UNIVERSIDAD AUSTRAL DE CHILE
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Respuestas ambientales a cambios climáticos y culturales en la Región de la Araucanía, Chile.

TESIS DOCTORAL

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Respuestas ambientales durante el Cuaternario tardío a cambios climáticos y culturales en la Región de la Araucanía, Chile.

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por

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LISTA DE ABREVIATURAS

UMG: Último Máximo Glacial

LGM: Last Glacial Maximum

ka AP: mil años calendario antes del presente

kyr BP: thousand calendar years before the present

SW: Southern Westerlies

STH: South Pacific Subtropical High-pressure System

ITCZ: Intertropical Convergence Zone

ENSO: El Niño Southern Oscillation

MS: Magnetic susceptibility

AMS: Acellerator mass spectrometer

msl: mean sea level

m a.s.l.: meters above sea level

HMT: Holocene Marine Transgresion

e.g.: for example

RESUMEN

Los valles intermontanos y costeros de la Cordillera de Nahuelbuta (38°) son un área clásicamente poblada por el pueblo Mapuche y por lo tanto, muy sencible para evaluar el impacto humano en la estructura del paisaje frente a cambios climáticos durante el Holoceno. Esta latitud representa una transición climático-vegetacional de la celda de alta presión (Anticiclón del Pacífico), al régimen de precipitaciones del cinturón de vientos del oeste y al efecto estacional de El Niño Oscilación del sur. Es de esperar entonces que variaciones durante el Cuaternario en estos tres sistemas climáticos hayan afectado la distribución y composición de la vegetación en el área. El objetivo de esta tesis es desarrollar un modelo paleoecológico y paleoclimático que permita comprender el efecto de posibles cambios ambientales asociados a variaciones climáticas y culturales en la Región de la Araucanía (38°S), Chile. Para lograr este objetivo se determinó la cronología, dirección y magnitud de los cambios ambientales considerando el de análisis de registros sedimentológicos, geoquímicos y biológicos, asociado a información histórica y arqueológica disponible en dos áreas de estudio: el valle Purén-Lumaco (38°S) y el Lago Budi (39°S).

El registro obtenido en el valle Purén-Lumaco abarca 26 mil años calendario antes del presente (ka AP), evidenciando uno de los posibles refugios glaciales para los bosques templados lluviosos (bosques de *Araucaria-Nothofagus*), asociados a un paleolago en el área y condiciones frío-húmedas características del Ultimo Máximo Glacial (UMG, 30-19 ka AP). El debilitamiento del Anticiclón del Pacífico permitió un desplazamiento hacia el ecuador del margen norte del cinturón de vientos del oeste y de la Circulación Circumpolar Antártica, implicando mayores precipitaciones y menos temperaturas en Chile central.

Durante el UMG, el Lago Budi constituía un río y el nivel del mar se encontraba cientos de metros más bajo que su nivel actual. A partir de 12 ka AP comienza una tendencia sostenida de calentamiento climático, comienza la sedimentación en el Lago Budi y el paleolago en Purén-Lumaco desaparece, formándose el sistema complejo de cuencas pantanosas del área. Entre 9 y 5 mil años AP se registra el periodo más cálido en ambos registros, en el Lago Budi como una transgresión marina y en Purén-Lumaco con el desarrollo de una turba y elementos cálidos del bosque templado. Por primera vez en Chile, ambos registros evidencian la presencia de polen de maíz (*Zea mays*) a partir de ~5 ka AP, apoyando el inicio de prácticas agrícolas y las interpretaciones arqueológicas de la Región de la Araucanía.

ABSTRACT

Nahuelbuta Coastal Range (38°S) has been inhabited by an extremely dense and ancient population of indigenous Mapuche communities thus represents an interesting area to evaluate the human impact in the landscape at different time scales during the Holocene. The climate-vegetacional transition at 38°S is associated with the effect of South Pacific Subtropical High-pressure System, the Southern Westerlies winds, and the ENSO variability. Quaternary variations of these three climatic systems are related to changes in the vegetation covers. The thesis aim is develop a paleoecologic and paleoclimatic model to understand the effect over environmental changes in association with the variation of climatic system and the human impact in the Araucanian region (38°S), Chile. Sedimentological, geochemical, and biological results from sediments cores from Purén-Lumaco valley (38ºS) and Lago Budi (39°S) show the environmental changes during the late Quaternary and Holocene. The Purén-Lumaco record covers the last 26 kyr, demonstrating an araucanian glacial refugium for temperate rainforest (*Araucaria-Nothofagus* forests) and the cold and per-humid climate conditions during the Last Glacial Maximum (LGM, 30-19 kyr BP). The weakening of South Pacific Subtropical High-pressure System induced the ecuatorward sift of northern most boundary of Southern Westerlies and the Antarctic circumpolar current, implicaying the high precipitation rates and cold temperatures in Central Chile.

During the LGM, Lago Budi was a river, the sea level was hundred meters down, and Purén-Lumaco was a lake. At 12 kyr BP start a warm regional climatic trend, start the sedimentation in Lago Budi, and the paleolake in Purén-Lumaco desapear. Between 9 and 5 kyr BP is the dry/warm period of early mid-Holocene in south-central Chile, interpreted by the marine transgression in Lago Budi and the warm-temperate taxa in Purén-Lumaco valley.

By the very first time, both records show the presence of maize pollen (*Zea mays*) at ~5 kyr BP supporting the onset of agricultural practice and the archaeological interpretations in Araucanian region.

CAPÍTULO 1

1.2 INTRODUCCION GENERAL

Comprender la evolución del paisaje es un problema complejo que requiere de la interacción de diversas disciplinas bajo un objetivo en común, donde se involucran variables humanas y variables ambientales, tales como el clima, la vegetación y la geomorfología. Esta investigación discute a partir de una estrategia transdisciplinaria, el cambio ambiental en diferentes escalas temporales asociado a la variabilidad del clima y a la influencia de grupos humanos en la Región de la Araucanía.

Los depósitos sedimentológicos, geoquímicos y biológicos en lagos y pantanos proveen información de largo plazo y alta resolución, para observar la dinámica de los ecosistemas que rodean una cuenca. El valle del río Purén-Lumaco (38°S), así como el Lago Budi (39°S) en la Región de la Araucanía, ofrecen una excelente oportunidad para establecer relaciones directas entre el cambio ambiental (clima y vegetación) con la ocupación humana desde periodos pre-hispánicos en el área; así dar luces sobre el rol de los grupos humanos y su cultura en la transformación del paisaje.

A diferentes escalas, las poblaciones humanas y el ambiente físico interactúan a través de procesos ecológicos dinámicos (Dillehay y Saavedra, 2003). La manipulación del agua, del bosque y las interacciones con otros organismos, constituyen la base de la explotación de la naturaleza por parte de la sociedad que la habita. Las actividades humanas, como el sedentarismo, la práctica agrícola, la explotación intensiva de los recursos naturales, alteran significativamente los procesos ecológicos y sociales (Dillehay, 1990). Así mismo, las respuestas humanas son determinadas, por lo general, por variables socioeconómicas que operan a escala de paisaje asociadas a la variabilidad ambiental como el cambio de la vegetación y del clima (deMenocal, 2001).

El rol de las actividades humanas en la transformación del paisaje, generando movimiento de material desde las cuencas hacia los lagos y/o pantanos ha sido monitoreado a través de estudios paleoecológicos en diversos lugares del mundo. Un ejemplo bien documentado es el de Guatemala, donde el objetivo principal fue evaluar el cambio de los ecosistemas a través del aporte de sedimentos en lagos en relación con disturbios culturales de la sociedad Maya y su desaparición asociada a la variación del régimen de precipitaciones en la región (e.g. Binford et al., 1987; Brenner et al., 2001).

En Chile, las modificaciones del paisaje realizadas por los grupos humanos han tenido distintas características e intensidad según el tamaño de las poblaciones y el nivel de desarrollo tecnológico adquirido (Donoso, 1983; Gasto, 1979). Los cambios experimentados en los ecosistemas forestales chilenos están ligados necesariamente a la política y legislación imperante en cada época de la historia y a las costumbres o condición cultural de las agrupaciones humanas. En la región de la Araucanía los grupos indígenas utilizaban el fuego para preparar los campos de cultivo de especies como la quinoa, el maíz, el mango, la teca y el madi, que más tarde fueron reemplazados por cultivos europeos (Gay, 1865; Donoso, 1983).

Los registros arqueológicos indican la temprana llegada de poblaciones indígenas en Chile centro-sur, como lo documenta la existencia de sitios antiguos (Periodo Arcaico, ~12 ka AP) en Chile central y sur, tales como Tagua-Tagua (33°S, Montané, 1968; Heusser, 1983) y Monte Verde (41°S, Pino & Dillehay, 1988). Algunos antecedentes generados por el proyecto Araucanian Polity Formation in Chile demuestran la temprana interacción humana y el ambiente en la Región de la Araucanía (38-39°S). El rasgo arqueológico más importante en el valle de Purén-Lumaco y en Lago Budi es el *Kuel*, un término Mapuche que significa montículo de tierra artificial. La presencia y extensión de estos *Kuel* reflejan el nivel de desarrollo social y económico que, en parte, explica por qué la región se constituyó en un centro de resistencia española en los siglos XVI y XVII (Dillehay y Saavedra, 2003). Las dataciones radiocarbónicas obtenidas para los *Kuel* comprenden desde 1200 d.C. y para un sitio arqueológico del valle Purén-Lumaco una edad de ~7 ka AP (Dillehay, 2006).

Asociado al rol de las poblaciones humanas en el paisaje, la vegetación se encuentra fuertemente determinada por el clima imperante en los gradientes latitudinales y altitudinales de la vertiente oeste de la Cordillera de los Andes (Schmithüsen, 1956). Durante el Cuaternario cambios climáticos han sido documentadas en los trabajos de palinólogos y cuaternaristas en Chile centro-sur. Los reiterados ciclos glaciales del Pleistoceno dejaron su huella en la vegetación del sur y andina que fue desplazada hacia los faldeos de la Cordillera de la Costa y Depresión Central (Darwin, 1859; Simpson, 1983; Heusser, 1990; Villagrán et al., 2004), representando áreas de refugios glaciales para muchas especies (Villagrán et al., 1998; Villagrán, 2001; Bull-Hereñu, 2005). Para el Holoceno existen estudios que reflejan la historia paleoclimática y vegetacional de Chile central (30-34°S) (Heusser, 1990; Maldonado & Villagrán, 2001; Villa-

Martínez et al., 2003) y sur (41-56°S) (por ejemplo, Heusser, 1966; Villagrán, 2001; Abarzúa et al. 2004; Moreno, 2004; Haberle & Bennett, 2004; Markgraf et al., 2007). Estos registros paleoclimáticos coinciden en describir el Holoceno temprano como un periodo severamente más cálido y seco que la actualidad, donde los elementos más xéricos/esclerófilos invadieron el paisaje en Chile central y centro-sur. Tales condiciones serían consecuencia de un debilitamiento del Cinturón de vientos del oeste e intensificación del Anticiclón del Pacífico (Caviedes, 1972; Villagrán & Varela, 1990; Lamy et al., 1999; Abarzúa & Moreno, 2008; Kaiser et al., 2008).

El la región de la Araucanía la dirección, magnitud, tasas de cambio y cronología de cambios vegetacionales y climáticos durante el Cuaternario son aún desconocidas. Un aspecto clave para la comprensión de los patrones y causas de cambios pasados en el paisaje es poder comparar la anatomía de cambios a múltiples escalas espaciales y temporales, sobre la base de una cronología común. Registros paleoambientales detallados provenientes de Chile centro-sur son indispensables para entender la globalidad del fenómeno climático a lo largo del país, sobre todo en un área sensible, climática e históricamente, a variaciones ocurridas durante el pasado.

Algunas de las preguntas que conducen esta investigación son:

- ¿De qué manera variaron la vegetación y las condiciones climáticas en la región de la Araucanía (38-39°S) durante el Cuaternario?
- ¿Ha sido el cambio climático un proceso de calentamiento continuo desde la última glaciación en Chile centro-sur?
- ¿Cuál es la cronología y magnitud del impacto humano en el paisaje que circunda el valle de Purén-Lumaco y el Lago Budi?; ¿Cuáles son sus evidencias sedimentológicas, estratigráficas o botánicas?
- ¿Es el fuego un factor importante y/o permanente en el modelamiento del paisaje de la región? Y ¿qué factores, humanos, climáticos o ambos, han condicionado la ocurrencia de fuego en la región?

Todas estas preguntas se enmarcan en preguntas de largo plazo en la región. Así, el siguiente estudio se encuentra bajo una estrategia transdisciplinaria y las implicancias de sus futuros hallazgos contribuirán en ámbitos diversos como la paleoclimatología, paleoecología, biogeografía, antropología, arqueología y ordenamiento territorial. Pese a la importancia y gran potencial de esta zona transicional vegetacional y climática en el centro-sur de Chile (38°S) en el ámbito paleoclimático, la información paleoambiental aún es deficitaria y los patrones de cambio climático Cuaternario todavía se encuentran en un estado rudimentario de desarrollo.

El objetivo general de esta investigación es desarrollar un modelo paleoecológico y paleoclimático que permita comprender el efecto de posibles cambios paleoambientales debido a influencias climáticas y culturales en ecosistemas boscosos del centro-sur de Chile (38°S) durante el Cuaternario.

Esta investigación ha sido organizada en dos grandes capítulos, el primero *Late Quaternary climatic and cultural reconstructions in Araucanian region, Chile"* presenta evidencias sedimentológicas para interpretaciones de cambio climático y vegetacional durante los últimos 26 mil años asociados a los hallazgos arqueológicos presentes en el valle de Purén-Lumaco (38°S).

El segundo capítulo *"Paleolimnological investigations at Lago Budi, Araucanian Region, Chile (38.9°S): Chronology of relative sea level changes and climatic indications during the Late Glacial and Holocene"*, discute evidencias sedimentológicas para el origen del Lago Budi en relación a variables climáticas y tectónicas en el centro-sur de Chile.

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CAPÍTULO 2

Late Quaternary climatic and cultural reconstructions in Araucanian Chilean Region.

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Abstract

A sediment core from the Purén-Lumaco valley (38ºS/73°W, 70m a.s.l.), south-central Chile, was analyzed for pollen, charcoal, sedimentologic and geochemical characteristics showing climatic changes and human impact at different time scales during the last 26 k cal yr BP. *Nothofagus-Araucaria* forests and grasslands covered the lowlands during the last glacial maximum (LGM, ~30-20 k cal yr BP) associated with a lacustrine environment and suggesting cold and per-humid climatic conditions. At 20.6 k cal yr BP the lake desiccated, replaced by a swamp and the increase of grass species. Warm-temperate taxa, Myrtaceae and *Prumnopitys andina* replaced the *Nothofagus dombeyi*/*Araucaria* forest by 15 k cal yr BP. This warming trend culminates between 8 and 5.7 k cal yr BP, when *Eucryphia*/*Caldcluvia*-type became abundant and fire frequency was extremely high. Thus, our data support the notion of an early Holocene dry/warm climate that has been documented from other pollen records between 30 and 43ºS in Chile. In climate terms this implies that the Southern Westerlies had shifted polewards. By 2 k cal yr BP, establishment of mixed grassland - *Nothofagus dombeyi*/*N. obliqua* woodland comparable to the present vegetation suggests present-day winter-rain dominated climate regime. Archaeological research in the area dates the beginning of human settlements to 7 k cal yr BP. The most striking archaeological evidence are artificial mound complexes (*Kuel*) built by Mapuche indigenous communities after AD 1300. The presence of ~350 *Kuel* in the valley reflects the social/economic development during the last millennium. Our palynological and geochemical data support the archaeological interpretation showing an early presence of maize (*Zea mays*) at ~5 k cal yr BP. Today the Purén-Lumaco valley is a complex wetland system dominated by exotic grasses and introduced tree species (*Tritricum aestivum, Pinus radiata* and *Eucalyptus spp*.). This highly modified landscape with its negative consequences for the subsistence economy of the local indigenous society makes it urgent to promote the rehabilitation of a relict and vanishing native forest ecosystem that today persists only as fragments on the crest of the Nahuelbuta Coastal Range (38°S).

Key words: Chile, Araucania, Temperate rainforest, Late Quaternary, Climate change, Mapuche culture, *Zea mays*.

1. Introduction

Modern landscape evolution is the product of complex interactions between human culture and natural processes that must be studied from a multidisciplinary perspective. The effects of people on their surroundings are only one way of viewing the relationship between humans and their environment (Redman, 1999). Advocates of "environmental determinism" view the interaction "in reverse," positing that the environment also limits human cultural development (de Menocal, 2001). The late Quaternary period, after peopling of the Americas, provides an excellent setting to analyze the evidence that climate, environment, and human cultures are intimately linked (e.g. Brenner et al., 2002).

Paleolimnological investigations have supplemented archaeological studies to provide the environmental context in which cultures arose, flourished, and collapsed. Analysis of lake sediments can be used to develop continuous, long-term records of environmental changes. These lacustrine deposits can be employed to infer regional ecological history; contain physical, chemical, and/or biological information about past conditions within lakes and in their surrounding watersheds. Multiple lines of sedimentary evidence are required as proxies for inferring past environmental conditions and to provide meaningful and coherent paleoenvironmental reconstructions (e.g. Binford et al., 1987).

