Parkland and North Patagonian and Subantarctic Evergreen Forests in the Southern Lake District–Isla Grande de Chiloé, where regionally today there exists Valdivian Evergreen Forest. The apparent degree to which vegetation differed during the Pleistocene provides a pathway for estimating past climatic parameters. In general terms, sets of temperature and precipitation data (Table 1) circumscribe existing vegetation conditions. Differences between sets are an approximation of amounts of temperature and precipitation variation that prevail between plant formations in southernmost Chile. Between Isla Grande de Chiloé and the extreme south at Cabo de Hornos in Magellanic Moorland, for example, the decrease in average summer temperature amounts to 6˚C and approaches the amount of temperature depression resulting from an assessment of reconstructed Pleistocene vegetation records. Precipitation, by comparison with temperature, is more difficult to estimate. At Cabo de Hornos at 56˚S, annual precipitation at sea level in Magellanic Moorland averages about 500 mm lower than on Isla Grande de Chiloé; by contrast, precipitation in moorland at 50˚S reaches maxima exceeding by as much as a factor of four amounts recorded at 42˚S.

With no modern analog, Subantarctic Parkland appears to be driven by conditions not unlike those prevailing in present-day Magellanic Moorland (Table 1). That the two kinds of vegetation bear a relationship to each other is indicated by shared limited diversity of an arboreal component (*Nothofagus, Drimys, Pilgerodendron*) and a common assemblage of shrubs and herbs (notably *Lepidothamnus, Astelia, Caltha, Empetrum*-Ericaceae, *Gunnera, Drapetes*, Umbelliferae). What is a formidable part of Subantarctic Parkland but not well represented in moorland, exclusive of localized distributions, are communities of grass (Pisano 1980; Dollenz 1980, 1981; Roig *et al.* 1985). An exception is the *Poa flabellata* grass community on treeless Islas Diego Ramírez (56°30'S, 68˚40'W), southwest of Cabo de Hornos (Pisano and Schlatter 1981). Mean summer temperature on Islas Diego Ramírez amounts to 6.8°C, annual precipitation averages about 1200 mm, and wind speeds recorded are as high as 167 km h^{-1} (Zamora and Santana 1979).

Islas Diego Ramírez and Magellanic Moorland climatalogical data (Almeyda and Sáez 1958; Miller 1976; Prohaska 1976) indicate lower summer temperatures and a decrease of annual precipitation at increasingly higher latitudes of southern Chile. Tree growth, progressively restricted along a gradient that extends southward and toward the outer coast, is a reflection of lower temperature but also of greater wind strength through the tension zone. Conditions limiting presence of trees in the southern part of the region, although probably not a clear analog of Subantarctic Parkland, serve as a model for interpreting climate restrictive to beech during the Pleistocene.

At modern treeline in the cordillera of Tierra del Fuego (55˚S), southern beech is under an estimated mean summer temperature of 6 ± 0.5°C (Puigdefábregas *et al.* 1988; Heusser 1989a). For Isla Grande de Chiloé, at a present-day mean at sea level of 14°C, the estimate implies a temperature depression at treeline of about 8°C. This amount of depression can reasonably be applied to altitudinally depressed treeline in Subantarctic Parkland during the Pleistocene, where beech during episodes of grass in the pollen record occurs in a 1:1 ratio. Higher ratios of grass imply more remote beech and greater temperature depression; conversely, higher ratios of beech indicate increasing proximity to treeline and less depression. Wind is not accounted for in this estimate of temperature at treeline. In southernmost Chile, treeline is uniformly within a narrow range of elevations, indicating that temperature is probably the foremost factor limiting beech.

Grass frequencies relative to southern beech between >50,000 and 14,000 ^{14}C yr BP at Taiquemó on Isla Grande de Chiloé (Fig. 20) are plotted with reference to a paleotemperature index (Fig. 29). Indices embrace a mean summer temperature range between modern treeline at 6˚C and a maximum 12˚C for Subantarctic Evergreen Forest (Table 1). In the accompanying plot, each unit of the index provides, on a scale of 1–5, a basis for estimating the amount of temperature depression relative to mean summer temperature. Bars shown are placed at every 500 ^{14}C years, each centered on a temperature value within an envelope of ± 0.5°C estimated error. After 14,000 ^{14}C yr BP, temperatures are approximated from the modern range applicable to North Patagonian Evergreen Forest. Values plotted fall within temperature ranges for Subantarctic-North Patagonian Evergreen Forest (10–14˚C), and are close to the limit (8–11˚C) of Magellanic Moorland (Table 1).

