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Climate variability over the last 9900 cal yr BP from a swamp forest pollen record along the semiarid coast of Chile

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Abstract

We present a fossil pollen analysis from a swamp forest in the semiarid coast of Chile (32°05′S; 71°30′W), at the northern influence zone of southern westerly wind belt. A ~10,000 cal yr BP (calendar years before 1950) palynological sequence indicates a humid phase characterized by dense swamp forest taxa dated between ~9900 and 8700 cal yr BP. The presence of pollen-starved sediments with only scant evidence for semiarid vegetation indicates that extreme aridity ensued until ~5700 cal yr BP. The swamp forest recovered slowly afterwards, helped by a significant increase in moisture at ~4200 cal yr BP. A new swamp forest contraction suggests that another slightly less intense drought occurred between ~3000 and 2200 cal yr BP. The swamp forest expansion begins again at ~2200 cal yr BP, punctuated by a highly variable climate. Comparisons between the record presented here with other records across the region imply major variations in the extent of the southern westerlies during the Holocene. This variability could have been caused either by latitudinal displacements from the present mean position of southern westerlies wind belt or by changes in the intensity of the South Pacific Subtropical Anticyclone, both of which affect winter precipitation in the region.

Keywords: Northern Chile; Holocene; Pollen record; Paleoenvironmental change; Paleoclimate; Southern westerlies; Semiarid; Swamp forests

Introduction

Coastal semiarid Chile extends from the central Mediterranean region to the south up to the Atacama Desert in the north. Dry summers and variable winter rains, accompanied by occasional winter drought, especially at its northern limit, characterize this portion of Chile (VanHusen, 1967). The winter-wet climate is generated from the interaction of two large systems that govern the extra-topical region of Chile: the southern westerlies (center of influence situated at 47°) and the South Pacific Anticyclone (SPA). During summers the SPA is displaced southwards, effectively blocking the westerly storm fronts north of 34°S. In contrast, during the winter the SPA weakens and migrates northwards, allowing frequent stormfronts associated with the southern westerlies to reach into the semiarid portion of the country (Garreaud and Aceituno, 2002; Miller, 1976).

The Chilean Mediterranean zone is highly sensitive to interannual variations associated with the El Niño-Southern Oscillation (ENSO). Negative phases of ENSO (associated with El Niño events) are associated with abnormally hot and wet winters whereas abnormally dry and cold winters prevail during the positive phase (associated with La Niña events) (Aceituno, 1988).

Seasonal latitudinal changes in the SPA, reduced frequency of westerlies related stormfronts, and ENSO-related effects all combine to produce a highly variable precipitation regime in north-central Chile that is sensitive to climate fluctuations. It is thus ideally suited for studying paleoclimatic conditions and reconstruction of past variations of the different climatic systems governing the region. Very few high-resolution paleoclimatic studies exist for central Chile (33–36°S) and adjacent Norte Chico (33–27°S) and most are not older than 6000 cal yr BP. All published records show alternations between wet and dry periods (Earle et al., 2003; Grosjean et al., 1997a, 1998; Jenny et al., 2002b; Maldonado and Villagrán, 2002; Villagrán, 1982; Villa-Martínez and Villagrán, 1997),

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although there is little agreement on how long these phases actually lasted. Most records agree, however, on the presence of a prolonged drought during the early and middle Holocene (Heusser, 1990; Jenny et al., 2002b; Kim et al., 2002; Lamy et al., 1999; Marchant et al., 1999; Veit, 1996; Villagrán and Varela, 1990; Villa-Martínez et al., 2003), although the timing and duration vary between different proxy records.

Detailed middle to late Holocene records have been obtained in the past from the coastal swamp forests of north-central Chile (Villa-Martinez and Villagrán 1997; Maldonado and Villagrán, 2002). Here, we present a record of paleoecological change from a small swamp forest record characterized by thick accumulations of organic sediments intercalated with soils. Our objective was to obtain a detailed and diverse fossil pollen record of past climatic variations that spanned the entire Holocene.

Study area

Swamp forests dominated by Myrtaceae (*Myrceugenia exsucca* and *Luma chequen*) are common along the north-central Chilean coast, between 36°30′S and 30°00′S (Fuenzalida, 1965; San Martín et al., 1988). These isolated, discontinous forests are commonly groundwater-fed systems restricted to particular geomorphic settings with periodic or permanent flooding (Ramírez et al., 1983, 1995; San Martín et al., 1988; Varela, 1981). Seven swamp forests can be found in small ravines between the coastal villages of Los Vilos and Pichidangui (from 31°50′ to 32°05′S; ~71°30′W). Most of these are very close to the coast and have an east–west orientation (Maldonado, 1999). These ravines are located on the coastal plain associated with small hydrographic basins where local groundwater recharge is determined by the infiltration along the adjacent coastal mountain range (which reaches up to 1000 m in elevation). Thus, forest hydrology depends chiefly upon local geomorphology, regional winter precipitation and groundwater recharge.

The coastal plains and adjacent mountain slopes are dominated by zonal vegetation characterized by plants from the family Asteraceae (*Baccharis vernalis* and *Bahia*