In south-central Chile multiproxy paleoenvironmental studies that focus on landscape changes associated with human and climatic influences are few. Chilean paleoclimatic records have shown that major changes in precipitation and temperature are strongly associated with the variability of the Southern Westerlies (SW) and the South Pacific Subtropical High-pressure System (STH) during the late Quaternary (e.g. Caviedes, 1972; Villagrán and Varela, 1990; Lamy et al., 1999; Abarzúa et al., 2004). These inferences are based on two pollen records from central Chile at 34°S (Laguna Tagua Tagua) showing increasing percentages of evergreen temperate forest taxa (*Nothofagus dombeyi*-type *sp.* and *Prumnopitys andina*) between 33 and 15 kyr BP (thousand calendar years before the present) (Heusser, 1990, Valero-Garcés et al., 2005). In southern Chile (41°S), pollen-based vegetation reconstructions show the prominence of hyper-humid vegetation (North Patagonian/Subantarctic forests and Moorlands) during the LGM (e.g. Heusser et al., 2006). These data would imply a northward shift of the vegetation zones during the last glacial period (~32 and 20 kyr BP) linked to enhanced moisture in central and southern Chile (~30-42°S) (Lamy et al., 1999; Kaiser et al., 2008). According to pollen records from central Chile, arboreal components of mediterranean vegetation disappeared during the early to mid-Holocene, between 8 and 5 kyr BP, replaced by grasses, *Chenopodiaceae* and xerophytic taxa (Heusser, 1990; Maldonado and Villagrán, 2002; Jenny et al., 2002; Villa-Martínez et al., 2003). A comparable trend was observed ~2 kyr earlier in the temperate rainforest region at 41-43°S, with the dominance of thermophilous arboreal taxa between 10 and ~6 kyr BP (Villagrán, 1988; Abarzúa et al., 2004; Moreno and León, 2004). Such evidence suggests that climate became drier and warmer than present until 5 kyr BP in central Chile (~30°S) and until ~7 kyr further south (~40°S), presumably driven by a southward shift of the Intertropical Convergence Zone (ITCZ), STH, and at least the northernmost boundary of the SW (e.g. Kaiser et al., 2008).

At 38° S in the Pacific margin of South America, the Araucanian region represents the current boundary between Mediterranean-type and Temperate-type climates (Schmithüsen, 1956; Di Castri and Hajek, 1976). Accordingly, this is a particularly sensitive area to decipher the climate change patterns that characterized the Late Glacial and Holocene periods in southwestern South America. In addition, the Araucanian region has been inhabited by an extremely dense and ancient population of indigenous Mapuche communities (Bullock, 1958; Bengoa, 2003). The Purén-Lumaco valley, in the Araucanian region (Fig. 1), is surrounded at present by extensive human-made agricultural systems (like terraces, raised, and canalized fields), associated with several archaeological sites from this ancient culture. In this valley there are more than 350 ceremonial *Kuel*; some of these ritual complexes are constructed around 40 mounds on top of artificially flat platforms for ceremonial purposes, but most of them are now small sites associated with nearby agricultural settlements (Dillehay et al., 2007; Dillehay & Saavedra, 2003). All *Kuel* structures and diagnostic ceramics date from AD 1000 to 1300; some *Kuel* are still in ceremonial use by a few Mapuche communities, inclusive in the Lago Budi area (Fig. 1; Dillehay et al., 2007). During the Holocene in south-central Chile it is unclear when strong human influence started, however it must be related to population size and the population's technological development (Gastó, 1979; Donoso, 1983). Usually, indigenous populations used fire for clearance of forested areas and wetlands were used to cultivate different plants, such as the Chenopodiaceae quinoa (*Chenopodium quinoa*), the grasses maize (*Zea mays*), mango (*Bromus mango*), and teca (*Bromus berterianus*), and the Asteraceae madi (*Madia sativa*) (Gay, 1865; Mösbach, 1930; Donoso, 1983; Aldunate and Villagrán, 1991). From these landscape features, it is possible to infer intense crop production in the Purén-Lumaco valley which would have required certain principles of order, organization, and social differentiation (Dillehay et al., 2007).

In many respects, the approaches used in paleolimnology and archaeology have much in common. Whereas archaeological excavations yield artifacts that enable inferences about past cultural development, paleolimnological analysis provides physical, chemical, and biological information buried in lake sediments allowing insights into paleoenvironmental conditions. Fragmentary evidence in both disciplines has to be interpreted with a measure of uncertainty. In this context we developed an interdisciplinary project to decipher the landscape history, based on analyses of swamp-sediment cores in the Purén-Lumaco valley applying the current state of knowledge concerning interactions among climate, vegetation, and ancient Mapuche culture.

2. Environmental Setting

Climate of the southern Andes is dominated by the southern Westerlies and their seasonal latitudinal shifts (Miller, 1976; Di Castri and Hajek, 1976; Rutland and Fuenzalida, 1991). The seasonal shifts of westerly storm tracks, related to seasonal shifts of the subtropical high pressure cell in the southwestern Pacific Ocean, produce a Mediterranean-type precipitation regime between 25°S and 39°S, with hot, dry summers and mild, wet winters. Mean temperatures of 9-20°C occur during the summer (DJF) and of 0.5-14°C during the winter (JJA). Mean annual precipitation is 1350-1500 mm, falling principally between March and August. ENSO variability also affects precipitation, producing higher amounts in spring during El Niño events (Montecinos and Aceituno, 2003). During the warm phase of ENSO (El Niño events), pressure is anomalously low over the Southeast Pacific, leading to a weakening of STH, and a consequent northward shift of the SW (Villalba et al., 1996; Kitzberger, 2002).

The climate in Traiguen city (38°15'S/72°40'W) is characterized by a 12 °C annual temperature and 1240 mm annual precipitation (Amigo and Ramírez, 1998). In contrast, south of 39°S at the coast, precipitation occurs essentially year-round, with mean annual values of over 5000 mm south of latitude 45°S. The topographic relief results in marked rain shadow effects on the lee side of the mountain ranges, in both Coastal and Andean ranges.

Latitudinal precipitation and temperature gradients are the primary controlling factors that determine the vegetation zonation in southern South America (Schmithüsen, 1956). West of the Andes, from 33°S to 37°S, Mediterranean-type climate is associated with sclerophyllous forests which includes patches of deciduous *Nothofagus* forest with *Nothofagus obliqua, N. alpina*, and *N. glauca* (Donoso, 1993). In the past decades, the natural vegetation has been increasingly disturbed by logging, burning, grazing, and replaced by commercial plantations of *Pinus radiata* and

Eucalyptus sp. plantations. Between 37°S and 40°S latitude these Mediterranean-climate forests grade into seasonal temperate rainforests, characterized by high diversity of mostly evergreen tree species (Arroyo et al., 1995).

Purén-Lumaco valley (38ºS/73ºW) is located in the eastern lowlands of the Nahuelbuta Coastal Range (Fig. 1). The Mapuche communities represent the 90% of rural population and the total watershed area has a high level of anthropogenic disturbance, presenting a mosaic of current land uses, including mainly crops, followed by pastures, and wetlands (Endlicher and Mäckel, 1985; Hauenstein et al., 2001). Native floristic associations that should potentially be present in the area based on climate are Deciduous Southern Beech forest (*Nothofago-Perseetum*), and wet forest "Temu-Pitra Hualve" (*Blepharocalyo-Myrceugenietum exsuccae*) (Schmithüsen, 1956). El Valle site is a small swamp (0.76 km^2) within a Tertiary bedrock depression at ~70 m a.s.l. with the seasonal winter-water input from the Purén river (Fig. 1). There are no carbonate rocks present in the drainage basin. El Valle swamp supports a high diversity of emergent and submerged macrophytes, which integrates a high diversity of bird nests. *Scirpus sp., Juncus sp., Sagittaria sp.* and *Myriophyllum sp.* dominates at water depths <1 m.

3. Methods

We developed a multiproxy study of Purén-Lumaco valley (38°S/73°W), based in sedimentological parameters, loss-on-ignition, geochemical, pollen, and charcoal analysis. Sediment cores were recovered from several swamps in the Purén-Lumaco valley using a Livingstone corer. El Valle (VM) site is the focus of our present work and interpretations. The sediment cores were split lengthwise and photographed in the laboratory. Non destructive textural descriptions and magnetic susceptibility analysis (10^{-6}SI) was performed every 0.1 cm along the entire length of VM3 core, using a Bartington meter with a MS2E-*sensor*. The VM3 sediment core was sampled every 5 cm for geochemical analysis; a total of 101 samples were dehydrated over 24 hrs at 60°C. Each sample was triturated in opal mortar, and sieved through a 40 µm mesh. 200 mg of sediment were used for the geochemical analysis. To estimate Fe content an atomic absorption spectrophotometer (AAS Flame-*Shimadzu AA-6800*) was used; for the CNS-element analysis the sediments were burned at >1200°C, and CO_2 content was measured by induction furnace under extra tungsten light and infrared spectrophotometer (*Vario EL*). Phosphor concentration (ppm) was measured using the Molybdenum-blue methodology with a UV-Spectrophotometer (*Shimadzu UV-2401PC*). The MS, geochemical, and pollen analysis were conducted in the Geography Institute, Friedrich-Schiller University of Jena, Germany.

For pollen analyses, 0.9 to 1.2-cm^3 volumetric sub-samples were taken at 2.5 cm, 5 cm, or 10 cm intervals and prepared using standard techniques (KOH deflocculation, HF digestion, and acetolysis (Faegri and Iversen, 1989). Pollen grains were identified at 400 and 1000x magnification. The basic pollen sum included at least 300 pollen grains of trees, upland shrubs and herbs. Fern spores and aquatic/paludal taxa were combined in a separate sum, and their percentages were expressed in reference to a super-sum that included the basic pollen sum and all ferns and aquatic/paludal taxa. *Lycopodium* tracer spores were added to each sample for calculation of pollen concentration (grains cm^{-3}). Changes in pollen percent and concentration were used to interpret past vegetation changes supported also by CONISS cluster analysis on terrestrial taxa $\geq$ 2%. Pollen data were analyzed and plotted using TILIA and TG View programs (Grimm, 1987).

In the pollen record, the dominant tree genus *Nothofagus* could be represented by eight species. Based on pollen morphology, only two pollen types can be differentiated: *Nothofagus obliqua*-type (including N. *obliqua, N. glauca*, and *N. alpina*, all of which grow in the summer dry region of the study area), and *Nothofagus dombeyi*-type (including *N. dombeyi, N. pumilio*, *N. antarctica, N. betuloides, N. nitida*, all of which occur primarily in the more mesic forests of the area). Other tree species were also grouped because of their similar pollen morphology, including *Eucryphia cordifolia* and *Caldcluvia paniculata* listed as *Eucryphia/Caldcluvia*-type; *Beilschmiedia sp.* and *Persea lingue* grouped into *Beilschmiedia/Persea*-type, *Aextoxicon punctatum* and *Escallonia spp.* grouped into *Aextoxicon/Escallonia*-type. In addition, we grouped all species in the Family category, such as woody Myrtaceae, Poaceae, Asteraceae, Chenopodiaceae, and Solanaceae.

In the each pollen slide charcoal particles were counted and their concentration calculated (particles cm^{-3}) in relation to the *Lycopodium* tracer; pollen concentration was calculated as well.

We analyzed the macroscopic charcoal content of sediment samples (2 cc) obtained from contiguous 1-cm thick slices to document the local fire history. The sediment samples were disaggregated in a 10% KOH solution, and sieved using 125 and 250 µm mesh. Charcoal particles were individually analyzed and tallied under a stereomicroscope at the Geosciences Institute, Universidad Austral de Chile.

The chronology of the sediment cores was developed on the basis of radiocarbon dates on plant remains and charcoal particles, measured at the University of Colorado, USA. To calibrate the dates we used Calib 5 Program (Stuiver et al., 2005). The dates younger than 11 kyr BP were calibrated using southern hemisphere calibration and Intcal 0.4 was applied to the older dates.

4. Results

4.1. Geochemical sediment description and chronology

We recovered three sediment cores from the El Valle (VM) site in the Purén-Lumaco valley showing the same stratigraphic changes that can be divided into eight sedimentological units (Fig. 2). The 400cm-long VM3 core (Fig. 3) is composed from the base at 400cm to 377cm depth light blue inorganic coarse sands, with <5mm large poorly sorted quartz grains (Unit 1). This is overlain at 377 cm by a sharp horizontal unconformity and bioturbated brown silty-sands. Between 361 and 257cm, the grayish-brown silty-clays are characterized by an increase in organic matter and several layers. At 310 and 275cm depth yellow concretions are interspersed, probably formed by Siderit (Vega, 2008), associated with peaks in MS, Fe, and P (Unit 3). Above this unit, between 257 and 241cm follow grey homogenic clays with erosive unconformities. Between 241 and 191cm depth the sediments are characterized by brownish silt with vertical little roots and increased organic matter (Unit 4). At 195cm depth the sediment gradually changes into more organic grayish silt (Unit 5) grading between 122 and 78cm depth into dark gray peats (Unit 6). Above 78cm depth is a gradual transition to less organic and bioturbated silts (Unit 7). Between 40 and 33cm depth the sediment is composed of light brownish gray silty-clays with high levels of organic matter, P and MS (Fig. 3). The upper 33 cm- are characterized by organic silt (Unit 8).

Six AMS radiocarbon dates were obtained on sieved plant material (Table 1, Fig. 2). We used linear interpolation between calibrated dates to develop the age model. Deposition rates ranged from 28 cm/yr between 26-22 kyr BP, to 200 cm/yr between 22-12 kyr BP, to ~60 cm/yr between 12-5.7 kyr BP, to 170 cm/yr between 5.7-0.741 kyr BP, and 15 cm/yr for the last 741 cal yr BP (Fig.4).

4.2. Pollen record

Almost all the record non-arboreal taxa (grasses and herbaceous taxa) are dominant in the pollen assemblages suggesting that like at present, grasslands were present in the valley and temperate rainforests grew primarily along the mountain slopes (Fig. 5). Based on temporal changes in terrestrial and aquatic taxa the pollen stratigraphy was divided into seven zones, also illustrated by the CONISS cluster dendrogram (Fig. 5; Table 2). The results of the palynological data are shown as average percent abundance inside each pollen zone.

Zone VM-I (374-330cm depth; 26-24.5 kyr BP) Poaceae (32%), *Nothofagus dombeyi*-type (22%) and *Araucaria araucana* (16%) dominate the pollen assemblage. Other trees present during this pollen zone are *Saxegothaea conspicua* and *Podocarpus nubigena*, reaching together 7% as well as non arboreal taxa Asteraceae (7.3%) and fern taxa, such as *Lycopodium sp.* (7.5%) and *Isoetes sp.* (11%). Traces (<2%) of *Nothofagus obliqua*-type, *Adenocaulon sp.*, and magellanic moorland taxa (*Astelia sp.*, *Donatia sp.*, and *Gentianaceae*-type) are present. Cyperaceae (20 to 50%) and the algae *Pediastrum sp.* (0.5 to 23%) rise throughout this zone.

Zone VM-II (330-241cm depth; 24.5-20.6 kyr BP) Is characterized by the dominance of arboreal pollen: *Nothofagus dombeyi*-type (39%), Poaceae (29%), and *Araucaria araucana* (10%), associated by the same taxa present in the preceding zone. Ferns taxa decrease and *Isoetes sp.* disappears.

Zone VM-III (241-210cm depth; 20.6-14.8 kyr BP) The pollen assemblage is again dominated by grass taxa: Poaceae (30 to 66%), *Nothofagus dombeyi*-type (26%), and *Araucaria araucana* (6%). Cyperaceae (11%) are replaced by the aquatic *Sagittaria sp.* (55%).

Zone VM-IV (210-170cm depth; 14.8-10.7 kyr BP) Grasses and *Nothofagus dombeyi*-type decrease: Poaceae (24%), *Nothofagus dombeyi*-type (21%), while *Prumnopitys andina* (15%), Myrtaceae (9%), *Nothofagus obliqua*-type (5%), and *Aextoxicon/Escallonia*-type (3%) increase. *Araucaria araucana* disappears from the record. Traces of *Eucryphia/Caldcluvia*-type and *Weinmannia trichosperma* are present. *Sagittaria sp.* (14%) decreases and Cyperaceae (30%) increase.

Zone VM-V (170-110cm depth; 10.7-7.5 kyr BP) Non arboreal pollen becomes important in this zone with Poaceae (32%), Chenopodiaceae showing a maximum in the beginning of the pollen zone (20%), and Asteraceae (3%). *Nothofagus obliqua*-type (9%) and *Weinmannia trichosperma* (5%) slightly increase, while *Nothofagus dombeyi*-type (7%) and *Prumnopitys andina* further decrease (2.4%). *Sagittaria sp.* (30%) increases while Cyperaceae (24%) decreases.

Zone VM-VI (110-60cm depth; 7.5-2.3 kyr BP) Grasses (26%) gradually decrease while several arboreal taxa increase, including *Eucryphia/Caldcluvia*-type (21%), *Nothofagus obliqua*-type (11%), accompanied by Myrtaceae (5%), Podocarpaceae (4%), and epiphytic taxa (*Hydrangea, Cissus, Lepidoceras* and *Misodendrum*). *Sagittaria sp.* and Cyperaceae are present both with ~20%.