Intervals of distinct temperature depression, indicated by peak paleotemperature indices (Fig. 29), extend over a range of -4 to -8°C, while mean summer temperatures are between 10 and 6°C. Times when temperatures apparently plunged the most occur at close to 25,000 and 21,000 ^{14}C yr BP; lesser temperature minima appear concentrated at >50,000, 35,000–32,000, and 15,000 ^{14}C yr BP; and least minima are at 49,000, 46,000, and 28,000 ^{14}C yr BP. Overall, times of low temperature and finitely dated glacial maxima are shown within limits to bear a relationship with one another. That there are instances of leads and lags between the two sets of data suggests that secondary factors, atmospheric moisture, for example, are coupled with temperature.

The Lago Llanquihue, Seno Reloncaví, Golfo

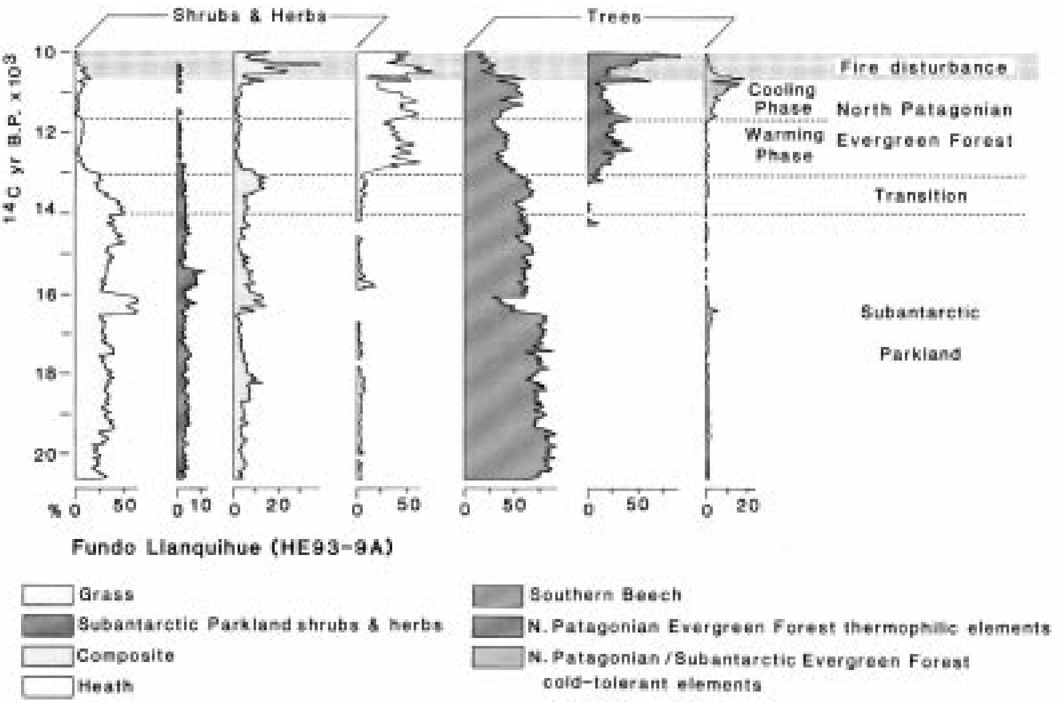


Fig. 26. Age plot of ecologically significant taxa, or groups of taxa, at Fundo Llanquihue (HE93-9A) for the last >10,000 ^{14}C years of the Pleistocene. Shrub and herb frequencies, illustrated from left to right, apply to grass, Subantarctic Parkland, composite, and heath; trees encompass southern beech and North Patagonian Evergreen Forest thermophilic elements and cold-tolerant elements (see text for taxa). Age model is based on interpolation and extrapolation of radiocarbon dates (Table 7; Fig. 13). Note non-uniformity in scales for frequency.