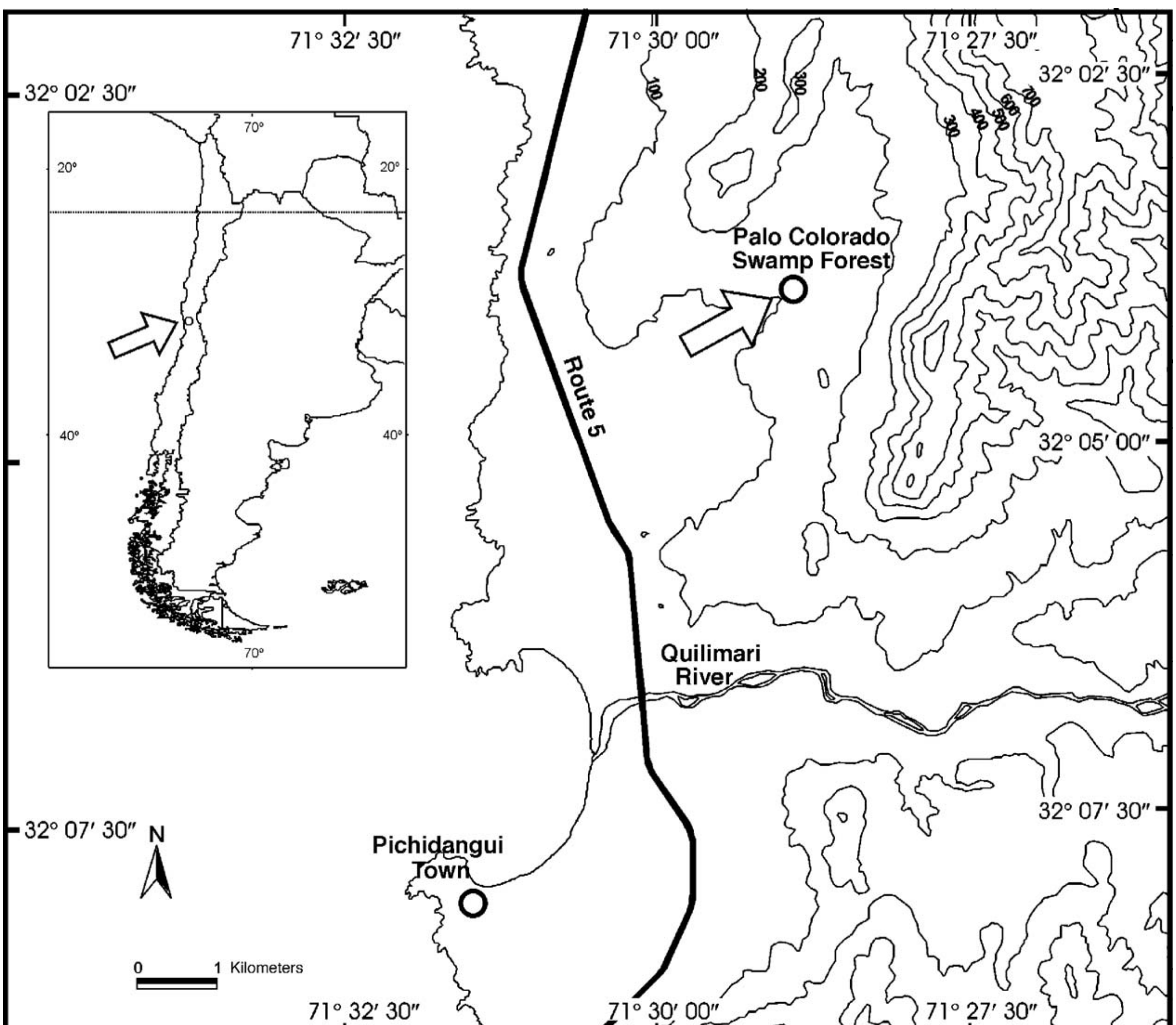

Figure 1. Study area map showing the locality and topography of Palo Colorado swamp forest (contour interval 100 m).

Table 1
Radiocarbon dates for Palo Colorado record: Laboratory number, depth, radiocarbon dating, calendar year calibration (maximum and minimum year), calibrated age (mid point), $\delta^{13}C$ and material dated

Laboratory no.	Depth, cm	Age ^{14}C yr BP	Age, max and min range cal yr BP (2 sigma; 95,4%)	Age, mid point cal yr BP	$\delta^{13}C$ ‰	Material
AA-63302	26–27	510 ± 37	502–628	565	−25.97	Charcoal
AA56375	29–30	90 ± 31	11–141	76	−27.5	Plant Macro-remains
AA-63303	61–62	903 ± 38	738–915	826	−27.32	Charcoal
AA-56374	96–98	1581 ± 33	1398–1538	1468	−27.58	Bulk
AA-63304	129–130	1958 ± 39	1825–1990	1908	−27.69	Bulk
AA-56376	159–160	2151 ± 34	2007–2306	2156	−28.2	Charcoal
AA-56373	205–206	3165 ± 54	3254–3553	3404	−27.81	Plant Macro-remains
AA-53359	226–228	3851 ± 43	4151–4413	4282	−28.28	Charcoal
Beta-204526	254–255	5550 ± 40	6287–6406	6346	−25.9	Bulk
AA-58073	277–279	7578 ± 59	8211–8536	8374	−26.3	Charcoal
AA-53358	285–286	8466 ± 84	9265–9595	9353	−27	Bulk

ambrosioides) associated with *Puya chilensis*, *Haplopappus foliosus*, *Fuchsia lycioides* and *Lithrea caustica*. The transition between zonal and azonal vegetation can be abrupt, depending on local geomorphology. Within a few meters, surverys of coastal matorral can shift into a swamp forest. These swamp forests are floristically very distinctive and dominated by myrtles (mainly *Myrceugenia exsucca* and *Luma chequen*) associated with other arboreal species such as *Drimys winteri*, *Escallonia revoluta*, *Rhaphithamnus spinosus* and the vine *Cissus striata*.

At Palo Colorado (Fig. 1), the transition between swamp forest and the coastal matorral is represented by a vegetation belt dominated by arboreal sclerophyllous species such as *Maytenus boaria*, *Quillaja saponaria*, *Schinus latifolius*, *Pouteria splendens*, and associated shrubs such as *Eupatorium salvia*, *E. glechonophyllum* and *Fuchsia lycioides*. The sclerophyllous forest is also abundant in central Chile, but along the semiarid coast of the Norte Chico, it is restricted to creek bottoms and wetter south-facing slopes of the coastal mountains.

Methods

We sampled sediment soils from the Palo Colorado swamp forest using a 5-cm-diameter Wright square-rod piston corer (Fig. 1; 32°05′S; 71°29′W). To describe the stratigraphic column we used X-ray images, texture analysis and sediment color. Samples were extracted at regular intervals from the sediment core for loss-on-ignition (LOI) and fossil pollen analyses.

The LOI analyses were performed by drying and burning sediment samples at 550°C and 925°C to eliminate organic matter and carbonates, respectively. We compared sediment weight before and after treatment to calculate percent and density of organic and inorganic matter as well as carbonates.

We extracted pollen from the stratigraphic cores using standard methods (Faegri and Iversen, 1989), including acetolysis. Pollen content from the samples was concentrated with ultrasound and samples were mounted using glycerine-jelly and glycerine.

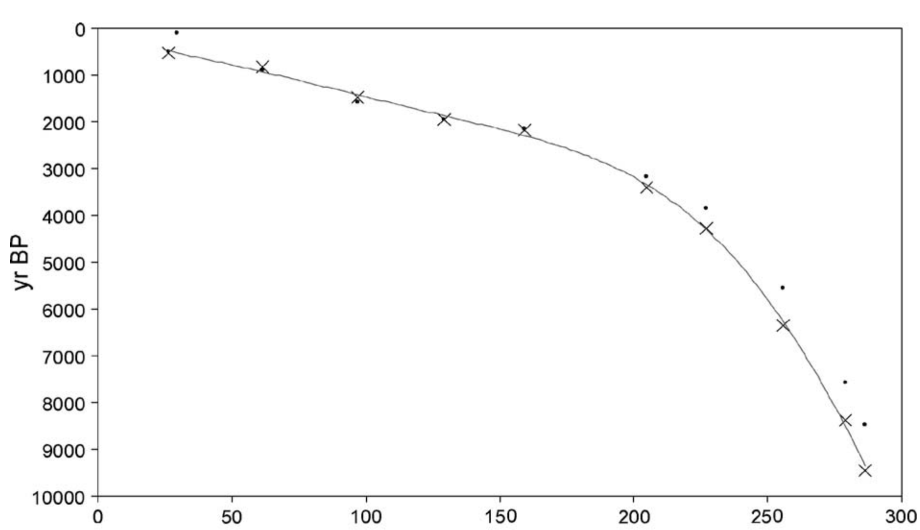

Figure 2. Graph showing radiocarbon (circles) and calendar (crosses) dates, and sixth-order polynomial regression against sediment depth.

