The last 7500 cal yr B.P. of westerly rainfall in Central Chile inferred from a high-resolution pollen record from Laguna Aculeo (34°S)

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Abstract

We report multiproxy analyses of a sediment core obtained from Laguna Aculeo that spans the past 7500 years. Laguna Aculeo (33°50′S, 70°55′W) is one of the few natural inland lakes located in the Mediterranean zone of Central Chile, near the northern margin of the influence of the southern westerlies. The record shows elevated pollen counts of halophytes and seasonally drying of the lake basin prior to 5700 cal yr B.P., indicating severe aridity and warmer-than-present conditions. This was followed by the establishment of a fresh-water lake, along with an increase in arboreal and herbaceous plant diversity between 5700 and 3200 cal yr B.P. An intensification of this trend started at 3200 cal yr B.P., along with the abrupt decrease of halophytes until 100 cal yr B.P. Within this humid period, pollen accumulation rates show large-amplitude fluctuations, coeval with numerous turbidite layers, suggesting a highly variable and torrential rainfall pattern. This intense and variable precipitation regime is probably associated with the El Niño–Southern Oscillation (ENSO) phenomenon. We suggest that the modern Mediterranean climate of Central Chile was established at ~3200 cal yr B.P. Paleovegetation and paleolimnological changes starting at 100 cal yr B.P. correlate with documented human activity surrounding the lake.

Keywords: Mid-Holocene; Westerlies; Central Chile; Laguna Aculeo; Climate change

Introduction

A growing number of studies have shown that complex and rapid climate changes took place throughout the Holocene on multiple time scales. Several authors have shown that the middle Holocene (8000–3000 cal yr B.P.) was a time of high climate variability (Sandweiss et al., 1999; Stager and Mayewsky, 1997; Steig, 1999). The development of high-resolution paleoclimate records has thus become imperative for understanding the geographic extent and phasing of millennial-scale climate variability and the mechanisms involved in its origin and propagation. These records are the only means by which mid-Holocene climate simulations as generated by general circulation models can be assessed, and recent hypotheses that have proposed a mechanism akin to the El Niño–Southern Oscillation (ENSO) as a generator of climate change at millennial timescales around the Pacific basin can be tested (Cane and Clement, 1999; Clement and Cane, 1999; Sandweiss et al., 1999; Steig, 1999)

North-Central Chile (30°–34°S) is a target region to monitor past changes in the westerlies, thanks to its transitional position between major components of the climatic systems in western South America: the South Pacific anticyclone (SPA) and the westerlies belt. Climate in this region is characterized by a summer-dry/winter-wet regime, related to seasonal changes in the position of the SPA. During summer months, the SPA migrates south and blocks northward incursions of westerly storm tracks. Conversely, during winter months the SPA shifts northward allowing penetration of westerly fronts. Large seasonal and interannual variations in winter precipitation are common in this region, in part caused by the El Niño–Southern Oscillation phe-

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nomenon. Pressure anomalies associated with the negative ENSO phase (El Niño), which allows a northward shift of westerly storms, cause higher-than-average annual precipitation in Central Chile. The positive ENSO phase (La Niña) reinforces the SPA, effectively blocking the westerlies and producing cold and dry conditions in this region (Aceituno, 1988, 1990; Aceituno et al., 1993; Rutland and Fuenzalida, 1991). This high climate sensitivity renders the subtropical latitudes of Central Chile one of the key areas in monitoring past variations of the westerly circulation belt and associated ENSO activity.

Despite its key geographical position for understanding paleoclimate changes at subtropical latitudes, including the onset and subsequent evolution of the ENSO, the paleoenvironmental history of Central Chile (30°–34°S) is still poorly understood, and high-resolution, continuous paleoclimate records are mostly lacking. The few Holocene paleoclimatic records that exist for Central Chile document major climate fluctuations, in the form of alternating wet and dry phases. Overall agreement is evident among these records regarding the prevalence of warm/arid conditions during the early and middle Holocene (Heusser, 1990; Lamy et al., 1999; Veit, 1996; Villagrán and Varela, 1990; Villa-Martínez and Villagrán, 1997). The poorly constrained chronology and temporal resolution in most of these records, however, impede further precision regarding on understanding of the timing and structure of these phases.

We previously reported on the sedimentological and geochemical data (Jenny et al., 2002a) and pollen data (Villa-Martínez et al., in press) from a short core that spanned the past 2000 cal yr B.P. and a multiproxy study from a long core (482 cm) that spanned the past 10,000 cal yr (Jenny et al., 2002b) from Laguna Aculeo (33°50′S, 70°55′W). In those studies we indicated that a generally wet and variable climate was present during the late Holocene at Laguna Aculeo, while the mid Holocene was warm and dry. Here we present high-resolution pollen, charcoal, and microalgae records from a longer core obtained at this site that spans the past 7500 cal yr B.P., and discuss their regional paleoclimatic implications.

The study area

Located 50 km SE of Santiago, Laguna Aculeo (33°50′S; 70°54′W, 350 m.a.s.l.) lies among the inland foothills of the Cordillera de la Costa of Central Chile (Fig. 1). Mean annual precipitation is ~550 mm and mean annual temperature is 14°C (Almeyda and Saez, 1958). With a surface area of 12 km^2 and a maximum water depth of 6 m, it is one of the largest natural lakes in the region. The lake has a small outflow on the eastern side, which runs dry in summer, is rarely filled with water even in winter, and at times in rainy winters even functions as an inflow (Cabrera and Montecinos, 1982). The major source of moisture comes from local precipitation. Summits near the southern end of the lake reach ~2000 m.a.s.l. (Altos de Cantillana), whereas those at the northern end reach 917 m.a.s.l. (Cerro La Caleta).

