The Lago Cardiel Basin, Argentina (49°S): Origin and evolution revealed by high-resolution multichannel seismic reflection studies


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The Lago Cardiel Basin, Argentina (49°S): Origin and evolution revealed by high-resolution multichannel seismic reflection studies

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Abstract

A multichannel, high-resolution seismic reflection survey was conducted with an airgun source in the closed lake system of Lago Cardiel, Argentina (49°S). As part of an ongoing study of interhemispheric correlations in climate change, it was intended to determine the maximum age and depth of the lake sediments and better understand the origin and evolution of the lake basin. In agreement with previous single-channel, 3.5-kHz surveys, six major seismic sequences throughout the lake's subsurface were mapped. The stronger seismic source of this study allows the deepest sequence (Sequence VI) to be interpreted as folded Cretaceous marls with a highly eroded surface. Further examination of this sequence reveals various stratigraphic signatures and mechanisms of the generally east–west orientation of tectonic compression. The nature and continuity of Sequence VI do not indicate a volcanic or impact-related origin of the lake. The original basin has a maximal depression of 154 ms (~114 m) deep beneath the modern lake surface and is overlain by an alluvial fan (Sequence V) of likely Pleistocene age in the western portion and late Quaternary lacustrine sediments (Sequences I–IV) everywhere else. The data confirm that southern Patagonia was dominated by extremely contrasting climatic conditions during the Quaternary.

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1. Introduction

Due to the technological advances of recent decades, high-resolution seismic reflection surveying has become useful in shallow-subsurface profiling offshore (Mosher and Simpson, 1999). This method has been a major tool for studying lake-level fluctuations and their paleoclimatic links (e.g., Johnson et al., 1987; de Batist et al., 1996; Abbott et al., 2000; Ariztegui et al., 2001). High impedance contrasts in sediments, continuity of images, and high surveying speed are among the strong points of this method. Moreover, it facilitates the determination of core locations and minimizes the number of necessary cores through the accurate mapping of lateral variations in seismic facies (e.g., Gilli et al., 2001).

As part of an ongoing study of interhemispheric correlations in climate change, Gilli et al. (2001, 2005) conducted high-resolution seismic reflection surveys in the closed lake system of Lago Cardiel, Argentina (Fig. 1), with 3.5-kHz and boomer seismic sources (i.e., single-channel). Their results reveal six major seismic stratigraphic sequences (I–VI, youngest to oldest) throughout the lake's subsurface. The combination of these seismic data with dated sedimentary cores and modern biological calibration data permit the continuous reconstruction of lake-level fluctuations and the paleoclimate since the late Pleistocene (Gilli et al., 2001, 2005; Schwalb et al., 2002; Markgraf et al., 2003). However, the limited penetration depth of both the seismic and the coring techniques left several unanswered questions regarding the deepest and oldest seismic
units, Sequences V and, especially, VI. These previous investigations conclude that the deepest units hold records of Pleistocene climatic conditions and information about the origin and evolution of the lake.

To investigate this information, new high-resolution seismic reflection data from Lago Cardiel are acquired in this study using a small airgun source and multichannel techniques. Previous studies show that such an acquisition system is well adapted for imaging relatively deep sediments and bedrock structures beneath lakes (e.g., Finckh et al., 1984; Morend et al., 2002; Beres et al., 2003; Gorin et al., 2003). More specifically, multichannel data show a deeper penetration and better signal-to-noise ratio than single-channel data (e.g., decimated) from the same location (Scheidhauer et al., 2000) and therefore can reveal complete images of lacustrine fill, even where it is very thick (Beres and Gorin, 2002). Although deeper sediment coring is not possible, geological and tectonic maps, as well as analogous seismic investigations, are used to interpret the new data. The goal is to determine various characteristics of the deepest units, such as seismic velocities, facies changes, stratigraphic correlations, and structural features that include several 3D geometrical relationships. The interpretations can supply crucial information about past tectonic and sedimentologic processes on a relatively local scale and simultaneously illustrate the advantages of these seismic methods. Particular questions about the deepest seismic units include the following:

1. Are they consolidated deposits, and what would be the implications for the timing of their formation?
2. What are the involved tectonic and erosional forces, and how are they affected by these forces?
3. What is their distribution, and how well do they correlate with the known stratigraphy in the region?
4. Is there any indication of a volcanic or impact-related origin of the lake?
5. Did leakage from the lake basin play a role in the documented lake-level fluctuations?

