Tracking abrupt climate change in the Southern Hemisphere: a seismic stratigraphic study of Lago Cardiel, Argentina (49°S)

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ABSTRACT

Lake sediments from a closed basin in southern Patagonia (Argentina) provide a continental archive with which to reconstruct climate change and to test the interhemispheric synchroneity of abrupt events. High-resolution sub-bottom seismic profiles of Lago Cardiel indicate substantial lake-level changes since the late Pleistocene, which were identified and dated in a series of long piston cores. These data allow the reconstruction of the regional water balance at 49°S since the late glacial. The seismic stratigraphy reveals a dry late glacial climate with a desiccation of the basin around 11 220 yr BP (^{14}C). Lake level rapidly increased by 135 m at the Holocene transition. Following the early Holocene highstand at + 55 m, lake level never dropped significantly below modern level. The palaeoclimate changes implied by the Lago Cardiel record are out-of-phase with those implied by records from tropical South America and demonstrate considerable latitudinal asynchroneity in the climate evolution of this continent.

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Introduction

Long lacustrine records from the Southern Hemisphere are required in order to test ongoing controversies concerning the occurrence and hemispheric synchronicity of palaeoclimate changes, in particular of abrupt events (e.g. Markgraf, 1991, 1993b; Ariztegui *et al.*, 1997; Bard *et al.*, 1997; Blunier *et al.*, 1998; Broecker, 1998; White and Steig, 1998; Markgraf *et al.* 2000). Lago Cardiel, Argentina, at 49°S, is a hydrologically closed, deep lake system, decoupled from glacial or meltwater input, in the very arid, but sensitive, rain-shadow west of the Andes. Within the framework of an international collaborative study (Patagonian Lake Drilling Project, PATO/PaLaTra[1]) and part of the Pole-Equator-Pole initiative (PEP 1), a seismic study and a coring campaign of the lake basin were undertaken, resulting in the first continuous record of late glacial-to-Holocene lake-level changes in this high southern latitude.

Lago Cardiel is located on the Patagonian Plateau (Fig. 1) at an elevation of 276 m a.s.l. The shape of the basin is near-circular, with a diameter of ≈ 20 km and a maximum water depth of 76 m. The lake sits in a tectonic depression of deformed Cretaceous shales and flat-lying Tertiary volcanics that outcrop in the watershed (Feruglio, 1950; Heinsheimer, 1959). The modern climate is characterized by a mean annual precipitation ranging from about 150 mm near the lake to a maximum of 500 mm in the catchment area, and a mean annual temperature of about 8.5 °C with prevailing winds from the west. Like many closed lakes in Patagonia, Lago Cardiel has been receding since 1940 (Stine and Stine, 1990).

Galloway *et al.* (1988) and especially Stine and Stine (1990) identified and dated Lago Cardiel highstands using radiocarbon methods on palaeoshoreline deposits. These studies documented the sensitive lake-level responses of this closed basin to changes in the evaporation/precipitation balance. The highest Holocene lake stand is dated after 9800 yr BP, when the lake reached an elevation of 55 m above today's level (Stine and Stine, 1990). A mid-Holocene [around 5130 yr BP] and four minor late Holocene lake-level highstands have also been documented. However, without data on the subaqueous geology, lake levels lower than modern have so far not been discerned.

Methods

A major seismic and coring campaign was carried out in October/November 1999 using a specially constructed steel-hulled catamaran. The seismic survey comprised a dense grid of ≈ 140-km high-resolution seismic lines (Fig. 1) using a 3.5-kHz profiling system. Approximately 40-km of additional seismic sections were acquired with a stronger 1–12 kHz GEOPULSE™ boomer source. Seismic profiles were digitally recorded in SEG-Y format using a nondifferential global positioning system (GPS). Processing of the seismic data included digital subtraction of constant shallow noise, a water bottom mute, and bandpass filtering.