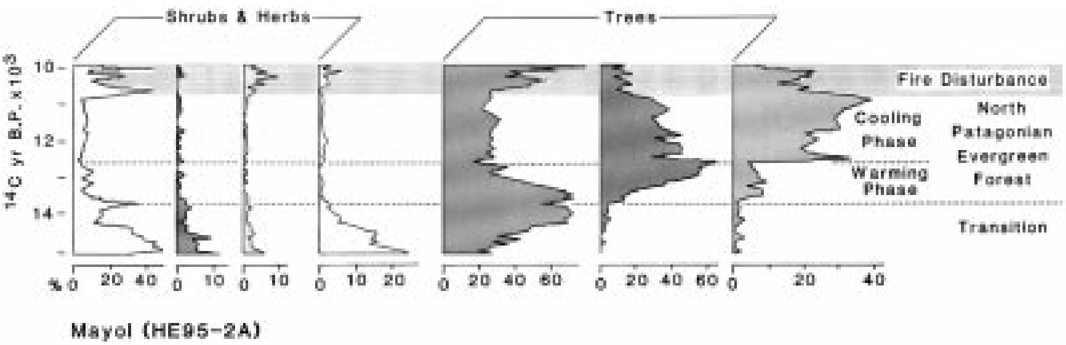


Fig. 27. Age plot of ecologically significant taxa, or groups of taxa, at Mayol (HE95-2A) for the last 5000 ^{14}C years of the Pleistocene. Age model derives from interpolation and extrapolation of radiocarbon dates (Table 17; Fig. 24). See Fig. 26 for color-coded identifications and text for taxa. Note non-uniformity in scales for frequency.

de Ancud, and Golfo Corcovado piedmont lobes all reached maxima after about 15,000 ^{14}C yr BP, triggered by uniformly cold climate, as implied by increased frequency of grass. A rise in mean summer temperature of 5–6°C after 14,000 ^{14}C yr BP, the most extensive temperature change of the entire record, caused piedmont glaciers in the Southern Lake District–Isla Grande de Chiloé to dissipate. Deglaciation at this time was likewise in effect at 46°30'S (Lumley 1993), 53°30'S (Clapperton *et al.*

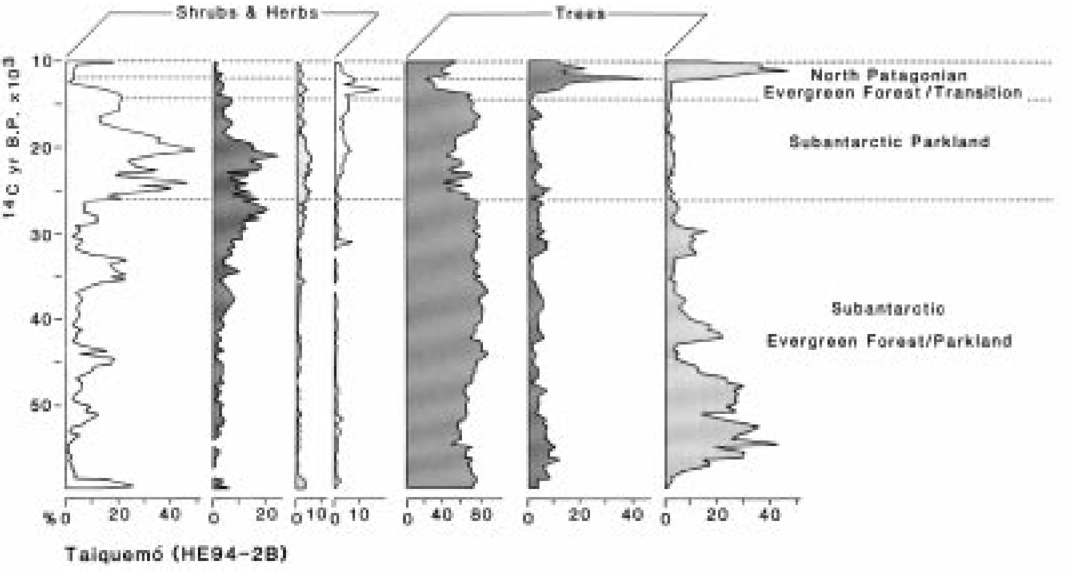


Fig. 28. Age plot of ecologically significant taxa, or groups of taxa, at Taiquemó (HE94-2B) for the past >50,000 years of the Pleistocene. Age model is produced by interpolation and extrapolation of radiocarbon dates (Table 14; Fig. 20). See Fig. 26 for color-coded identifications and text for taxa. Note non-uniformity in scales for frequency.

1995), and 55°S (Rabassa *et al.* 1990). In the Andes of Chiloé Continental, deglaciation by 12,300 ^{14}C yr BP at Cuesta Moraga (43°31'36"S) had proceeded to elevations above 700 m (Heusser *et al.* 1992).

