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Quaternary Pollen Record from Laguna de Tagua Tagua, Chile

Abstract. *Pollen of southern beech and podocarp at Laguna de Tagua Tagua during the late Pleistocene indicates that cooler and more humid intervals were a feature of Ice Age climate at this subtropical latitude in Chile. The influence of the southern westerlies may have been greater at this time, and the effect of the Pacific anticyclone was apparently weakened. The climate today, wet in winter and dry in summer, supports broad sclerophyll vegetation that developed during the Holocene with the arrival of paleo-Indians and the extinction of mastodon and horse.*

The basin of Laguna de Tagua Tagua (34°30'S, 71°10'W), some 50 km^2 in area, is located 120 km southwest of Santiago, Chile, at an elevation of 200 m on the eastern edge of the coastal cordillera (Fig. 1). The basin is formed by Andean laharic deposits overlain by lacustrine sediments (*1*). Laguna de Tagua Tagua (*2*) was visited early in the 19th century by the naturalist Gay (*3*) who described the "*grand et superbe lac*" with its remarkable floating islands. Later, it was visited by Darwin (*4*) who also wrote of the islands: "As the wind blows, they pass from one side of the lake to the other, and often carry cattle and horses as passengers." In the mid-19th century, a ditch was dug to drain the laguna, at which time the bones of extinct Pleistocene mammals, notably mastodon and horse, were exhumed (*5*). At a depth of 2.3 to 2.4 m, artifacts of human industry were found in association with the animal remains. Charcoal from this level was dated at 11,380 ± 320 radiocarbon years before the present; the age of sediments 1.0 m deep is 6130 ± 115 years (*6, 7*).

The site of the laguna, at present largely cultivated, is surrounded by broad sclerophyll vegetation with hilltops over 500 m high occupied by species of deciduous southern beech, *Nothofagus obliqua* and *N. glauca* (*8, 9*). Evergreen beech, *N. dombeyi*, occurs in the Andes north to about 34°40'S at an altitude close to 1500 m where it grows with *N. obliqua*, *N. glauca*, and *N. alpina*. At about 35°50'S, *N. antarctica* reaches the northern end of its range at about 1750 m; *N. pumilio* is its associate north to about 36°40'S. Species of podocarp, important along with beech in the vegetational history at the laguna, are the montane *Podocarpus andinus*, which ranges to around 36°S in the Andes at altitudes of about 1700 m, and the lowland *P. salignus* to 35°30'S (*9, 10*). The regional climate is dry in summer, influenced by the Pacific anticyclone, and wet in winter when cyclonic storms of the southern westerlies move northward (*11*). Precipitation annually averages about 800 mm with 84 percent received during autumn and winter; summer is virtually without rain. Average temperature in summer is about 20°C and in winter 8°C (*12*).

The pollen stratigraphy (Fig. 2) of sediments in the basin was studied (*13*) from a 10.7-m core with an age of more than 45,000 years (QL-1674). The coring location is where an access road from the upland in the northeastern sector crosses the drainage ditch, some 1200 m from the shoreline before the lake was drained (*14*). Pollen of the chenopods and amaranths (Chenopodiaceae-Amaranthaceae), grasses (Gramineae), and composites (Compositae) dominates Holocene sediments (pollen assemblage zone 1). The chronological setting of zone 1 is estimated from the ages of 11,380 and 6130 years (*6, 7*). Percentages of chenopods and amaranths, indicative of warm and dry intervals, reach maximums in zone 1c and secondary peaks in zones 1a and 1e. Grasses increase in zone 1b, after about 6000 years ago along with trees, and in zone 1d. They increase in conjunction with *Gunnera* and Umbellif-

