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Full- and Late-Glacial paleoenvironmental scenarios for the west coast of southern South America

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I. INTRODUCTION

Paleoclimatic comparisons between the west coasts of North and South America are difficult at the present time, partly because of the incomplete data base, and also because of the natural asymetries and asynchronies of paleoclimatic events across hemispheres (Salinger, 1981). Asymmetries result mainly from the contrasting distribution of ocean and land masses in both hemispheres (Pittock, 1978; Wells, 1986; other papers in this workshop). In addition, global climatic anomalies, such as the El Niño-Southern Oscillation, which currently affect the Pacific coast of America (Aceituno et al. 1991), could have had a different effect in the past (Martin et al. 1992, Mörner 1992).

We will discuss here the vegetational history of southern South America in Full and Late Glacial times (18,000-10,000 yr B.P.). The discussion will be based mainly on the palynological evidence available from various sites ranging from subtropical to subantarctic latitudes (32-55°S) in South America (Fig. 1). We will attempt to relate the vegetational changes observed during this period to the corresponding paleoclimates in the hope that these hypothetical scenarios can provide the groundwork for future comparative studies.

II. FULL-GLACIAL VEGETATION AND CLIMATE

A. Paleobiological evidence

According to palynological studies in Isla de Chiloé (42- 43°S), hygrophilous plant formations expanded down the mountain slopes and northward along the Coastal Range during the Late Pleistocene in southern Chile. North Patagonian-Subantarctic forests developed in Chiloé Island between 40,000-33,000 yr B.P., probably an interstadial (Villagrán, 1985, and unpublished manuscript), at the sites Pid-Pid and Molulco (Fig. 1). This vegetation was composed mainly of Nothofagus woodland, associated with trees such as Podocarpus, Lomatia Drimys, Fitzroya/Pilgerodendron, Myrtaceae. Herbs were mainly Gramineae. The full-glacial sections (Villagrán, 1988b, 1991b; Heusser, 1990a) reveal the presence of a Magellanic Moorland mosaic with wetlands, cushion bogs of Astelia and Dacrydium, and Nothofagus woodland. This type of landscape suggests that cooler and wetter, but ice-free, conditions prevailed in the lowland sites of Chiloé during the Last Glacial Maximum. Between 12,000 and 10,000 yr B.P., Magellanic Moorlands persisted in Chiloé Island only on the mountaintops of the Coastal Range (Villagrán, 1991c). Today, the center of distribution of Magellanic moorland vegetation is located about 6° further south, along the west coast of Tierra del Fuego, where the maximal annual rainfall and the highest records of wind velocity have been recorded.

Further north along the Chilean coast, between 37-42°S, late-glacial pollen sequences (Heusser, 1966, 1974, 1981), indicate the dominance of Nothofagus dombeyi-type, and substantial amounts of nonarboreal pollen (Gramineae, Compositae and Cyperaceae). Evidence from sites east of the Andes show predominantly nonarboreal pollen during the same period (Markgraf, 1983, 1989). Both, Makgraf and Heusser have interpreted these vegetational patterns as evidence of a seasonally drier and overall cooler climate for the Late Pleistocene at mid latitudes.

Based on the pollen sequence from the sediments of the now dry basin of Lake Tagua-Tagua (34°30'S, 200 m altitude), Heusser (1983, 1990b) postulated that Late Pleistocene precipitation was more abundant in central Chile than today, as indicated by the northward displacement of the distributional ranges of Nothofagus dombeyi and N. obliqua-types, Podocarpus saligna and Prumnopitys andina. These elements were then found 5° north of their present range. In association with this vegetation, a rich extinct megafauna, including mastodons, megatheria, giant ground sloth, native horses, Camelidae, and deer, has been documented (Moreno et al. 1992). The abundance of

Gramineae pollen in most glacial profiles (see below) indicates that prairies and open woodlands predominated in Chile during this period, providing habitat and food resources for the extinct megafauna.