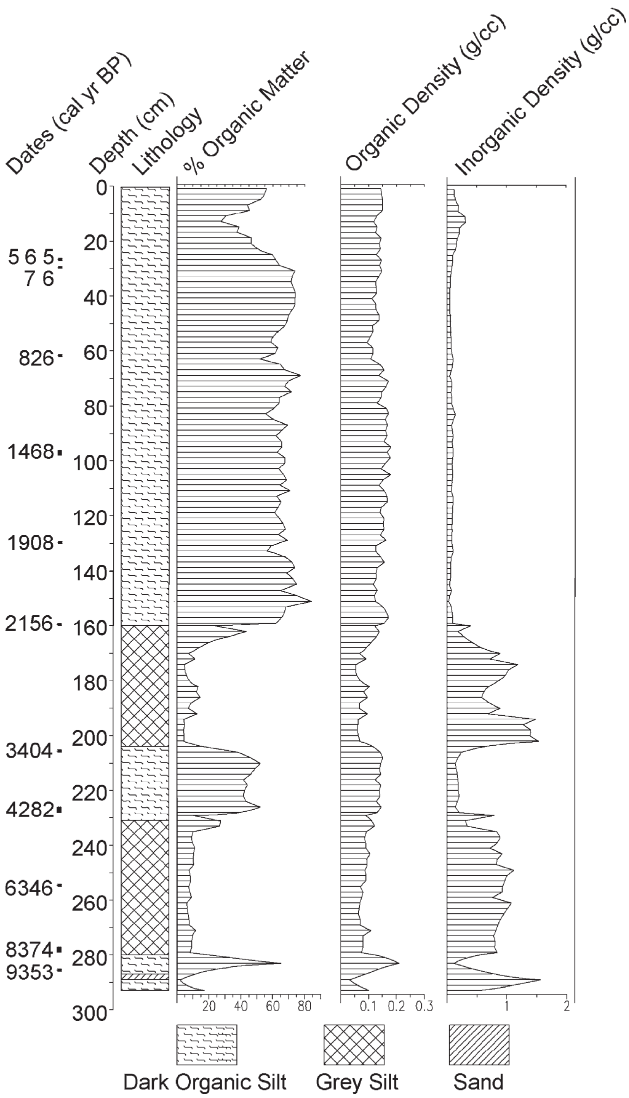

Figure 3. Results from loss on ignition analysis in Palo Colorado record showing radiocarbon dates (cal yr BP), sediment depth, lithology, % organic matter, organic matter density (g/cc) and inorganic matter density (g/cc).

The basic pollen count for each sample includes at least 300 terrestrial pollen grains (excluding aquatics and ferns taxa). The results are expressed in percent per taxon. *Lycopodium* spore tablets (2 tablets per cm^3 sediment) were added to calculate pollen concentration and accumulation rates (influx) (Stockmarr, 1971). Pollen zones were defined with the aid of a pollen affinity dendrogram generated by the Contrained Incremental Sum of Squares (CONISS) program (Grimm, 1987) and also considering changes in lithology.

Major breaks in stratigraphy were sampled and the sediments radiocarbon dated at the Accelerator Mass Spectrometry (AMS) Laboratory of the University of Arizona (USA) and Beta Analityc INC. (USA). Results were calibrated to calendar years using CALIB 5.1 (Table 1; (Reimer et al., 2004). A sixth-order polynomial regression ($R^2 = 0.9997$) was used to interpolate between radiocarbon dates along the age-depth profile (Fig. 2). Only one date (90 ± 31 ^{14}C yr BP) was excluded owing to probable contamination from modern root systems (Table 1; Fig. 2).

Results

Stratigraphy and chronology

The Palo Colorado record reaches a depth of 292 cm with a maximum date of ~9400 cal yr BP close to the base of the column. Ten radiocarbon dates are given in Table 1 and plotted in Figure 2 against core depth. Sediments from the middle to late Holocene (from 4200 cal yr BP) accumulated at a much higher rate than those from the early to middle Holocene (9900–4200 cal yr BP).

Basal core sediment is composed of a 12-cm-thick organic silt layer with a few sand intercalations (Fig. 3). Gray silts with low organic content (10%, from LOI analysis) are prevalent from 280 cm to 231 cm. These sediments were pollen-starved and counting was infeasible. A depositional hiatus in this section is, however, not very probable as indicated by a ^{14}C date at 254 cm (Figs. 2 and 3). This is followed by a section of organic-rich sediments (50% organic matter content) to 204 cm depth. From this point upwards, gray silt sediments with low organic content reappear up to 160 cm. The upper section is dominated by high organic content in the sediments (~70%). The last 30 cm exhibits a moderate decrease in organic content, which reverses towards the top (Fig. 3).

Although organic matter density displayed similar trends as the lithology, the changes are less distinctive. Inorganic matter density agrees more with the data from percent organic matter content (Fig. 3). Carbonates exhibited very low percentages throughout the entire sequence (<7%, data not shown but considered within the error measure range from the LOI method).

Percent pollen diagram

The percentage diagrams (Fig. 4) document the vegetation history from Palo Colorado over the last ~10,000 cal yr BP. The diagram is divided into three pollen zones, based on conspicuous changes in the pollen stratigraphy according to stratigraphically constrained CONISS ordination, using square-root transformed data and the Edward and Cavalli-Sforza's chord distance as a dissimilarity coefficient (Grimm, 1987).

Zone PC-1 (~10,000 to ~8700 cal yr BP)

Swamp forest indicators, mainly pollen of Myrtaceae (probably *Myrceugenia exsucca* and *Luma chequen*; ~35%) and *Escallonia* (probably *Escallonia revoluta*; ~30%), are dominant. Other swamp forest taxa are present in smaller proportions, such as *Drimys winteri* (<6%) and the vine *Cissus striata* (<7%). Of note are the trees *Maytenus* and Anacardiaceae (*Schinus* and *Lithrea*), both forest-edge taxa. Non-arboreal taxa are present in smaller proportions: Poaceae (<17%), Asteraceae-Tubuliflorae and Asteraceae-Liguliflorae (<22% and <25% respectively). Aquatic taxa and fern spores