Evidence of the warming trend after 14,000 ^{14}C yr BP, noted repeatedly in the pollen stratigraphy, is also found in remains of obligate forest beetle fauna (Hoganson and Ashworth 1992) and in the early presence of waterfern (*Azolla filiculoides*) on Isla Grande de Chiloé (Heusser *et al.* 1996a). Apparently insensitive to low-order temperature change, beetles under forest conditions indicate continuous warming into the Holocene. Their performance contrasts late-glacial lowering of mean summer temperature between about 12,000 and 10,000 ^{14}C yr BP of ≤ 2–3°C, an estimate based on significant increase in frequency of cold-tolerant forest elements (Heusser *et al.* 1996b). With cooling, glaciers in the Southern Andes would be expected to have been active at this time, which covers the Younger Dryas chronozone. In one instance recorded in proglacial Lake Mascardi in the Argen-

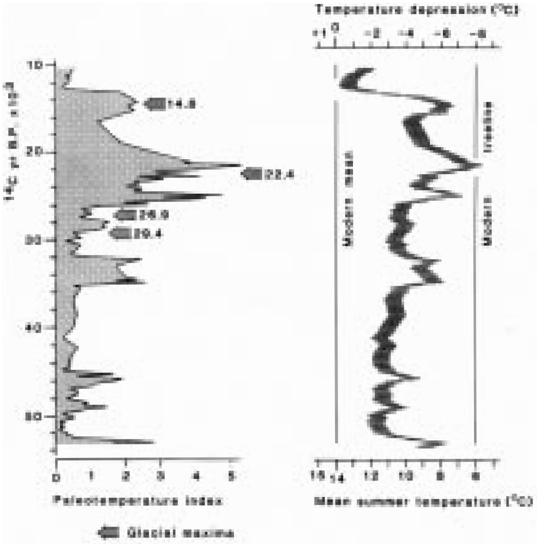


Fig. 29. Paleotemperature index calibrated from *Nothofagus*–Gramineae ratios at Taiquemó in relation to radiocarbon-dated glacier maxima. Each unit of the index is a measure relative to mean summer temperature and amount of temperature depression. Bars are centered on temperature values (estimated error of ± 0.5°C) at 500-year intervals. Data apply to Subantarctic Evergreen Forest and Subantarctic Parkland between >50,000 and 14,000 ^{14}C yr BP. After 14,000 ^{14}C yr BP, values approximated fall within the temperature range applicable to North Patagonian Evergreen Forest. See text for additional explanation.

tine Andes at 41°15'S east of Lago Llanquihue, glacial readvance is dated between 11,400 and 10,200 ^{14}C yr BP (Ariztegui *et al.* 1997). In another, beyond the southern margin of the Southern Patagonian Icefield (51°S), end moraines are bracketed by dates of 11,880 and 9180 ^{14}C yr BP (Marden 1997).

The implication of the pollen-derived climatic data is of glacier activity primarily tied in with temperature minima. Predictable to a lesser degree is precipitation variability, as a factor bearing on conditions during stades and interstades. Providing a possible framework for precipitation, as well as temperature, are the lacustrine conditions that replaced mire, including the frequency pattern of the aquatic *Isoetes* at Taiquemó (Fig. 20). *Isoetes,* increasing after 47,000 ^{14}C yr BP with development of the lacustrine setting, is a reflection of rising precipitation. Its numbers reduced at 34,000–32,000 ^{14}C yr BP, possibly by cold climate during an important episode of grass (Fig. 29), *Isoetes* later reached peak frequency at 26,000 ^{14}C yr BP. Although aquatic conditions continued until an estimated 14,000 ^{14}C yr BP, *Isoetes* after 22,600 ^{14}C yr BP became a nonentity, as temperature fell during a major episode of grass at 21,000 ^{14}C yr BP. The long record of high humidity revealed by *Isoetes* at Taiquemó indicates that precipitation was not a limiting factor in glacier alimentation during middle and late Llanquihue glaciation.

Ice fields in the Andes between glacial maxima hypothetically were maintained by substantial precipitation during cool interstadial climate, much in the same manner that ice fields in the Southern Andes exist at present. The impetus for glaciers to advance was evidently provided by a drop in temperature. Glacier collapse occurred with an increase in temperature, rise of snowline, and greater ablation in the cordillera. Stades probably were associated with greater wind strength up until the time of glacial maxima, while outbreaks of maritime and continental antarctic air forced the maritime polar air mass, embracing the Southern Westerlies, equatorward. During interstades, outbreaks were evidently fewer, when antarctic air affected middle latitudes less.