Phytogeographical evidence also suggest wetter climatic conditions along the coast of central Chile during the Pleistocene. Patches of deciduous Nothofagus forests and of evergreen rain forests dominated by Aextoxicon punctatum occur today on the summits (about 600 m elevation) of coastal hills and in some ravines in central Chile (Villagrán, 1990), near the coastal towns of Zapallar, El Tabo and Pichilemu (32-34° S). These patches may represent remnants of a continuous band of rain forest found along the coast of central Chile during the Pleistocene. In the semi-arid Norte Chico, the pollen record (Villagrán and Varela, 1990) and paleontological evidence (Núñez et al., 1983) from Quebrada Quereo, near Los Vilos (32°S), also support the hypothesis that rainfall was more abundant in the semiarid coastal desert during the Late-glacial. Similar islands of relict vegetation from a more humid period are found between 400 and 700 m on the coastal mountains of Chañaral and Taltal (25-26°S) in the southern Atacama desert (Johnston 1929, Rundel et al. 1991).

In contrast, north of 27°S, floristic evidence indicates that little if any climatic change occurred during the glacial age in the inland Atacama desert and in the Andean slopes (Villagrán et al., 1983; Kalin et al., 1988). Specific affinity between the floras of the Andean Altiplano (18°-26°S) and the Andes of central Chile (30-33°S) is presently very low (up to 6.7%), despite the continuous connection through the Andes. We infer from this low floristic similarity that the extreme aridity, which prevails today in north-central Chile, reached the Andean highlands during the Quaternary, thus obstructing the exchange of flora between the northern Altiplano and central Chile. These floristic differences are not the result of recent climatic shifts, because taxa from the mesic, northern and southern ends of the gradient do not show a discontinuity in their distribution along the Andes.

A. Full glacial climate

What was the paleoclimatic scenario along the coast of southern South America during the Last Glacial Maximum? CLIMAP's (1981) reconstruction of sea surface temperatures (SST) at the time of the Last Glacial Maximum, c. 18,000 yr B.P., shows an increased proportion of the southern Southern Hemisphere ocean covered by polar water. Accordingly, subpolar marine assemblages shifted equatorward, to aproximately 30°S. Transitional marine assemblages were thus compressed beneath the subtropical gyres, and there was a steepened thermal gradient. As a consequence, surface water circulation in the ice-age was probably more energetic than today and surface currents were intensified, causing increased upwelling along the Pacific coast of South America.

Does this glacial paleo-scenario fit with the palynological data from mediterranean and temperate regions in Chile? Both the widespread distribution of Magellanic moorlands in Chiloé Island, and the presence of Nothofagus parkland in the Lake district and central Chile, extending 5° to the north of their present range during glacial times, have been interpreted as evidence of increased rainfall. These wetter conditions were probably the result of a northward displacement of the westerlies wind belt (Caviedes 1972, 1990, Heusser 1984a, 1989a; Villagrán, 1988b, 1990), which cause much of the winter precipitation in south-central Chile.

Data from oceanographic studies support the postulated northward displacement of the westerlies during glacial times. A deep-sea core (Groot and Groot, 1966), taken 175 km off the coast of Valparaiso (34°30'S-74°19'W), in the eastern Pacific ocean, show five repeated cycles of cool-moist climate, possibly associated with glacial advances, alternated with warm-dry intervals, presumably interglacials. Peaks of Podocarpus pollen were considered as indicators of glacial ages with cool-moist conditions. These peaks coincided with a higher carbonate content of samples, probably because of increased ocean upwelling. These results strongly support the view that during glacial times storm activity was more intense and displaced equatorward along the Pacific coast of South America. Stronger westerlies during the full glacial has also been suggested by Thiede (1979) to explain the patterns of deposition of wind-blown quartz particles off the east coast of Australia in the southwestern Pacific.

Geological evidence documenting shifts in the position of modern and Pleistocene snowlines in the semiarid region of north-central Chile (Hastenrath 1971) provides additional evidence for the intensification and northward displacement of the westerly wind flow during full glacial times.

Pleistocenic snowlines were lower on the western than on the eastern flank of the Andes south of 28° S, marking the northern limit of the westerly wind flow at that time. Further north the snowline depression was stronger on the eastern side, suggesting an easterly moisture source (Fox & Strecker 1991).