2. Study site and geologic setting

Lago Cardiel is a roughly heart-shaped basin with a diameter of approximately 20 km, a modern lake area of about 370 km², and a maximum modern water depth of 76 m. It is located on the Patagonian Plateau (Argentina) between the Andean Cordillera and the South Atlantic coast at a latitude of 49°S (Figs. 1 and 2). According to geomorphologic investigations, the Andean outlet glaciers never reached the Lago Cardiel catchment area (Mercer and Sutter, 1982; Rabassa and Clapperton, 1990; Wenzens, 2002, 2004). Río Cardiel, which enters the lake from the southwest and drains a catchment of approximately 4500 km², is the main perennial inflowing river.

Geologic mapping and structural studies of the Lago Cardiel region (Fig. 2; Feruglio, 1950; Heinsheimer, 1959; Ramos, 1982, 1989) show Mesozoic sedimentary sequences that include Early Cretaceous marine deposits of the Río Mayer Formation (up to early Aptian) and Piedra Clavada Formation (Late Aptian–Albian) and continental deposits of the Cardiel Formation (Cenomanian). The Río Mayer Formation is composed of black shales that prograde from the northeast and cover most of the Magallanes Basin (Biddle et al., 1986). Overlying prograding sandstones mark the shift to continental conditions, and the Cardiel Formation is described as green and red siltstones of distal alluvial facies (Arbe, 1987). The Posadas Basalt (Paleocene–Eocene) is the substratum of the so-called “Patagonian transgression,” which includes the Centinela Formation (Oligocene). This marine deposit is an eastward-prograding sequence of coarse conglomerates, sandstones, and fossil-rich shale. Continental beds of the Santa Cruz Formation (Early Miocene) represent a high-energy fluvial environment and comprise sandstones and silts with conglomerate lenses. This unit and the La Ensenada conglomerates of similar age are unconformably overlain by an extensive sequence of horizontally layered basalt flows (Miocene–Pliocene).

Two uplift phases characterize the Patagonian Cordillera at these latitudes: the Pehuenchic (Late Oligocene) and the Quechuic (early Late Miocene) phases. East-dipping reverse faults (Fig. 2) are related to the asymmetric, gentle folding observed in outcrops. A detachment probably occurs beneath Lago Cardiel, near the base of the Río Mayer Formation. The detachments of the Tucu Tucu and Loma Pelada root deeper and correspond with the
underthrusts and the corresponding anticline west of the lake (Fig. 2).

3. Investigation methods

A total of 65 km of seismic reflection data were acquired using a custom-made catamaran (Fig. 3). Most lines crossed the entire lake, and their locations were chosen on the basis of previous seismic studies (Fig. 1). A 1-in³ air-gun, with a dominant frequency of 400 Hz and a nominal pressure of 80 bar, was employed as the seismic source. In relatively shallow lake sediments, this source provides a theoretical vertical resolution of approximately 2 m, about 10 times lower than that of the 3.5-kHz echosounder used by Gilli et al. (2001, 2005). For recording, we used a 12-channel streamer (1 hydrophone per channel), a 24-bit seismograph (Geometrics Strataview), and onboard GPS. The GPS software triggered the shots at timed intervals that could be adjusted to changes in the ship velocity to minimize the variation in distance between shots (Pugin et al., 1999). Receiver, shot, and offset spacing were all 7 m, which yields a nominal sixfold data coverage and a nominal common depth-point (CDP) spacing of 3.5 m.