The seismic data were used to select the locations for piston coring. A series of ten piston cores (up to 11 m in length) were recovered using the ETH-Kullenberg coring system (Kelts *et al.*, 1986). An additional core (CAR 98-2L) with a length of more 10 m was

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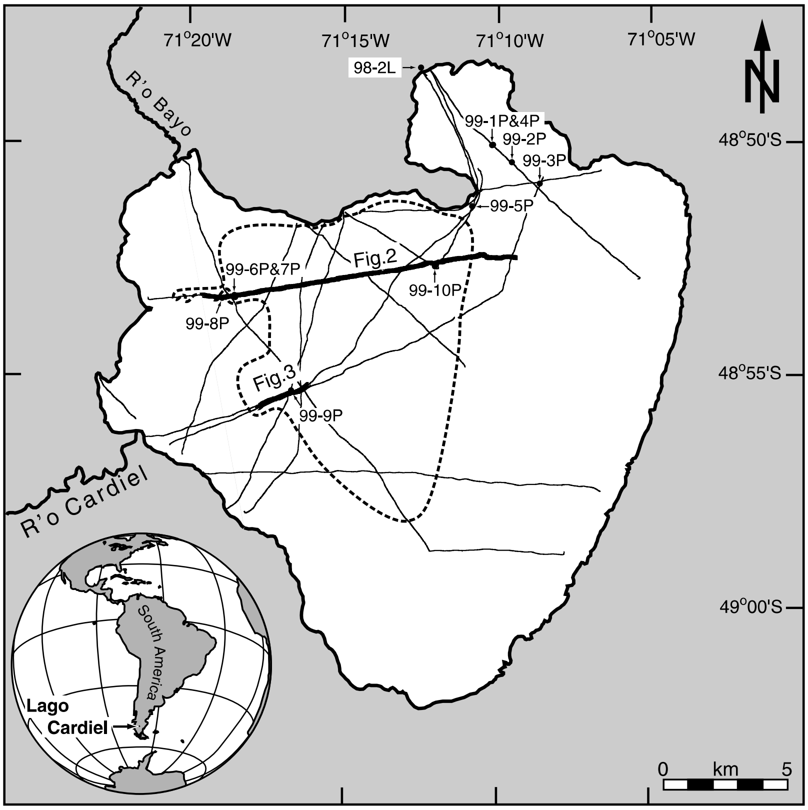

Fig. 1 Map of Lago Cardiel with locations of seismic lines and coring sites (labelled dots). The line sections displayed in this paper are in bold (Figs 2 and 3). The dashed line marks the maximal extent of the palaeolake at the end of the Pleistocene corresponding to a lake level 76 m below the modern level (sequence boundary IV/III).

retrieved along the northwestern shoreline using a square-rod Livingstone-type piston corer. All cores were scanned before opening in the ETH Limnogeology Laboratory, using a GEOTEK™ multi-sensor core logger to obtain petrophysical data. The cores were subsequently opened, photographed, described and sampled for ^{14}C-AMS analyses. All presented age data are uncalibrated radiocarbon ages.

Seismic sequence stratigraphy

Acoustic penetration of up to 60 m allowed discrimination of six major seismic sequences (I–VI; Figs 2 and 3). The top of Sequence VI, the acoustic basement of the present study, can be traced throughout the basin. Seismic penetration into Sequence VI was limited to the uppermost 5–15 m and revealed reflections with varying dip-directions (up to 3°). The contact between Sequence VI and the overlying units is unconformable (Fig. 2). Sequence V appears only along the southwestern margin of the basin as a mostly transparent unconformable wedge < 16 m thick (Fig. 3). Sequence IV comprises a package, < 21 m thick, of parallel, horizontal reflections of variable amplitude. All reflections within Sequence IV are laterally onlapping Sequence VI, or, where present, Sequence V (Figs 2 and 3). A sharp, high-amplitude reflection at the top of Sequence IV marks the maximum lateral extent of this sequence that is confined to the deeper parts of the basin and covers less than a quarter of the modern surface area of the lake (dashed line extent in Fig. 1). Sequence III overlies IV conformably but extends laterally with rather uniform character and thickness (~ 6 m) over the modern basin (Fig. 2). The seismic sequence appears relatively transparent, with some faint parallel reflections to the west. The upper boundary is a narrow-spaced, high-amplitude double reflection. Sequence II displays well-defined internal reflections that document a gentle wedging out from a thickness of 9 m in the east to a few cm in the west (Fig. 2). Sequence II is transitional in character between the upper and lower sequences. The upper sequence boundary is defined by a single, medium-amplitude reflection. The top of Sequence II appears truncated to the west and is downlapped by Sequence I, which displays an even stronger westward wedging of the sediments, with a 18-m-thick package in the east becoming extremely condensed or absent in the west (Fig. 2). Sequence I is imaged by well-stratified, regular and thin-spaced, internal reflections. In all the seismic profiles, no evidence for recent active faults or deformation is present, pointing towards a stable neotectonic situation.

