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Lake-level stratigraphy and geochronology revisited at Lago (Lake) Cardiel, Argentina, and changes in the Southern Hemispheric Westerlies over the last 25 ka

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ABSTRACT

Paleoshorelines around Lago (Lake) Cardiel in southern Argentina (S48.9°, W71.3°; ~275 m) record substantial changes in lake area over the past 25 ka. Our results combined with previous research show that during the last glacial maximum (or LGM, 23–21 ka), the lake stood at near modern levels, but had nearly dried up by ~13 ka. Between 11.3 and 10.1 ka the lake reached its highest point (+54–58 m) and greatest extent in at least the last 40 ka. Lake levels dropped thereafter and experienced two lower-lake periods: 8.5–7.5 ka and 5–3.3 ka; and two higher-lake periods: 7.4–6 and ~5.2 ka. In the last 3.5 ka, the lake has remained generally near or slightly above its present level.

The depth and surface area of Lago Cardiel are controlled mainly by precipitation onto the lake and surrounding catchment, air and water temperature, and wind-speed related to local strength of the Southern Hemispheric Westerlies (SHW). Our lake-level reconstruction combined with evidence from other studies suggest that on average the core of the SHW was located well to the north (<45°S) of the Cardiel basin during the deep lake phase associated with the LGM, and was well to the south (>55°S?) during the hydrologic maximum of Cardiel in the early Holocene. The lower phases of the lake at 20.0–11.5, 8.5–7.5, and 5.0–3.3 ka generally correspond to cold conditions in other records, when we infer that the SHW were strongly focused around the latitudes of Cardiel at 49°S.

1. Introduction

Lake records have made a fundamental contribution to our understanding of the Earth's changing moisture state during the Quaternary. Past fluctuations of a hydrographically closed lake constitute a clear record of changes in moisture balance within that lake's drainage basin. These changes, in turn, can be used in concert with other paleoclimatic records to infer past shifts in atmospheric circulation. For example, closed-lake systems and other records show that the temperate mid-latitudes in both hemispheres experienced episodes markedly wetter conditions than today during last full to late-glacial period 23–12 ka (Oviatt et al., 1992; Moreno et al., 1999; Benson et al., 2013; Torfstein et al., 2013). But there are also some intriguing exceptions to this global pattern, such as the subject of this study, Lago Cardiel in southern (48.9°S) South America (Fig. 1), where Stine and Stine (1990) showed that this lake rose to its highest levels 11–10 ka, markedly later than nearly all other lakes in the mid to high latitudes.

Similar to the study of Stine and Stine (1990), we focused on the evidence from paleoshorelines and other naturally exposed lake deposits to reconstruct changes in lake size. The study of shorelines has the advantage over core-based studies in that lake levels are not inferred through various proxies but by direct observation, visually where the shorelines are exposed, or seismically where paleoshorelines are submerged. The seismic evidence is especially vital at Lago Cardiel, because the lake today is closer to its hydrologic maximum than minimum, and therefore submerges most of the pre-modern shorelines (Gilli et al., 2005a). Lake area is easily determined in shoreline studies, a key term in hydrologic mass balance equations that allows reconstruction of precipitation required to grow or shrink lakes (e.g. Kutzbach, 1980; Placzek et al., 2013). The main disadvantage of shorelines is the incomplete nature of the record, caused by erosion of older deposits during lake transgressions and regressions. Hence, multiple sites must be

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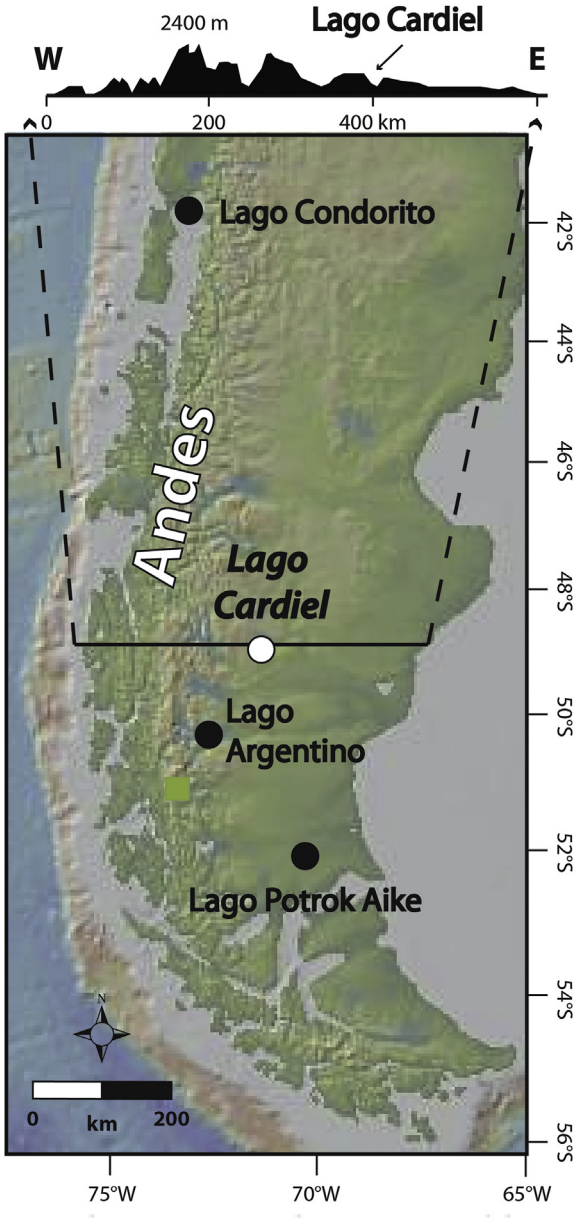

Fig. 1. Regional map and topographic profile showing the location of Lago Cardiel east of the Andes in southern South America. Also shown are Lagos Condorito, Argentino, and Potrok Aike discussed in the text.

studied in order to fill in the stratigraphic gaps. The shorelines at Lago Cardiel are well preserved and amply exposed, providing many opportunities for dating and stratigraphic replication.