It becomes axiomatic in the light of available data that both vegetation and glacier stadial/interstadial behavior resulted from repeated latitudinal shifting of the Southern Westerlies, a process that apparently has continued to take place in the Southern Andes on a smaller scale during the Holocene (Heusser 1995). Evidence for movement/strengthening of the westerlies at lower latitudes during the Pleistocene, by reference to their present latitude, is reported from assorted sources (Paskoff 1970; Hastenrath 1971; Villagrán 1988b, 1990; Heusser 1989b, 1990b, 1991, 1994b; Caviedes 1990; Villagrán and Varela 1990). A case in point, emerging from studies in the Southern Lake District–Isla Grande de Chiloé, is the discordant relative extent of the Lago Llanquihue and Golfo Corcovado piedmont lobes during the 22,400 and 14,800 ^{14}C yr BP maxima. Both lobes, responding in unison to cooling, advanced to positions that were greater for the Lago Llanquihue lobe during the earlier of the two maxima and greater for the Golfo Corcovado lobe during the latest maximum. The assumption is that the lobes at these times were differentially nourished by snowfall because of latitudinal displacement of the moisture-laden Southern Westerlies.

Modeling experiments independently show displacement of the westerly wind belt to lower latitudes (COHMAP members 1988), but there is, contrary to a wealth of evidence, a view toward concentration of the westerlies at higher latitudes (Kutzbach and Guetter 1986; Markgraf 1989). The latest modeling of glaciers and climate at the last glacial maximum in the Southern Andes (Hulton *et al.* 1994) points to concentration of westerly wind strength northward by 5° of latitude. This amount of change is comparable to the extent of movement of the oceanic Antarctic Polar Front in the western Atlantic, which is coincident with the northern edge of the westerly wind belt (Morley and Hays 1979). Recurring migration of the atmospheric polar front is corroborated by widespread multiple glaciation in the subtropical Andes (Caviedes and Paskoff 1975; Espizúa 1993). The influence of an oscillating front also may explain the origin of the loess–paleosol complex in northwestern Argentina (Sayago 1995), geomorphological and pedological features in northern Chile (Veit 1996), and cold-indicative transformation of vegetation in southeastern Brazil (Ledru 1993).

Possible modification by volcanic activity of the paleoclimatic signal interpreted from the reconstructed vegetation requires discussion. Volcanoes in the Andes (Fig. 1) were sources of pyroclastics contributed to the Valle Central via glacier and alluvial transport, airfall deposition, and a variety of flows (Langohr 1974; Moreno and Varela 1985). In addition to pyroclastics in soils at the surface of the drift, glass shards and fragments of pumice make up the matrix of much of the intertill organic silt at Puerto Octay, Frutillar Bajo, and Dalcahue (Figs 8, 9, and 23), and ash and lapilli, as noted in the core from Fundo Llanquihue (Fig. 12), form a regional, early Holocene tephra layer. Glass in the silt appears weathered, the result of attrition by reworking, while the sharp features of glass in the tephra layer infer direct, *in situ*, subaerial deposition and preservation.

In the absence of abrupt changes in the intertill pollen stratigraphy, as well as of lithological features interrupting the general uniformity of the associated sediments, the records show no clear instance of vegetational alteration that would suggest, other than temporary episodes of plant succession (<200 years duration), catastrophic effects of pyroclastic flows or other volcanic activity. Over the time of record, which is some 10,000 ^{14}C years at Puerto Octay and Frutillar Bajo and >15,000 ^{14}C years at Dalcahue, pollen in the organic silt occurs with relatively high density and is both well-preserved and mostly unoxidized. Loss on ignition measurements record a minimum of variation, and charcoal particulates, indicative of major conflagration caused by pyroclastic flows, are infrequent in the deposits. At Taiquemó (Fig. 20), about 20 km north of Dalcahue, lacustrine sediments in the same time range as Dalcahue, also much diffused with microscopic fragments of volcanic glass, show neither discrete lithostratigraphic horizons nor distinctive pollen assemblage modification, the result of volcanic-related activity. The effects of debris flows at Puerto Varas (Fig. 11) younger than 14,430 ^{14}C yr BP and of deposition of a singular, regionally recorded tephra layer dated close to 9500 ^{14}C yr BP (Heusser 1966; Heusser *et al.* 1995) are likewise little recognizable, if at all, in pollen sequences monitoring vegetation at these times.