Lithology and chronology of the cores

The core records were used to date the seismic sequences. The uppermost part of Sequence VI was cored only at two sites (Core CAR 99-8P, Core CAR 99-4P) where the overlaying sequences are strongly condensed. Core CAR 99-8P (Fig. 2, left side) yielded 10 cm of coarse sandy clay with decomposed (carbonized) plant remains and altered volcanic fragments. In the northeastern bay of the lake, Core CAR 99-4P (Fig. 1), bottomed in silty clay with intercalated sand layers containing quartz, feldspar and weathered volcanic grains. Neither lithological nor chronological data are available for Sequence V. The upper 2.5 m of Sequence IV was recovered in Core CAR 99-7P (Fig. 2, left side). The lithology comprises banded, light greenish-grey silty clays that grade into a metre of dark monosulphide-pigmented clay. The radiocarbon age of abundant plant macrofossils (*Ruppia*) at the base of Core CAR 99-7P is 12 340 ± 135 yr BP (Table 1). The sequence boundary IV/III is marked by coarse sand layers intercalated with layered clays, woody debris and plant fragments. A piece of wood from this interval was dated to 11 220 ± 85 yr BP. The base of Sequence III at 53 m below the modern level was dated in Core CAR 99-4P to be 9810 ± 100 yr BP. Another minimum age for the transgression