The lake record at Lago Cardiel has already been studied from a variety of perspectives. Galloway et al. (1988) but especially Stine and Stine (1990), were the first to study the lacustrine deposits around Lago Cardiel. Stine and Stine (1990) focused on a fairly small area, mainly mapping and dating of deltaic deposits naturally exposed in the walls of stream cuts along the Rio Cardiel, Rio Bayo, and Arroyo Cerro Goro (Fig. 2). Terrestrial organic matter is abundant in these deltaic deposits, providing a firm basis for dating the lake-level fluctuations. Wenzens (2005) documented possible shorelines much higher than those identified by previous work, which he speculated were produced by discharge into the basin by a diversion of Rio Chico along the Tres Lagunas Valley (Fig. 2). In addition to shoreline deposits, another advantage of Lago Cardiel is that it has a rich subsurface record that can be synthesized with former lake-level findings, from two coring efforts (Gilli et al., 2001; Markgraf et al., 2003), and by seismic imaging (Gilli et al., 2005a; Beres et al., 2008).

Despite prior work, the exposed lake deposits around Lago Cardiel still constitute a prime opportunity for further study and replication, since there are many unstudied localities at multiple paleolake levels which record the details of the repeated rise and fall on lake. Our intent in this paper is to revisit Lago Cardiel, test and build on the lake level reconstruction of Stine and Stine (1990) and Wenzens (2005) with significantly more sampling and dating, merge the shoreline observations with that of the core records, and interpret the lake record in terms of an up-to-date understanding of the changing position or strength of the Southern Hemispheric Westerlies (or SHW) and changing temperature over the past 25 ka.

2. Lake Basin characteristics and modern climate

Lago Cardiel lies at 48.9°S and 71.2°W in Santa Cruz province of southern Patagonia (Figs. 1 and 2). The current lake level is at ~275 masl, and the lake is ~75 m deep, covers 370 km^2 in area, and occupies ~8% of the catchment basin encompassing ~4500 km^2 in area. High-standing plateaux or "mesetas" underlain by mostly late Neogene basalts (Ramos, 1982) hydrographically isolate the Cardiel basin from the Andes to the west. Reaching 1940m in elevation, the mesetas supply most of the recharge to the basin. Rio Cardiel, the main inflow into Cardiel today, heads in the mesetas, as does the smaller Rio Bayo. The Cardiel area has not been glaciated on the timescale of this study, perhaps since the Miocene (Wenzens, 2006).

The Lago Cardiel basin is cold due to its high latitude and interior position, with a mean annual temperature of 7.5 °C. It lies in the rain shadow of the Andes and so is quite dry, with a mean annual precipitation 210 mm/yr, even though Cardiel lies near the center of the modern SHW, due to orographic blockage of SHW precipitation by the Andes as well as perhaps the Southern Patagonian Ice Field to the west. Vegetation in the basin around the lake is treeless shrub steppe (or Patagonian steppe of Mancini et al., 2008).

Lago Cardiel, at 48.9°S, lies within the main belt of the SHW between 43 and 53°S. The core position shifts by ~ 5–6° seasonally. In summer, the SHW are more narrowly focused between ~50 and 55°S, and austral summer winds in Patagonia around the latitude of Cardiel are stronger. In winter precipitation belt expands northwards to ~35–40°S (Fig. 3; Lawford, 1996; Lamy et al., 2010), and with this broadening, winter winds slacken. Precipitation from moist marine air carried by the SHW makes the western flank and high passes of the Andes in southern Chile one of the wettest (mean annual precipitation = 4000–11,000 mm/yr) and cloudiest regions in the world (Schneider et al., 2003). The SHW lose most of their moisture before reaching the eastern side of the Andes where they descend and warm, reducing precipitation to ~210–250 mm/yr at Lago Cardiel (Heinsheimer, 1958). The dry but strong SHW dominate the "foehn" or "zonda" winds in this region, falling in the 4–8 m/s range (Heinsheimer, 1958; Schneider et al., 2003).

Garreaud (2007) has pointed out that strong SHW winds, at both low and high tropospheric levels, tend to promote precipitation on the windward side of the southern Andes but suppress it on the leeward side. Barros and Mattio (1978) and Stine and Stine (1990) appear to be the first to stress the importance of the Atlantic over the Pacific Ocean as the main source of moisture east of the Andes in eastern Patagonia. Further evidence presented in Schneider et al. (2003), Mayr et al. (2007), Moy et al. (2008), and most comprehensively in Agosto et al. (2015) demonstrate that in fact rain and snow falling east of the Andes at this latitude come dominantly from the Atlantic and are borne by easterly, not