The dominant vegetation at Laguna Aculeo is described as *espinal*, a savanna-like scrub characterized by the tree *Acacia caven*, and mostly introduced herbs (Rundel, 1981; Schmithüsen, 1956). An altitudinal survey of the sclerophyllous forests that surround the lake (Fig. 1) reveals the following vegetation zones:

(1) Sclerophyllous forest (400–1250 m.a.s.l.): dominant trees are *Quillaja saponaria, Lithrea caustica, Cryptocarya alba,* and *Peumus boldus.* Moist ravines and canyon bottoms are dominated by *Persea lingue, Crinodendron patagua, Beilschmiedia miersii,* and *Maytenus boaria.* A shrubland of *Talguenea trinervis* and *Acacia caven* commonly occupies drier areas that have been cleared by human disturbance.
(2) Sclerophyllous mountain matorral (1250–1900 m.a.s.l.) succeeds the sclerophyllous forest at higher elevation. This community includes the trees *Lithrea caustica, Schinus montanus, Escallonia pulverulenta, Baccharis linearis, B. concava, Azara* sp., and *Kageneckia angustifolia.* Important among the herbs that dominate the dry slopes are the Andean grasses *Stipa* and *Poa,* together with *Acaena alpina, Mulinum spinosum, Chuquiraga oppositifolia, Mutisia spp., Tetraglochin alatum,* and *Chaetanthera* sp.
(3) Monospecific stands of *Nothofagus obliqua* occur between 1900 and 2000 m.a.s.l., interspersed and succeeded by a high-elevation scrubland, which contains species also found in the high Andean vegetation, such as *Chuquiraga oppositifolia, Verbena spathulata, Tetraglochin alatum, Laretia acaulis,* and *Viola cotyledon.*

We collected soil surface samples for pollen-rain analysis along the same vegetation transects. The overall correspondence between the vegetation transects and their respective surface samples (Fig. 2) is supported by a CONISS ordination, which revealed the following altitudinal zonation:

(1) High proportions of shrubs dominate below 800 m.a.s.l.; these include Euphorbiaceae (5–40%), Compositae (15–30%), Chenopodiaceae (20%), and Gramineae (10–20%). This cluster represents the local vegetation surrounding the immediate vicinity of the lake.
(2) Between 800 and 1550 m.a.s.l. the sclerophyllous forests are represented by *Quillaja saponaria* (10–20%), *Lithrea caustica* (5–20%), *Escallonia* (5–15%), and Euphorbiaceae (5–50%).
(3) High percentages of Compositae (> 50%) and low percentages of *Escallonia* (5%), *Azara* (5%), and *Mulinum spinosum* (5–15%) represent the montane sclerophyllous matorral between 1550 and 1950 m.a.s.l.