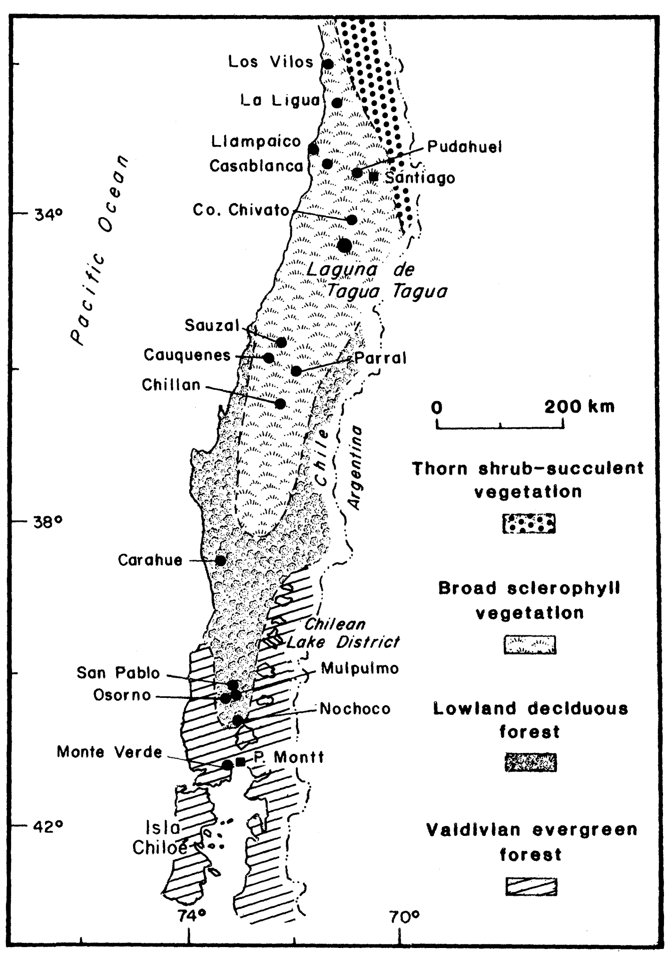

Fig. 1. Location of Laguna de Tagua Tagua in relation to zones of generalized vegetation (*8*) and distribution of late Pleistocene mastodon sites in central and southern Chile (*6, 22–24*).