Zone VM-VII (60cm depth; last 2.3 kyr BP) This zone is characterized by the abrupt decrease of *Eucryphia/Caldcluvia*-type to <2%, coupled with an increase in *Nothofagus dombeyi*-type (15%) and *Nothofagus obliqua*-type (12%). There is a relative increase of woody sclerophyllous taxa, *Persea/Beilschmiedia*-type and *Cryptocaria sp.* (4%), along with traces of woody vine *Proustia sp.* The top of this pollen zone records the presence of exotic trees *Pinus radiata* and *Eucalyptus sp.* Poaceae (33%) and other herbaceous taxa dominate the pollen sum, as well Asteraceae (8%), Solanaceae (2%), *Plantago sp.* and *Rumex acetosella*. *Sagittaria sp.* and Cyperaceae both increase to ca 28%.

4.3. Charcoal record

The macroscopic (sieved) charcoal record from El Valle (VM2 core) is shown in Figure 6. The concentration data exhibit abrupt changes in fire regimes over the last ~26 kyr BP. Four salient features are evident in the macroscopic charcoal record (Fig. 6): (i) near zero values in the interval between ~26 to 13.3; (ii) low values are recorded between 6.5 to 1.8, and 0.635 to 0 kyr BP; (iii) a moderate rise between 11.8 to 9.5, and 1.8 to 0.635 kyr BP; and (iv) high values between 13.3 to 11.3, and 9.5 to 6.5 kyr BP. The microscopic charcoal in the pollen slides in VM3 core (Fig. 5) shows two major features during the record: (i) moderate values between 13 to 11, and during the last 4 kyr BP, and (ii) high and fluctuating values between 11 and 4 kyr BP, with maximum values at 9 kyr BP.

5. Discussion

Our results indicate the dominance of cold temperate forest taxa, including *Araucaria araucana, Nothofagus dombeyi*-type and *Saxegothaea conspicua* between 26-14.8 kyr BP suggesting cold and per-humid conditions in the lowlands of Araucanian region (south-central Chile, ~38°S). At this time the Purén-Lumaco valley was covered by a large lake with abundant grasses in the surround. The presence of Magellanic moorland taxa, such as *Donatia fascicularis, Astelia pumila*, and *Gentianaceae*-type suggests climatic conditions characteristic of the crest of the coastal mountains and southern Moorlands (south 48°S). Actually, these vegetation types are associated with high rainfall, low temperatures, poorly-drained soils, exposure to high winds, and bed-rock

Andean intrusive origin (Ruthsatz and Villagrán, 1991). Today *Araucaria araucana* has a narrow geographic distribution of only three degrees of latitude (~37 to 40°S) on both sides of the Andean Range (Chile and Argentina), and two disjunct populations in the Coastal Range of Chile (Fig. 1). In the Andes its distribution is related to disturbance including volcanism and fire. Because of their size dispersal of both seeds and pollen is limited (Muñoz, 1984; Heusser et al., 1988), our results provide new and quantitative evidence at lower latitude for glacial distribution of the conifer *Araucaria araucana* and other cold-temperate forest taxa as well as Moorland taxa in the Araucanian region. The cold and per-humid conditions characteristic of glacial times did not present an ecological barrier for the conifer species, like *Fitzroya cupressoides*, *Pilgerodendron uviferum, Austrocedrus chilensis,* and *Prumnopitys andina* (Villagrán, 2001). According to our data from 38°S the present-day vegetation characteristic for the high elevation of the Coastal Range (*Araucaria araucana* forest) was dominant and major distribution in the lowlands during the LGM. The Purén-Lumaco record provides new evidence for the existence of a glacial refugium for temperate rainforest taxa in the region. Persistence during glacial times of forest taxa in favorable habitats throughout southwestern South America has been proposed from pollen records (Markgraf et al., 1995). The hypothesis of multiple glacial refugia in the Andes and the Coastal Range with the possibility of having been connected along the coastal and lowland regions is supported by studies on the genetic variability of *Araucaria araucana* within its modern distribution (Premoli et al., 2000; Bekessy et al., 2002). The present distribution of all southern conifers is a remnant of their more extensive former distribution during glacial times (Villagrán, 2001), which has been severely diminished by logging, human-set fires and land clearing since European colonization (Veblen, 1982). The absence of fires in the Purén-Lumaco valley during LGM times agrees with cold and per-humid climate interpreted from these plant associations. The high amount of Fe in the sedimentological record between 26 and 22 kyr BP (Fig. 3) supports strong precipitation resulting in enhanced run-off of iron-rich sediments mixed with fluvial fine particles from the mountains (Lamy et al., 2001; Stuut and Lamy, 2004). It also supports the suggestion of cold oceanic temperatures at ~23 to 21 kyr BP as proposed by Kaiser et al. (2008) at 30°S. All aspects in the Purén-Lumaco record agree with the hypothesis of a northward displacement and intensified circulation of the SW during glacial times in south central Chile (e.g. Villagrán, 1988; Heusser, 1990; Lamy et al., 2001).

Purén-Lumaco pollen record reveals three warming pulses following the deglaciation process (Figs. 3, 5): 21, 15 and 11.7 kyr BP shown by the decrease of *Nothofagus dombeyi*-type, increase of pollen concentration (arboreal and herbaceous), and change of sedimentary characteristics. However, our low resolution age model between 22-12 kyr BP, complicates to establish the exact timing of those warming pulses. The date of 11,985 cal yr BP at 195 cm depth (Fig. 4; Table 2) defines the end of the glacial interval. The paleo-lake had completely desiccated, *Araucaria araucana* disappeared, and instead warm-temperate taxa, such as *Prumnopitys andina*, Myrtaceae, *Hydrangea serratifolia* and *Aextoxicon punctatum* expanded. The nearby pollen record from Rucañancu (38°30'S) documents the *Prumnopitys andina* expansion between 12.2 and 11.6 kyr BP, interpreted as 5-8°C lower temperatures and 2000 mm higher precipitation compared to present (Heusser, 1984). Present-day distribution of *Prumnopitys andina* is between 36-39°S in the Andean range growing on shallow and volcanic soils, under greatly variable soil humidity and extreme temperatures, is associated with *Nothofagus obliqua* in Nahuelbuta Coastal Range and limited or null regeneration (Hechenleitner et al., 2006). It is possible that the modern distribution is only a consequence of recent land-use changes. However, between 13-11.3 kyr BP intense fire-disturbance regime (Figs. 6) associated with more variable climate trend in the glacial-Holocene transition could contribute to the *Prumnopitys andina* expansion in the Purén-Lumaco valley. This fire-disturbance regime were wide-spread in south-central Chile (42°S) (Abarzúa and Moreno, 2008), as well Purén-Lumaco valley persisted until 6 kyr BP, when *Nothofagus dombeyi*-type reached minimum values and *N. obliqua*-type, *Weinmannia trichosperma*, Chenopodiaceae species increased (Figs. 5, 6), possible related to more warm/dry conditions.

The date of 8289 cal yrs BP at 142cm depth in VM2 core, defines the driest period in the record, associated with maximum charcoal concentrations and peat sediment. *Eucryphia cordifolia* and *Caldcluvia paniculata* forests were abundant between 8 and ~5 kyr BP. At present *Eucrcryphia-Laurelia* forests are dominant in the lowlands of the Nahuelbuta Coastal Range (Cotulmo National Park) to an elevation of 400 m a.s.l. (Endlicher et al., 1985). In the Laguna de Tagua Tagua pollen record the arboreal components disappeared during the early to mid-Holocene, whereas grass taxa and Chenopodiaceae reached their highest values during 6-2 kyr BP (Heusser, 1990). Laguna Las Totoras pollen record from the crest of Nahuelbuta Coastal Range evidences the colonization of *Araucaria* forest at ~6 kyr BP suggesting warm climate conditions (Villagrán, 2001). Pollen records from a coastal swamp forest located at 31.5°S show that an open and herbaceous vegetation dominated by xerophytic taxa prevailed between 6 and 4 kyr BP (Maldonado and Villagrán, 2002), while in another record located at 32°S pollen is absent between 8 and 5.7 kyr BP (Maldonado and Villagrán, 2006). Low lake levels and a dominance of

Chenopodiaceae were recorded at Laguna Aculeo (34°S) prior to 5.7 kyr BP (Jenny et al., 2002; Villa-Martínez et al., 2003). The same trend was observed in south-central Chile, with the dominance of thermophilous taxa in temperate rainforest at 42°S between 10 and 7 kyr BP (Villagrán, 1988, 1985; Abarzúa et al., 2004; Moreno, 2004). All these results suggest that the climate was dry and warm (~2°C) between 10 and 5 kyr in central Chile until 38°S interpreted to reflect a southward shift of the ITCZ linked to the position of the STH and a southward shift of the SW (e.g. Caviedes, 1972), or at least of its northern boundary (Kaiser et al., 2008) and representing the SW's "extreme interglacial mode" (Moreno and León, 2003). This lack time difference during the early Holocene climatic signal and vegetation responses between northern and southern Chilean pollen records can reflect the displacement of the main climatic system to the current position. Climatological data suggest that the latitudinal position of the SW are strongly related to the position of the ITCZ (Broccoli et al., 2006), to the strength of the STH (Markgraf et al., 2002), which in turn is closely associated with the El Niño-Southern Oscillation (ENSO) (Rutllant and Fuenzalida, 1991; Villalba et al., 1996; Kitzberger, 2002). For example, during the warm phase of ENSO (El Niño events), pressure is anomalously low over the southeast Pacific, leading to a weakening of the STH and a consequent northward shift of the SW (like in glacial conditions). On the opposite, in the early and mid-Holocene, the ITCZ was shifted northward strengthened the easterly winds, favored upwelling, and caused an SST cooling in the east Pacific. I.e. La Niña-like conditions, in agreement with dry conditions in north central Chile between 10 and 5 kyr BP (Kaiser et al. 2008; Garreaud et al. 2008). This would further imply that subtropical gyre circulation was intensified during the mid-Holocene; years with weaker SW over the continent are associated with large areas burned, even though El Niño events might have been absent (Whitlock et al., 2007). Therefore, we suggest that the STH shifted southward during the early Holocene, together with the SW, and possible the Antarctic Circumpolar Current (ACC). Other possibility is that ENSO influence was quasi absent during the early to mid-Holocene to explain the arid conditions at that time (e.g. Jenny et al., 2002), probably linked to a northward displaced ITCZ as mentioned above.

After ~5 kyr BP, the ITCZ shifted southward and the frequency of El Niño events increased, causing higher humidity in the eastern Pacific (Moy et al., 2002; Abarzúa & Moreno, 2008). During that time human related environmental disturbance is documented in the Purén-Lumaco record. The presence of cultivated taxa (e.g. Chenopodiaceae, Solanaceae, Asteraceae, Fabaceae, and Poaceae), traces of maize pollen (*Zea mays)*, decrease in arboreal taxa, and high phosphorous concentration reflecting high erosion rates indicate high human impact (Brenner et al., 2002). The catchments approach through geochemical and sedimentological analysis provides a powerful tool to evaluate quantitative changes caused by both natural and anthropogenic alterations (Likens, 2001). The impact on soil erosion by converting native forest can thus be evaluated by quantification of the phosphor export from the catchments. Phosphor is mainly lost from soils in particulate and dissolved forms through erosion and runoff (Sharpley et al., 1992; Oyarzún et al., 2007).

Our pollen, sedimentological and geochemical data clearly document the onset of human-disturbance regimes in Purén-Lumaco valley. Preliminary archaeological data document settlements in Purén-Lumaco valley at ~7 kyr BP (Dillehay, unpublished data) and more intense landscape transformation during the last 1 kyr. Settlements of hunting and gathering communities are abundant in coastal Araucanian areas since 7 kyr BP (Quiroz and Sanchez, 2004), probably related to the warm early-mid Holocene climates. Oral tradition of local indigenous Mapuche today states that maize, potatoes and beans were produced in the fields by the past native people. Macro-plant remains of several cultigens, including maize (*Zea mays*), tarweed (*Madia sativa*), quinoa (*Chenopodium quinoa*) and an unspecified seed (Poaceae), have been recovered by the arqueological work from platforms, canalized fields and nearby agricultural villages in the Purén-Lumaco valley. Raised and canalized fields have been documented in several areas of the northern and central Andes, but never before in the Araucanian region of South America (Dillehay et al., 2007). Preliminary studies suggest that the varieties of maize and quinoa recovered from excavated sites in the Purén-Lumaco valley have morphological affinities with central Andean varieties (Dillehay, 2007). The Araucano variety of maize (4 to 12 rows) grown in south-central Chile today is likely derived from varieties in Bolivia, Peru, or northern and central Chile (Sánchez et al., 2004). The origin of Araucanian quinoa also is not well understood, but probably has its roots in the central Andes or central Chile. The presence of this cultivated species has been dated in other valleys in Araucanian region to around 3 kyr BP (Planella and Tagle, 2005). In the Purén-Lumaco valley social differentiation, horticulture, incipient mound-building, settlement aggregation, and a simple chiefdom society had begun by at least AD 800 to 1000, and like in other archaeological sites, the cultural patterns are associated with wetlands and coastal estuaries. The large-scale transformations of Purén-Lumaco and Budi areas (Fig. 1) reveal a late prehistoric complexity not documented before now in the southern cone of South America (Dillahey et al., 2007).

However, the most evident human impact in the Purén-Lumaco valley occurred during the last centuries with "modern" agriculture (wheat and barley) and exotic forest plantations (*Pinus radiata* and *Eucalyptus sp.*), associated to Spanish and Chilean colonization (s. XIV - XIX), respectively. Today the Purén and Lumaco Rivers carry large quantities of sediments eroded from the surrounding uplands, and the Mapuche agriculture shows a decline until the present days. The modern conflict between the Chilean government, forest logging companies, Mapuche communities, concerns about native forests and biodiversity requires urgent new strategies for the future of the Araucanian region. Human interaction with the physical environment has increasingly transformed Earth-system processes. On the other hand, climate anomalies and other processes of environmental change of natural and anthropogenic origin have been affecting, and often disrupting, societies throughout history. Transient impact events, despite their brevity, can have significant long-term impact on society, particularly if they occur in the context of ongoing, protracted environmental change. Major climate events can affect human activities in critical conjunctures that shape particular trajectories of social development.

5. ***Summary and conclusions***

- Cold and per-humid conditions during the LGM prevailed between 26 and 14.8 kyr BP in the lowlands of the Araucanian region (south-central Chile, ~38°S), based on the presence of *Araucaria araucana - Nothofagus dombeyi*-type forests and abundant grasses.
- The inferred high precipitation and very low temperatures support the hypothesis that the southern westerlies were displaces equatorwards and intensified during glacial times in south central Chile.
- The El Valle pollen record reveals three warming pulses during the deglaciation between 21 and 12 kyr BP.
- The beginning of the Holocene period is characterized by intense fire-disturbance regimes in the Purén-Lumaco valley, shortly after the expansion of the conifer *Prumnopitys andina*, and several other warm-temperate forest taxa such as *Nothofagus obliqua*-type, *Weinmannia trichosperma* and Myrtaceae species.
- During the Holocene, the climate was dry and warm (~2°C) between 10 and 5 kyr in central Chile interpreted to respond to a northward shift of the ITCZ linked to the positioning of the STH and a southward shift of the SW, or at least of its northernmost boundary.
- After ~5 kyr BP, the ITCZ shifted southward and the frequency of El Niño events increased, causing higher humidity in the eastern Pacific, time when high disturbance signal in El Valle record is associated with high human impact (presence of cultivated plants, like maize, decrease in arboreal taxa, and high phosphorous concentration). These data agree with the archaeological findings in Purén-Lumaco valley.
- In Purén-Lumaco valley social differentiation, horticulture, incipient mound-building, settlement aggregation, and establishment of a simple chiefdom society had begun by at least AD 800 to 1000, and like in other archaeological sites the cultural patterns are associated with wetlands and coastal estuaries. The large-scale transformations of the Purén-Lumaco and Budi areas reveal a late prehistoric complexity not documented before in the southern cone of South America.

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Figures and tables

Figure 1: Study area: Upper left map shows the ITCZ, STH, and SW during July and January in South America. Lower left altitude map shows the Nahuelbuta Coastal Range in south-central Chile. Right hand map shows the present-day land cover between 37-40°S in south-central Chile, the location of study sites (Purén-Lumaco valley and Lago Budi), and the main cities. Bellow, photography of El Valle site (R. Vega).