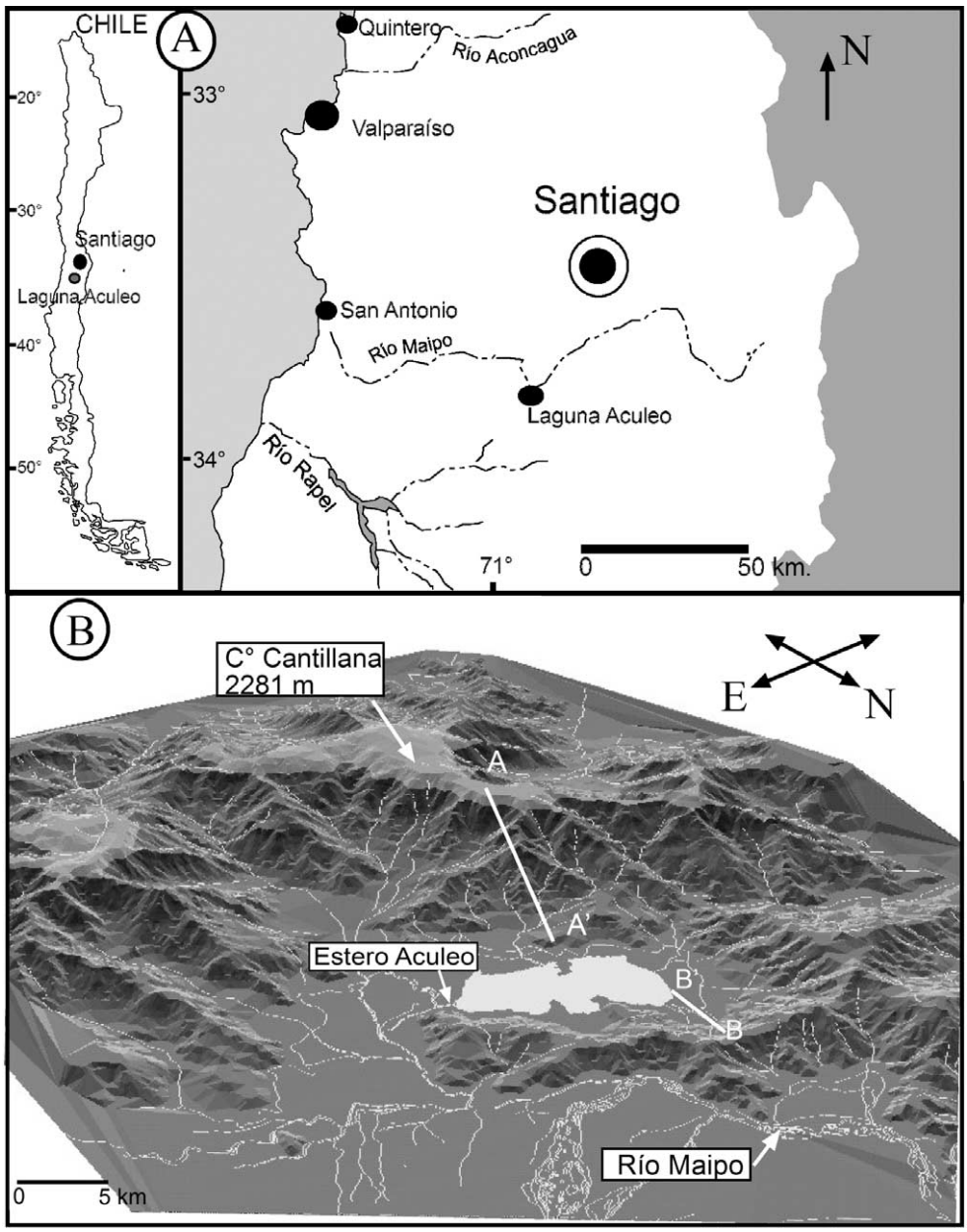

Fig. 1. (A) Map indicating Laguna Aculeo in the Mediterranean climatic region of Central Chile, just within the northern border of the regular influence of the westerlies. (B) Oblique view of the study site, showing the *rinconada* (amphitheater) formed by the encircling eastern slopes of the Cordillera de la Costa. The vegetation surveys were conducted along transects between points A–A′ and B–B′.

(4) *Nothofagus obliqua* (60%) and *Quinchamalium chilensis* (20%) predominate above 1950 m.a.s.l., representing deciduous forests and high Andean formations.

Materials and methods

We obtained sediment cores from the deepest part of the lake using a 5-cm-diameter modified Livingstone piston corer. The sediments was dated using 15 ^{14}C (Table 1) and 15 ^{210}Pb (Jenny et al., 2002a) dates. A radiocarbon date near the base of the core gave an age of 8340 ± 230 ^{14}C yr B.P. Radiocarbon samples were converted to "calendar" years using the Calib 4.2 program (Stuiver and Reimer, 1993). Based on these results we developed a calendar-age model to assign interpolated calibrated ages to the pollen levels (Fig. 3). The age model, which incorporates both ^{210}Pb and ^{14}C dates, consists of a second-order polynomial equation ($r^2 = 0.99$; $p < 0.0001$). The sediments consist (Fig. 4) of organic mud (*Gyttja*) between 0 and 215 cm; mainly silt

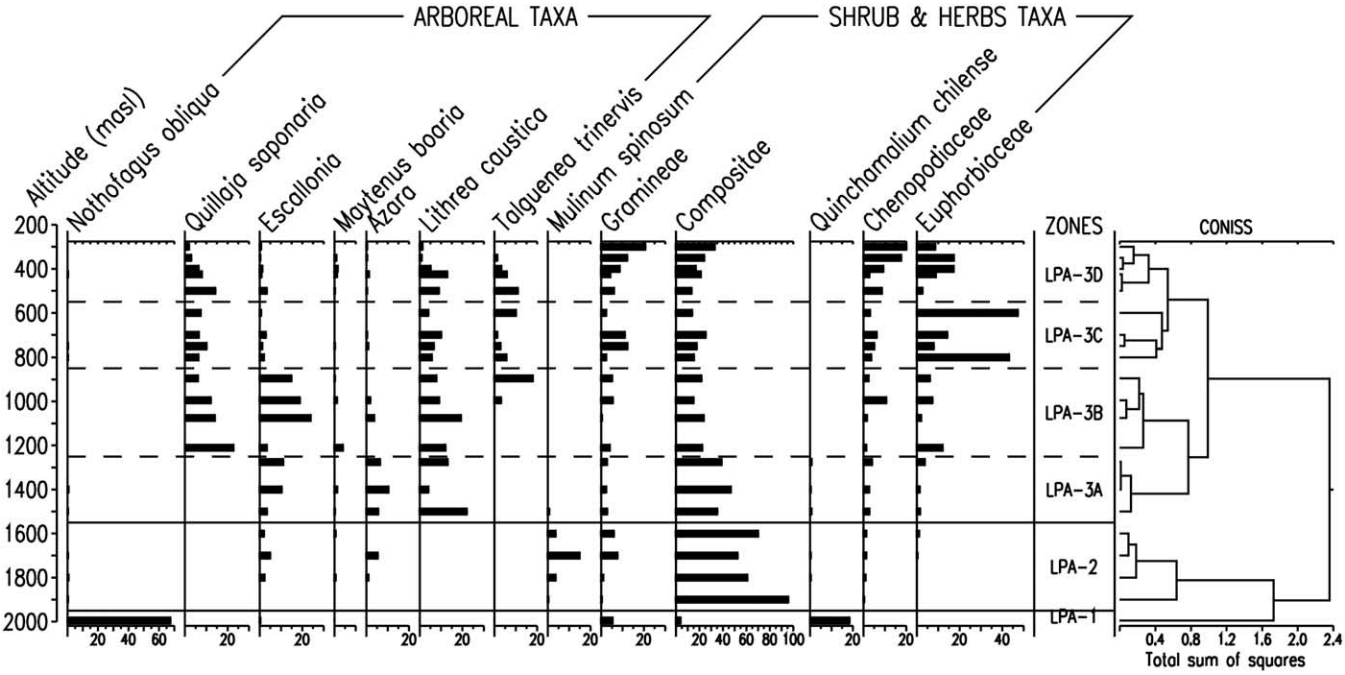

Fig. 2. Pollen-rain contents of surface soils samples obtained from the Laguna Aculeo watershed. Surface soil samples were taken in the same vegetation surveys. The samples (3 cm^3) were processed according to standard techniques (Faegri and Iversen, 1989), and pollen counts follow the fossil pollen.

between 215 and 300 cm; sandy silt with carbonate mud between 300 and 395 cm; and fine sand with gravel lenses and silt with carbonate and gypsum between 395 and 482 cm. About 30 clastic layers (turbidites) occur in the sediments; 8 of them occur in the upper 50 cm (A.D. 1948–1998), coinciding with El Niño years (Jenny et al., 2002a). We subtracted the thickness of the flood layers (turbidites), for the purpose of calculating the interpolated ages.