Data processing and interpretation were performed with PC-based software (Eavesdropper from Kansas Geological Survey, REFLEX from K.J. Sandmeier, and Kingdom Suite from Seismic Micro-Technology Inc.) and basically followed the oil industry standard (Yilmaz, 1987). Processing included geometry assignment, trigger-delay correction (10-ms bulk shift), first-arrival muting, trace editing, velocity analysis (discussed subsequently), CDP sorting, normal-moveout correction, stacking, bandpass filtering (100–150–1500–1700 Hz), spiking deconvolution, and trace mixing. A phase-shift time migration was tested but, due to generally small dips, produced no significant correction of reflection geometry and position.

With the multichannel data, it is possible to determine a seismic velocity (for the time-depth conversion) at any point on the seismic line by the normal-moveout principle (i.e., increasing signal travel time with receiver distance). Due to the limited fold (six traces) however, constant velocity stacking (Yilmaz, 1987) is the only efficient and reliable
type of velocity analysis. In our case, we repeatedly stack large portions of lines (i.e., several km long) with a range of constant velocities and choose the velocity that gives the highest overall signal-to-noise ratio.

In some key areas, we attempt to distinguish velocities of individual seismic stratigraphic sequences. For this detailed velocity analysis, the field data are left unstacked but sorted into CDP gathers, and using the PC-based processing software, synthetic hyperbolas are automatically matched to the reflections in selected gathers (Yilmaz, 1987). To increase accuracy, we choose gathers containing relatively high-amplitude, continuous, flat reflections. The analysis gives only approximate values because the limited fold, as well as some noisy channels, make it difficult to distinguish hyperbolic moveout in the field data. However, it is sufficiently accurate to detect significant changes in velocity (Fig. 4).

4. Results

4.1. Multichannel aspects

Interval velocities (solid line) and stacking velocities (dashed line) for two CDP gathers are presented in Fig. 4. The left vertical axis indicates a water column up to 66 m deep and overlying the interpreted seismic sequences (labeled in Roman numerals), which have differing thicknesses. Stacking velocities of about 1475 m/s at the bottom of Sequence IV and 1525 m/s within the upper portion of Sequence VI were obtained by analyzing several gathers. This abrupt velocity increase is illustrated by the high acoustic impedance contrast (high amplitudes) at the upper Sequence VI boundary and, according to other studies, indicates the transition from unconsolidated Quaternary deposits to the bedrock surface (Benjumea et al., 2003; Beres et al., 2003). If present, Sequence V exhibits high reflectivity and intermediate velocity values, which suggest that it is relatively compact but unconsolidated (Fig. 4a). Just below the Sequence VI boundary, stacking velocities may be somewhat less than 1525 m/s, implying the presence of a weathered zone (Fig. 4b). In any case, the calculated seismic velocities of Sequence VI are consistent with those of shale (see Section 5.2) at relatively shallow depths (Sheriff and Geldart, 1995). Although this velocity analysis has limited accuracy on a small scale, the velocities of the shallowest sediments are comparable to those obtained by core analysis (Gilli et al., 2001).

To evaluate the effectiveness of the multichannel methods at the study site, the northeastern portion of the stacked airgun line 2 (Fig. 5a) is compared with a near-trace (i.e., single-channel) plot of the same line (Fig. 5b). Despite the relatively low-fold data and noisy channels, the stacked line shows deeper penetration and a higher signal-to-noise ratio. A comparison with a nearly coincident single-channel, 3.5-kHz line of the same length (Fig. 5c) demonstrates the dramatically inferior signal penetration. These echo-sounder data have the advantage of a decimetric vertical resolution, but unlike the airgun data, they fail to image the upper boundary and internal reflections of Sequence VI in many areas beneath the lake.