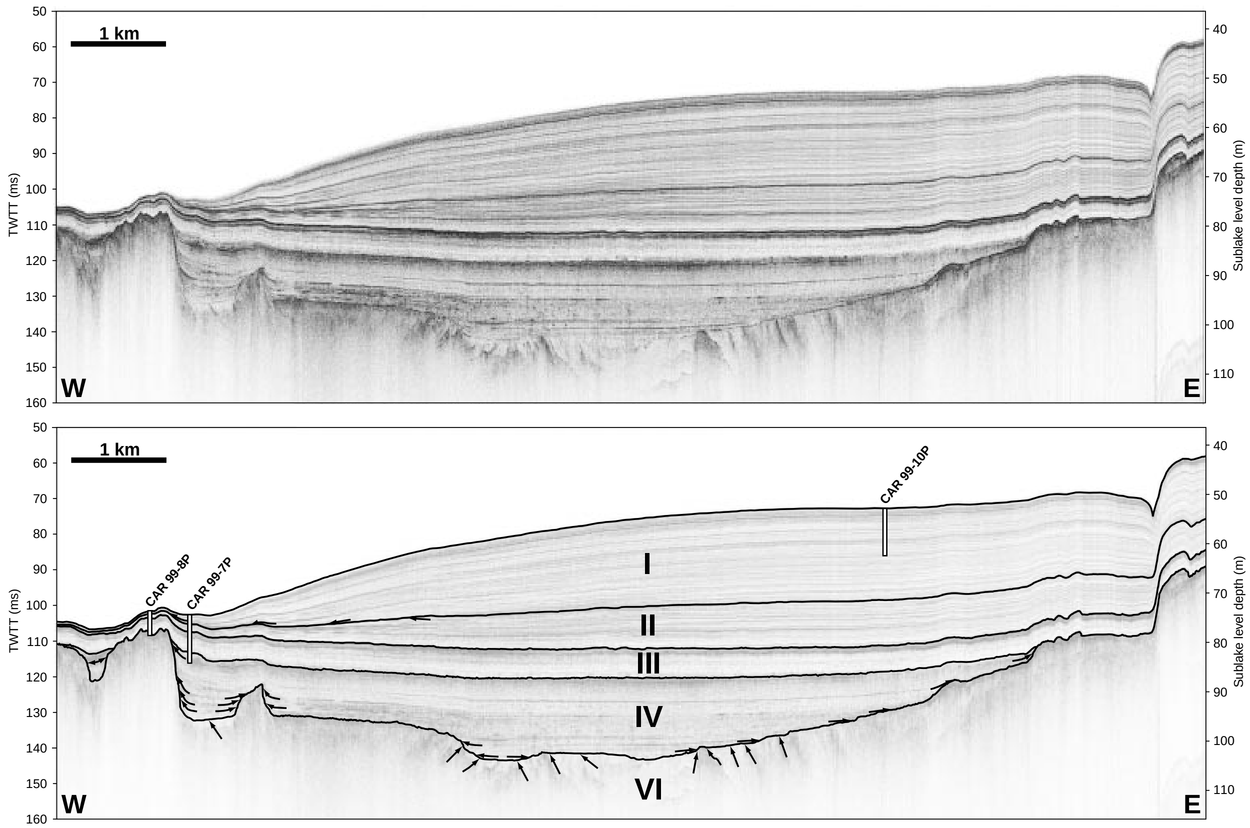

Fig. 2 Processed 3.5 kHz E–W seismic section across the northern part of the central lake (see Fig. 1 for location) as both uninterpreted (above) and interpreted (below). Seismic sequences are indicated in roman numbers; reflection terminations as black arrows and coring locations are labelled. TWTT, two-way traveltime in milliseconds. Depth conversion based on a P-wave velocity of 1450 m s^{-1}.

was determined in the Livingstone Core CAR 98-2L (Fig. 1), which penetrated into Sequence III near the modern shoreline elevation. A piece of wood embedded in lacustrine sediments at a total core depth of 626 cm was dated at 10 230 ± 65 yr BP. Sequences II and I consist of cm-scale banded silty clay with variable contents of authigenic carbonates. Sequence boundaries II/III and I/II are delineated by tephra layers of a few cm thickness, which also outcrop embedded in lacustrine sediments near today's shoreline. The sources of these two tephras have been identified microscopically as the Hudson 1 event [6700 yr BP; Stern, 1991] and one of the NAVZ (Northern Austral Volcanic Zone) volcanic events [3010 yr BP], respectively. These seismic sequence boundaries are identified clearly in the petrophysical logs (Fig. 4) allowing a precise core-to-seismic correlation to be made.

Reconstructed lake history

The seismic and core data were used to reconstruct past lake-level fluctuations in Lago Cardiel during the late Pleistocene and the Holocene (Fig. 5). The smoothly dipping reflections within Sequence VI may represent either the Cretaceous/Tertiary claystone basement or an earlier lacustrine phase. The coarse lithology and unconformity at the top of Sequence VI indicates a significant period of desiccation. The age and duration of this interval are uncertain. Additional seismic investigations in the near future using an air-gun source should better clarify the origin of Sequence VI. The geometrical shape of Sequence V and position in front of the modern inlet of Río Cardiel suggest that this sequence may have been an alluvial fan deposited during this desiccation period.

Subsequently, the formation of the modern lake occurred in the centre of the basin. The onlapping geometry of Sequence IV and the occurrence of the shallow aquatic plant *Ruppia* indicate a shallow lake with slightly varying water levels. Extrapolation of the two C-14 ages at the top and at 2.5 m depth from Sequence IV, assuming a constant sedimentation rate, suggests that Sequence IV was formed between 20 800 and 11 200 yr BP. The presence of wood and coarse sand at the top of Sequence IV indicates desiccation around 11 200 yr BP. There is no evidence for erosion of the upper surface of the sequence in the central part of the basin, suggesting that the dry interval was short. The date 11 200 ± 85 yr BP of this short-lived dry phase is nearly synchronous with the beginning of the Younger Dryas Chronozone (YDC) in the northern hemisphere (Peteet, 1995). However, the rapid lake level rise of up to 75 m