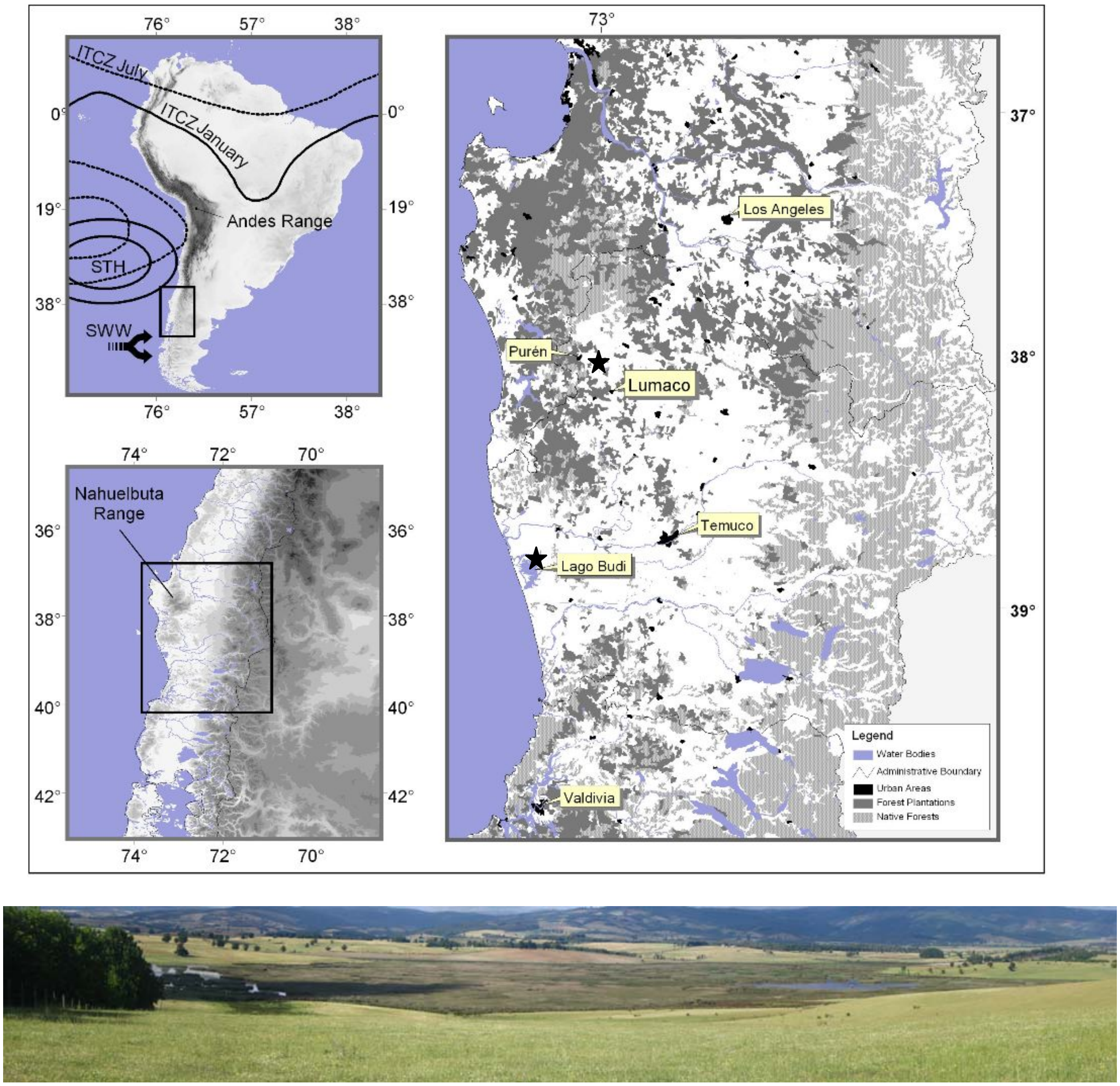

Figure 2: Lithology, ^{14}C datings, and sedimentological unit of VM 1-3 cores from El valle site. Lower panel: Photography of 400cm-long VM3 sediment core. We are waiting for the XXX ± XX date.

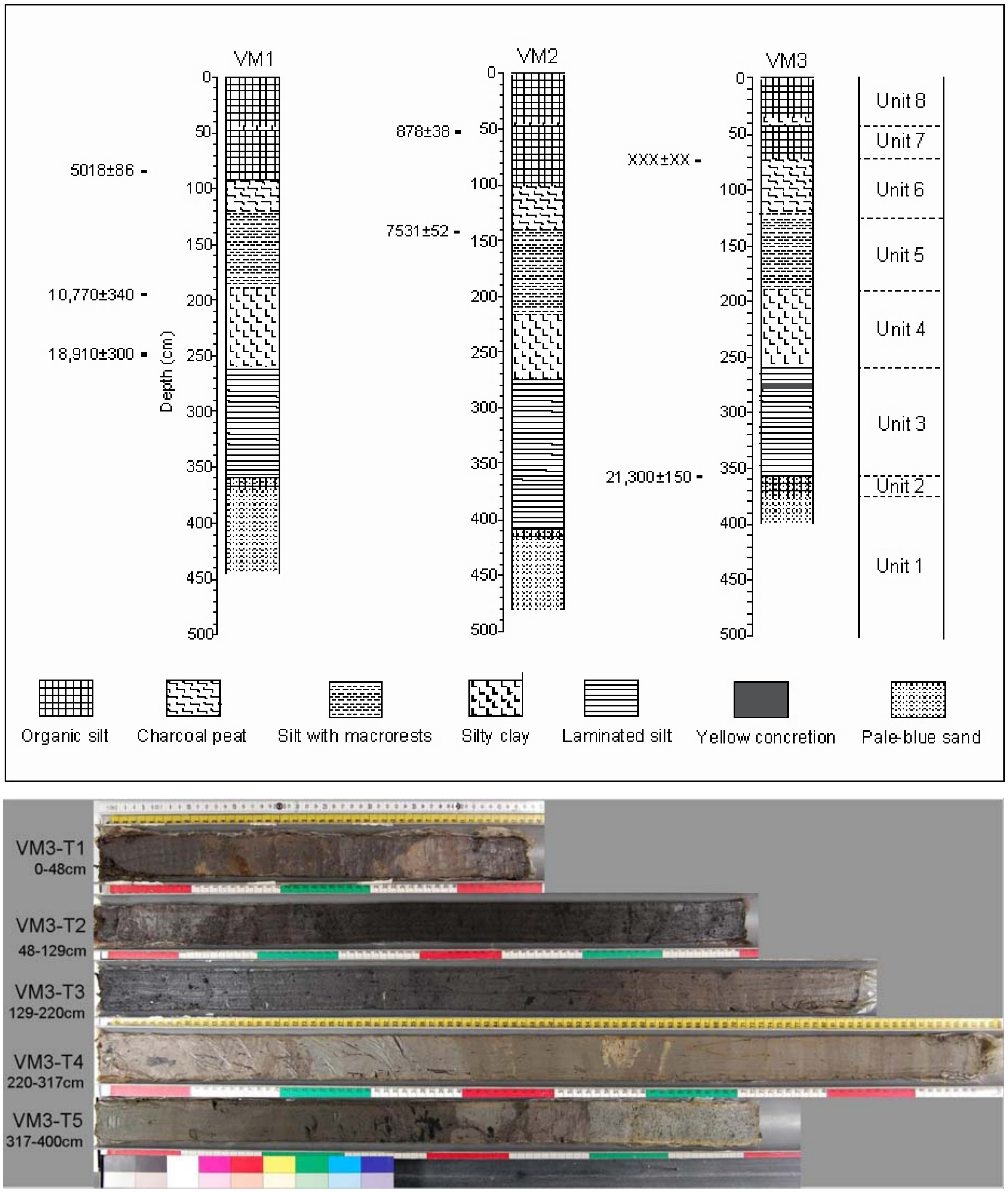

Figure 3: Sedimentary features, calibrated dates, biogeochemical characteristics (Fe-P), and loss-on-ignition results from VM3 core, El Valle site in Purén-Lumaco valley. Notice the differences in between X-axes.

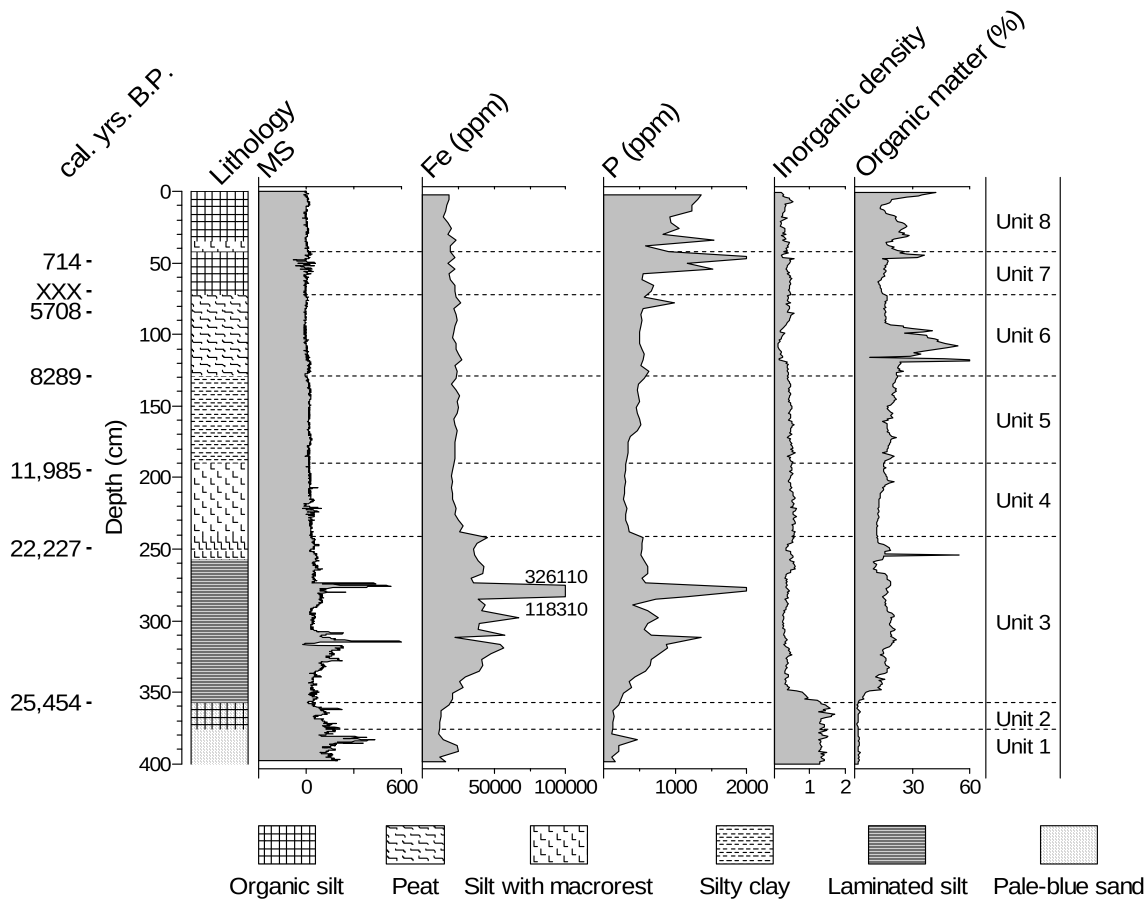

Figure 4: Age model from El Valle (VM3) sediment core, lineal interpolation between dates.

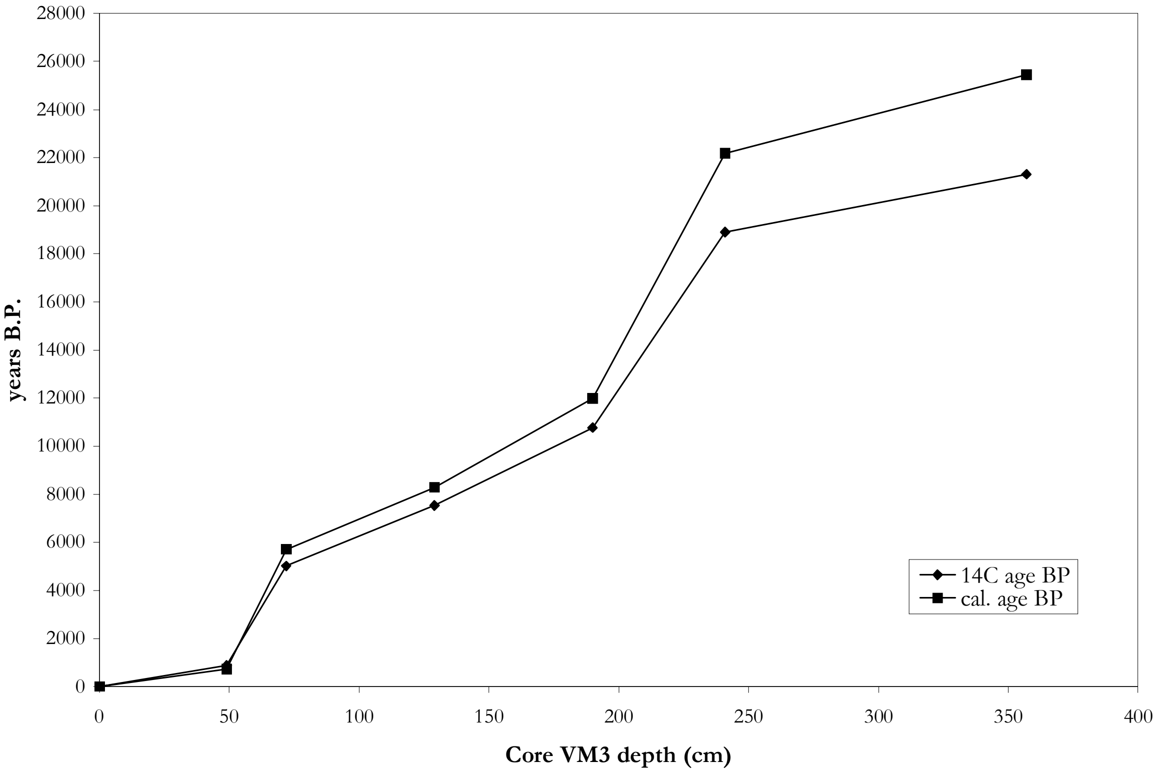

Figure 5: Summary pollen record from El Valle, showing calendar age model, and CONISS statistical analysis. Upper graph shows the arboreal pollen taxa (%) and micro-particles of charcoal concentration (particles cm-3). Lower graph shows the non arboreal pollen, spores, and algae taxa. Note the differences in between X-axes.

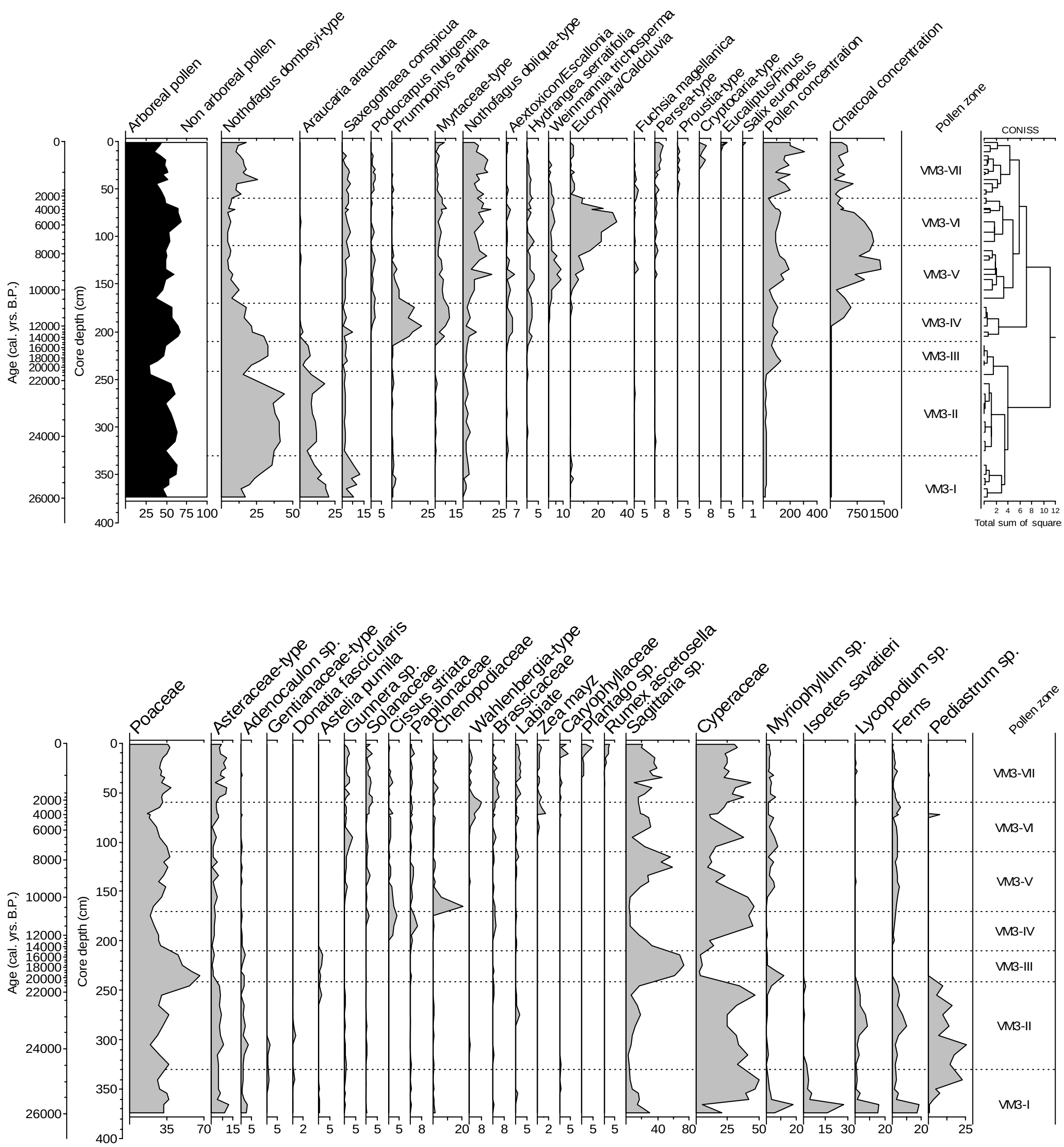

Figure 6: Charcoal record and loss-on-ignition results from VM2 core. Data were produced in collaboration with the Bachelor thesis of Alejandra Martel from Instituto de Geociencias, Universidad Austral de Chile.