4.2. Seismic sequences

All six seismic sequences of the previous studies (Gilli et al., 2001, 2005) are also identified in this study (Figs. 6–9). They show similar geometries and reflection characteristics. The internal reflection patterns are also similar but, due to the lower-frequency seismic source, have a lower vertical resolution (see Section 3).

The oldest unit, Sequence VI, underlies the entire lake basin (Figs. 6–9). The entire upper sequence boundary of Sequence VI is strongly reflective and highly irregular. In
3D, it basically forms a northeast–southwest-striking elongated basin that contains two angular-shaped depressions, separated by a local swell (Fig. 10). The southwestern depression is approximately 1.5 km wide and 2 km long and reaches approximately 154 ms (~114 m) beneath the modern lake surface to make the deepest portion of the palaeotopography formed by the upper boundary of Sequence VI (Figs. 8–10). When disregarding the peripheries of the Sequence VI surface, the topographically highest portions are located within 2 km east and north of the deeper depression and have minimum depths of 122 ms (~90 m) and 118 ms (~87 m) beneath the lake surface, respectively (Figs. 7, 8 and 10). These highs are up to 3 km long and, similar to the depressions, have angular shapes.

Gilli et al. (2001, 2005) describe the facies and interpretation of Sequences I–V in detail. Sequence V overlies Sequence VI, and its extent is limited to the western part of the lake basin (Figs. 6, 8 and 9). It is characterized by irregular upper and lower sequence boundaries and commonly transparent seismic facies, but it has a few internal reflections (e.g., Fig. 6) that indicate an eastward progradation (Gilli et al., 2005). The maximum thickness of Sequence V is 46 ms (~34 m) and occurs approximately in the center of the southwestern depression of the upper Sequence VI boundary (Fig. 8). If present, Sequences V, IV, and III overlie Sequence VI with an angular unconformity. Sequence IV exhibits laterally onlapping internal reflections and is confined to the central areas. In contrast, Sequences I–III extend throughout the entire lake basin. This extension indicates a major transgression, in which the deposition of Sequence III reaches at least the modern lake level. Mounded depositional patterns characterize Sequence II and especially Sequence I. They represent contourite drifts from the onset of a lake current system that is most likely driven by strong westerly winds (Gilli et al., 2005). In general, the reflection pattern of the upper four sequences is subhorizontal, very continuous, and low to medium amplitude, typically of lower amplitude than that of their boundary reflections.

4.3. Sequence VI internal reflections

As expected, the internal reflection patterns of Sequence VI are better imaged in the airgun data than in the echo-sounder data (Fig. 5). They are strikingly different from those of the overlying sequences: wavy or inclined, generally continuous, and medium-to high-amplitude. A km-scale fold wavelength and a maximum dip of 3° can also be identified.

To better understand the tectonic history of the Lago Cardiel Basin, an azimuth map showing bedding dip directions within Sequence VI was produced (Fig. 11a). At all
azimuth measurement points along the seismic lines (small triangles), the apparent dips of bedding within Sequence VI were also measured, and a dip map was constructed where these measurement points were densest (Fig. 11b). A constant velocity of 1525 m/s was used for the depth conversion (see Fig. 4). During this process, two zones were identified that differ from the km-scale fold wavelength of the bedding. Zone A has minor faults and fold wavelengths of 1 km or less, represented in vertical sections by airgun line 2 in the northwestern part of the deep paleobasin (Fig. 7). Zone B has a discontinuous to chaotic reflection pattern in which dips are difficult to distinguish and is located east of Zone A. Although the map lacks detail because of the limited number of seismic lines and limited data quality at depth, the fold-axis strike can be distinguished at numerous locations. Basically, the strike is north to south in the eastern part of the lake basin and north–northwest to south–southeast in the western part.