Overprinting by volcanism, based on available evidence, is not considered to be a deterrent factor upsetting the primary control of vegetation by climate during the >40,000 ^{14}C years of record. Consequences of volcanic activity in the extra-Andean Southern Lake District–Isla Grande de Chiloé sector appear to have been relatively minor and no more than short-term and infrequent, as the patterns of continuous pollen data with high temporal resolution indicate.

Late Pleistocene midlatitude vegetation and climate of the Southern Hemisphere: Southern South America, New Zealand, and Tasmania

Some noteworthy similarities are seen between millennial-scale climate changes implied by pollen data from Chile and midlatitude sites elsewhere in the Southern Hemisphere. Existing radiocarbon chronology, however, allows only a broad parallel to be drawn among climatic implications from the Southern Chilean Lake District–Isla Grande de Chiloé, New Zealand, and Tasmania. High resolution comparison is precluded by the nature of evidence from the southwest Pacific. New Zealand pollen records of Younger Dryas age made reference to by McGlone (1995), for example, derive from six sections sampled at intervals of 10 or 20 cm with only three of 12 radiocarbon dates applicable to the Younger Dryas. Restraints also apply with regard to the chronology of the last glaciation, which places the latest maxima in New Zealand–Tasmania at <25,000 and >14,000 ^{14}C yr BP (Suggate 1990; Colhoun and Fitzsimons 1990; Fitzsimons 1997). An earlier interstade in New Zealand dates to >31,600 ^{14}C yr BP (Moar and Suggate 1979) and in Tasmania to >44,000 ^{14}C yr BP (Colhoun *et al.* 1988).

McGlone (1988) in an account of stadial vegetation on northern South Island, New Zealand, at 22,000–14,000 ^{14}C yr BP describes grassland/herbfield in the interior, as well as to the east, and shrubland in coastal sectors; trees at <20%, and frequently at <10%, were almost exclusively southern beech. Climate of the virtually treeless grassland/shrubland is interpreted as relatively cold, dry, and windy; average annual temperature is estimated at ≥5°C below the present. During an earlier interstade (>31,000–~26,000 ^{14}C yr BP), according to Moar and Suggate (1979), shrubs and trees, including beech, formed the preponderant vegetation of western South Island under what appears to have been a cool and more humid climate.

Vegetation at the last glacial maximum in Tasmania portrayed by Colhoun *et al.* (1988, 1994) consisted of grassland, containing *Astelia*, composite, and high-elevation, shrubby eucalypt. Communities, dated at 21,250 ^{14}C yr BP and indicative of cold, stadial climate, followed an interstade (>43,800 to about 25,000 ^{14}C yr BP), characterized by near-treeline shrubs under moderated cool, moist climate. Communities of grass-epacrid heath, also in evidence during the last glacial maximum, replaced interstadial *Microstrobos* shrubland that dominated from >34,500 to 23,600 ^{14}C yr BP. Stadial and interstadial temperatures are estimated, respectively, at about 6.5 and 4.5°C below present. Late-glacial climatic warming that brought about arboreal replacement of grassland/shrubland dates to between about 14,500 and 11,500 ^{14}C yr BP in New Zealand (Suggate 1990;

McGlone 1995) and 14,000 and 12,000 ^{14}C yr BP in Tasmania (Macphail 1979; Colhoun and Fitzsimons 1990). The absence of pollen stratigraphic evidence of a late-glacial reversal of climate suggests that warming continued uninterruptedly into the Holocene.

New Zealand–Tasmania climate of the last 40,000 ^{14}C years of the Pleistocene is on a large scale fundamentally similar to the climate of southern South America: cold stadial conditions, equated with late Llanquihue glaciation, preceded and followed by warmer interstades. Stadial climate, comparatively dry in New Zealand–Tasmania, was evidently more humid in the Southern Lake District–Isla Grande de Chiloé, where higher levels of precipitation maintained Subantarctic Parkland with beech in amounts generally >50%. Before being decimated by cold at the last glacial maximum, interstadial woodland and shrub/herb communities of near-treeline, subantarctic affinity were well established.

After 14,000 ^{14}C yr BP during deglaciation, vegetation reconstructed from pollen data in New Zealand and Tasmania does not reveal evidence of renewed cooling, as is observed in the Southern Lake District–Isla Grande de Chiloé by about 12,000 until 10,000 ^{14}C yr BP. Moreover, a paradox exists, shown by opposing directional changes expressed by vegetational and glacial behavior: while no interruption in the warming trend is seen in the vegetation (Colhoun *et al.* 1994; McGlone 1995), advances dated 11,050 ^{14}C yr BP of Franz Josef Glacier (Denton and Hendy 1994) and 10,250 ^{14}C yr BP at Cropp River (Basher and McSaveney 1989) in the Southern Alps, New Zealand, are viewed as responses to climatic cooling. The implication of the glacial activity at the time of the European Younger Dryas chron (11,000–10,000 ^{14}C yr BP; Mangerud *et al.* 1974) is of coincidental atmospheric forcing in the polar hemispheres.