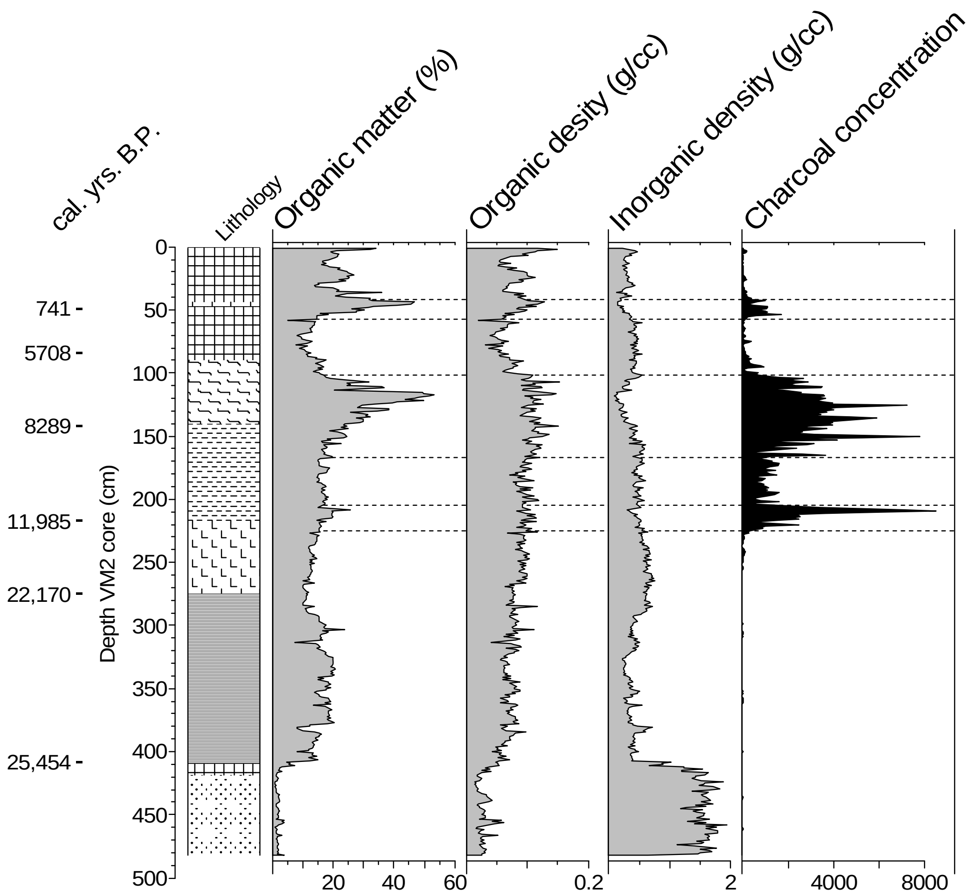

Table 1: Radiocarbon dating and calibrated ages from El Valle sediment core.

Lab code	Core	Core depth (cm)	Material dated	$\delta^{13}C$	^{14}C age BP	± age	cal. age BP
AA81801	VM2T2	49	vegetal tissue	-27.2	878	38	741
XXX	VM3T2	72	vegetal tissue				
AA75322	VM1T2	84	charcoal	-29.4	5018	86	5708
AA81802	VM2T3	142	wood	-27.1	7531	52	8289
AA75326	VM1T3	195	charcoal	-26.8	10,770	340	11,985
AA75323	VM1T4	249	charcoal	-27.6	18,910	300	22,170
AA81803	VM3T5	357	charcoal	-28.8	21,300	150	25,454

Table 2: Summary of age and pollen assemblages in each pollen zone from El Valle pollen record.

Pollen zone (cm depth)	Age (kyr BP)	Pollen assemblage	Percentage sum
VM-VII (60-0)	Last 2.3	Poaceae – *Nothofagus dombeyi*-type – *Nothofagus obliqua*-type	60%
VM-VI (110-60)	7.5-2.3	Poaceae – *Eucryphia/Caldcluvia*-type – *Nothofagus obliqua*-type	58%
VM-V (170-110)	10.7-7.5	Poaceae – *Nothofagus obliqua*-type – *Nothofagus dombeyi*-type	48%
VM-IV (210-170)	14.8-10.7	Poaceae – *Nothofagus dombeyi*-type – *Prumnopitys andina*	60%
VM-III (241-210)	20.6-14.8	Poaceae – *Nothofagus dombeyi*-type – *Araucaria araucana*	86%
VM-II (241-330)	24.5-20.6	*Nothofagus dombeyi*-type – Poaceae – *Araucaria araucana*	78%
VM-I (330-374)	26-24.5	Poaceae – *Nothofagus dombeyi*-type – *Araucaria araucana*	71%

CAPÍTULO 3

Paleolimnological investigations at Lago Budi, Araucanian Region, Chile (38.9°S): Chronology of relative sea level changes and climatic indications during the Late Glacial and Holocene.

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3.1 Abstract

Lago Budi is a brackish lagoon located in the west side of coastal range of southern Chile (38°53'S/73°18'W). Currently, Lago Budi is connected to the Pacific Ocean by a seasonally active channel, thus the surface of the lagoon exhibits an ideal marker for the mean sea level (msl). Relative changes in the system ocean-continent (eustatic and tectonic) are recorded in the lagoon deposits of Lago Budi during the Holocene. Multiproxy hydro acoustic, sedimentologic, bio and-geochemical analyses supported by numerous AMS-^{14}C dates were achieved to compile a chronological framework of Lago Budi genetic phases (marine-brackish-freshwater). The central part of the lagoonal basin exhibit a striking unconformity attributed to fluvial erosion in the local catchments during the LGM (~30-19 kyr BP). Since ~12.2 kyr BP continuous sedimentation started in Lago Budi, at 9.4 kyr BP occurred the first Holocene marine transgression (16.5 m below the current msl), and a subsequent steady sea level rise is registered with 6.8 m/kyr on average. The highest level (1.5 m above the current msl) occurs during the early and mid Holocene, latter at ~7 kyr BP open-marine conditions ended and a brackish lagoon evolved, the sea level reached its current position, and diatom associations show no distinctive freshwater phase until present days. During the lagoonal phase at least two regressive cycles are evident at 6 and 2 kyr BP. These regressive phases coincide with striking tsunami events, and are probably linked to seismic vertical movements (land uplift) during giant earthquakes. In contrast to the adjacent areas north of Rio Imperial (Nahuelbuta Coastal Range segment) and south of Rio Calle Calle (Bueno Coastal Range segment) which, according to literature, show pronounced continuing Quaternary uplift of >2 m/kyr, the Lago Budi segment shows a quite stable position without major net-uplift/subsidence trends during the Holocene. With regard to environmental conditions the data at Lago Budi show temperate rainforests and Mediterranean species between 9 and 5 kyr BP, showing a striking transition to rather dryer and warmer conditions which lasted till ~2.8 kyr BP. Since ~5 kyr BP the presence of *Zea mays* pollen associated with raised charcoal values in colluvial sediments surrounding Lago Budi, which show enormous accumulation rates, are linked to the early appearance and interventions of humans in the Lago Budi area.

Key words: Lagoonal evolution, postglacial sea level change, tectonic movements, climate and vegetation history, human impact, Southern Chile.

3.2 Introduction

The different morphological units accompanying our coasts display important archives for the reconstruction of past coastal forming processes like neotectonic, eu- and isostasy or natural disasters (e.g. storm surges, tsunamis). Especially along the Southern Chilean coasts such tracks are commonly covered by the action of strong exogenous forces within the prevailing Southern Westerlies winds (SW), resulting in destroyed marine beach ridges (Lomnitz 1969, Atwater et al. 1992). In addition scarce datable fossil material in the Pleistocene terrace remains rather eliminates a reliable chronology (Radtke 1991, Schellmann and Radtke 1999). Lagoons and coastal wetlands, as an interface between ocean and continent, offer the opportunity to investigate archives with a high potential for preservation combined with excellent dating alternatives regarding past coastal forming processes.

Paleolimnological studies of lagoonal and coastal deposits in South America are common on the east coast e.g. in Uruguay (García-Rodríguez et al., 2004, García-Rodríguez, 2006, Inda et al., 2006) or in Argentina (Brückner et al., 2007, Espinosa et al., 2003, Isla and Espinosa, 1995). Along the chilean continental margin comparable researches are rather sparse. The existing results concerning relative sea level (RSL) changes, associated with tectonic movements, are usually obtained by observations directly after seismic events (Alvarez and Saint-Amand, 1963), by geomorphologic investigations (Bartsch-Winkler and Schmoll, 1993, Bookhagen et al., 2006, Hervé and Ota, 1993, Nelson and Manley, 1992, Pino and Navarro, 2005, Schellmann and Radtke, 1999), and by morphometric satellite image-based analyses (Rehak et al., 2008). In south-central Chile the time and magnitude of RSL-changes relative to eustatic and tectonic origin are quite hard to evaluate. The coastal margin of Chile is subdivided in several tectonic segments, which become typically apparent by frequent destructive megathrust earthquakes accompanied by locally varying uplift and/or subsidence rates of the continent (Nelson and Manley, 1992, Plafker and Savage, 1970, Rehak et al., 2008). Thus, the data for the Holocene Marine Transgresion (HMT) along the Chilean coasts vary conspicuously between 3-5 m above the present msl at ~30°S at 6.4 kyr BP (calendar thousand years before the present) (Ota and Paskoff, 1993) and up to 33 m above msl at Isla Mocha (38.4°S) at 5.8 kyr BP (Nelson and Manley, 1992) (Fig. 1). A general Holocene sea level curve will remain elusive for the south Chilean coasts in the future, in this sense, close network of data is necessary to discriminate segments with similar tectonic behaviour. Our investigations at Lago Budi close to Nahuelbuta

Coastal range will improve the knowledge related to the changes in the sea level in the area where detailed sedimentological data are almost absent.

Beside the natural processes contributing to the evolution of coastal lagoons and wetlands also the consequences of anthropogenic interventions are of great interest, especially the onset and degree of landscape and vegetation changes associated with human influence. The Araucanian region is characterized by dense and ancient populations of indigenous people (Mapuche culture). According to archaeological reports, based on ceramic findings and several artificial ceremonial mounds (*Kuel*), human settlements were present in the area at least since 1 kyr, and probably since 7 kyr B.P (Dillehay et al., 2007, Quiroz and Sánchez, 2004). The cultivation of introduced crops like maize (*Zea mays*) or quinoa (*Chenopodium quinoa*) is evident in the near proximity of Lago Budi. Traces of partly complex agricultural techniques (Dillehay and Saavedra, 2003) are common, but the onset of cultivation is still unknown. As the archaeological site of Monte Verde shows, situated approximately 300 km south of Lago Budi, early human settlements in the region since 12 kyr B.P. (Dillehay and Collins, 1988, Waters and Stafford, 2007). Beside few works near 37°S (Cisternas et al., 2000) multiproxy studies deciphering the environmental changes associated to human and climatic control are almost absent in the coastal region of Southern Chile. Information in terms of changing sediment composition and increasing sedimentation rates or high amounts of colluvial material are archived in the lagoonal deposits of Lago Budi and its surroundings. Palynological analyses of the sediments will show the vegetation development subjected to climate changes and human interventions (e.g. forest clearing by human-set fire).

3.3. Environmental settings

Lago Budi (38º42'-39º01'S; 73º04'-73º26'W) is located approximately 60 km west of Temuco, in the Araucanian region of Chile (Fig. 1). Is a typical coastal lagoon characterized by mixohyaline water; Lago Lanalhue (37°55'S), Lago Lleu Lleu (38°09'S), and Lago Budi (surface approx. 57 km^2) are coastal lagoons in Southern Chile, situated outside the quaternary glacial area. In contrast to the numerous glacial originated lakes of the adjacent Andean Range the genesis of Lago Budi is controlled by tectonic features interacting with glacio-eustatic sea-level changes.

In its 503 km^2 watershed the most important land use, which is inhabited predominantly by native Mapuche communities, is composed of agriculture carried out mostly by traditional sowing methods. The 98% of total watershed area presents high level of disturbance, high fragility, and different land-use cover (Hauenstein et al., 2001). The most important land use in the watershed is the agriculture (29.4%), followed by pastures (14%), and wetlands (13%). Native forests only represent 1.2% of total area of Lago Budi (Peña-Cortés et al., 2002). Forests have been largely eradicated to open land for agriculture and pastures. Native floristic associations that should potentially be present in the area based on climate are Deciduous Beech forest (*Nothofago-Perseetum*) and wet forest "Temu-Pitra Hualve" (*Blepharocalyo-Myrceugenietum exsuccae*) (Schmithüsen, 1956). Intensified land management and growing forest industries during the last decades led to increasing nutrient enrichment (Peña-Cortés et al., 2006a, 2006b) and a high proportion of allochthonous macrophyte species (Hauenstein et al., 1999), thus the status of Lago Budi has to be considered as eutrophic.

Currently the lagoon is connected to the Pacific Ocean by a few hundred meters wide and about 10 km long channel (Rio Budi) in the northern part of the lagoon. Due to higher precipitation rates during the winter season the lagoon drains into the Ocean by the Rio Budi, suggesting that the lake level of Lago Budi is situated slightly above the msl. During the summer the mouth of Rio Budi is closed by a more than 100 m broad beach wall and an exchange of water is largely disabled. In the summer 2006 a diffusion of sea water into the lagoon was observed superficially pointing to a slightly lower lake level than the msl. The maximum water depth of the lagoon is fluctuating around 8.2 m below msl with annual amplitudes of ±0.7 m and thus, during a yearly loop, the surface of Lago Budi can be considered as an ideal proxy for the msl. The river drainage system discharging into Lago Budi is very well developed and covers a relatively small, local catchments area of approximately 340 km^2. Connections exist neither to the Andean hinterland nor to the longitudinal valley.

The direct surroundings of Lago Budi are characterized by an undulating morphology of rounded hills and smooth valleys bordered by the Rio Imperial by the north and the Rio Toltén in the south. The elevations reach 60 to 110 m asl, the highest peaks appear by the east of the lagoon and don't exceed 350 m asl. Along the constantly 160° striking linear coast up to 40 m high cliffs show perfect outcrops of the surrounding volcanoclastic rocks, probably of Tertiary age ("Formación Budi" by Lomnitz, 1968). These outcrops along the coast are interrupted by up to 2 km broad dune covered strips, which display possible former connections between the Pacific and the lagoon. Worth mentioning appears the striking black color of the dune sands, consisting of a high magnetite content. East of the lagoon appear metamorphous, Palaeozoic basement rocks characteristic of the Coastal Range.

Due to the proximity to the Pacific the climate can be characterized as oceanic, temperate-humid with Mediterranean influence (Di Castri and Hajek, 1976). The mean annual precipitation varies between 1200 and 1400 mm by medium thermal amplitudes between 0.5° and 24°C (mean 11.5°-12°C). Precipitation rates are controlled by the SW, highest values occur in June (200-300 mm) and lowest during December-February (each <40 mm). The precipitations also dominated by the stational position of South-tropical Pacific Anticyclone (Rutland and Fuenzalida, 1991) and the ENSO cycles increase the spring precipitations during El Niño events (Montecinos and Aceituno, 2003).

3.4 Methods

In a first step a comprehensive hydro acoustic survey of Lago Budi was carried out during February 2005 using a parametric system of INNOMAR (SES 96 light) with a primary frequency of 100 kHz and secondary frequencies between 4 and 12 kHz. A GPS-controlled grid of profiles of approximately 250 km was performed to get extensive information about the sedimentary inventory of the lagoonal basin for evaluating coring sites and additionally to calculate the first bath Lago Budi. In a second step the sediment sampling procedures were performed. Several short sediment cores (<1.2 m) were recovered by using a modified gravity corer (Meischner and Rumohr, 1974) with diameters of 64 mm. Four up to 11 m long cores were recovered out of the lagoon via a piston coring system (UWITEC, Austria). Additionally the adjacent shores were sampled by four up to 15 m long percussion cores (Wackerhammer). We used 5 m, respectively 2 m core chambers; each core section has overlapping sequences of 1 m.