Samples for pollen analysis were obtained at regular 5-cm intervals throughout the sediment core, using a constant volume (3 cm^3). Pollen samples were selected to avoid turbidite layers. The sediment samples were pretreated according to standard techniques (KOH, HF, and acetolysis) (Faegri and Iversen, 1989). *Lycopodium* spore tablets (Stockmarr, 1971) were added to calculate accumulation rates (influx). The basic pollen sum for each level includes at least 300 terrestrial pollen grains (excluding aquatics and fern taxa), which were analyzed at 400× and 1000× magnification. The results are expressed in percentage and accumulation-rate diagrams, using the results of the calendar-age model. Pollen zones were defined with the aid of a constrained incremental sum of squares (CONISS) cluster analysis (Grimm, 1987), applied to the terrestrial pollen taxa with abundance ≥2%, after recalculation of sums and percentages. The basal portion of the core, between the depths 360 and 482 cm, did not contain enough pollen for analysis.

Table 1
Radiocarbon dates and calibrated ages for the Laguna Aculeo record

Depth [cm]	Age [^{14}C yr B.P.]	Age [cal yr B.P.]	δ^{13}C [‰ PDB]	Material dated	Laboratory code
5	>AD 1963		−17.6	OM (organic matter)	Hv-23487
89.5	755 ± 65	730 (670) 650	−24.8	OM	Ua-16877
110	920 ± 65	920 (790) 730	−29.6	Small wood piece, charcoal	Ua-15089
116	1065 ± 165	1270 (950) −760	−24.6	OM	Hv-22728
145.5	1630 ± 55	1540 (1520 1410	−28.5	wood	NSRL-10855
162	1800 ± 40	1730 (1710) 1630	−15.6	Aquatic plants	NSRL-10856
169.5	2195 ± 95	2330 (2150) 2010	−22.9	OM	Hv-22729
212	2960 ± 45	3210 (3110) 3000	−28	Charcoal, Chenopodiaceae seed	NSRL-11019
245	3450 ± 40	3720 (3660) 3640	−18	Plants	NSRL-10859
281	4680 ± 45	5470 (5390) 5320	−25.2	Chenopodiaceae, Carex	NSRL-10857
325	5380 ± 110	6280 (6140) 5950	−25.8	Charcoal, fruits	Ua-15090
369	7640 ± 215	8600 (8400) 8180	−25.5	OM	Hv-23962
398.5	8340 ± 220	9530 (9350) 9010	−25.1	OM	Hv-23963
444	8390 ± 230	9550 (9380) 9030	−25.6	OM	Hv-23488

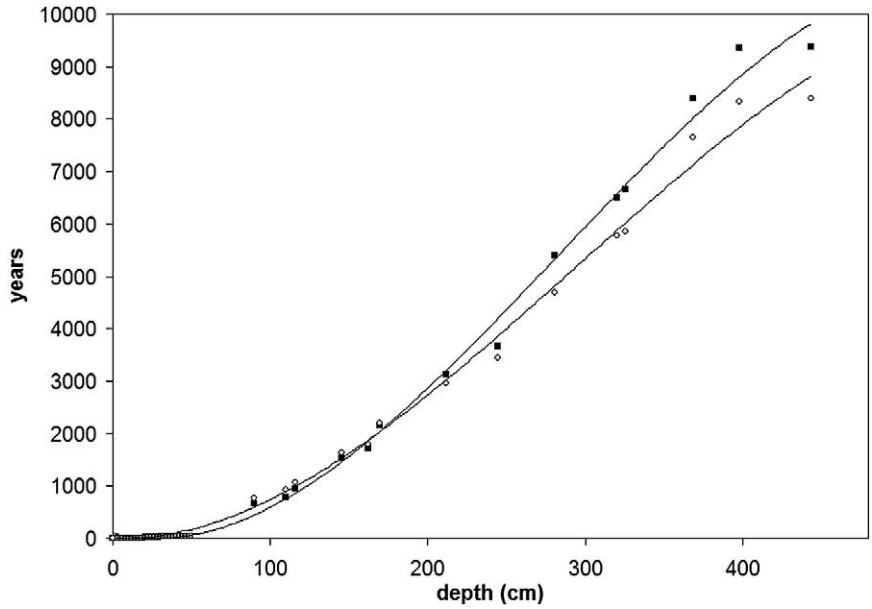

Fig. 3. Age-depth curve for the Laguna Aculeo record. Filled squares represents calendar years, open squares ^{210}Pb dates, and open circles indicate ^{14}C dates.

Results

Pollen stratigraphy

The percent and accumulation rate diagrams (Figs. 4, 5) document the vegetation history from Laguna Aculeo during the last 7500 cal yr B.P. Both diagrams were divided into three pollen zones, based on conspicuous changes in the pollen stratigraphy and a CONISS ordination.

Zone LA 1 (7500–5700 cal yr B.P.)