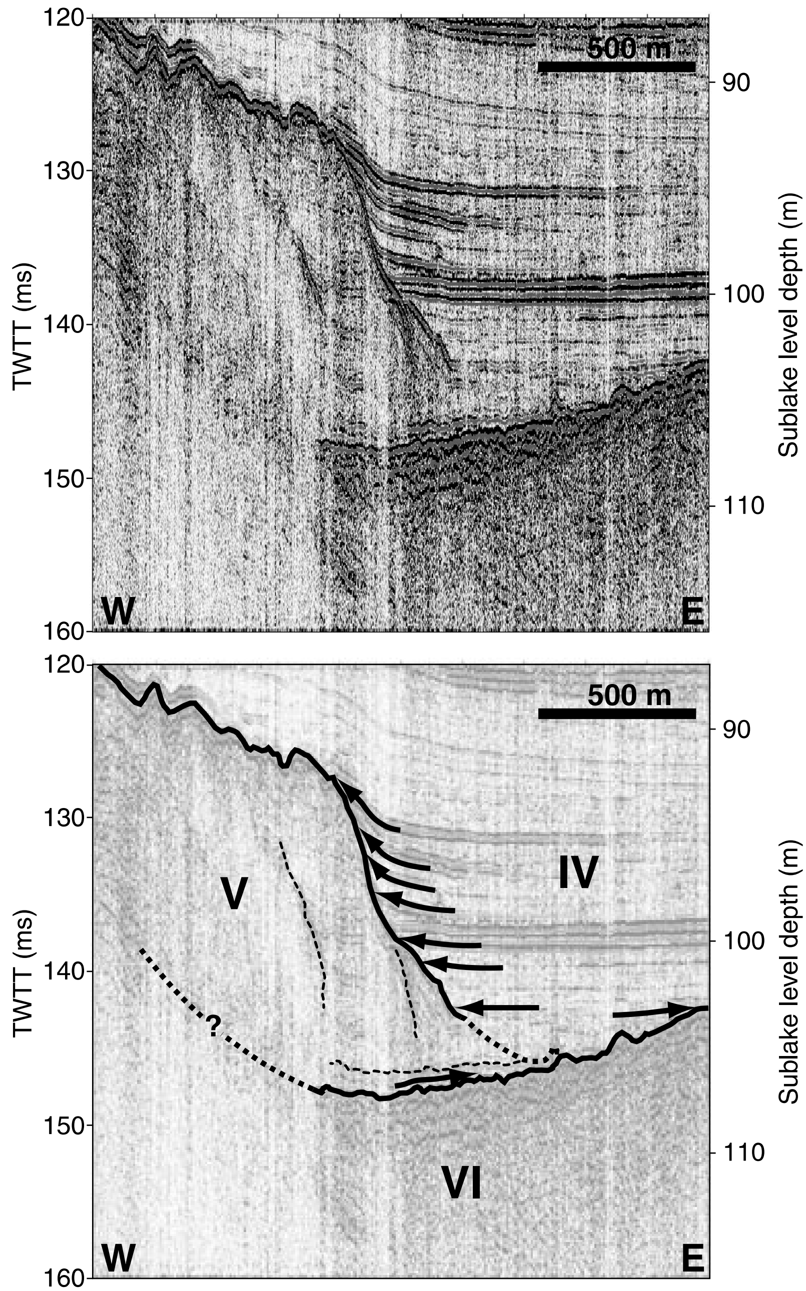

Fig. 3 Detailed section of a boomer profile near the SW basin margin illustrating the prograding character of Sequence V over Sequence VI, and the onlap relationships of reflections from Sequence IV.

by 10 230 ± 65 yr BP thereafter indicates a wet interval during the remaining time of the YDC (Fig. 5).

The base of overlying Sequence III marks a rapid and massive lake-level transgression up to at least the modern lake level. At a sublake level of 53 m below the present level, the base of Sequence III, and thus the transgression, is dated at 9810 yr BP (Fig. 5). The C-14 date of 10 230 yr BP at the base of the Livingstone core CAR 98-2L is a minimum age for lacustrine conditions near the modern shoreline elevation. This transgression probably correlates with the shoreline at +55 m above modern lake level dated to 9650 yr BP (Stine and Stine, 1990). This implies a lake-level rise of over 135 m within a few hundred years.

Seismic data in the shallow lake areas show no evidence of erosion (except near the shore due to the wave action) throughout the Holocene and, thus, no signs of a major lowering of the lake level. The change in sedimentation pattern in the middle of Sequence II from a uniform drape to a focusing in centre of the lake (see left side of Fig. 2), suggests the onset of a circular current in the mid-Holocene. Strong winds induce a clockwise current transporting the sediment from the Rio Cardiel inflow to the central area of the basin.