Although the evidence examined so far supports the proposed northward displacement of the westerlies wind belt, fossil pollen assemblages from subtropical and mid-latitudes introduce some questions (Markgraf, 1989). Why are Valdivian rain forest and sclerophyllous taxa absent from the pollen profiles in the Central Depression? Instead, the landscape was dominated by Gramineae, Compositae and Nothofagus/Conifers-Parkland. In both Chilean and Argentinean sites, Cyperaceae and other marshy and aquatic taxa are also well represented. Seasonal reconstructions of the SST for the last Glacial Maximum (Climap 1981) show that the glacial Winters in the southern hemisphere were characterized by increased equatorward flow of cool waters to just above 30° S. The thermal equator, and possibly the Intertropical Convergence, should have been displaced to the north. In contrast, during the glacial summers of the southern hemisphere, the thermal equator was considerably further south of its present position, which is between 0° and 20° S, and nearer the eastern Pacific. It seems likely that the notable contrast between glacial summer and winter temperatures in the South Pacific caused a pronounced seasonality in south-central Chile, during the glacial period. This marked seasonality is considered unprecedented today, except perhaps in the most continental sites, favoring the dominance of deciduous Nothofagus and conifer species, rather than Valdivian rain forest species which thrive in more equitable climates. Local climatic differences between coastal and inland sites should have been important in supporting different forest types. Valdivian rain forest taxa may have persisted in coastal refuges. Studies of fossil pollen assemblages from coastal locations, currently unavailable, are needed to test this prediction.

III. ENVIRONMENTAL CHANGES DURING THE LATE GLACIAL

A. Palynological evidence

All the fossil pollen assemblages known from the Lake District (39-43°S) in south-central Chile, indicate that tree establishment leading rapidly to a closed forest began synchronously at around

13,000 yr B.P. To explain this rapid process of forest expansion, we must postulate that glacial forest refugia must have been located nearby the glaciated areas, probably in the coastal ranges of Valdivia and Chiloé (Villagrán, 1985, 1988a, b; Heusser, 1966, 1982, 1984b). Initially, colonizing trees belonged mainly to the cold-temperate, North-Patagonic forest (Nothofagus and conifers). The early presence of these hygrophilous taxa in the pollen profiles reveals that conditions were very rainy. Regional differences in the floristic composition of late-glacial forests have been inferred from maps of isopollen-lines (Villagrán, 1991a). These maps show that Podocarpus nubigena, Fitzroya/Pilgerodendron and Nothofagus dombeyi-type dominate first the montane, oceanic sites of the Lake District. In lowland sites of the Lake District, the more thermophylous Myrtaceae taxa were the first colonizers. In the wetlands closer to the lakes, the successional series began with aquatic and swamp taxa, suggesting the gradual filling of lakes and ponds following ice melting (Villagrán, 1988b, 1991b). On the summits of the coastal ranges there was a simultaneous development of Magellanic moorland. Pollen spectra show an uninterrupted sequence of development of peatlands, ranging from minerotrophic, with peaks of Astelia pumila, to ombrotrophic characterized by successive peaks of Donatia fascicularis and Gaimardia australis (Villagrán, 1991c).

The beginning of the Holocene in the Lake District was marked by the rapid expansion of the more thermophylic Valdivian rain forest elements in all the pollen profiles. Eucryphia/Caldcluvia and Weinmannia trichosperma were the most relevant taxa. These species are known to be more resistant to seasonal drought than the North-Patagonic species which prevailed in the Late Glacial (Villagrán, 1991b). The Andean profiles show that deciduous Nothofagus procera/obliqua dominated the mountain slopes at the beginnig of the Holocene (Fig. 2). Since 3,000 years B. P. these species begin to be replaced by North-Patagonic taxa in the Andes (Villagrán, 1980).

In Central Chile, at Quebrada Quereo (32°S), wet conditions prior to 10,000 yr B.P. are shown by the abundant pollen of swamp and wetland plants, such as Cyperaceae and Myriophyllum, with only traces of arboreal pollen (Villagrán and Varela, 1990). A trend towards radically drier conditions began in the early Holocene, as implied by the substantial decrease of both arboreal and aquatic taxa and a general decrease in the diversity of shrubland indicators. The fossil pollen assemblage from Lake tagua-Tagua (Heusser, 1983; 1990b) shows, at the saem time, a sudden change from woodland indicators to strong dominance by Chenopodiaceae/ Amaranthaceae, indicators of warmer and drier conditions.