Dominated almost exclusively by Chenopodiaceae pollen (80%) with other herbaceous and aquatic taxa amounting to <20% of the total sum. Traces of arboreal pollen

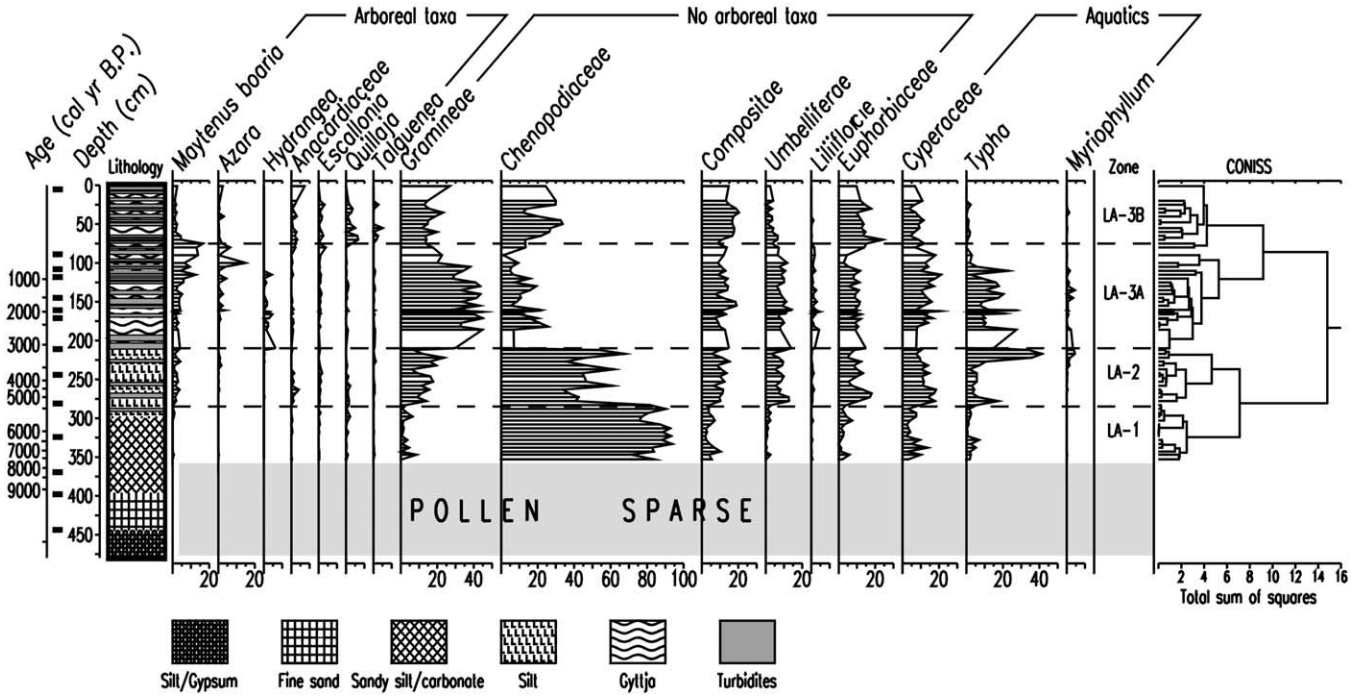

Fig. 4. Percentage diagram of selected taxa from the Laguna Aculeo record. The stratigraphic column is modified from Jenny et al. (2002b). Dashed lines indicate major changes in pollen stratigraphy. Black rectangles indicate the position of radiocarbon dates.

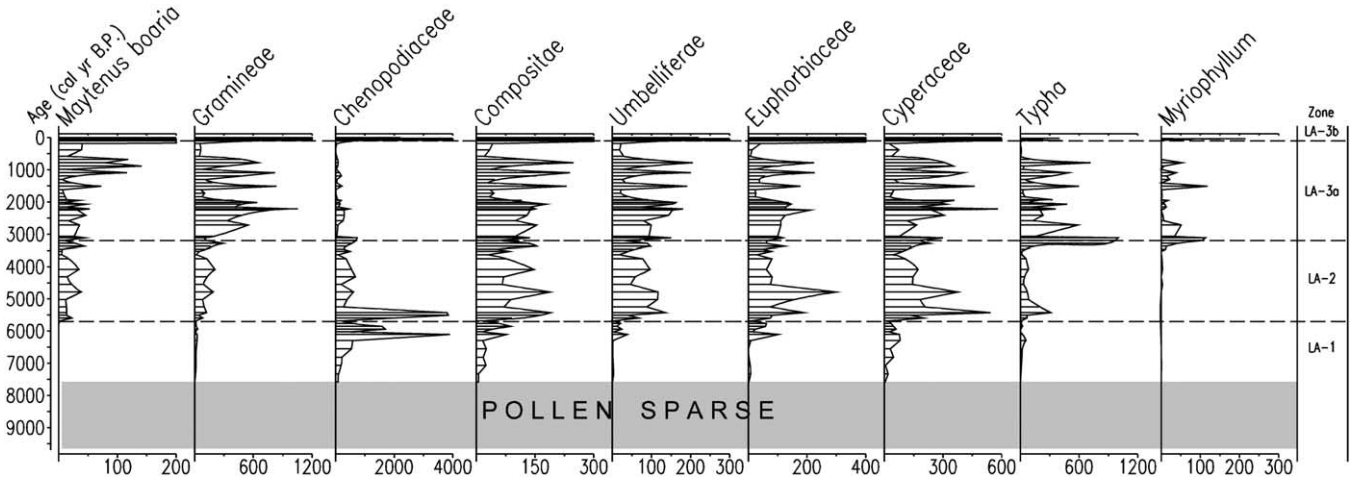

Fig. 5. Pollen accumulation rates for selected taxa from the Laguna Aculeo record. Note truncation of the past 100 yr for visualization purposes. Note different scales for the taxa shown.

include *Quillaja saponaria, Escallonia,* and Anacardiaceae. Low pollen accumulation rates (Fig. 5) characterize this zone, except for Chenopodiaceae, which exhibit exceptionally high values with strong fluctuations. *Q. saponaria,* Compositae, and Euphorbiaceae all increase their accumulation rates toward the upper part of the zone.

Zone LA 2 (5700–3200 cal yr B.P.)