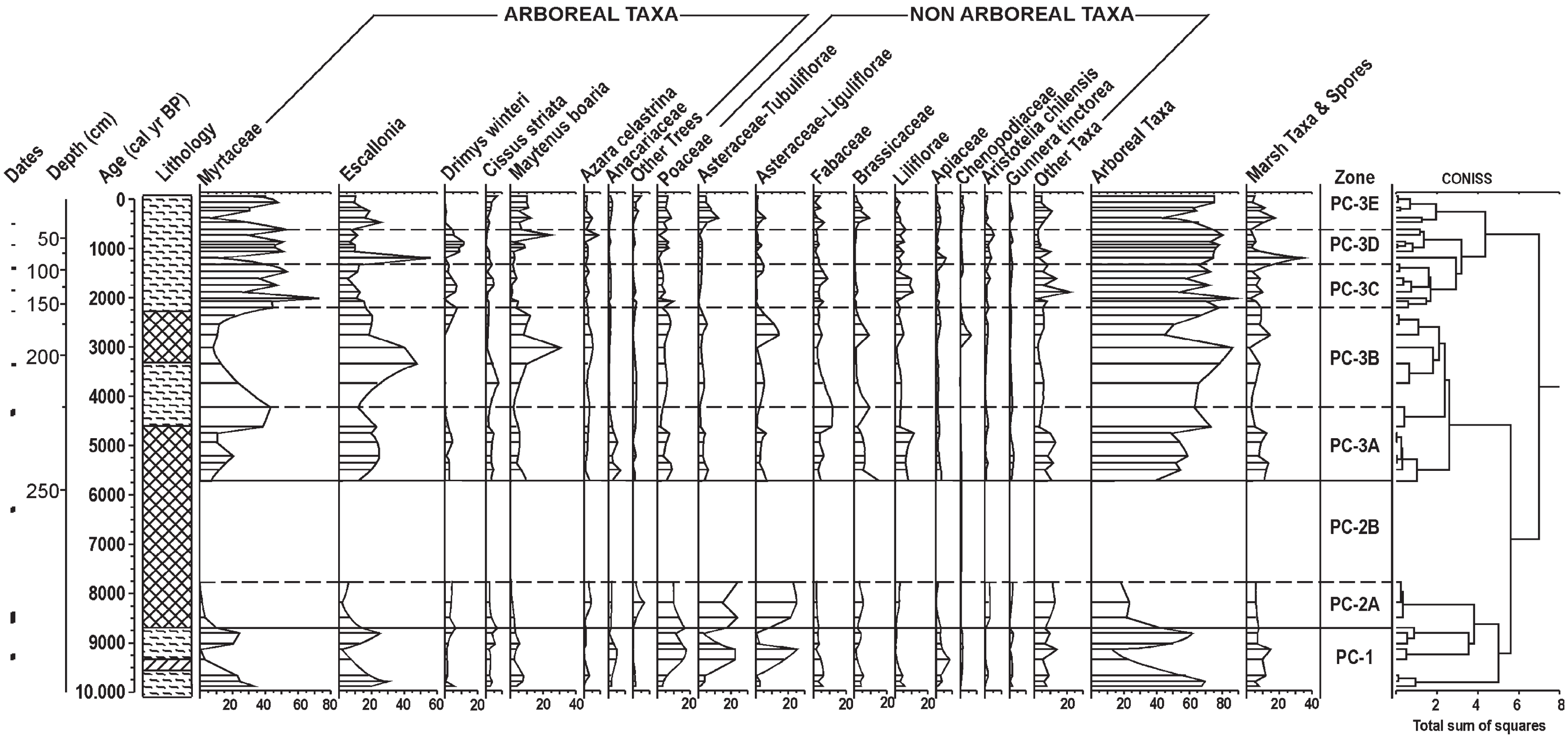

Figure 4. Palo Colorado percentages pollen diagram showing dates, depth, age (cal yr BP), lithology, zones and CONISS dendrogram.

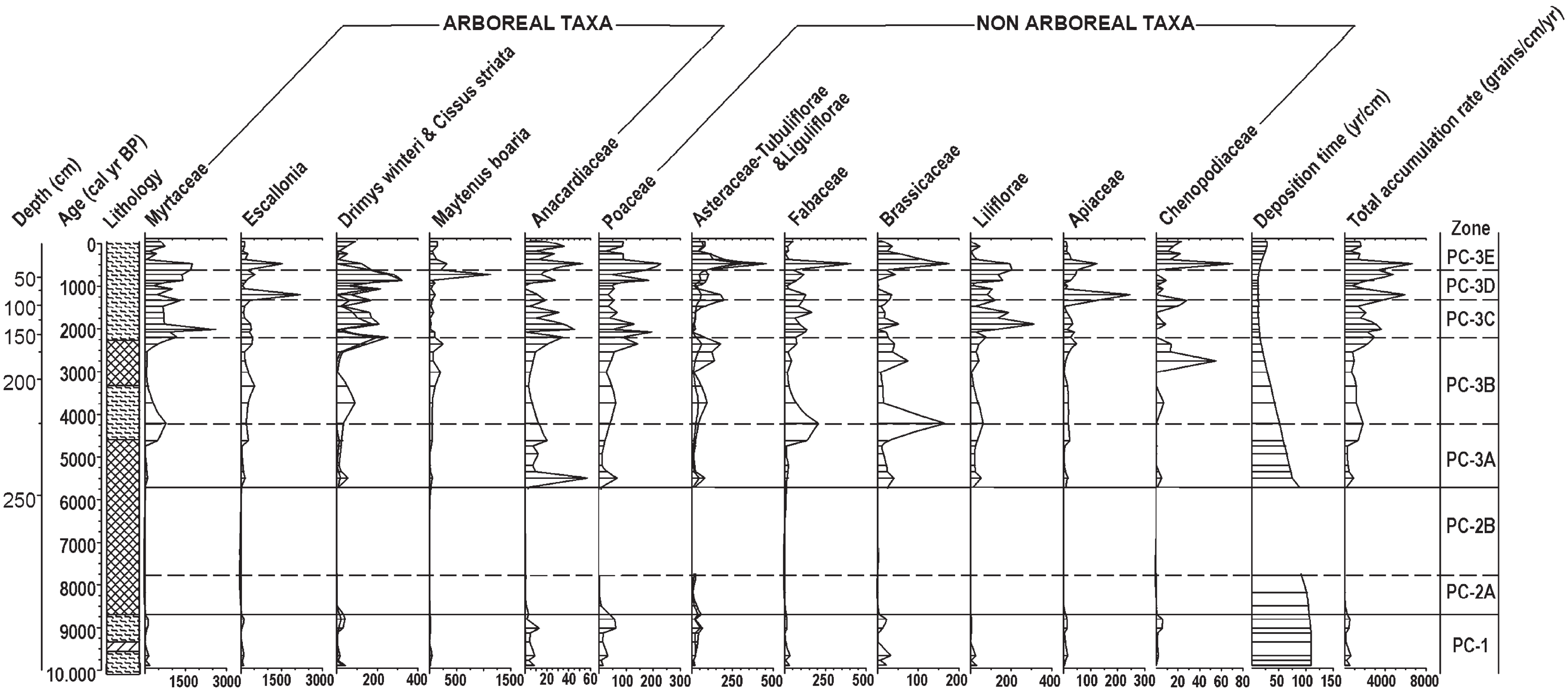

Figure 5. Influx diagram of selected taxa from Palo Colorado record, showing depth, age (cal yr BP), lithology, deposition times (yr/cm), total accumulation rates (grains/cm^2/year) and zones.

exhibit low but constant proportions (<12%). The middle of this zone displays a decrease in arboreal taxa and concomitant increase in Poaceae and Asteraceae. Sediments during this interval display a mostly sandy texture.