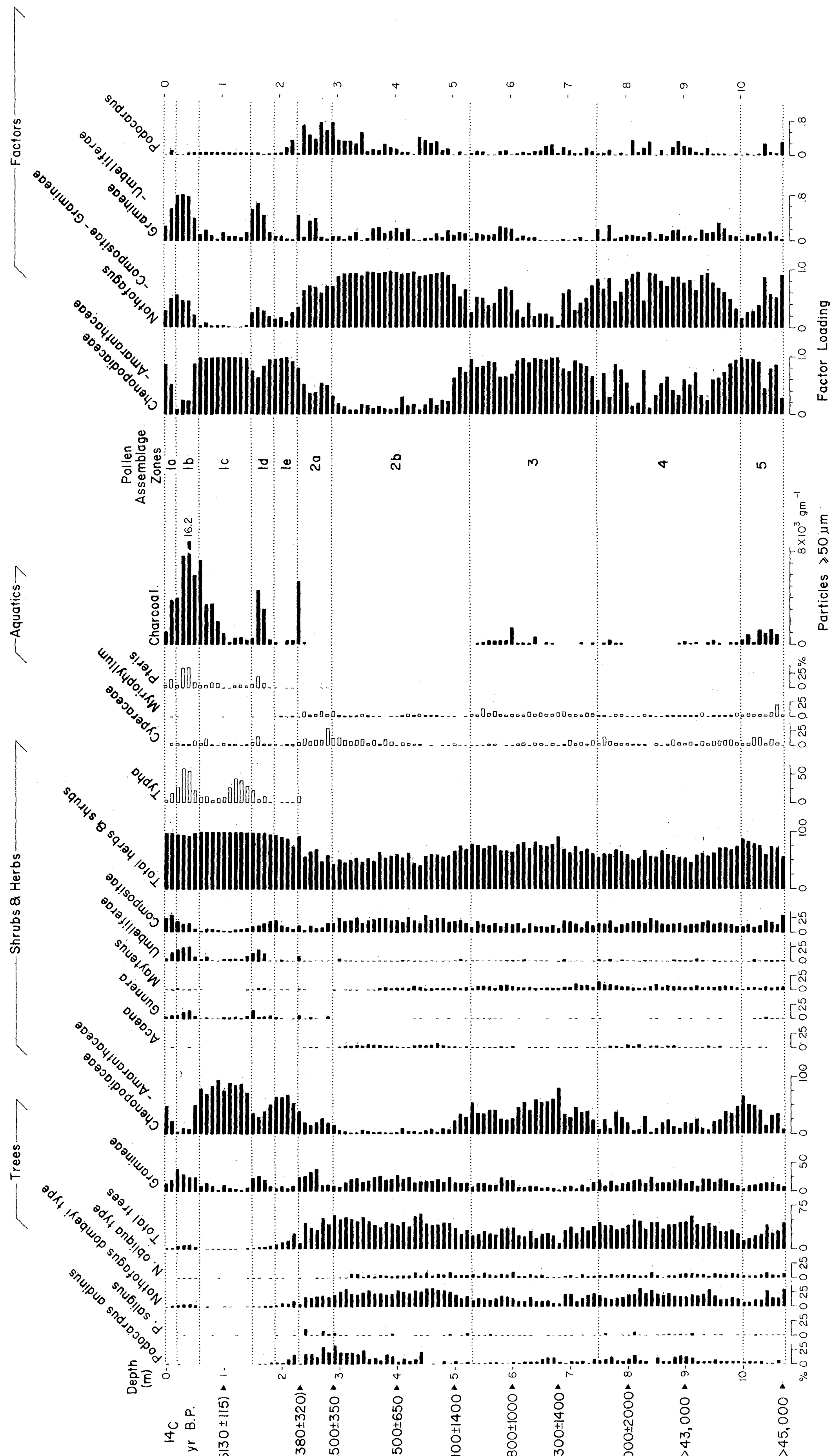

Fig. 2. Diagram of pollen frequency, charcoal density, and factored pollen data for the core from Laguna de Tagua Tagua.

erae and also brake fern (*Pteris*), suggesting times of greater humidity. The succession of water milfoil (*Myriophyllum*) by cattail (*Typha*) probably results from a changing of lake level caused by modified precipitation and evaporation.

Beech (*N. dombeyi* type) and montane podocarp (*P. andinus*) increase at depth from less than 10 percent (zone 1e) to 60 percent of the pollen sum (zone 2b). This change takes place through the interval estimated to date from before 11,380 to between 21,500 ± 650 (QL-1667) and 28,100 ± 1400 years ago (QL-1668); additionally, the boundary between zones 2a and 2b is dated at 14,500 ± 350 years old (QL-1666). Zone 2b contains maximums of *N. dombeyi* type (32 percent) and of *P. andinus* (33 percent) and minimums of chenopods and amaranths. Below zone 2, the interplay between amounts of total trees and of herbs and shrubs is accentuated by increases of chenopods and amaranths in zones 3 and 5. Zone 3 contains a date of 29,800 ± 1000 years old (QL-1669), and the zone 3–4 boundary is between 33,300 ± 1400 (QL-1670) and 37,000 ± 2000 years old (QL-1671) while the base of zone 4 is over 43,000 years old (QL-1672). Of the four leading factors shown by principal components analysis (*15*), higher loadings of the *Nothofagus*-Compositae-Gramineae and *Podocarpus* factors signify increased humidity, decreased evaporation, and lower ranges of temperature in comparison with the present. Prominence of the *Podocarpus* factor in zone 2a underscores late Pleistocene temperature depression, possibly coupled with incipient summer drought.

Vegetation about the Pleistocene laguna, as indicated by the pollen data (Fig. 2), differed from today's and is in contrast with vegetation changes that took place during the Holocene. Pleistocene plant communities contained not only more and a greater variety of trees but these included *N. dombeyi* type beech and podocarp, species that today do not range as far north and as low in elevation as the laguna (*9*). The considerable amounts of shrubs and herbs in the pollen data suggest open space associated with woodland. Episodes with a greater proportion of chenopods and amaranths, particularly manifest during the Holocene, were perhaps associated with local invasions of halophytic species when lake level was low. In the Chenopodiaceae, for example, *Atriplex chilense*, *A. ripandum*, and *A. philippi* are found today in saline basins of the central and northern Chilean provinces (*16*). Few pollen grains come from broad sclerophyll vegetation—for example, species of *Lithraea*, *Maytenus*, *Schinus*, and *Kageneckia*, which are insect pollinated. Aside from *Maytenus*, these genera are simply included as tree types (Fig. 2).