The reconstructed lake-level fluctuations (Fig. 5) reflect changes in the regional water balance. The lowstand and the desiccation phases at the beginning, between and at the end of Sequence IV, are indications for dry climatic conditions prior to 11 200 yr BP covering probably the period of the Last Glacial Maximum. Pollen records in this region of Patagonia reveal an extremely arid climate during the end of Sequence IV (Markgraf, 1993a; Paez *et al.*, 1999) when the southern westerlies were located more

Table 1 Radiocarbon dates for cores taken from Lago Cardiel, Argentina

Core	Section	Section depth (cm)	AMS C14 age (yr BP)	$\delta^{13}C$ (‰)	Sample no.	Material
CAR 99-7P	0B	15.5–16.5*	3010†			NAVZ Tephra
CAR 99-7P	4	56–62*	6700‡			Hudson 1 Tephra
CAR 99-7P	9	55–59	11 220 ± 85	−24.3 ± 1.2	ETH-22124	Wood
CAR 99-7P	11	99–100	12 340 ± 135	−20.6 ± 1.2	ETH-22125	Ruppia
CAR 99-4P	5	61–62	9810 ± 100	−23.5 ± 1.2	ETH-22123	Ruppia and Chara macro rests
CAR-98-2L	–	626§	10 230 ± 65	−22.6	NSRL-11433	Wood

*Both tephras have been identified in core CAR 99-7P at depths shown in the table. †We dated the NAVZ tephra (Northern Austral Volcanic Zone) in an outcrop embedded in peat east of Lago Cardiel. ‡The Hudson 1 tephra was dated by Stern (1991). §Total depth (cm).

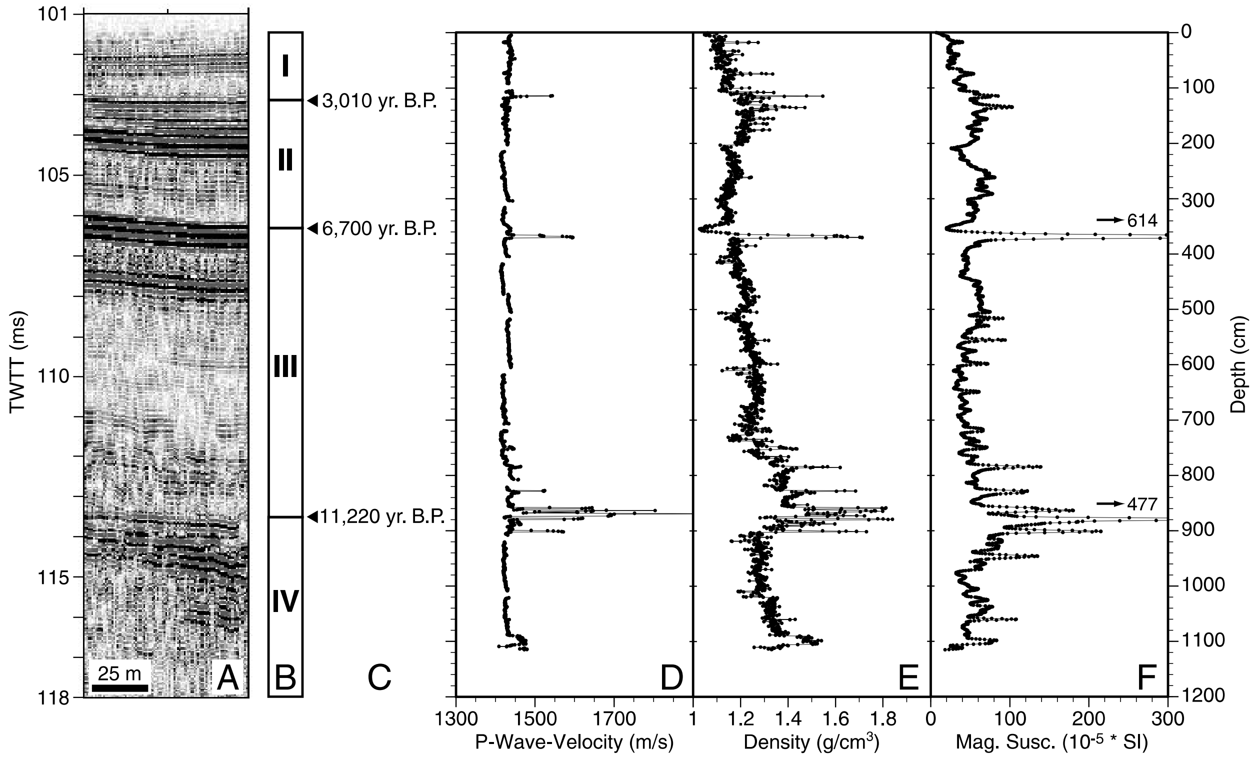

Fig. 4 Comparison of seismic response and petrophysical data (P-wave-velocity, bulk density and magnetic susceptibility) of piston core CAR 99-7P: (a) original seismic record at core site; (b) interpreted seismic sequence; (c) age of sequence boundaries (for details see Table 1); (d) P-wave velocity (m s^{-1}); (e) gamma-ray attenuation bulk density (g cm^{-3}); and (f) magnetic susceptibility (10^{-5} * SI). P-wave velocity and bulk density data from section ends were removed because end caps did not allow proper measurement procedure. The sharp petrophysical signatures of the key horizons allow a precise identification of the seismic sequence boundaries in the cores and provide excellent core-to-core correlation.