Chenopodiaceae pollen percentages drop substantially (from ~80% to ~40–60%), whereas the remaining herbs (Gramineae, Compositae, Umbelliferae, and Euphorbiaceae) show considerable increases, along with a slight increase of the tree *Maytenus boaria.* Among the aquatic taxa, Cyperaceae pollen percentages are close to 20%, and *Typha* reaches its maximum (~40%) near the upper and lower zone limits. Despite generally low influx values (Fig. 5), the herbaceous taxa (Gramineae, Umbelliferae, and Euphorbiaceae), trees (*M. boaria, Quillaja saponaria*), and aquatics (*Typha,* Cyperaceae) increase in their percent abundance.

Zone LA-3 A and B (3200–0 cal yr B.P.)

The most prominent change in the pollen record occurs during this time. Chenopodiaceae percentages fall to their lowest values at ~25%, along with a major increase in Gramineae that reach values >30%. Other herbaceous taxa, however, show no significant increases relative to previous zones, excepting Liliiflorae and the aquatics. Pronounced increases in *Azara* and *Maytenus boaria* occur among the arboreal taxa. *Hydrangea serratifolia,* a rainforest vine currently absent from the modern vegetation and pollen rain of the Aculeo watershed, appears for the first time in the pollen record during this zone. An important pattern displayed by the accumulation rates (Fig. 5) is the almost synchronous behavior of all the indicators. Thus, absence of Chenopodiaceae pollen co-occurs with abrupt increases of all other herbaceous and aquatic taxa (Gramineae, Liliiflorae, Compositae, Umbelliferae, *Typha,* and *Myriophyllum*). The vine *Hydrangea serratifolia* and the trees *M. boaria* and *Azara* also increase in unison. During the past 100 years (Zone 3B), the influx values of *M. boaria* and Gramineae decrease, concomitant with an expansion of *Quillaja saponaria, Talguenea trinervis,* and Chenopodiaceae. The high influx values exhibited by most taxa during Zone 3B contrast with the low values recorded in the previous zones.

Charcoal and microalgae stratigraphy

The accumulation rates of microscopic charcoal particles (Fig. 6) reached their maxima during successive peaks between 5000–4500 and 3200–2500 cal yr B.P., as well as during the past 100 cal yr B.P. The first peak occurs at the beginning of pollen zone LA-2, synchronous with the beginning of the decline in Chenopodiaceae and the expansion and diversification of herbs. The second peak occurs during a prominent rise in Gramineae, and the third peak occurs during historic times (Zone 3B).

The analysis of microalgal remains (Fig. 6) reveals the presence of *Pediastrum* near the start of zone LA-2, at ~5500 cal yr B.P. Low values of *P. boryanum* and *P. duplex* occur between 5000 and 3200 cal yr B.P., followed by major increases between 3200 and 100 cal yr B.P. (Zone LA-3). An important expansion of *P. simplex* and *Scenedesmus sp.* occurs over the last 100 years.

Discussion

The Laguna Aculeo record shows the absence of palynomorphs in sediments older than 7500 cal yr B.P., which most likely attests to the presence of an ephemeral water body in the lake basin, under very arid and warm conditions. The presence of gravels, sands and calcitic- dolomitic silts with gypsum prior to 7500 cal yr B.P. also suggests a

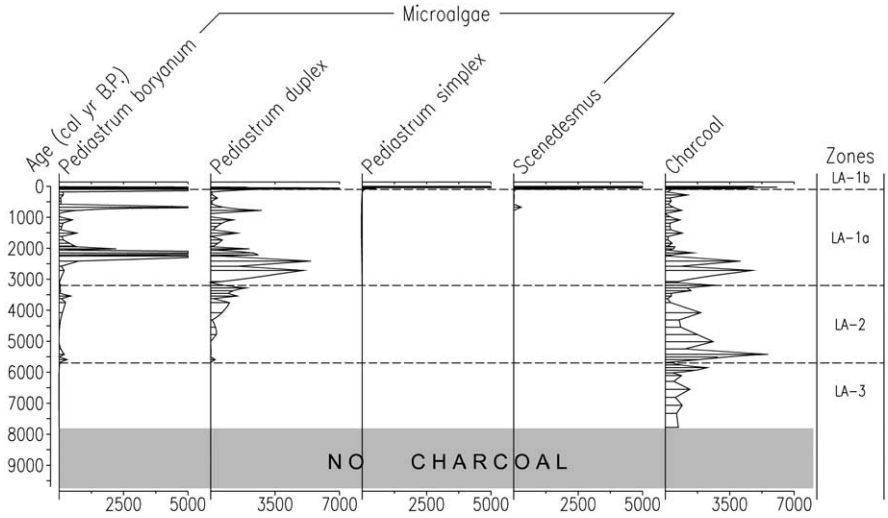

Fig. 6. Accumulation-rate diagram of charcoal microparticles and microalgae from Laguna Aculeo. Note truncation of the past 100 yr for visualization purposes. Note different scales for the taxa shown.

shallow-water saline lake under arid conditions with high evaporation rates (Fig. 7). Chenopodiaceae dominates the pollen record between 7500 and 5700 cal yr B.P. (Zone LA-1, Figs. 4, 5), and all other taxa are practically absent. These Chenopodiaceae-dominated assemblages do not have analogs in the modern vegetation and pollen rain from Laguna Aculeo (Fig. 2) and are comparable with surface samples from a coastal lagoon shore near Quintero (32°47 S)(Villa-Martinez, 1995). In Central Chile these halophytes thrive on lake shores affected by seasonal water level fluctuations (Heusser, 1990; Villa-Martinez, 1995), suggesting a playa-like saline environment and seasonally fluctuating lake levels. The fluctuating accumulation rates observed in Chenopodiaceae (Fig. 4) suggest strong variability in the extent of Laguna Aculeo. This scenario is supported by the presence of low organic content, gypsum, and variable amounts of carbonates within this interval, which are interpreted as reflecting a seasonally fluctuating saline lake (Jenny et al., 2002b). The absence of green microalgal remains is consistent with this interpretation, along with the absence of diatoms before 5500 cal yr B.P.(Jenny et al., 2002b). Thus, all paleoenvironmental indicators strongly suggest extreme aridity and/or warm conditions at the lake, which implies a strong SPA and infrequent westerly stormtrack incursions that currently provide much precipitation in this area.