When we compare fossil pollen assemblages from mediterranean and temperate latitudes of Chile, with sites located south of 50° S, we notice that paleoclimatic changes have been asynchronous and unequal over latitudinal range analysed (Fig. 2, 3, 4). Pollen records from Tierra del Fuego (c. 55°S), provide evidence for cold and dry conditions prevailing between 13,000 and 10,000 years B. P., when sites located at lower latitudes were more humid. The vegetation of Tierra del Fuego during that period was dominated by Empetrum and Gramineae. Nothofagus forests developed after 10,000 yr B.P. (Fig. 3), presumably as a response to increased precipitation (Heusser and Rabassa, 1987; Heusser, 1989b, c; Rabassa and Clapperton, 1990). At Puerto Edén (c. 50°S), nonarboreal taxa dominate the pollen-profile before 13,000 yr B. P., whereas pollen of Nothofagus increased between 13,000 and 10,000 yr B.P. (Fig. 3). It was only from 10,000 yr B.P. on that Magellanic moorland indicators become important (Fig. 4), suggesting wetter conditions (~~Markgraf~~ Aschwort et al., 1991).

The changes in the distribution of Magellanic moorlands, and the latitudinal advances and retreats of the Nothofagus parkland are the best indicators of changing patterns in precipitation in Chile during the Glacial-Holocene transition (Figs. 2, 3, 4). At the Glacial Maximum, moorlands were conspicuously present in lowland sites at 42°S (Fig. 4). From 13,000 yr B.P. onwards Magellanic moorlands became restricted to the mountaintops of the Coastal Range in Chiloé Island. Finally, in the last 10,000 yr moorland taxa colonized the Chilean Channels Region, at 50° S, where this plant formation is a major component of the present vegetation. Accordingly, the modern climate of austral Chile was established in the early Holocene.

Nothofagus dombeyi-type and Gramineae (Fig. 3) were the dominant taxa of mediterranean as well as temperate regions in Chile during the full-Glacial forming a parkland. Subsequently, a rapid warming trend, associated with abundant rainfall favored the colonization of the North-Patagonic forest at mid latitudes. The Nothofagus parkland extended southward, up to Puerto Edén, at 50°S, at a time when sites located further south were still dominated by Gramineae (Fig. 2-3). Nothofagus parkland colonized the southern tip of South America in the early Holocene, presumably in association with higher rainfall. In contrast, Nothofagus obliqua-type (Fig. 2), which was present in central Chile (34°30'S) during the Pleistocene, expanded south along the Andes to mid-latitudes (until 42° S) during the early Holocene, probably reflecting decreased precipitation during this period.

B. Climate during the Glacial-Holocene transition

In this section, we present a possible scenario for the late glacial in southern South america. The timing of forest expansion in southern Chile during this period agree with the timing of glaciar regressions in the Lake District (Heusser, 1990a; Porter, 1981; Mercer, 1976, 1984; Clapperton, 1990). These authors proposed dates between 15,000-14,500 yr B.P. for the latest advances of glaciers in the area. A rapid and uninterrupted deglaciation followed, in response to a warming trend that began about 13,000 yr B.P. This trend is supported by the record of SST inferred from a deep-sea core taken at 42°S, 80°W, in the Subantarctic region (Salinger, 1981; Shackleton, 1978). Around 15,000 yr B.P. SST's at that latitude were close to the glacial minimum, and by 10,000 yr B.P. they had raised to values near the Holocene maximum levels.

A similar trend is show by two 65,000 yr-ice cores from Antarctica (Jouzel et al., 1987, 1989). These cores show a coincident and pronounced increase in isotopic contents (O^{18} and deuterium) at 15,000 yr B. P., when temperatures were the lowest. Maximum temperatures were reached around 9,500 years ago. Salinger (1981) and Harrison et al. (1984) argued that changes in SST in the Southern Hemisphere preceeded changes in the Northern Hemisphere by about 3,000 yr. The Maximum Holocene warming in Chile occured around 9,500 yr B.P., about the same time as in New Guinea, Australia and New Zealand. The warmest period in Europe and North America, in contrast, occurred only about 6,000 yr ago.

The different timing of deglaciation processes and the thermal maximum in the northern and southern hemispheres can explain the increase in rainfall in Chile during the Glacial-Holocene transition. Because of the asynchronous ice-melting in each hemisphere the position of the thermal equator was displaced to the south during the Late-Glacial, when temperatures were rising in the south, but not in the north. As a consequence of this displacement the South Pacific Anticyclon was greatly weakened.