to the north. Such a pattern coincides with the enhanced Patagonian dust deposition on the Antarctic ice-shield during the Last Glacial Maximum that has been linked to a lower wash-out rate resulting from lower precipitation (Grousset *et al.*, 1992; Yung *et al.*, 1996). The Holocene transition shows a massive and rapid rise of about 135 m indicating an exceptional change in water balance. Maximum level of moisture for the early Holocene deduced from pollen analysis (Markgraf, 1993a; Mancini, 1998) supports the increase in lake level and indicates the onset of the southern westerlies at these latitudes (Markgraf *et al.*, 1992). Such an abrupt change during the late glacial–Holocene transition conflicts with recent pollen evidence that suggests a smooth transition at this latitude (Bennett *et al.* 2000). The start of drift deposition in the mid-Holocene was synchronous with the modern seasonal shift of the southern westerlies with a more northward position during austral winter (Markgraf *et al.*, 1992; Lamy *et al.* 2001). Comparing the Lago Cardiel record presented herein with other lake-level records along a N–S transect in South America, reveals major latitudinal differences (Ariztegui *et al.*, 2001; Bradbury *et al.*, 2001). An out-of-phase relationship for the tropical South America record from the Bolivian Altiplano (Baker *et al.* 2001) underlines the need of palaeoclimatic transects, such as the Pole-Equator-Pole initiative (PEP), to identify latitudinal changes in the climate behaviour of the past.

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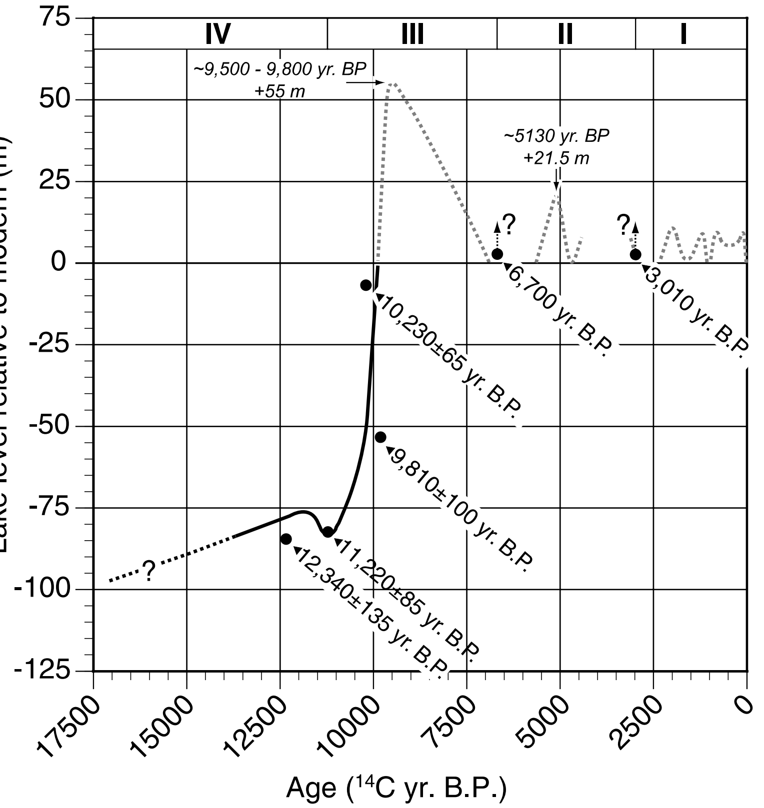

Fig. 5 Interpreted lake-level history of Lago Cardiel for the late Pleistocene and the Holocene based on presented seismic and lithological data combined with previously published records of higher lake levels than today (Stine and Stine, 1990). The top bar marks the timing of deposition for Sequence I to IV.

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