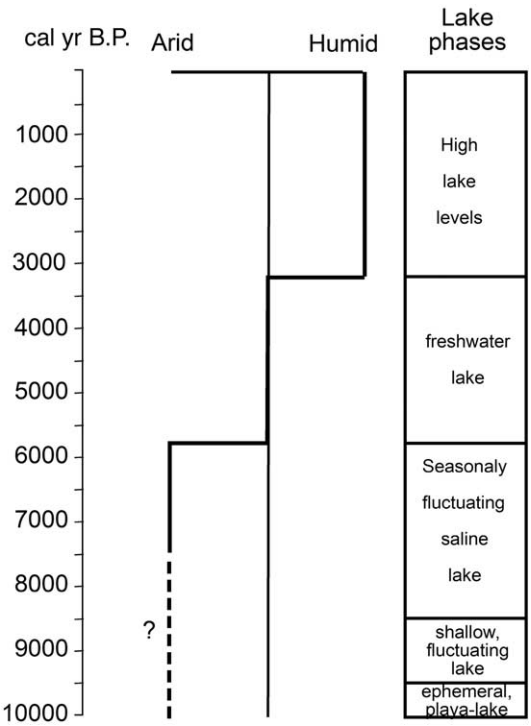

Fig. 7. Paleoclimatic interpretation of the Laguna Aculeo record and a comparison with lake history. Lake phases are based on Jenny et al. (2002b).

Starting at about 5700 cal yr B.P. (zone LA-2), Chenopodiaceae pollen declines and other herbaceous taxa and trees (*Maytenus boaria*) increase in importance, suggesting a rise in humidity, which we interpret as increased westerly activity. This assemblage is most similar to the surface samples collected below 500 masl in the modern watershed and imply an increase in vegetation cover. Concomitantly, the organic matter in the sediments increases and carbonates disappear (Jenny et al., 2002b), suggesting overall higher lake levels due to increased moisture. Low values of *Pediastrum boryanum* and *P. duplex* occurred during this interval. *P. boryanum* is an indicator of oligotrophic lake conditions, whereas *P. duplex* prefers more mesotrophic conditions, according to modern distributions of both species in the Lake District and central Chile (Thomasson, 1963; Vila et al., 1987). A shift from oligo- to mesotrophic

lake conditions is thus implied at Laguna Aculeo for this time.

The most prominent change in the pollen record occurs at 3200 cal yr B.P., and consists of a large drop in Chenopodiaceae and expansion of Gramineae, along with *Typha*, Cyperaceae, and the hygrophilous vine *Hydrangea serratifolia* (absent from the present-day flora in this area) and *Maytenus boaria* (which prefers moist soils, S. Tellier and C. Le Quesne, personal communication, 2000). This vegetation change implies a significant rise in moisture in the watershed. One important feature in this part of the record is the synchronous, fluctuating behavior displayed by all the pollen and microalgal accumulation rates (Figs. 5, 6), suggesting high variability in precipitation, and varying oligo- to mesotrophic conditions. The onset of organic mud deposition documents a profound limnological change that may imply an overall increase in lake depth (Fig. 7).

An increase in the Chenopodiaceae/Gramineae pollen ratio, decline in aquatic taxa (*Typha* and *Myriophyllum*), and the replacement of *Maytenus boaria* by *Quillaja saponaria* over the past 100 years (Zone LA-3b) are all indicative of increased aridity. We cannot reject human disturbance, however, as the cause for the vegetation changes observed during this recent interval. In fact, during this interval the accumulation rates of charcoal, green microalgae *Pediastrum simplex* and *Scenedesmus sp.* (Fig. 6), both eutrophic indicators (Hutchinson, 1957; Reynolds, 1997), and diatoms (Jenny et al., 2002b) reach the highest values of the Holocene. Hypereutrophy, which has intensified during the past 30 years, is most likely associated with increased human activity at the lake related to tourism and agricultural use (Cabrera and Montecinos, 1982).

Fire history

Three major increases in microscopic charcoal particles occurred over the past 7500 years in the Laguna Aculeo record (Fig. 6). The youngest charcoal peak, dated at 100 cal yr B.P., is associated with modern human activity in the basin (Villa-Martínez et al., in press). Additional charcoal peaks occurred between 3000 and 2500 cal yr B.P. and between 5500 and 5000 cal yr B.P., linked both to major pollen changes that indicate onset wetter conditions. These charcoal maxima also occur at Laguna Tagua Tagua, which exhibits charcoal peaks during moist intervals between 9000 and 6800 and 2750 and 160 cal yr B.P. (Heusser, 1990).

Why would increases in microscopic charcoal particles correlate with the expansion of vegetation with higher moisture demand? One explanation may relate to ignition by electrical storms, which would occur more frequently during times of increased frontal activity. Although electrical storms are currently very rare in Central Chile (Miller, 1976) they can occur when cold-air, high-altitude nuclei reach the area during summer and fall (P. Aceituno, personal communication, 2001). Alternatively, fires may have resulted from prehispanic human activities. The Laguna Tagua Tagua record shows charcoal peaks during the Holocene, which were interpreted as indicative of human burning (Heusser, 1990). Additionally, the presence of *Phaseolus* pollen at ~5600 cal yr B.P. in the Cuchipuy archeological site (Rojas, 1991), demonstrates the permanent or semipermanent presence of human populations in the Laguna Tagua Tagua basin. Very little is known, however, regarding human occupation in the Laguna Aculeo watershed and the archaeological record at present extends back only 1000 years (F. Falabella, personal communication, 2001).