To support *N. dombeyi* type beech and montane podocarp at the Pleistocene laguna there was apparently more precipitation than today's average of 800 mm per year and summer temperatures would have been some degrees lower than the present 20°C. In the Andes where *P. andinus* grows farthest north, for example, precipitation is between 1200 and 3000 mm per year; in the Chilean lake district (Fig. 1) where *N. dombeyi* type species become important, annual precipitation rises to between 1500 and 5000 mm with summer temperatures averaging as much as 5°C lower than at the laguna (*12*). Surface pollen sample studies (*17*) show that *N. dombeyi* type is unimportant at low altitudes north of 39°S at the northern end of the lake district.

A shift in the belt of the southern westerlies in the direction of the equator could account for the Pleistocene climate of central Chile. This would bring cooler and more humid conditions to the region, thus modifying the influence of the Pacific anticyclone. Evidence from other sources indicates displacement of atmospheric and oceanic circulation toward the equator (*18, 19*). With the close of the Pleistocene, the belt of westerly winds apparently moved south, giving rise to the modern winter-wet, summer-dry climate at the laguna. At times during the Holocene, when dryness and warmth appear to have been pronounced, winter storms at the latitude of the laguna were probably less frequent than they are now. Studies in southern Chile (*20*) show that late Quaternary climatic changes at different latitudes were not uniform. Whereas the time of the last glaciation was evidently cooler and more humid at the laguna, it was colder and drier at Isla Chiloé (Fig. 1).

Charcoal in the core (Fig. 2) serves as an index of past fires, as well as of inferred paleo-Indian use of fire for hunting (*6*). In the first marked instance of charcoal (zone 2a), at which depth approximately the oldest evidence of human industry was dated at 11,380 years old (*6, 21*), the number of particles per gram increases sharply to more than 5000. Later (zone 1d), a second sharp increase occurs, and after about 6130 years ago (zone 1b), quantities reach a maximum of more than 16,000. Charcoal particles in Pleistocene-age levels, by contrast, are absent or number fewer than 1000. Amounts, in general, show an inverse relation with fluctuations of chenopods and amaranths. These taxa, more so than other pollen of other taxa in the core, reflect warm and dry conditions, and their maximums, correspondingly, indicate intervals of desiccation and a low lake level. Thus, paleo-Indian populations may have been small or unsustained when these plants spread.

Mastodon bones in the excavation at Laguna de Tagua Tagua were found scattered without anatomical arrangement, splintered as if by blows, and with portions burned (*6*). Their association with flake scrapers is considered evidence that these animals were dismembered by humans. Mastodons apparently thrived in the woodland of beech and podocarp about the laguna and became extinct at the end of the Pleistocene (Fig. 1); their bones are dated as early as 18,700 but no later than 11,380 years ago (*6, 22–24*). Extinction appears to have been accelerated by paleo-Indian hunting, but other factors, including the inability of the animals to adapt to a diet imposed by changing vegetation, are likely to have been important.

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drainage, preserved beneath spoil cast up when the ditch was dug, was recovered and represents the surface from which the core was taken. Location is on Map N.2618, Laguna de Tagua Tagua, Departamento de Cachapoal, Instituto Geográfico Militar, scale 1:25,000 (1930).
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Spasmodic Tremor and Possible Magma Injection in Long Valley Caldera, Eastern California

Abstract. *Intensive microearthquake swarms with the appearance of volcanic tremor have been observed in the southwest part of Long Valley caldera, southeastern California. This activity, possibly associated with magma injection, began 6 weeks after several strong (magnitude 6+) earthquakes in an area south of the caldera and has continued sporadically to the present time. The earthquake sequence and magmatic activity are part of a broad increase in tectonic activity in a 15,000-square-kilometer region surrounding the "White Mountains seismic gap," an area with high potential for the next major earthquake in the western Great Basin.*

On 25 May 1982, 2 years after the occurrence of four earthquakes of local magnitude (M_L) 6.0 to 6.3, the U.S. Geological Survey (USGS) issued a "Notice of Potential Volcanic Hazard . . ." for the Mammoth Lakes area, eastern California (*1*). Events cited as having heightened the concern of USGS scientists included uplift of the floor of Long Valley caldera by about 10 inches (*2*), observation of spasmodic tremor at a single site in the southwestern part of the caldera, progressive movement of earthquakes toward the surface at this same site, and formation of a new group of fumaroles. This report describes the last three of these observations.