This paleoscenario for the last deglaciation period is supported by geomorphic data and studies of paleosols in the semiarid region of Chile. Relict paleosols originated during a more humid period have been described for the end of the late glacial in the semiarid coast of Chile (27-33° S) (Veit, 1991). On the other hand, it has been documented that paleolakes in the Peruvian-Bolivian Altiplano covered an area about four times as large as their present one from 12,500 to 11,000 yr B. P. (Hastenrath and Kutzbach, 1985). It was estimated that average annual rainfall must have been 30-50% higher than it is today. Increased summer rains, associated with a southward shift of the Atlantic Intertropical Convergence, may account for the wetter conditions in the Altiplano during the Late Glacial (Kessler, 1985; Servant et al., 1981; Servant and Villarroel, 1979).

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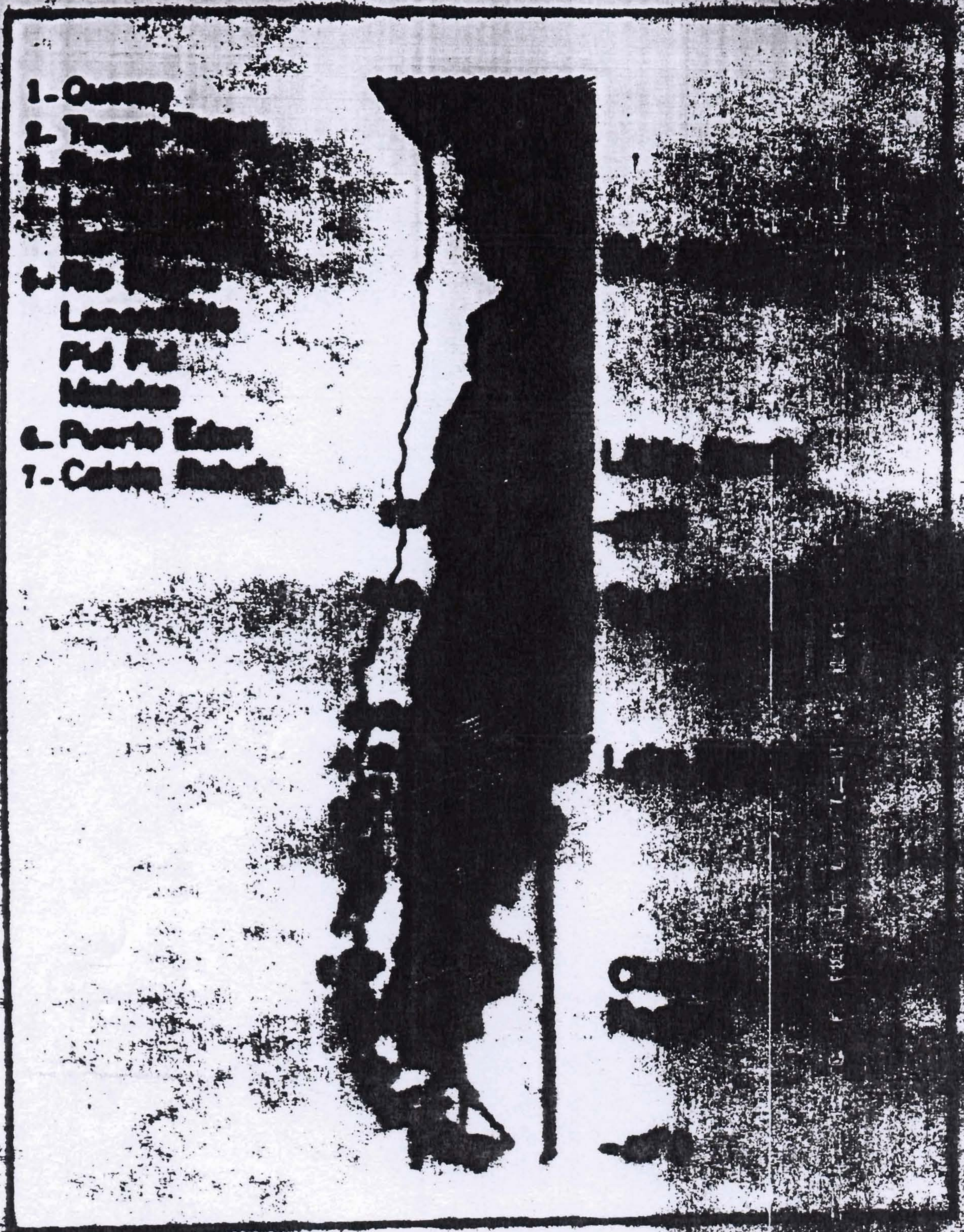