In addition to the dip measurements, a horizon picked along the most continuous internal reflection of Sequence VI is presented in Figs. 6–9 (dashed bold lines). By interpolation, a 3D image of this fold structure can be visualized in the form of a contour map (enlargement of boxed area in Fig. 11b). Although this surface is limited in extent, it illustrates the asymmetric geometry of synclines and anticlines in the central part of the lake basin and shows a maximum fold amplitude of nearly 40 ms (30 m). Moreover, it documents that the fold axes dip about 1° toward the south or southeast.

5. Discussion

5.1. Sequence VI structure

The seismic data show fold axes of Sequence VI that primarily strike north–south. This observation is consistent with outcrop studies and indicates a generally east–west orientation of tectonic compression. In general, the low-angle dips and lack of major faults in the data represent relatively minor compression, which can be explained by the position of the lake on the periphery of regional deformation (Fig. 2). Closer observation reveals that Zone A represents an area of relatively complex deformation, which ultimately led to its higher variability in paleotopography (Figs. 10 and 11). This zone is located just west of the leading edge of deformation (Ramos, 1989; Fig. 2) and shows bending in the fold axes strike to the north–northwest, small-wavelength folds, and abrupt north–south changes in dip. These characteristics point to the presence of transverse fault zones, which are located in the vicinity of the minor dip-slip faults in airgun line 2 (Fig. 7). Studies using 3D high-resolution seismic reflection methods (Beres et al., 2003) also suggest that regional thrust zones are linked with transverse faults that can cause a lateral variation in the fold-axis strike. In the eastern part of the lake basin, beyond the leading edge of deformation, fold amplitudes decrease relative to the western part, and fault zones are either not present or obscured by the chaotic reflection pattern of Zone B.

Two main areas where the bedding dips within Sequence VI are highest (1.5–3°) can be distinguished (Fig. 11). One large area (a1) is located west and southwest of Zone A and may be explained by its relative proximity to the underlying thrust fault. The other area (a2) is located just west and south of Zone B. It seems to reflect a higher local deformation that may be associated with the faulting in Zone A and the creation of the basalt flows along the northern coast of

Fig. 5. Comparison between (a) multichannel and (b) near-trace airgun line 2 (northeastern portion) after processing. (c) A nearly coincident, single-channel, 3.5-kHz line is also shown for comparison. See Fig. 1 for location. Vertical exaggeration is approximately 50×.
Lago Cardiel (Fig. 2). Zones A and B therefore may represent part of the postcollision decompression of the subslab asthenosphere that eventually led to the Late Miocene and Pliocene basalt eruptions (Ramos and Kay, 1992; Gorring et al., 1997). Shallow bedding dips (0–1.5°) are found along fold axes and beneath much of the eastern lake margin, which is beyond the leading edge of deformation and in the presence of Upper Cretaceous units (discussed subsequently).

5.2. Sequence VI stratigraphy

Outcrops around the lake help interpret Sequence VI as Cretaceous marls. A geologic cross-section across Lago Cardiel (Fig. 12) was produced by integrating the interpretation of airgun line 1 (Fig. 6) and the field data from previous studies (Fig. 2). It reveals the relation between paleotopography and stratigraphic units at a relatively small scale. This relation can give some general insights into the initial processes of the lake basin development.

The folded Río Mayer Formation (Lower Cretaceous) comprises the majority of the lake basin and is overlain by the Piedra Clavada Formation (Upper Cretaceous) along the western and eastern margins of the basin (Figs. 11 and 12). Seismic data from the western part show no distinct boundary between the two formations, but it may be related to the significant difference in paleotopography: the lake basin deepens by nearly 100 ms (74 m) within 2 km east of the Piedra Clavada Formation. This sudden change points to preferential erosion of the more erodible lithology of the deeper Río Mayer Formation. The erosion of this formation is greater in the west than in the east because of the focused deformation (and weakening) by faults, as well as the proximity to the erosive forces of Río Cardiel. On a smaller scale, the irregular western surface of the Piedra Clavada Formation may denote preferential erosion associated with minor faults (Fig. 2), some of which are indicated in Figs. 6, 9 and 12. Similar observations of tectonics controlling subsequent erosion and drainage patterns are made in high-resolution seismic reflection profiles from Swiss lakes (Beres et al., 2003; Gorin et al., 2003) and in statistical analyses of data from numerous wells in southwestern Ontario, Canada (Eyles et al., 1997).