Zone PC-2 (~8700 to 5700 cal yr BP)

Characterized by the absence of arboreal pollen, with dominance of shrubs taxa at the base, but sediments are pollen-starved above.

Phase PC-2A (~8700 to 7800 cal yr BP)

Abrupt decrease in arboreal taxa and replacement by shrub indicators (Asteraceae <50% both Liguliflorae and Tubuliflorae and Poaceae <15%). Aquatic and fern spores are at low and constant levels throughout (~6%). This phase displays the lowest pollen influx values throughout the entire column.

Phase PC-2B (7800 to 5700 yr cal BP)

Pollen-starved sediments. Only traces of open area vegetation (Asteraceae-Liguliflorae) were observed, probably due to pronounced droughts which exposed and oxidized sediments leading to poor pollen preservation.

Zone PC-3 (5700 cal yr BP to the present)

Characterized by a series of pollen oscillations indicative of current swamp forests. From these changes and from the sediment sequence we distinguished five different phases.

Phase PC-3A (~5700 to 4200 cal yr BP)

Swamp forest indicators reappear and are dominated by *Escallonia* (<25%), Myrtaceae (<40%), *Maytenus* (<9%) and Anacardiaceae (<8%). Non-arboreal taxa, Brassicaceae (<16%), Poaceae (<9%) and Liliflorae (<11%, mainly Amaryllidaceae and Liliaceae) are also present. Aquatic taxa and spores display little variation.

Phase PC-3B (~4200 to ~2200 cal yr BP)

Swamp forest taxa increase in abundance, initially Myrtaceae (<43%) and then *Escallonia* (<48%). The second half of the phase shows an increase of a sclerophyllous arboreal species: *Maytenus boaria* (<30%) along with a decrease in swamp forest species. Asteraceae-Liguliflorae (<14%) also increased towards the second half of the phase.

Phase PC-3C (~2200 to 1300 cal yr BP)

Widespread recovery of swamp forest indicators, chiefly Myrtaceae (<74%), *Escallonia* (<56%) and *Drimys winteri* (<7%). In contrast, sclerophyllous species *Maytenus boaria* and *Azara celastrina* together with non-arboreal indicators (with exception of Fabaceae and Liliflorae) decrease substantially.

Phase PC-3D (1300 to 600 cal yr BP)

Characterized by mostly high but variable percentages of swamp forest taxa. This phase begins with a decrease in Myrtaceae and high percentages of *Escallonia*, followed by maximum values (<11%) of *Drimys winteri*. Towards the end, high values of *Maytenus boaria* are indicated.

Phase PC-3E (~600 cal yr BP to the present)

A new decrease in swamp forest pollen indicators, particularly in the Myrtaceae, which reach minimum values at around 470 cal yr BP *Maytenus boaria* percentages (<11%) remain high and constant as well as Asteraceae-Tubuliflorae (<10%). Other non-arboreal taxa, such as Poaceae (<8%) and Brassicaceae (<9%), increase slightly.

Influx diagram

The influx diagram (total pollen grains per cm^2 per year) shows a good correspondence between pollen frequencies and lithology (Fig. 5).

Zone PC-1: very low pollen influx. Total pollen accumulation reaches only 600 grains/cm^2/yr and sediment deposition is very slow (ca. 100 yr/cm). Best-represented taxa are the swamp forest indicators Myrtaceae (<175 grains/cm^2/yr) and *Escallonia* (<175 grains/cm^2/yr). Poaceae is also present (<65 grains/cm^2/yr).

Zone PC-2: nil or very low pollen influx. Total pollen accumulation rates are very low, fluctuating between 20 and 70 grains/cm^2/yr. Deposition times are as low as the previous zone. Non-arboreal taxa are best represented; Asteraceae, Tubuliflorae and Liguliflorae jointly attain 30 grains/cm^2/yr.

Zone PC-3: The first phase is also characterized by low pollen influx, increasing only at the end. Total accumulation and deposition times at the base are similar to that of previous zones. *Escallonia* shows maximum values of <130 grains/cm^2/yr together with Anacardiaceae (~60 grains/cm^2/yr) and non-arboreal Poaceae and Asteraceae (<60 grains/cm^2/yr).

Although pollen influx in the second phase begins with similar values as the end of the first phase, almost all taxa increase their influx values in the upper portion. Higher total accumulation rates are reached at the end of this phase. Depositional times per cm are still high although they tend to decrease to ~17 yr/cm.

The third phase shows a trend towards increasing influx throughout the whole period. Arboreal taxa showed the highest values during this phase. Non-arboreal taxa (Poaceae, Fabaceae and Brassicaceae) showed higher values than during the previous phase with maximum values of Liliflorae, while Apiaceae increase towards the end. Depositional times decrease to very low values, ~13 yr/cm.

The two next phases display high pollen influx for almost all taxa at their initiation. From 470 cal yr BP onwards, influx values decrease in all taxa. Depositional times fluctuate between 28 and 11.8 yr/cm.

Discussion

Paleoclimatic interpretation

The basal section of the Palo Colorado record (zone PC-1, ~10,000 cal yr BP) displays dark silt with high organic matter content and a pollen record dominated by swamp forest indicators. Clearly, wet conditions prevailed during the early Holocene. These conditions changed in zone PC-2. The prevalence of non-arboreal taxa (mostly Asteraceae) together with overall low pollen influx and the abundance of inorganic sediments all indicate that an open landscape with very arid conditions existed between ~8700 and ~7800 cal yr BP. This was followed by deposition of increasingly pollen-starved inorganic sediments (insufficient for counting), which together with traces of Asteraceae pollen suggest that aridity became even more intense between 7800 and 5700 cal yr BP. As previously stated, we rule out the possibility of any significant depositional hiatuses based on the stratigraphy and chronology of the record.

This pronounced drought ended at ~5700 cal yr BP, when swamp forest indicators at Palo Colorado began to reappear. Climate changed only gradually until 4200 cal yr BP, when both the percent pollen diagram and the influx pollen diagram show important increases. This shift is also associated with a marked increase in organic matter content in sediments (zone PC-3).