Seeking an explanation for the paradox, McGlone (1995) suggests that glacial advance was possibly caused by greater cloudiness in conjunction with an increase of moisture-laden, westerly wind and snowfall. Temperatures need not have been significantly lower, as the westerlies during their retreat poleward following the last glacial maximum became temporarily concentrated in the latitude of the Franz Josef–Cropp River glaciers. A modern analog of this situation is seen in the differential behavior of glaciers in the Cordillera Darwin of southern Chile (Holmgren and Fuenzalida 1995). Under a warming trend of the past 50 years with no change in precipitation, glacier advance on the windward slope of the cordillera compared with retreat to leeward is likewise attributed to the strength and pattern of the Southern Westerlies.

Contrasting behavior of the vegetation and glacier systems cannot be fully explained without additional essential data. A refined pollen stratigraphy is fundamental, controlled by a pool of radiocarbon dates and based on close-order sampling in the late-glacial time frame. Likewise, supplemental chronologies from additional glacier systems, both in the Southern Alps and Southern Andes, are needed to test the strength of climatic forcing at the time of the Younger Dryas.

Polar hemispheric records: Southern South America versus the Southern Ocean–North Atlantic and Antarctica–Greenland

Two long-term pollen sequences in marine cores controlled by ∂^{18}O stratigraphy from the Southern Ocean are directly correlated with nearby New Zealand and Tasmania stadial–interstadial pollen data (van de Geer *et al.* 1994; Heusser and van de Geer 1994; Colhoun *et al.* 1994). Although the sequences are correlated in turn with pollen and isotope records from the North Pacific Ocean off Japan and the American northwest coast, providing a measure of synchrony of global vegetational–climatic change, their deglacial accounts are broadly constrained. For detail of the last deglaciation, marine cores from the Indian sector of the Southern Ocean display high-resolution ∂^{18}O measurements and transfer functions applied to radiocarbon AMS-dated foraminifer assemblages (Labracherie *et al.* 1989). Data indicate a warming trend between 13,000 and 10,000 ^{14}C yr BP, interrupted by colder climate at 12,000–11,500 ^{14}C yr BP, the interval of cooling predating the European Younger Dryas chron by a millennium. In southern Chile in the American sector of the Southern Ocean, the episode of cooling is shown to continue until 10,000 ^{14}C yr BP (Heusser, 1998), while in the Indian sector, the episode apparently ended at 11,500 ^{14}C yr BP.

Correlation of climatic events in Antarctica with those in Chile is clearly dependent on age models for antarctic ice cores. Using a 1987 model to interpret late-glacial ∂^{18}O stratigraphy of ice cores at Dome C in East Antarctica, Jouzel *et al.* (1987a) showed apparent warming trends at 15,500–13,200 and at 11,600–10,200 ^{14}C yr BP, broken by a cooler interval at 12,800–11,600 ^{14}C yr BP. These changes tend to mirror the Indian Ocean phasing, again indicating the absence of Younger Dryas-age cooling. Although dating uncertainties exacerbate the problem of the chronological setting in Antarctica, atmospheric methane fluctuations in Greenland (GRIP) and Antarctic ice cores (Dansgaard *et al.* 1993; Chappellaz *et al.* 1993) provide some measure of a chronology to ~40,000 ^{14}C yr BP. During oxygen-isotope Stages 2 and 3, major climatic trends shown by the ∂D record of the Vostok core from East Antarctica (Jouzel *et al.* 1987b) and by pollen data from the Southern Lake District–Isla Grande de Chiloé are generally alike. Differences between the timing of climatic events in Antarctica, Greenland, and southern South America may be expected to reflect individualistic behavior of regional climatic–oceanic systems at the time of deglaciation. At the moment, correlation remains tenuous until reliable, closely dated records become established.