After opening the cores, each half was described and digitally photographed, whereas the other half was measured continuously for magnetic susceptibility (1 mm steps, Bartington sensor MS2E). For pollen analysis, 0.9 cm^3 volumetric subsamples were taken at 10 cm intervals and prepared using standard techniques (KOH deffloculation, HF digestion, and acetolysis) (Faegri and Iversen, 1989). Pollen grains were identified at 400 and 1000x magnification. A basic sum that included 300 pollen grains of trees, upland shrubs and herbs were counted per each level. All ferns and aquatic/paludal taxa were combined in separate sum, and their percentages were expressed in reference to a supersum that includes the basic pollen sum and all ferns and aquatic/paludal taxa. *Lycopodium* tracer spores were added to each sample for calculation of pollen concentration (grains cm^{-3}). Changes in pollen percent and concentration were used to interpret past vegetation changes supported by CONISS cluster analysis. Pollen data were plotted using TILIA programs (Grimm, 1987). In the pollen record, the dominant tree genus *Nothofagus* is represented by eight species. Based on pollen morphological characteristics, only two pollen types can be differentiated: *Nothofagus obliqua*-type (including N. *obliqua, N. glauca*, and *N. alpina*, all of which grow in the summer dry region of the study area), and *Nothofagus dombeyi*-type (including *N. dombeyi, N. pumilio*, *N. antarctica, N. betuloides, N. nitida*, all of which primarily grow in the more mesic forests of the area). Other species were counted together by the morphology similarity, l*ike Eucryphia cordifolia* and *Caldcluvia paniculata* into *Eucryphia/Caldcluvia*-type; *Beilschmiedia sp.* and *Persea lingue* into *Beilschmiedia/Persea*-type, all species of Myrtaceae; Poaceae; Asteraceae, and Solanaceae were graphed together.

3.5 Results

1. Sedimentology and chronology of Lago Budi

Thus, the following aims got realized during this study: i) age, origin and evolution of Lago Budi subjected to seismic movements and eustatic sea level changes ii) palynologic reconstruction of vegetation, climate, and anthropogenic history outside the main glacial area of the southern Andes.

We recovered several sediment cores from the base of Lago Budi and other terrestrial sediment descriptions from the surrounding area (Fig. 2). In the central part of Lago Budi, the 1084 cm-long LB 3/05 core is composed from the base at 1084 to 967 cm light blue inorganic coarse sand sediments, with <5mm quartz bad sorted gravels, and high magnetic susceptibility (MS), interpreted as Paleogley soil (Fig. 2, 3, 4). At 967 cm there are sharp unconformity and homogenic silt sediments until 920 cm. At 906 cm depth start more bioturbated brown silty-sand marine sediments with mollusk shells (*Agropecten purpuratus, Venus antiqua,* and *Kingiella chilenica*). Silt marine sediments are present until 706 cm depth. Between 706 and 294 cm depth laminated olive silt, sandy-silt, and low MS characterized the next lagoon period, except between 385-371 cm where are a tsunami layers associated with high MS values. The superior 294 cm are principally gray silt lagoon sediments and small mollusk shells (<1.5 cm) of *Mactra sp.* This sedimentological description is registered in the others sediment cores from Lago Budi, as well as, is recorded silt lagoon sediments in the terrestrial PDO records (Fig. 2).

The ages from radiocarbon dating over shell and plant remains reveals 9.7 kyr depositions in Lago Budi (Table 1, Fig. 3). The chronology support the timing for the Holocene marine transgression between 9.3 and 5.1 kyr BP and the subsequent lagoonal period associated with several tsunami layers dating in 6.3, 6.9, 5.7, 5.3, 4.6, 3.9, 3.1, 1.4 kyr BP (Fig. 3, Table 1). The tsunami layers are recorded trough the MS in the LB 1/05 and LB 3/05 cores (Fig. 4), as well as dark lines in the seismic profile in Lago Budi in the Unit III, associated with abundant shell remains (Fig. 5).

2. Pollen and charcoal record

We analyzed the pollen and spores content of two sediment cores fom Lago Budi. The first LB01/05 core of 770cm long and the second LB03/05 core was analyzed between 720 and 925cm depth. Throughout the record, the pollen assemblages are co-dominated by grasses and forest taxa, suggesting that, like at present, opened areas were abundant and forest inhabited the mountain slopes (Fig. 6). The pollen stratigraphy was divided into five zones, based on temporal changes in terrestrial and aquatic taxa, also illustrated by the cluster CONISS dendrogram (Fig. 6; Table 2). The results of the palynological data are shown as average percent abundance inside each pollen zone.

Zone LB-I (950-830 cm depth; 9.8-8.3 kyr BP) is dominated by the assemblage Poaceae-*Nothofagus obliqua*-type-*Nothofagus dombeyi-type* (Σ=59% of the basic sum), along with the trees *Aextoxicon/Escallonia* (6%), Myrtaceae (3%), *Gevuina avellana* (2.4%), the vine *Hydrangrea serrratifolia* (2.4%), and the species of Asteraceae (2.5%). This is accompanied by trace percentages (mean<2%) of *Embothrium coccineum, Drimys winteri, Gomortega keule,* and *Saxegothaea conspicua.*

Zone LB-II (830-600 cm depth; 8.3-5 kyr BP) features the assemblage Poaceae-*Nothofagus dombeyi*-type-*Nothofagus obliqua*-type (Σ=52% of the basic sum), along with *Saxegothaea conspicua* (7.5%), *Beilschmiedia/Persea* (5.3%), *Gomortega keule* (3.5%), Myrtaceae (3.5%), *Aextoxicon/Escallonia* (2.8%), *Drimys winteri* (2.5%). Traces of *Embothrium coccineum, Drimys winteri, Araucaria araucana* and *Lomatia* sp. are present. The non arboreal pollen is lower in this zone (28%), traces (<1%) of *Zea* *mays* appear in the top zone. High content of charcoal is registered in this zone, until 5800 particles cm^{-3}.

Zone LB-III (600-240 cm depth; 5-2.8 kyr BP) is characterized by the most notably vegetation change in the record. The zone is dominated by the assemblage Poaceae – *Nothofagus obliqua*-type –Chenopodiaceae (Σ=47% of the basic sum), along with *Nothofagus dombeyi-type* (9.4%), *Beilschmiedia/Persea* (8.9%), *Saxegothaea conspicua* (3.8%), and *Aextoxicon/Escallonia* (3.1%). Traces of *Cryptocaria alba, Gomortega keule, Peumus boldus, Lomatia* sp. are present. In the non arboreal species (43%) emphasize the presence of Solanaceae family (3.5%) and the persistence of *Zea mays* pollen.

Zone LB-IV (240-90cm depth; 2.8-1.5 kyr BP) features the Poaceae – *Nothofagus obliqua*-type – *Beilschmiedia/Persea*-type assemblage (Σ=60% of the basic pollen sum). Conspicuous changes during this zone include the increases in *Beilschmiedia/Persea* (12%) and the decrease of *Aextoxicon/Escallonia* and *Saxegothaea conspicua*. The others arboreal species maintain low percentages, and the non arboreal species tend to rise (45%), like the Asteraceae family. Its observable traces of *Zea mays*. There is also an increase of charcoal concentration in this pollen zone, until ~4000 particles cm^{-3}.

Zone LB-V (60-0cm depth; last 1.5 kyr BP) is dominated by the assemblage Poaceae-Chenopodiaceae-*Beilschmiedia/Persea*-type (Σ=50% of the basic pollen sum). The arboreal pollen is characterized by the decrease of almost all species, and the start of exotic trees and herbs species likes *Pinus radiata* (3%), *Rumex acetosella* (2%), and *Plantago sp.* (2%). Its observable traces of *Zea mays* until 1.8%.

3. Vegetation and climate reconstruction

The modern distribution and floristic composition of coastal vegetation in south-central Chile is largely a result of colonization and succession processes without the direct impact of Pleistocene glaciers, and subsequent reshuffling driven by climatic fluctuations (Villagrán, 2001). In this sense, Holocene climate variations would seem crucial for understanding plant distributions and the vegetation mosaic on this biodiverse area (Arroyo et al., 1995). The Lago Budi pollen record (Fig. 6) reveals interesting vegetation changes during the Holocene (last 9.8 kyr) in relationship to the present degraded landscape in the area. The pollen assemblage in the zones LB-I and LB-II, between 9.8 – 5 kyr BP (Fig. 3), is dominated by typical temperate species from humid coastal areas in the Araucanian region, like Myrtaceae family, Podocarpaceae family (*Saxegothaea conspicua* and *Podocarpus nubigena*), *Araucaria araucana*, *Aextoxicon punctatum, Escallonia spp.*, *Drimys winteri, Embothrium coccineum, Nothofagus dombeyi*-type, and vines (*Hydrangea serratifolia*). This spectrum documents the closed-canopy forest input into Lago Budi. To emphasize the presence of *Gomortega keule* tree in the pollen record (LB I-II), giving the first evidence in the palynological chilean records. Actually, *G. keule* grows in very small relict populations, only in coastal humid areas under Mediterranean and warm temperate climate-type, between 36-38°S (Le Quesne and Stark, 2006). Their presence in the Lago Budi pollen record reveals a major southern distribution during the Holocene, as well as their recent northern and fragmentary distribution can be associated with the land use changes in the area. Other tree species which show a similar trend are *Beilschmiedia sp.* and *Persea lingue*. The difficulty to separate these pollen types involves the fossil interpretation, however both species present a fragmentary distribution related to human interventions. The genus *Beilschmiedia* grows principally in coastal areas, between 32-36°S, associated with the similar climate conditions than *Gomortega keule* (Gajardo, 1994; Cabello, 2006; Cabello et al., 2006). *Persea lingue* present a major southern distribution, until 41°S, always associated with warm and humid climate conditions (Donoso and Escobar, 2006). *Beilschmiedia/Persea* taxa is also important during the next pollen zone (LB-III, 5-2.8 kyr BP), as well as the taxa from the preceding zone, and is remarkable the appearance of sclerophyllous taxa, like *Cryptocaria*-type and *Peumus boldus*. The last taxa are characteristics from Mediterranean-type climate, associated with less precipitation and more temperatures, suggesting a warm and drier period in Lago Budi record. During this pollen zone becomes important the non arboreal pollen taxa, principally Poaceae, Solanaceae, and Chenopodiaceae families, associated with particles of charcoal in the sediment. Its remark the presence of *Zea mays* pollen (<1%) at ~5 kyr BP, and their persistence in the area of Lago Budi. This pollen evidence grants the first evidence of human cultivation and possible landscape transformation in the local catchments. A recent modern *Zea mays* pollen/vegetation calibration suggest than maize pollen is underrepresented in modern sediment samples, where 1% maize pollen reflect 0.03 km^2 of local cultivation in central Chile (Gajardo, 2008). The same trend is observed in aerial pollen traps, and can be related to the high pollen size, between 60-90 µm (Fig. 7), and low dispersion, only 500-800 m (Madane and Millones, 2004). Thus, the presence of 1 or 2 pollen grains in the pollen slide evidence the crop cultivation in the catchment area.

The following pollen zones reach the same trends, associated with more charcoal particles and the increase of non arboreal pollen taxa until the present, where is possible to observe during the last centuries the exotic forest plantations (*Pinus radiata*), and the exotic grasses (*Rumex acetosella* and *Plantago sp.*) associated with Spanish and Chilean colonization in the Araucanian region (s. XIV - XIX), respectively.

3.6 Discussion and conclusions

Our results document the tectonic origin and evolution of Lago Budi in relationship to the changes of sea level, tsunami events, climate changes during the Holocene, and human impact in south-central Chile. The deposition of terrestrial base-sediments rich in organic matter, which show infinite ages (>41,2 kyr, >46,9 kyr) (Table 1), and the following date 12,2 kyr BP in old terrestrial deposits suggest a lack of deposition in the central part of the lagoonal basin (Fig. 2). This time span corresponds to the Last Glacial Maximum (LGM) which was defined in the Lake Region (~41°S) between 30-19 kyr BP (Denton et al., 1999). The central part of the lagoonal basin exhibit a striking unconformity and the presence of Paleogley soil are attributed to fluvial erosion in the local catchments during the LGM. During the MIS-2 (30-20 kyr BP) the relative sea level was 120 m lower than present, associated with extreme cold and wet climate conditions implying enormous glaciated areas in the both pole and high latitudes (Lamberk et al., 2002). The geomorphology of the coast in south central Chile was totally different than current time. In deed, Lago Budi supports the presence of riparian environment, as well as Lago Lanalhue and Lago Lleu-Lleu in Araucanian region (38°S) (Echtler et al. 2008). At 12.2 kyr BP continuous sedimentation started in Lago Budi area, recorded in the terrestrial samples characterized by lagoon sediments (Fig. 2), indicating the increase of sea level and/or the coastal margin uplift during that time. In Lago Budi record is clear the first Holocene marine transgression occurred at 9.4 kyr BP (16.5 m below the current msl, Fig. 2), and a subsequent steady sea level rise is registered with 6.8 m/kyr on average. The highest level during the mid and younger Holocene remained beneath +1,5 m above the current sea level, however there is no evidence for a higher level on the basis of existing data. Evidences for the HMT along the Chilean coasts vary conspicuously between 3-5 m above the present msl at ~30°S at 6.4 kyr BP (Ota and Paskoff, 1993) and up to 33 m above msl at Isla Mocha (38.4°S) at 5.8 kyr BP (Nelson and Manley, 1992). This contrasting data are possible if we considered the active coastal margin in south-central Chile, but still is necessary added more well dated, high resolution records to decipher the magnitude of sea level, related to the climate changes in the study area. The pollen record is dominated by typical temperate species from humid coastal areas in the Araucanian region, however during the HMT exhibits a mixture with more warm elements (actually northern distribution), like *Gomortega keule* and *Beilschmiedia sp*. The presence of these taxa can reflect an extralocal pollen input, but also is according with the global early-Holocene warming in central and southern Chile (e.g. Lamy et al., 2001; Abarzúa et al. 2004; Kaiser et al,. 2008). During the Holocene, an extremely rapid warming pulse of about 2.5°C at 8 kyr BP occurred in the Southeast Pacific Ocean (Kim et al., 2002). Pollen records from a central Chile (31-34°S) show open and herbaceous vegetation between 8 and ~5 kyrs BP (Heusser, 1990; Jenny et al., 2002; Villa-Martínez et al., 2003; Maldonado and Villagrán, 2002; 2006). The sediment records of Lago Lanalhue and Lleu-Lleu (38°S) indicate a long-term climatic trend with significant more arid conditions between 8 to 4.2 kyr BP (Stefer et al., 2008). The same trend was observed in south-central Chile, with the dominance of thermophilous taxa in temperate rainforest at 42°S between 10 and 7 kyr BP (Villagrán, 1988, 1985; Moreno, 2004; Abarzúa and Moreno, 2008). All these results suggest that the climate was dry and warm (~2°C) between 10 and 5 kyr in central Chile until 38°S by a northward shift of the ITCZ linked to the southward position of the STH and SW (e.g. Caviedes, 1972), or at least of its northern boundary (Kaiser et al., 2008) and representing the SW's "extreme interglacial mode" (Moreno and León, 2003). Climatological data suggest that the latitudinal position of the Southern Pacific Westerlies (SW) are strongly related to the strength of the Southeast Pacific subtropical high (STH) (Markgraf et al., 2002), which is in turn closely associated with the El Niño-Southern Oscillation (ENSO) (Rutllant and Fuenzalida, 1991). According the literature, during the early Holocene, ENSO was almost absent or with a low sigmal. At least, if ENSO was present, was principally characterized by La Niña event (Kaiser et al., 2008).

During the lagoonal phase in Lago Budi at least two regressive marine cycles are evident at 6 and 2 kyr BP. These regressive phases coincide with striking tsunami events, and are probably linked to seismic vertical movements (land uplift) during giant earthquakes recorded in southern Chile (Cisternas et al., 2005). In contrast with the adjacent areas north of Rio Imperial (Nahuelbuta Coastal Range segment) and south of Rio Calle Calle (Bueno Coastal Range segment) which show pronounced continuing Quaternary uplift of >2 m/kyr, the Lago Budi segment shows a quite stable position without major net-uplift/subsidence trends during the Holocene (Rehak et al., 2008).