Between 3000 and 2200 cal yr BP, the decline in swamp forest taxa and arboreal taxa in general, together with the increase of sclerophyllous tree *Maytenus boaria* and in the relative proportion of Asteraceae-Liguliflorae, again suggest onset of (albeit milder) drought conditions, with a maximum peak in aridity at ~2750 cal yr BP. Beginning at 2200 cal yr BP (PC-3C), Myrtaceae and *Drimys winteri* slowly recovered, suggesting optimal swamp forest conditions most likely associated with a return to wetter conditions. The high degree of variability displayed by swamp forest pollen, taken together with the variations in the proportion of arboreal/non-arboreal taxa and the relative increase in Liliflorae (monocot bulb plants adapted to arid regions with variable precipitation regimes), suggest a highly variable climate regime within an overall humid general context. Influx values and deposition rates suggest that this humid phase may have been more intense than the earliest humid period recorded at the bottom of sequence. A new decline in swamp arboreal taxa occurs during the last phase of the record (PC-3E, from ~620 cal yr BP) with an increase in *Maytenus boaria* and Asteraceae Tubuliflorae and the almost complete disappearance of *Drimys winteri*. These changes may be attributable to recent anthropogenic disturbance.

Regional correlations

Similar evidence for an early Holocene wet phase is also indicated in other paleoclimate records from Central Chile and Norte Chico. Using paleopedological methods between 27 and 33°S, Veit (1996) suggest wet conditions at the beginning of Holocene at ~8300 cal yr BP. In Central Chile, the Laguna Aculeo record (33°50′S) indicates arid conditions from the early to mid-Holocene (>5700 cal yr BP); however, a gyttja sediment layer present in this record at ~9000 cal yr BP is interpreted as a brief lake beach phase followed by fluvial sedimentation (Jenny et al., 2002b). Evidence from marine sediments of the coast of Central Chile (33°S) have also been interpreted in terms of increasing aridity culminating at ~8000 cal yr BP (Lamy et al., 1999). Alkenone analyses from the same cores indicate that sea surface temperatures between 10,000 and 8000 cal yr BP were similar to modern conditions (Kim et al., 2002). At the continental scale, an increase in humidity is inferred from sites along the south coast of Peru, associated with onset of an ENSO-like signal (Carré et al., 2005; Sandweiss, 2003) (Fig. 6, Table 2).

Aridity intensified from 8700 to 5700 cal yr BP, as inferred by the predominance of non-arboreal taxa followed by pollen sterile sediments at Palo Colorado. Other records for Mediterranean Chile and the Norte Chico also indicate hot and dry conditions. For example, paleopedological evidence reveals an overall >3°C temperature increase between ~8000 and ~5900 cal yr BP (Veit, 1996). An ephemeral shallow lake that existed at Laguna Aculeo until 8500 cal yr BP was followed by a saline lake with carbonate precipitation until 5700 cal yr BP (Jenny et al., 2002b). The dominance of Chenopodiaceae pollen beginning at 7500 cal yr BP is indicative of high evaporation rates at Laguna Aculeo, concordant with increased salinity and a hot and dry climate (Villa-Martínez et al., 2003). Arid stable conditions between 8000 and 4000 cal yr BP associated with a sea surface temperature increase of 2.5°C within the span of 500 yr, beginning at 8000 cal yr BP, have been estimated from offshore marine cores (Lamy et al., 1999). According to Kim et al. (2002), sea surface temperatures may have been at their warmest at 6500 cal yr BP Geomorphological data at Algarrobo (33°22′S) also suggest a sea-level rise of 3.8 m at 6500 cal yr BP with respect to the modern shoreline (Hervé et al., 2003). Furthermore, the maximum marine transgression for the region (~30°S) is registered at 6800 cal yr BP (Ota and Paskoff, 1993). In the high Andes, the Laguna del Negro Francisco record (4000 m, 27°S), also located in the influence zone of the westerlies, indicates that a saline lake persisted in an arid climate between 6800 and 4200 cal yr BP (Grosjean et al., 1997a). Arid conditions are also indicated by swamp forest pollen records in Central Chile and the Norte Chico. At Ñague, the pollen record (~32°S) shows a dominance of matorral at 6100 cal yr BP, later replaced by wet indicators at 4200 cal yr BP (Maldonado and Villagrán, 2002). At Quintero, (33°S, site Quintero II) hot and dry conditions are suggested by the dominance of Chenopodiaceae between 6900 and 4500 cal yr BP (Villa-Martínez and Villagrán, 1997). Even though the precise chronologies may vary, the evidence for an arid phase during the early to middle Holocene is pervasive throughout all the available records. Differences in timing and signal are most likely due to the sensitivity of the different proxy-data used. The trends indicated in the sea surface temperature proxy records suggest an abrupt beginning followed by a gradual demise of the early to mid-Holocene arid phase (Kim et al., 2002). One mechanism for creating this arid phase is through an enfeebling of the westerly winds.

Consensus has yet to be reached, however, on whether this arid phase had any impact in the Chilean central Andes and adjacent Atacama Desert (Betancourt et al., 2000; Grosjean, 2001; Grosjean et al., 2003; Latorre et al., 2003; Quade et al., 2001). If the central Andes was dry during this period, as the majority of the paleoclimatic evidence demonstrates (Abbott et al., 2003; Baker et al., 2001; Grosjean, 1994, 2001; Grosjean