In the eastern part of the basin, the boundary between the Río Mayer and the Piedra Clavada formations is represented by sudden changes in seismic facies and paleotopography (Fig. 12). The Piedra Clavada Formation is characterized by low seismic penetration and exhibits low-frequency, low-amplitude internal reflections with an eastward dip that is lower than that in the western part, according to the dip map (Fig. 11b). Farther to the east, the Cardiel Formation overlies the Piedra Clavada Formation. Its internal reflections have low eastward dip and are low-frequency, wavy, and high-amplitude. Both of these
Upper Cretaceous units demonstrate an abrupt increase in paleotopography (i.e., altitude of the sequence boundary). The Cardiel Formation, however, is generally more friable, and its negative relief relative to the Piedra Clavada Formation is visible in outcrops and indicated in the seismic profile.

5.3. Early lake basin history

The nature and continuity of Sequence VI beneath the lake point to a tectonic origin of the lake. Widespread Tertiary basalt flows in the region and the nearly circular shape of the lake, however, may imply volcanic or impact-related origin. Despite erosion, large impact structures often retain relatively high-relief structures, which basically consist of an uplifted rim with extensive faulting, a central peak, and an impact breccia infill (Grieve and Pesonen, 1992; Tsikalas et al., 1998; Karp et al., 2002; Poag et al., 2002). Beneath Lago Cardiel, limited and localized faulting, low structural relief, and preserved stratification throughout the basin contradict the impact model. Zone B represents a chaotic reflection pattern within Sequence VI and may suggest the presence of impact breccia, but it is neither extensive nor centered within the lake basin (Fig. 11).

Erosion from structurally controlled rivers flowing from the southwest and northwest (Figs. 1 and 2) probably is responsible for the angular, irregular, highly reflective, unconformable surface of Sequence VI. Comparing Fig. 1 with Fig. 10 shows that these two river directions correspond to the main orientations of the deepest portions of this sequence. These portions represent maximum erosion and are basically located beneath the western margin of the present-day lake, where the friable black shales of the Río Mayer Formation were most disrupted by the underlying thrust plane. The same erosion processes seem responsible for the high-relief surface of the Piedra Clavada Formation, which was apparently weakened by the tectonic forces in the western part of the basin (Fig. 12).
On the basis of its distribution, shape, and internal structures, Sequence V is interpreted as a former alluvial fan unit that fills the deepest incisions and coincides with the inflow of Río Cardiel (Gilli et al., 2005). The prograding and undeformed internal reflectors, the relative transparency (typical of poorly sorted, coarse-grained sediments), the sloping upper boundary, and the thickening toward the source (despite erosion) support this alluvial fan interpretation. Assuming closed basin conditions, any fine lake sediments associated with this fan were likely exported by aeolian erosion during a period of subaerial exposure. The irregular, highly reflective, unconformable, and in places, discontinuous upper boundary of Sequence V signifies another major desiccation period that occurred chiefly along its western side and prior to the onset of lacustrine sedimentation (Sequences I–IV). Relatively low seismic velocities of this sequence (Fig. 4a) indicate it is much younger than Sequence VI and probably of Pleistocene age.

The results of this study further illustrate the extremely varying Quaternary climate portrayed by previous investigations, including: (1) a drier period corresponding to the hiatus at the top of Sequence VI, (2) a wetter period leading to the deposition of Sequence V, (3) a drier period causing the hiatus at the top of Sequence V, and (4) a wetter period covering at least the late Pleistocene and the Holocene and producing the lacustrine deposits of the four youngest seismic sequences (Stine and Stine, 1990; Gilli et al., 2001; Markgraf et al., 2003). Due to the limited penetration of the sedimentary cores (Gilli et al., 2001), no accurate chronological constrains are available for the first three events in this stratigraphic succession.