Polar hemispheric synchrony of Pleistocene millennial-scale climatic fluctuations, described in our initial report from exploratory glacial and pollen data (Lowell *et al.* 1995) and now updated (see Denton *et al.* 1999a), implicates the role of atmospheric water vapor in climate-related terrestrial and marine events, particularly during termination of the last glacial cycle. Out-of-phase relationships between the timing, duration, and amplitude of paleoclimate pulses in Antarctica and elsewhere (Sowers and Bender 1995) are currently interpreted as evidence that Antarctic ice cores are a reflection of Southern Ocean/North Atlantic asynchrony in thermohaline oceanic circulation (Broecker 1997). Spectral analyses of Antarctic stable isotopes (Yiou *et al.* 1991) show very high frequency oscillations, as do North Atlantic and Indian Ocean proxies (Bond *et al.* 1997; Sirocko *et al.* 1996). Spectral analysis of the southern Chilean pollen data also reveal sub-Milankovitch cycles centered on ~12 kyr and ~5 kyr, which are recognized in other geologic records (Heusser *et al.* 1999). Although dating techniques do not yet permit resolution of phase relationships between these high-frequency cycles, the existence of variance at comparable high frequencies in Southern and Northern Hemisphere climate signals suggests interhemispheric linkages.

Conclusions

Vegetation reconstructed on Isla Grande de Chiloé during middle–late Llanquihue glaciation, dated between >50,000 and 10,000 ^{14}C yr BP, consisted initially of Subantarctic Evergreen Forest under cool, humid interstadial climate. The forest, developed optimally at >47,000 ^{14}C yr BP, was later stepwise reduced in extent, so that by 26,000 ^{14}C yr BP under increasingly cold and humid climate, it became replaced by Subantarctic Parkland through a series of stades and interstades.

Subantarctic Parkland, marked essentially by interplay between southern beech and grass, exhibits higher frequencies of grass under cold climate during late Llanquihue glaciation. Parkland with beech and grass pollen approaching a 1:1 ratio occurs shortly after 25,000 and just before 21,000 ^{14}C yr BP with the last episode of grass beginning shortly before 16,000 and lasting until 14,000 ^{14}C yr BP. At >35,000 ^{14}C yr BP, mean summer temperatures are estimated as 2–3°C lower than at present, while during stades between 25,000 and 21,000 ^{14}C yr BP, temperatures were as much as 8°C lower than today.

In the Southern Lake District, the extent of the record shows Subantarctic Parkland dominant from about 40,000 to 14,000 ^{14}C yr BP. Subsequently throughout the Southern Lake District–Isla Grande de Chiloé, deglaciation as a series of steps began after 14,800 ^{14}C yr BP. Supplanting parkland, transitional beech woodland communities during an initial step became diversified after 14,000 ^{14}C yr BP with the formation of North Patagonian Evergreen Forest during an abrupt rise in mean summer temperature estimated at 5–6°C. By 12,500 ^{14}C yr BP during the rise in temperature, closed-canopy, North Patagonian Evergreen Forest became established. In a later step, expansion of a cold-tolerant element created by an apparent ≤2–3°C drop in temperature after 12,000 until 10,000 ^{14}C yr BP caused restructuring of forest communities at low elevation. This stepwise climatic sequence is observed at all late-glacial locations.

A paleotemperature index, calibrated from beech–grass ratios during episodes of increased grass frequency on Isla Grande de Chiloé, bears a relationship to glacial activity at >50,000, 29,400, 26,800, 22,400 and 14,800 ^{14}C yr BP. While higher indices antedate some maxima, implying low-temperature forcing before, or leading up to, advances of piedmont lobes, others appear to be closely correlative with maxima. Precipitation was continuously high throughout the time span, controlled in accordance with storm tracks of the Southern Westerlies. Pleistocene climate in the latitude of the Southern Lake District–Isla Grande de Chiloé need not have been vastly different from climate today at subantarctic latitudes in the Southern Andes, where extensive ice fields and valley glaciers exist at present. Hypothetically, a temperature depression at least in the order of the temperature difference between the two regions would be required for glacier lobes to reach not only the floor of the Valle Central but also to be of sufficient size to override southern Isla Grande de Chiloé.

Midlatitudes of the Southern Hemisphere during the last >40,000 ^{14}C years of the Pleistocene feature high-frequency climatic variability. During marine oxygen-isotope Stages 2 and 3, pollen records from southern Chile and New Zealand–Tasmania offer large time-scale correlation of vegetation and climate, while late-glacial fluctuations are inconsistent. The records in conjunction with chronologies of glacial maxima, when posed with climatic events in the Northern Hemisphere, are indicative of polar hemispheric synchrony. Data from Antarctic ice cores and Southern Ocean marine cores, however, point to asynchronous climatic behavior compared with the North Atlantic.

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