Concomitantly, at ~5 kyr BP the pollen record revelas the presence of Mediterranean taxa (*Cryptocaria*-type and *Peumus boldus*) and cultivated families (eg. Chenopodiaceae, Solanaceae, Asteraceae, Fabaceae, and Poaceae). We emphasize the presence of maize pollen (*Zea mays)*, the decrease in arboreal taxa, and high sediment accumulation (colluvial terraces) in the surrounding Lago Budi dated at 5.1 kyr BP (Table 1). All these evidence are connected with the onset of human-disturbance regimes in Lago Budi area. Archaeological data documents settlements in Purén-Lumaco valley at ~7 kyr BP and more intense landscape transformation during the last 1 kyr (Dillehay, unpublished data). In Lago Budi raised and canalized fields have been documented as the first evidences in the Araucanian region (Dillehay et al., 2007). Hunters and collectors-human settlements in coastal Araucanian areas are abundant also since 7 kyr BP (Quiroz and Sanchez, 2004), probably supported by the warm early-mid Holocene conditions. In Chile the presence of maize in archaeological sites is quite sparse. Inclusive, maize pollen type is absent in all Chilean fossil pollen records, possible by the big pollen size and low dispersion (Madane and Millones, 2004; Gajardo, 2008). The archaeological site Las Morrenas in central Chile (33°S) reveals the presence of maize during the late archaic (after 3.2 kyr BP) (Planella et al. 2005), also maize pollen is registered in Isla Santa Maria (37°S) at ~1 kyr BP (Haberle unpublished data). In South America, phytoliths analysis in coastal Ecuador (~3°S) document the presence of maize around 6 kyr BP in association with squash cultivation. In Amazonian Ecuador at 5.3 kyr BP, maize is associated with the increased disturbance taxa and charcoal particles (Pearsall, 2002). However, these old dates and methodologies are strongly discussed suggesting only 2.2 kyr BP for the introduction and largely ceremonial use of maize in Ecuador (Staller, 2003). Same ages are observed in the Peruvian Andes (~7°S) where maize pollen first occurred at 2.6 kyr BP, indicating a minimum age for local agriculture (Weng et al., 2006). Our results in Lago Budi, as well as the data from Purén-Lumaco valley (~38°S) (Abarzúa in prep) in south-central Chile reveals a new minimum age for maize cultivation and/or ceremonial use at ~5 kyr BP. Preliminary studies suggest that the varieties of maize (*Zea mays*) recovered from excavated sites in the Purén-Lumaco valley have probable morphological affinities with central Andean varieties, like Bolivia, Peru and north Chile (Dillehay, 2007). The large-scale transformations of Lago Budi and Purén-Lumaco areas (Fig. 1) reveal a late prehistoric complexity not documented before now in the southern cone of South America.

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Figures and tables

Figure 1: Study area: Superior links map shows the ITCZ, STH, and SWW during July and January in South America. Inferior link altitude map shows the Nahuelbuta Coastal Range in south-central Chile. Right map shows the land use cover between 37-40°S in soth-central Chile, the study sites (Purén-Lumaco valley and Lago Budi), and the main cities.

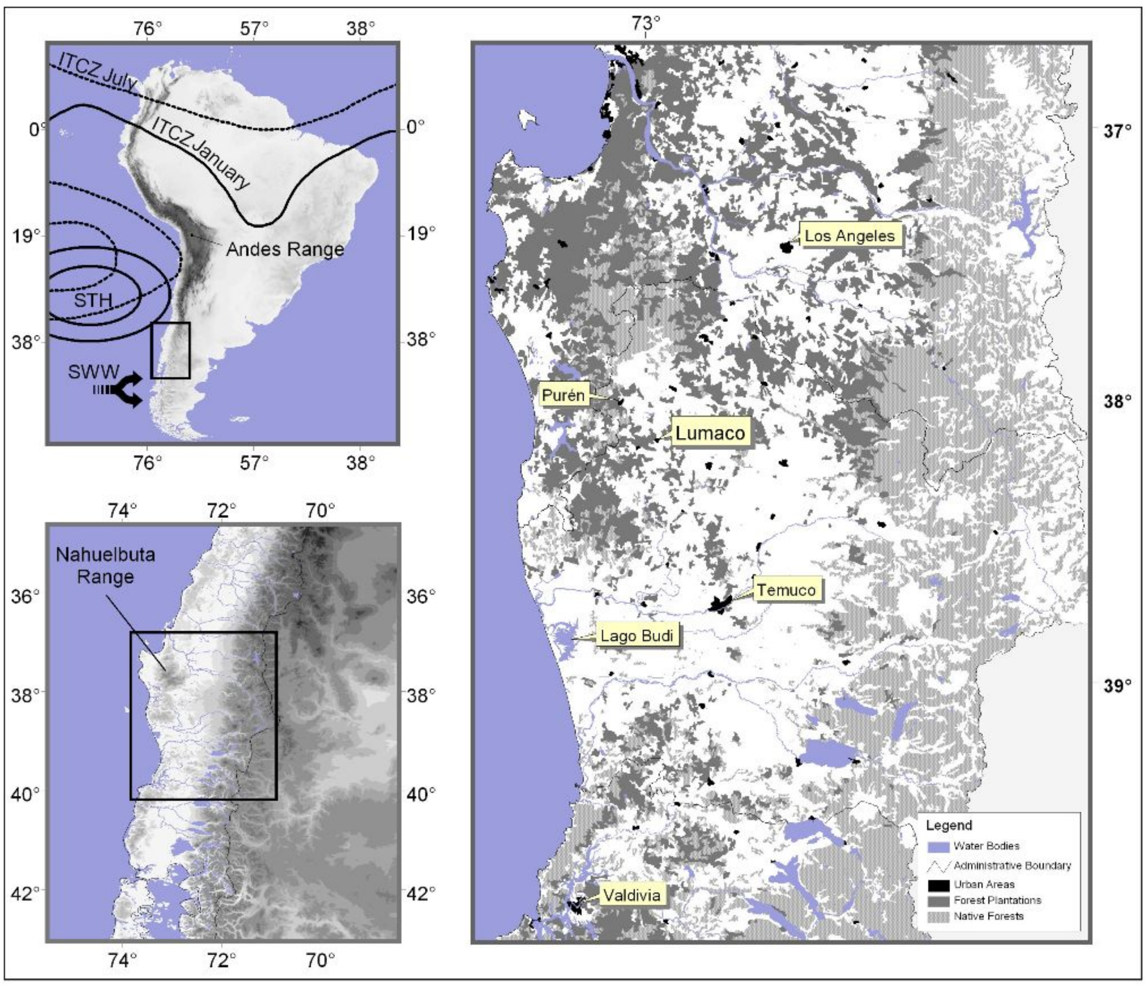


Figure 2: Lithology and calibrated dates from Lago Budi sediment cores (LB 1,3,4, and 10) and terrestrial sediments (PDO 1, 4). (From Wallner, 2008)

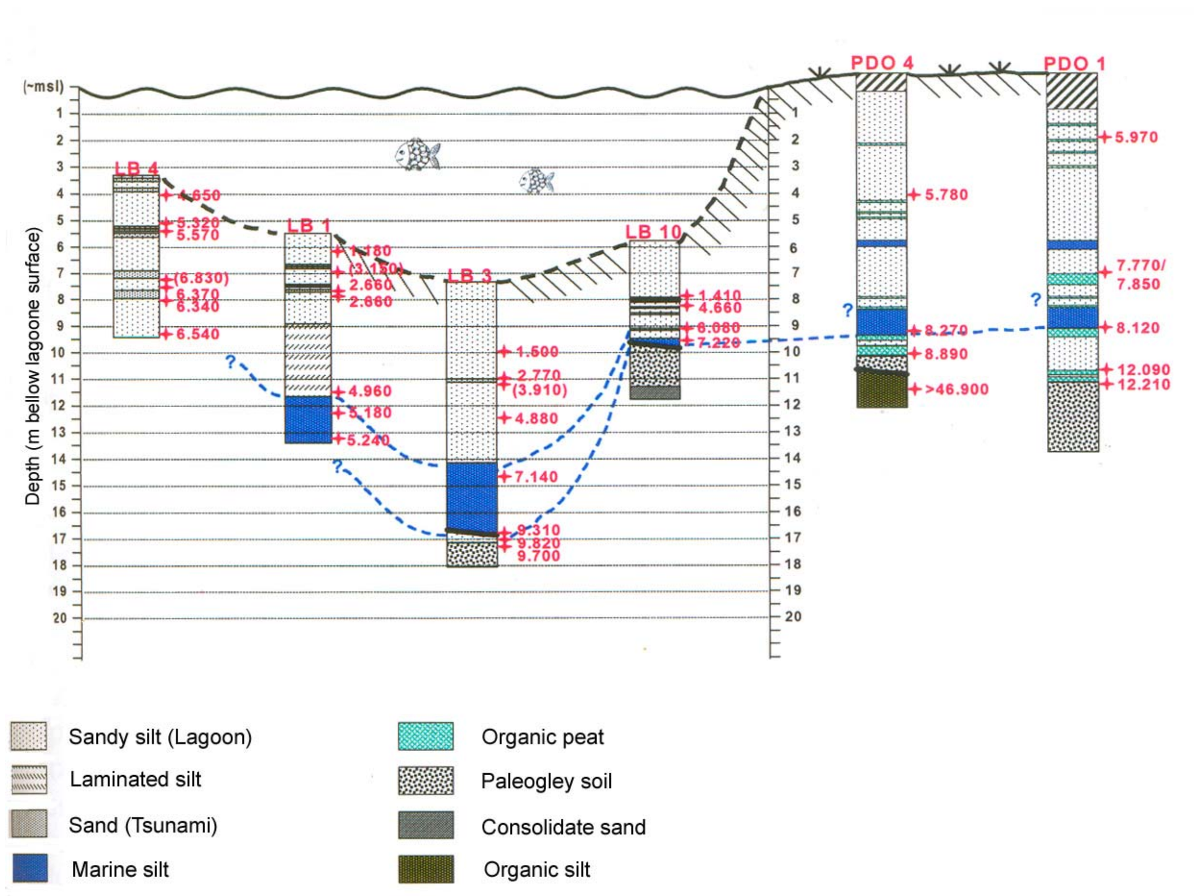


Figure 3: Lithology, Tsunami layers, and calibrated dates from Lago Budi sediment cores (LB 1,3,4, and 10). (From Wallner, 2008)

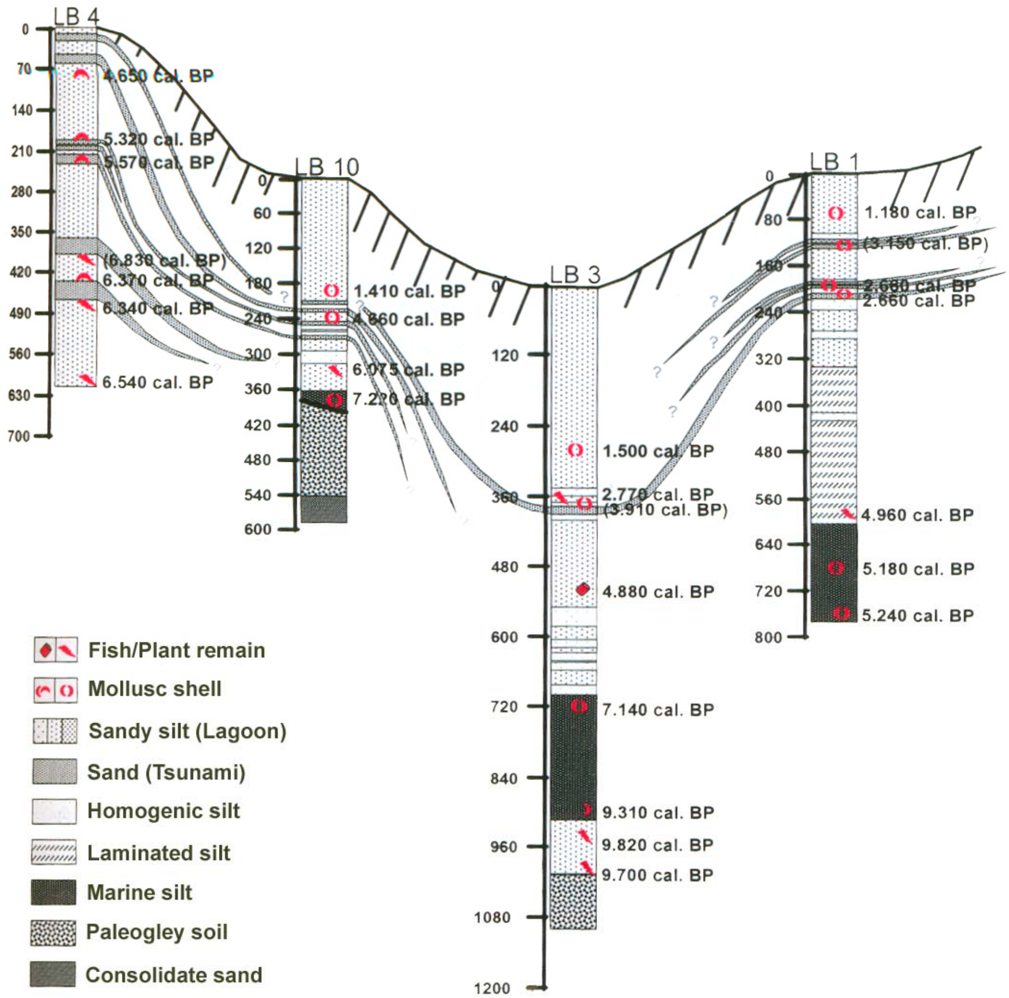


Figure 4: Magnetic susceptibility and calibrated ages of LB1/05 (superior) and BL3/05 (inferior) cores from Lago Budi. (From Wallner, 2008)

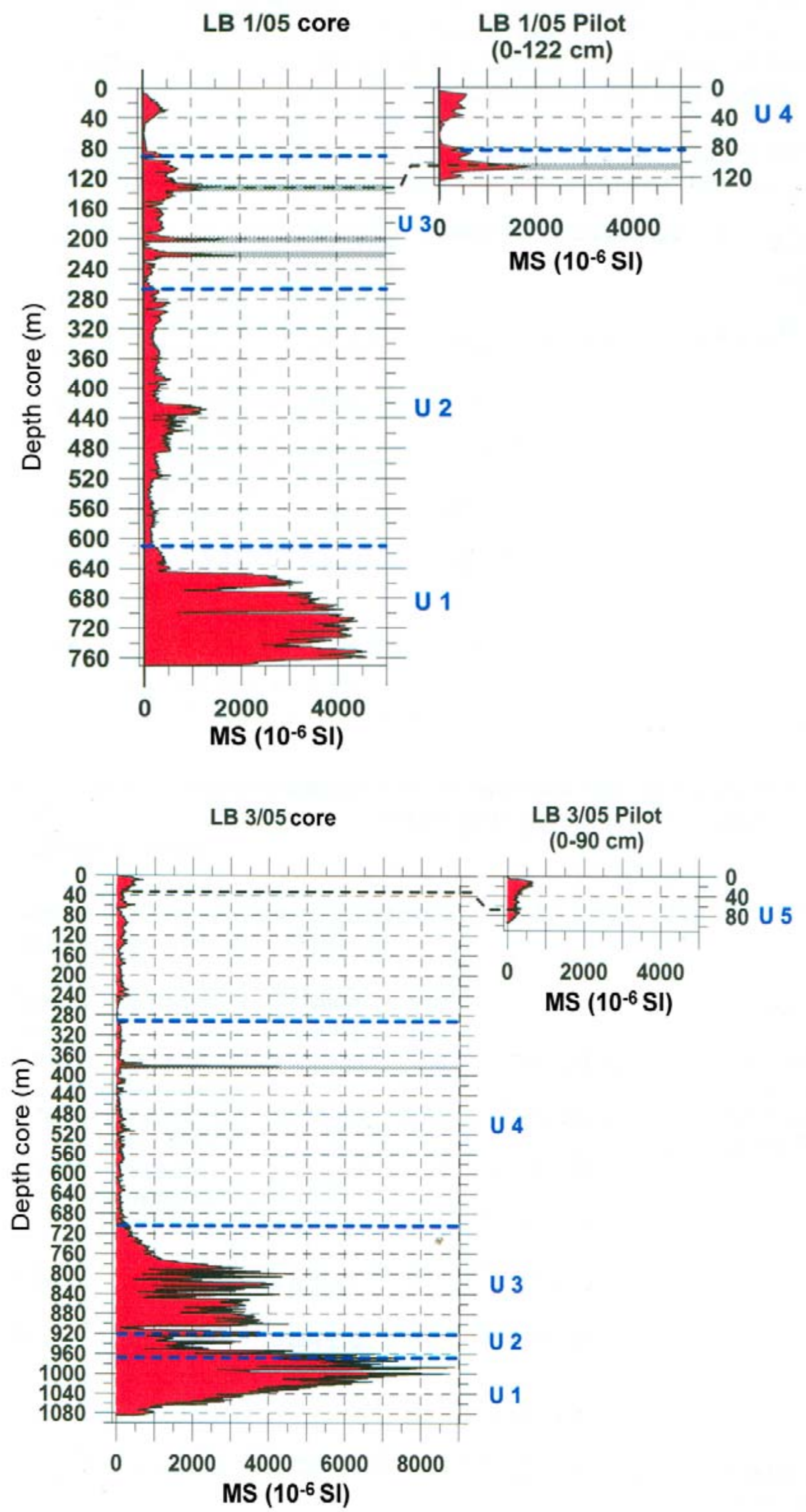


Figure 5: Seismic profile and LB 1/05 core from Lago Budi. To emphasize three seismic sequences characteristics of the sediments and four lithologic units. (From Wallner, 2008)