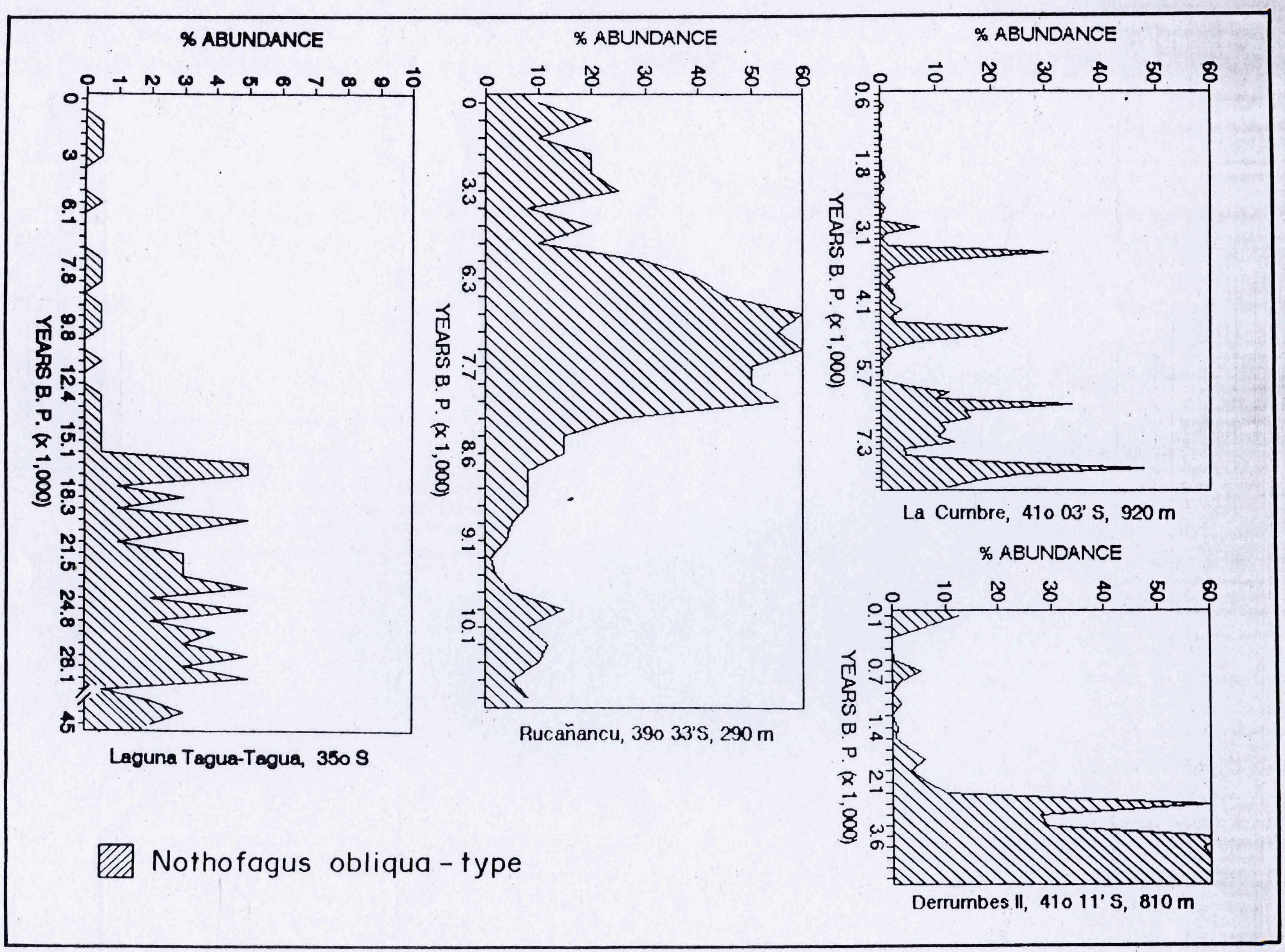
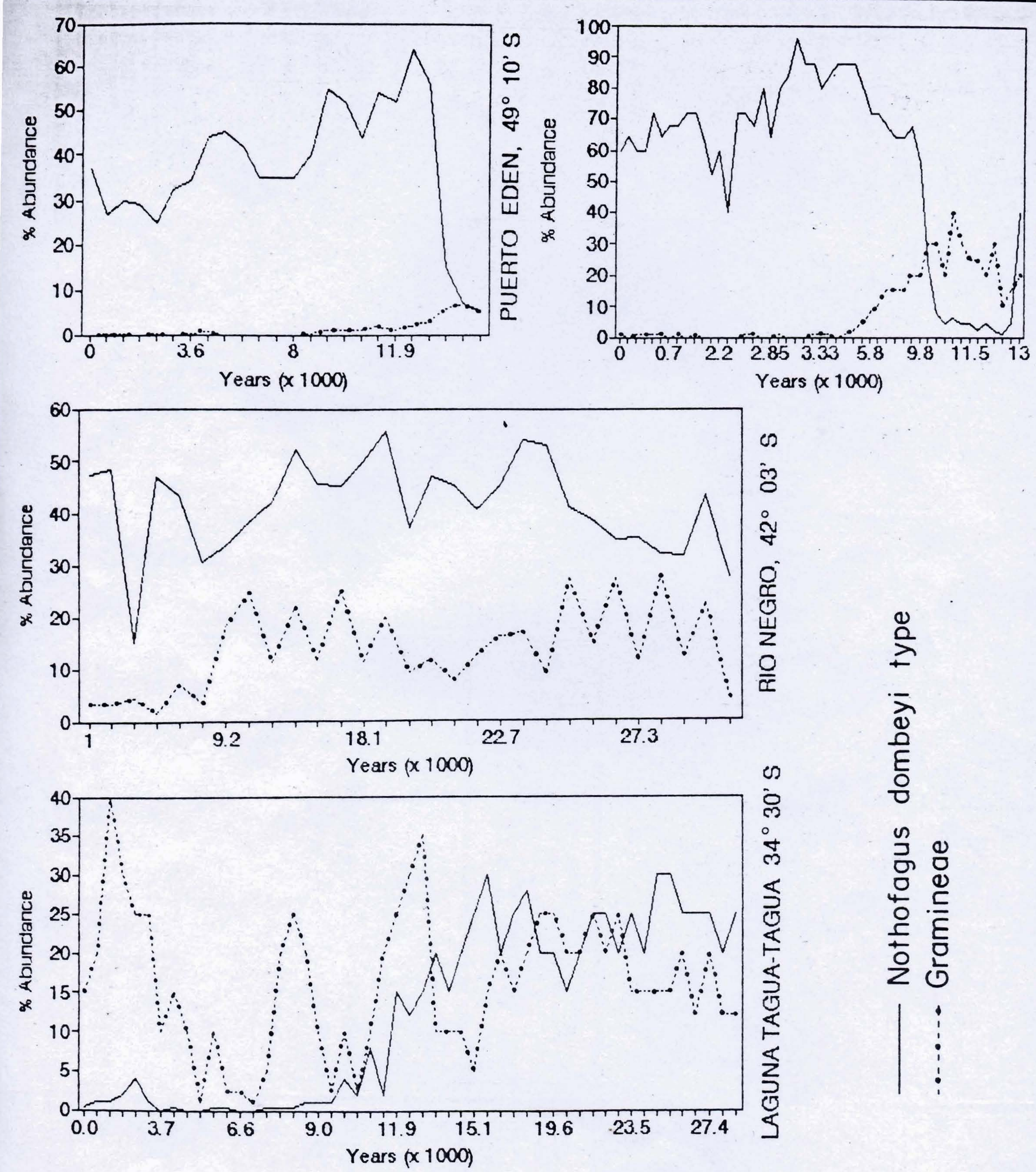

6.- Puerto Eden
7.- Caleta



% ABUNDANCE
YEARS B. P. (x 1,000)
La Cumbre, 41o 03' S, 920 m
Derrumbes II, 41o 11' S, 810 m
Rucañancu, 39o 33'S, 290 m
Laguna Tagua-Tagua, 35o S
Nothofagus obliqua - type

Figure 3



PUERTO EDEN, 49° 10' S
CALETA ROBALO 54°
RIO NEGRO, 42° 03' S
LAGUNA TAGUA-TAGUA 34° 30' S
% Abundance
Years (x 1000)
Nothofagus dombeyi type
Gramineae