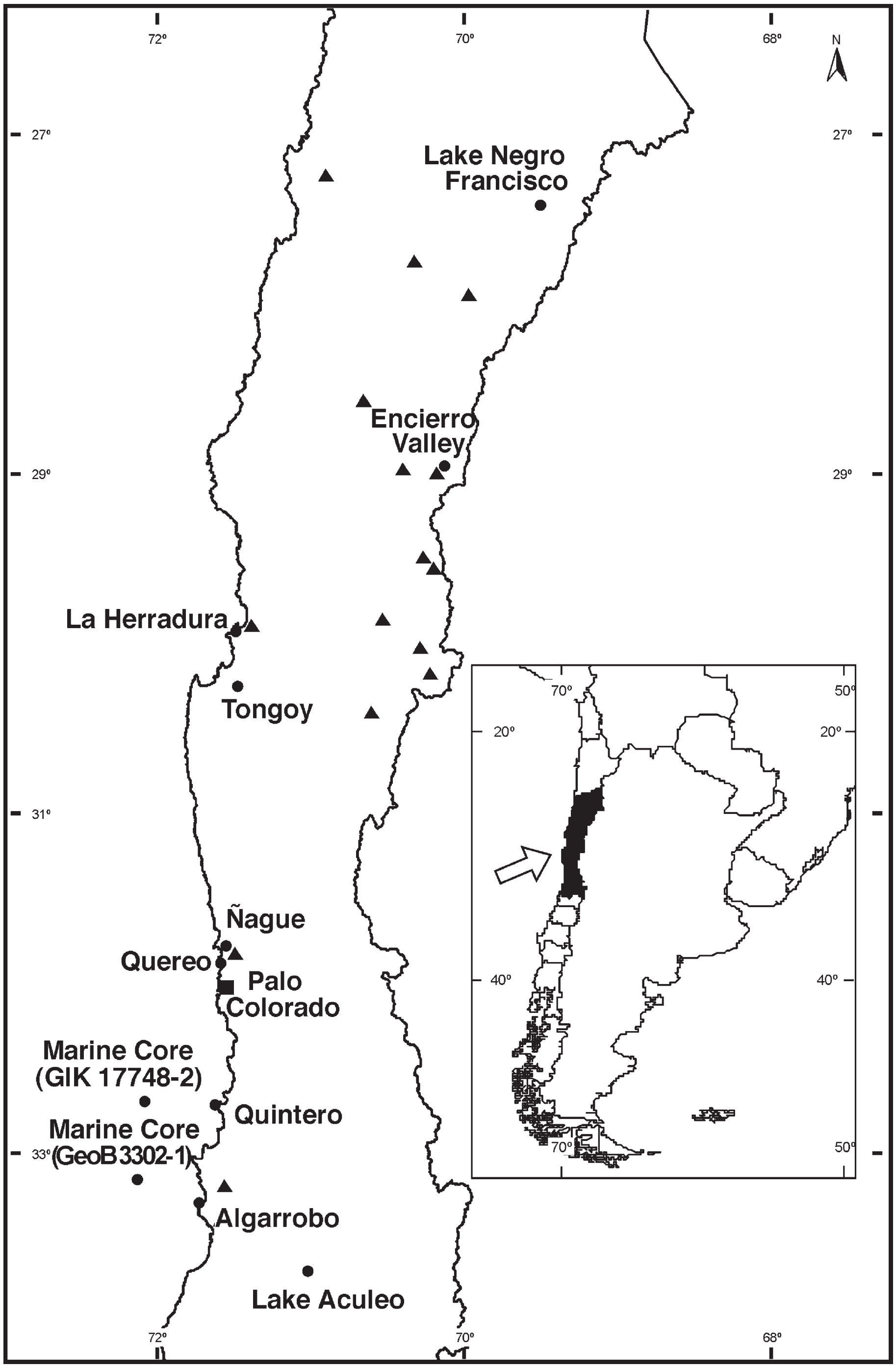

Figure 6. Map showing paleoclimate sites discussed in the text for the central and semiarid region of Chile (circles, and triangles for Veit's localities) and the Palo Colorado site (square).

et al., 1997b, 2003; Grove et al., 2003; Maldonado et al., 2005; Paduano et al., 2003; Rigsby et al., 2003; Servant and Servant-Vildary, 2003; Tapia et al., 2003). The combined evidence would suggest a weakening of both the tropical and extra-tropical circulation. The first would be withdrawing towards the equator and the second towards the pole, thus significantly widening the South American "arid diagonal" during this period.

The Palo Colorado record indicates that the climate became increasingly wetter between 5700 and 3000 cal yr BP, followed by a period of high variability from 2200 cal yr BP to the present. Other records across the region also indicate an increase in climatic variability during the late Holocene (Jenny et al., 2002b; Marchant et al., 1999; Riedinger et al., 2002; Villa-Martínez et al., 2003). At Laguna Aculeo, a wet and variable period began at 1800 cal yr BP and continues to the present (Jenny et al., 2002a,b). The Quintero swamp forest became established at ~1600 cal yr BP (Villagrán and Varela, 1990) and at 1950 cal yr BP in Quintero II (Villa-Martínez and Villagrán, 1997). Arid phases at the coastal Palo Colorado site,

Table 2
Summary of paleoclimatics sites and reconstructed climatic conditions discussed in the text for the central and semiarid region of Chile

Geographics location	Proxi-data and temporal range	Interpretation	References
Chile Between 27 and 33°S	Paleosols (11,000–0 cal yr BP)	Increased influence of the westerlies (more humidity) between 11,000–8160, 5800–4100, 3200–1800 300–0 cal yr BP.	Veit, 1996
Lake Negro Francisco (27°28′S; 69°14′W; 4125 m)	Lacustrine sediments (6800–0 cal yr BP)	6800–4200 cal yr BP arid conditions After 4200 humid increase with 2 peaks, between 3200–2800 and 2400–1800 cal yr BP.	Grosjean et al., 1997a
Encierro Valley (29°05′S; 69°55′W; 4500 m)	Glacial geomorphology (4000–1900 cal yr BP)	20–30% more humidity on the area, between 3200 and 1800 cal yr BP Glacial advance younger than 2700 cal yr BP.	Grosjean et al., 1998
La Herradura and Tongoy beach (29°58′S; 71°20′W; 0 m and 30°17′S; 71°32′W; 0 m)	Shorelines (6800 cal yr BP)	High marine level at 6800 cal yr BP.	Ota and Paskoff, 1993
Ñague (31°50′S; 71°28′W; 50 m)	Pollen record (6200–0 cal yr BP)	6200–4200 cal yr BP relatively arid condition 4200–3200 cal yr BP relatively humid conditions 3200–1300 cal yr BP relatively arid conditions 1300–0 cal yr BP relatively humid conditions a recent date show this start at 1700 cal yr BP.	Maldonado and Villagrán, 2002 Maldonado and Jackson, 2005[a]
Quereo (31°55′S; 71°30′W; 10 m)	Pollen and sedimentology (13.000–0 cal yr BP)	13,000–11,300 cal yr BP humid conditions 11,300–3000 cal yr BP arid conditions 3000–0 cal yr BP humid conditions	Villagrán and Varela, 1990
Quintero (32°47′S; 71°32′W; 10 m)	Pollen (6700–0 cal yr BP)	6700–5800 cal yr BP arid conditions 5800–4500 cal yr BP arid conditions, with mash taxa 4500–2000 cal yr BP humid conditions 2000–0 cal yr BP more humid conditions	Villa-Martínez and Villagrán, 1997
Marine Core offshore of Valparaiso (GIK-17748-2, 32°45′S; 72°02′W; −2545 m and GeoB-3302-1, 33°13′S; 72°06′W; −1498 m)		Sediments and Alkenones (33.000–0 cal yr BP) Sediments: trend toward arid condition between deglaciation and 8000 cal yr BP; 8000–4000 cal yr BP, stable conditions, with increased aridity in the Coastal Range. 4000–0 cal yr BP more variability and more humid conditions. Alkenones: between 10.000 and 8000 cal yr BP, sea surface temperature (SST) was similar to modern conditions. Between 8000 and 7500 cal yr BP SST increased 2.5°C, high SST are maintained between 7500 and 5000 cal yr BP, after that SST disminuye gradualmente hasta lo actual.	Lamy et al., 1999 Kim et al., 2002
Algarrobo beach (33°22′S; 71°45′W; 6 m)	Sedimetology (6500 cal yr BP)	High marine level at 6500 cal yr BP.	Hervé et al., 2003
Lake Aculeo (33°50′S; 70°54′W; 350 m)	Pollen and Sedimetology (9500 cal yr BP)	Sediments: 9500–5700 cal yr BP arid period 5700–0 cal yr BP humid conditions increasing, with modern levels at 3200 cal yr BP and little arid phase between 2200 and 1800 cal yr BP. Fluvial units were deposited before 9000 cal yr BP an after 5700 cal yr BP and more frequent since 3200 cal yr BP. Flood events, possibly ENOS-related occurs between 1800–1600, 1500–1300, 700–300, 150–0 cal yr BP. Pollen: 7500–5700 cal yr BP drying indicators 5700–3200 cal yr BP humidity indicators	Jenny et al., 2002a,b Villa-Martínez et al., 2003 Villa-Martínez et al., 2004