Over the last 1000 years the charcoal record of Laguna Aculeo shows a single peak, at about 100 cal yr B.P., and is associated with European settlement in the basin. Apparently, prehispanic activities did not exhert any influence in the microscopic charcoal record from Laguna Aculeo, highlighting the possibility that prehispanic fires were driven solely by climatic conditions. If this interpretation is correct, Holocene fires around Laguna Aculeo may have resulted from high climate variability, when the probability of natural fires may have increased during the dry seasons.

Regional implications

The paleoclimate trends revealed by the Laguna Aculeo record are comparable with previous studies in the region. Some of those studies suggest widespread arid and warm conditions in Central Chile during the early to middle Holocene. The pollen record from Laguna Tagua Tagua (34°30′ S), indicates dry and warm conditions between ~7000 and 3000 cal yr B.P., when the lake reached its lowest Holocene levels (Heusser, 1983; Heusser, 1990). Based on geomorphologic and paleopedologic evidence from the Norte Chico area (27°–30°S), Veit (1996) inferred arid conditions between 7600–5600 cal yr B.P. Warm and dry conditions are also implied by deep sea sedimentary records off the Valparaiso (33°S) coast between 8000 and 4000 cal yr B.P. (Lamy et al., 1999).

Few records in Central Chile document the onset of the humid phase at 5700 cal yr B.P. Paleosoils from the Norte Chico (Veit, 1996) indicate the beginning of this phase at 5600 cal yr B.P. Pollen records along coastal north central Chile also imply an increase in humidity during this time, as inferred by the cessation of dune formation at Quintero (32°47′ S)(Villa-Martínez and Villagrán, 1997).

The late Holocene wet phase has been profusely documented in other paleoenvironmental records from Central Chile. A more humid climate based on the expansion of Gramineae and the presence of *Nothofagus dombeyi*-type was inferred at Laguna Tagua Tagua (Heusser, 1983; Heusser, 1990) and was concomitant with the appearance of Myrtaceae swamp forests along the coast (Maldonado and Villagrán, 2002; Villagrán and Varela, 1990; Villa-Martínez and Villagrán, 1997).

The Laguna Aculeo record shows frequent, large-magnitude fluctuations in the pollen and microalgal accumulation rates starting at 3200 cal yr B.P. The presence of

numerous clastic layers, the most massive of which coincides with the bottom of zone LA-3A (~3200 cal yr B.P., Fig. 4), have been interpreted as flooding probably during very rainy winters (Jenny et al., 2002a). These flooding events could explain the synchronous fluctuations observed in the pollen influx rates and also suggest an overall increase in precipitation variability. We infer that this may partly be caused by high-frequency variability similar to El Niño–Southern Oscillation, which at present affects central Chile by generating increased winter rainfall on interannual to decadal timescales (Aceituno, 1988, 1990). Clastic layers in the Laguna Aculeo record represent the distal, subaqueous expression of alluvial events throughout the watershed, possibly related to torrential rains during strong El Niño events. According to Jenny et al. (2002b) flood layers (turbidites), deposited before 9000 cal yr B.P., appear to have been absent during the mid-Holocene until about 5700 cal yr B.P., but became especially abundant after 3200 cal yr B.P.

The pattern documented here agrees well with descriptions in several other records which indicate that ENSO has been active mainly during the past 6000–5000 years (Markgraf, 1998; McGlone et al., 1992; Rodbell et al., 1999; Sandweiss et al., 1996, 2001). Based on analysis of fossil mollusks from coastal archaeological sites in Peru, Sandweiss et al. (2001) suggested that El Niño events were less frequent than today between ~5800 and 3200–2800 cal yr B.P., with modern recurrence intervals achieved only after that time. Based on an alluvial sediment record from Laguna Pallcacocha in Ecuador, Rodbell et al. (1999) suggested that ENSO frequency has increased progressively over the past 7000 cal yr, with the establishment of modern frequencies at ~5000 cal yr B.P. Based on coral records from Papua New Guinea, Tudhope et al. (2001) suggested that the amplitude of ENSO events has been significantly larger over the last 3000 cal yr. Moreover, deep-sea records off the coast of Central Chile (33°S) show elevated variability in planktic foraminifera composition, which was interpreted as caused by increases in precipitation, coupled with strong, El Niño-like, climatic variability over the past 3000 years (Marchant et al., 1999).

Our results show that over the last 3200 years the vegetation composition, altitudinal distribution and lake levels resemble to modern scenario observed in Laguna Aculeo. During this time pollen assemblage is most similar to modern vegetation below 500 masl. Moreover, the precipitation variability related to ENSO started at 3200 cal yr B.P. These findings imply that the modern Mediterranean climate of Central Chile and their association with high-frequency precipitation variability became established at about 3200 cal yr B.P.

Conclusions

The high-resolution, multiproxy record from Laguna Aculeo indicates that more arid conditions relative to the present prevailed in Central Chile prior to 5700 cal yr B.P. The absence of palynomorphs between 9500 and 7500 cal yr B.P., along with the sedimentological inference of a dry playa environment, suggests warm and arid conditions. Increased aridity in this region suggests a strong blocking influence of the Pacific Anticyclone and/or subdued westerlies. A rise in precipitation started at ~5700 cal. yr B.P., implying an increase in westerly storm-track activity. A further intensification of this trend started 3200 cal yr. B.P., along with increased rainfall variability at sub-centennial time scales. We interpret this condition as resulting from more frequent/intense El Niño-like activity. The modern Mediterranean climate of central Chile with high precipitation variability was established at 3200 cal yr. B.P. For the past 100 years the landscape around Laguna Aculeo has been transformed by increased human activity.

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