Figure 1a shows the location of 386 earthquakes of the Mammoth Lakes sequence for the period 4 October 1978 to 24 May 1980, and Fig. 1b shows 1088 events from 25 May 1980 to 1 October 1982. The epicenters shown in Fig. 1 were determined by using the HYPO71 algorithm (*3*) and are accurate to within about 1 km; location of the events changed only slightly in test runs with a range of reasonable crustal models. Similarly, we estimate that the accuracy of focal depth determinations is of the order of ±1 to 2 km for events in the southwest part of the caldera, the only area for which event depth is discussed in this report.

As illustrated by Fig. 1b, this sequence was not associated with a single fault, but involved complex brecciation of an irregular-shaped crustal block extending 30 km in a northwest-southeast direction and 25 km from north to south. As noted earlier (*4*), the sequence began with an M_L 5.7 shock on 4 October 1978, 15 km southeast of the caldera; over the next 18 months the epicentral zone grew toward the northwest, and activity gradually concentrated in an area just south of the caldera (Fig. 1a). On 25 and 27 May 1980, six events occurred with M_L 5.7 to 6.2, and the epicentral zone extended to the south and west. During 1981 seismicity was concentrated along the southern caldera boundary and in a north-south zone extending 7 km into the caldera and 15 km south of it. The largest shock in 1981, on 30 September, had M_L 5.7.

Primary (P) wave fault-plane solutions for 44 events of this sequence show strike-slip mechanisms for all events shallower than 9 km, and oblique- to dip-slip (normal faulting) for those deeper than 9 km (*5*). Orientation of the axis of minimum compressive stress for all of the solutions is consistent with crustal extension along the north-northwest–trending Sierra Nevada frontal fault system—deeper shocks resulting from normal or oblique movement on faults striking north-northwest and dipping east, and shallow events reflecting conjugate right- and left-lateral shear on nearly vertical fractures striking, respectively, west-northwest and north-northeast. Hill (*6*) proposed a model in which conjugate shear failures of this type accompany the formation of magma-filled dikes, to explain the predominance of strike-slip mechanisms in volcanic regions prone to earthquake swarms. Comparison of his model with focal mechanisms for the Mammoth Lakes sequence suggests that events with strike-slip mechanisms may be associated with the formation of clusters of magma-filled dikes at depths less than 9 km. The existence of magma at shallow depth in the caldera is indicated by a relative delay of about 0.3 second for teleseismic P waves recorded in the west-central part of the caldera (*7*), by secondary arrivals on a refraction pro-

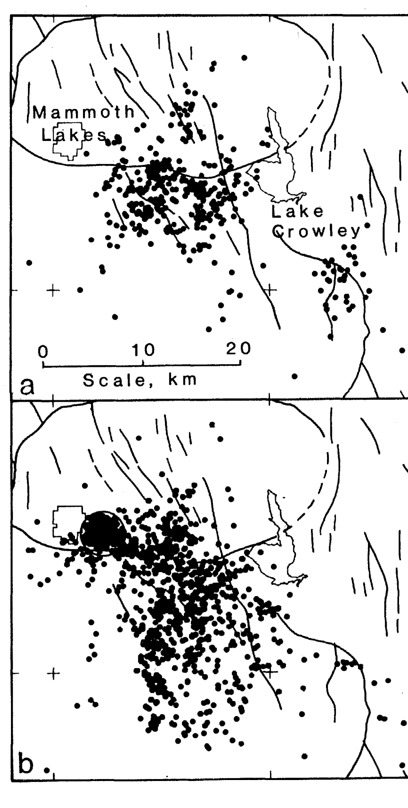

Fig. 1. Seismicity in the Mammoth Lakes area before and after 25 May 1980. Outline of Long Valley caldera and prominent faults are shown by heavy lines. (a) The 386 earthquakes in the period 4 October 1978 to 24 May 1980. Sequence began with an M_L 5.7 event in the cluster southeast of Lake Crowley, and gradually moved northwest over the next 18 months. (b) The 1088 earthquakes in the period 25 May 1980 to 1 October 1982. Swarms with the appearance of spasmodic tremor were located in the circle just east of the town of Mammoth Lakes in (b). Only events with location quality C or better are shown.