[a] Holocene climate change and human settlement on the semiarid coast of Chile (32°S).

however, occur between 3000 and 2200 cal yr BP, whereas records from the High Andes indicate a humid phase with maximum moisture at 2600 cal yr BP (Grosjean et al., 1998). This suggests that past changes during the late Holocene may not occur synchronously along the Andes and the coast. One possible explanation is that the Andean highlands receive part of their moisture during the summer wet season (i.e. through a tropical source). These sources must have been of considerable magnitude for glaciers advance to occur during episodes of drought in the lowlands to the west of the divide. Another possibility is that glacier equilibrium lines may in fact also depend on lower temperatures in this region. This would explain why these changes might go completely undetected in the coastal areas, where slightly to moderately decreased temperatures would have very little impact on vegetation distributions.

Paleorecords from Central Chile (Jenny et al., 2002a,b; Maldonado and Villagrán, 2002; Villagrán, 1982; Villa-Martínez and Villagrán, 1997; Villa-Martínez et al., 2003) are in good agreement with the inferences made from the last portion of the Palo Colorado pollen record, all of which indicate some degree of anthropogenic disturbance. Such influence is suggested here by the decrease in swamp arboreal taxa and an increase in *Maytenus boaria* and non-arboreal taxa (i.e., Poaceae, Asteraceae and Brassicaceae).

Many authors have recently emphasized the importance of ENSO events in the Holocene (Jenny et al., 2002a,b; Marchant et al., 1999; Moy et al., 2002; Riedinger et al., 2002; Rodbell et al., 1999; Sandweiss et al., 1996, 2001b). Most authors agree that little or no ENSO influence was present during the early to middle Holocene (Jenny et al., 2002b; Marchant et al., 1999; Moy et al., 2002; Riedinger et al., 2002; Rodbell et al., 1999). These authors disagree, however, when ENSO actually began; some propose 5700–5800 cal yr BP (Jenny et al., 2002b; Sandweiss et al., 2001), whereas others suggest a slow gradual increase in ENSO periodicity from 7000 cal yr BP (Moy et al., 2002; Riedinger et al., 2002; Rodbell et al., 1999). Nevertheless, authors concur in finding an increase in frequency of ENSO events beginning at 3200 cal yr BP. Many authors also postulate that current ENSO dynamics began at this time (Jenny et al., 2002b; Marchant et al., 1999; Riedinger et al., 2002; Sandweiss et al., 2001; Villa-Martínez et al., 2003). In a more detailed analysis, Moy et al. (2002) suggested a gradual increase in ENSO events with a superimposed variability signal at millennial time scales during the Holocene. They propose that this trend culminated at ~1200 cal yr BP and has since declined. Sedimentary records from the Galapagos Islands also show a higher frequency of ENSO events between ~1950 and ~930 cal yr BP (Riedinger et al., 2002). Results from climate simulation models studying the evolution of ENSO during the Holocene also suggest an increase in frequency between 2000 and 1000 yr BP (Clement et al., 2000). This agrees with our record from Palo Colorado, which indicates increased variability in Myrtaceae pollen frequencies during the period between 2200 and 1300 cal yr BP.

From the evidence presented above, we conclude that the variability recorded at Palo Colorado between ~2200 and 1300 cal yr BP is correlated with periods of higher occurrence of ENSO events (particularly El Niño events). Although modern ENSO events have an average recurrence of between 3 and 6 yr (Trenberth, 1976), and despite the fact that the Palo Colorado record reaches a maximum resolution of 14–15 yr/cm of sediment during this period, the accumulation of several El Niño events in a sample can be expressed by relatively high values of pollen of Myrtaceae and geophytes (bulb plants). Conversely, less frequent El Nino events should be expressed by a relative decrease in the pollen production of the hygrophilous indicator, i.e., Myrtaceae, which would explain the large influx and percentage variations displayed by these taxa during the period in question.

Records of La Niña events in this system are difficult to observe because a pollen sample takes several years to record (in this case up to 15 yr). It is possible that recurrent la Niña events that lack a direct pollen indicator may remain obscure in our record, even assuming that concomitant decreases in pollen production and absence of certain taxa, such as the geophytes, did occur. Nevertheless, both pollen types, as well as the majority of the other records previously cited (Jenny et al., 2002a,b; Moy et al., 2002; Riedinger et al., 2002; Rodbell et al., 1999; Villa-Martínez et al., 2003), are indicative exclusively of El Niño and not La Niña events, which questions whether both events (El Niño and La Niña) had a high frequency during this period, or if only El Niño events increased in frequency.

Conclusions

The palynological record from the Palo Colorado swamp forest enables us to infer the following paleoclimatic event sequence for Central Chile:

A brief wet phase during the early Holocene (between ~10,000 and ~8700 cal yr BP), characterized by swamp forest indicators, was followed by a prolonged arid phase when arboreal taxa disappeared and open vegetation taxa dominated (between ~8700 and 7800 cal yr BP). This culminated in an extremely arid phase characterized by absence of pollen and high inorganic sediment content. These climatic conditions agree with previous paleoclimate studies from Central Chile and *Norte Chico*, suggesting that the westerly wind belt was in all probability displaced southwards during times of strengthened anticylconic circulation in our study area.

Swamp forest recovery at Palo Colorado began at 5700 cal yr BP with a non-linear increase in moisture, peaking at 4200 cal yr BP. Between ~3000 and 2200 cal yr BP, a less pronounced episode of drought occurred (i.e. less intense than the previous one). Afterwards, highly variable moisture conditions beginning at ~2200 cal yr BP prevailed. These conditions suggest that the influence of the westerly wind belt was similar to the present. Between 2200 and 1300 cal yr BP, however, precipitation was more variable than the present, suggesting greater ENSO frequency and prevailing wet conditions.

The climatic events described here from the Palo Colorado pollen record are consistent with both physical and biological records of paleoclimate across the region. We therefore propose that the local precipitation record inferred from our dataset is in all probability reflecting a regional climatic signal, associated with changes in both the westerly wind belt influence and the SPA intensity.

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