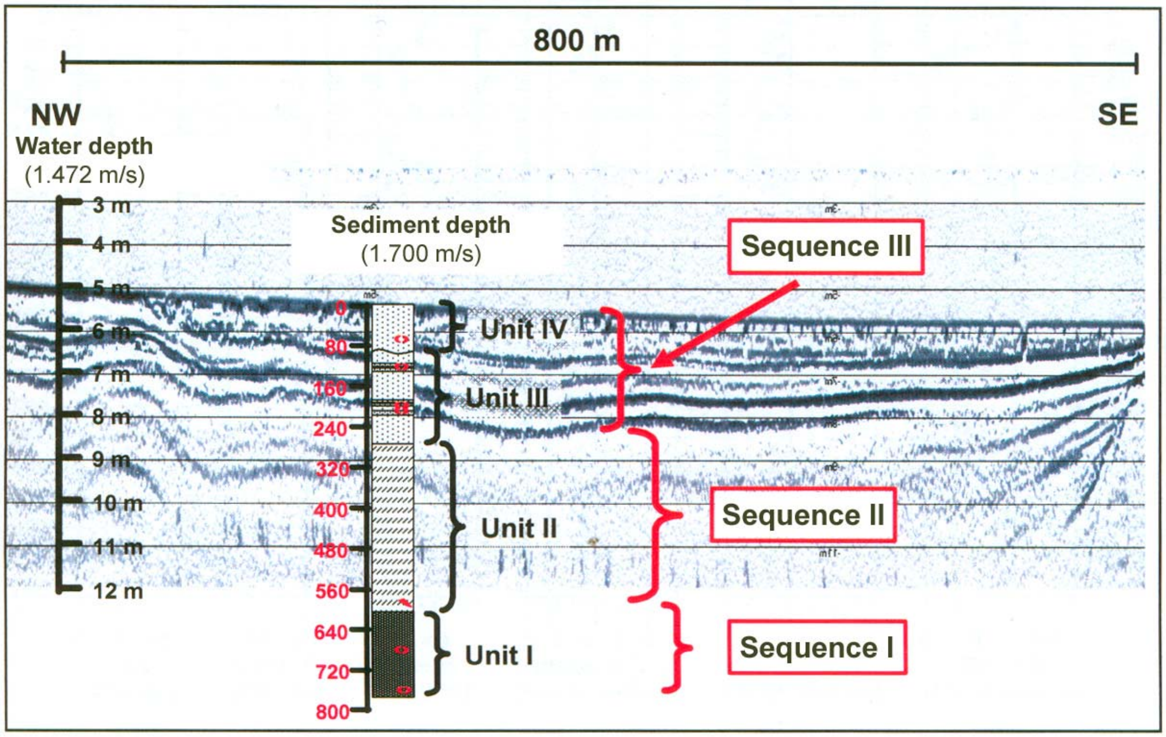
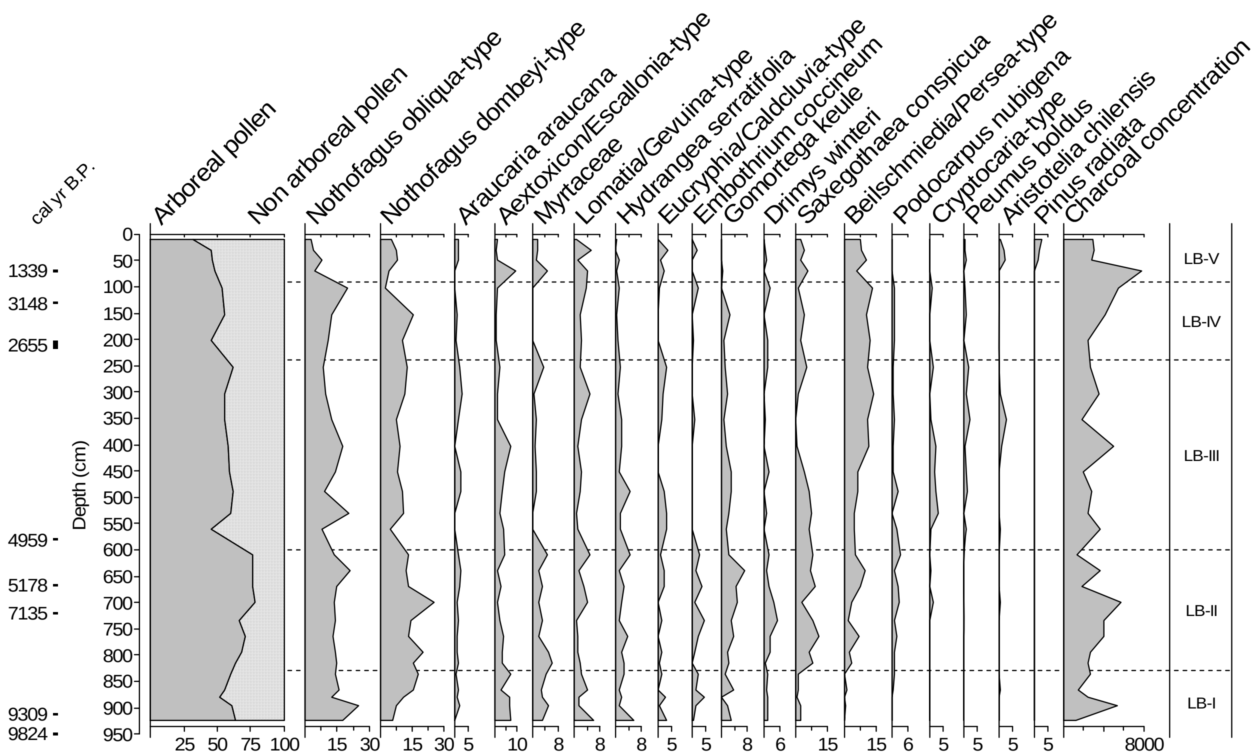


Figure 6: Summarize Lago Budi pollen record, calendar dates, and CONISS statistical analysis. Superior graph shows the arboreal pollen taxa (%) and micro-particles of charcoal concentration (particles cm^{-3}). Inferior graph shows the non arboreal pollen, spores, and algae taxa. Notice the differences in between X-axes.



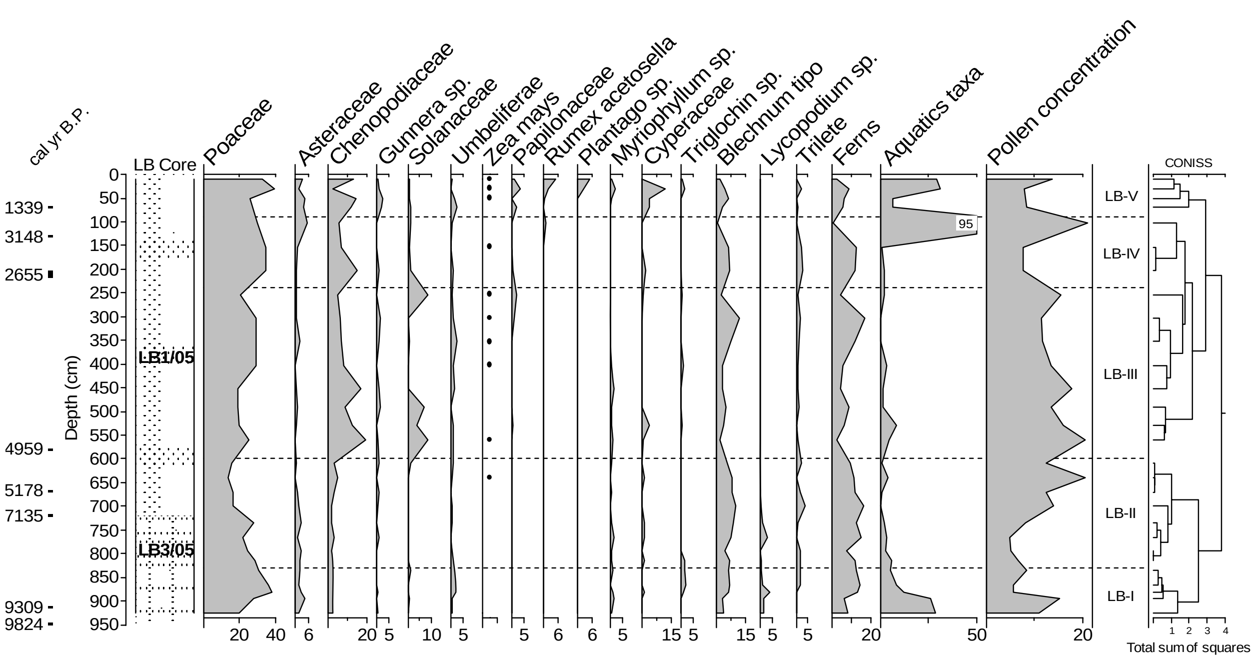


Figure 7: maize (*Zea mays*) pollen at 1000x magnification.

Table 1. Radiocarbon dating and theirs calibrated age from Lago Budi sediment cores. (From Wallner, 2008)

Lab. no.	Core	depth(cm)	Material	^{14}C yr BP	$\delta^{13}C$	cal yr BP
ERL10639	LB1/05	69	mollusc shell	1,645±53	-5.6	1339 (AD 766)
ERL10640	LB1/05	131	mollusc shell	3,302±55	-7.4	3148
Beta224874	LB 1/05	203	mollusc shell	2,910±40	-1.5	2655
Beta224875	LB 1/05	219	mollusc shell	2,910±40	-1.9	2655
Beta224876	LB 1/05	580	plant debris	4,440±60	-17.0	4959
Beta224877	LB 1/05	667	mollusc shell	4,890±40	+0.7	5178
ERL9204	LB1/05	762	mollusc shell	4,924±66	-0.2	5237
ERL10641	LB 3/05	284	mollusc shell	1,948±53	-2.6	1662 (AD 451)
ERL10642	LB 3/05	376	plant debris	2,673±56	-25.7	2770
ERL10643	LB 3/05	384	mollusc shell	3,933±60	-7.8	3912
ERL10644	LB 3/05	517	fish bone	4,651±63	-8.3	4879
ERL10645	LB 3/05	720	mollusc shell	6,625±66	-0.2	7135
ERL10646	LB 3/05	912	mollusc shell	8,667±70	-6.5	9309
ERL10647	LB 3/05	949	plant debris	8,759±170	-29.9	9824
ERL10648	LB 3/05	973	plant debris	8,700±116	-28.2	9697
Beta245049	Koll	230	charcoal	4730±40	-26.3	5177
ERL9210	PDO 2	1510	wood	>41,200±14.200	-27.3	-
ERL9213	PDO 4	1192	wood	>46,900±20.000	-30.5	-

Table 2: Summarize age and pollen assemblage in each pollen zone from Lago Budi pollen record.

Pollen zone (cm depth)	Age (cal yrs BP)	Pollen assemblage	Percentage sum
LB-V (0-90)	Last 1500	Poaceae – Chenopodiaceae – *Beilschmiedia/Persea*-type	50%
LB-IV (90-240)	1500-2800	Poaceae – *Nothofagus obliqua*-type – *Beilschmiedia/Persea*-type	60%
LB-III (240-600)	2800-5000	Poaceae – *Nothofagus obliqua*-type – Chenopodiaceae	47%
LB-II (600-830)	5000-8300	Poaceae – *Nothofagus dombeyi*-type – *Nothofagus obliqua*-type	52%
LB-I (830-950)	8300-9800	Poaceae – *Nothofagus obliqua*-type – *Nothofagus dombeyi*-type	59%

CAPÍTULO 4

DISCUSIÓN GENERAL

Los ecosistemas forestales están sujetos a modificaciones derivadas de factores que forman parte de su dinámica ecológica y a cambios derivados de la acción humana. Su acción ha ejercido y ejerce variados efectos dependiendo del tamaño de las poblaciones, del nivel de desarrollo tecnológico y de su actitud frente a la naturaleza. Los bosques de la Región de la Araucanía son un claro ejemplo de las modificaciones del paisaje a partir de factores relacionados con el clima y el impacto humano. Diversos son los autores que describen el paisaje araucano antes de la llegada de los españoles. Encina (1940-1952) por ejemplo, se refiere incluso a una población de 1.070.000 indígenas entre Aconcagua y Chiloé (citado en Gasto, 1979), los cuales utilizaban el fuego para cocinar, calentarse y abrir campos de cultivo donde crecían papas, maíz, quinoa, teca, madi, entre otros (e.g. Bullock, 1958). De esta manera, los bosques del tipo Roble-Laurel-Lingue (*Nothofagum-preseetum*; Schmitsüsen, 1956) de la Depresión Intermedia habrían sido los más explotados por las comunidades indígenas y posteriormente, por las sucesivas colonizaciones y el desarrollo agrícola moderno (españolas, italianas, suizas, alemanas y chilenas) provocando profunda erosión en los suelos de la región (Cunill, 1974; Donoso, 1983). Los valles intermontanos y costeros de la Cordillera de Nahuelbuta (38°) fueron y están densamente poblados por el pueblo Mapuche. El paisaje está caracterizado por la intensa explotación humana, escasos son los remanentes o fragmentos de bosque nativo en el área y cada vez aumentan las plantaciones de especies exóticas, tales como *Pinus radiata* y *Eucalyptus spp.,* generando serias consecuencias en la población (e.g. cambio del uso del suelo, erosión y disminución de la cantidad de agua bebestible) (Iroumé et al., 2005). Es un área que a su vez representa una importante transición climático-vegetacional (Mediterráneo-Templado). Tal transición se debe principalmente al efecto combinado entre la celda de alta presión (Anticiclón del Pacífico), al régimen de precipitaciones del cinturón de vientos del oeste y al efecto estacional de El Niño Oscilación del Sur (Di Castri and Hajek, 1976; Rutland and Fuenzalida, 1991; Montecinos & Aceituno, 2003; Garreaud et al., 2008).

El registro sedimentológico, geoquímico, palinológico y de carbón fósil obtenido en el valle Purén-Lumaco abarca los últimos 26 mil años, evidencia uno de los posibles refugios glaciales para los bosques templados lluviosos (bosques de *Araucaria-Nothofagus*), asociados a un paleolago en el área y condiciones frío-húmedas características del Ultimo Máximo Glacial (UMG, 30-19 ka AP. Kaiser et al., 2008). El debilitamiento del Anticiclón del Pacífico permitió un desplazamiento hacia el ecuador del margen norte del cinturón de vientos del oeste y de la circulación circumpolar Antarctica, implicando mayores precipitaciones y menos temperaturas en Chile central (Lamy et al., 2001).

Durante el UMG, el Lago Budi constituía un río, el nivel del mar se encontraba ~120 m mas bajo que su nivel actual (Lamberk et al., 2002). A partir de 12 mil años AP comienza una tendencia sostenida de calentamiento climático, comienza la sedimentación en el Lago Budi y el paleolago en Purén-Lumaco desaparece, formándose el sistema complejo de cuencas pantanosas caractísticos del valle.

Entre 9 y 7 mil años AP se registra el periodo más cálido en ambos registros, en Lago Budi es afectado por la Transgresión Marina de Holoceno temprano (Ota and Paskoff, 1993), reconociéndose en ese momento una mezcla de elementos templados y mediterraneos en el área. En Purén-Lumaco se evidencia el desarrollo de elementos cálidos del bosque templado, abundancia de partículas de carbón como indicadoras de eventos de fuego y la presencia de una turba en los sedimentos hasta 5 mil años AP. Todas estas evidencias apoyan la hipótesis del periodo cálido y seco del Holoceno temprano em Chile central y sur, asociado a la intensificación del Anticiclón del Pacífico y debilitamiento del aporte de lluvias del cinturón de vientos del oeste (e.g. Kaiser et al., 2008).

Por primera vez en Chile, ambos registros de polen (Lago Budi y Purén-Lumaco) evidencian la presencia de polen de maíz (*Zea mays*) a partir de ~5 mil años AP, apoyando el inicio de prácticas agrícolas y las interpretaciones arqueológicos de la Región de la Araucanía. También se registra la presencia de familias típicamente utilizadas en cultivos agrícolas, como Poaceae, Asteraceae, Chenopodiaceae y Solanaceae. La presencia combinada de elementos esclerófilos y templados, posiblemente es consecuencia de una variación de mediano plazo en los montos de precipitación estival, propia de la transición mediterránea-templada, que caracteriza actualmente el área de estudio.

Los registros sedimentarios son una herramienta excelente para describir cambios ambientales asociados una cuenca, sin embargo, las tasas de sedimentación no suelen ser constantes en el tiempo. Ambos registros, Lago Budi y Purén-Lumaco, presentan periodos en los cuales la sedimentación fue nula o muy baja, lo cual implica una baja resolución temporal y dificultad en la interpretación de la variabilidad ambiental. En términos de miles de años, es posible realizar un modelo de cambio ambiental, pero resulta inadecuado extrapolar este modelo a variaciones ocurridas en siglos o decenas de años.

Un modelo cronológico basado en abundantes fechados radiocarbónicos permite robustecer las interpretaciones paleoambientales. En el registro de Lago Budi se obtuvieron suficientes dataciones que revelan los tiempos de cambios del nivel del mar y tsunamis ocurridos en las costas de Chile centro-sur durante los últimos 9 mil años. Para el caso del registro de Purén-Lumaco la menor cantidad de dataciones radiocarbónicas realizadas permiten hacer inferencias a una escala milenial, pero difícilmente a una escala de siglos. Estos modelos, a pesar de sus limitaciones, son comparados con las tendencias de cambio climático aportadas por otros registros (terrestres, marinos y de hielos) mejor datados a nivel local, regional y global.

Futuros registros son escenciales para la comprensión de cambios climáticos durante el Cuaternario, asi es de esperar la integración de registros paleoambientales con la arqueología y antropología presente en un área determinada. De esta manera la comunicación de los nuevos hallazgos es profundamente necesaria para que el conocimiento pueda ser utilizado en futuras proyecciones, planificaciones y desarrollo a nivel local, regional y de país.

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