5.4. Lake basin leakage?

To link paleoclimate models confidently to fluctuations in lake levels, it is necessary to know the input and output processes of the lake water. Because the modern Lago Cardiel is a closed basin, the only apparent output of water is evaporation. However, studies of other lakes throughout the world show that water can leak through the lake bottom if it has zones of high permeability. This permeability can result from karst development (Fernandes et al., 2001; Crilley and Torak, 2003) or seismic activity that periodically readjusts bedrock positions along shallow faults and produces an alternation of sediment deposition and erosion (Cawley et al., 2001).

The bedrock beneath Lago Cardiel is interpreted as mostly shale, with resistive sandstone and siltstone along the basin margins. Such lithologies are considered rela-
tively impermeable, and furthermore, no major karst development is known in the region. Reflections within Sequence VI are generally quite continuous, including in the areas where paleotopography is highly variable. Even where faults in Sequence VI seem evident (Fig. 7), they are overlain by thick packages of undisturbed sediments. The sediment overburden is thinner along the lake margins, but no major faults within Sequence VI are recognizable in the data from these areas. Considering the Tertiary history of the region, it is likely that any large fissures in the vicinity of the lake would have been filled with basalt eruptions. High-resolution seismic reflection studies of lakes in central Europe show faults in bedrock similar to those of Lago Cardiel, and in the more seismically active areas, slumps (e.g., Schnellmann et al., 2002; Gorin et al., 2003), faults, and fluid-escape features (Chapron et al., 2004) in the overlying sediments are indicated by the data. Despite such relatively recent disturbances, these lakes show no evidence of leaking. In Lago Cardiel, the seismic reflection data from this study and previous studies show that the Quaternary sediments are not disturbed by tectonic-related activity; it is therefore even less likely that major leaking of lake water from the basin occurred. This conclusion reinforces the climatic implications of the previously published lake-level changes.

6. Conclusions

The following conclusions can be drawn from the seismic reflection survey in Lago Cardiel, Argentina:

1. Although several different types of offshore, high-resolution, seismic reflection systems exist, this study shows that a system using multichannel receivers and pneumatic sources can be powerful and yet transportable for application in remote sites. It can provide images and seismic velocity information from thick lacustrine sequences as well as the underlying bedrock.

2. Sequence VI, the deepest of six major seismic sequences identified by previous studies, has an angular, irregular, highly reflective, unconformable surface that signifies erosion from structurally controlled rivers. Its nature and continuity do not point to a volcanic or impact-related origin of the lake. The fold-axis strike of the Sequence VI bedding is north to south in the eastern part of the lake basin and north–northwest to south–southeast in the western part. This change in strike probably relates to a central zone of transverse faults.

3. Sequence VI is interpreted as Cretaceous marls. The folded Río Mayer Formation comprises the majority of the lake basin and is overlain by the Piedra Clavada Formation along the western and eastern margins of the basin. Farther to the east, the Cardiel Formation overlies the Piedra Clavada Formation.

4. Sequence V consists of relatively compact but unconsolidated sediments. In agreement with previous studies, Sequence V most likely represents an alluvial fan of possi-
ble Pleistocene age. This study indicates that it is not much older than the overlying lake sediments (Sequences I–IV). Lacustrine sediments older than those of Sequence IV cannot be obtained from the Lago Cardiel Basin.

5. The seismic stratigraphy, geomorphologic aspects, and core analyses of previous investigations show that during the Quaternary, southern Patagonia was dominated by extremely contrasting climatic conditions, which include significant desiccation events during dry periods.

6. The seismic reflection data of this study and previous studies show no evidence of major leaking of lake water from the basin and thus reinforce the climatic implications of the previously published lake-level changes.

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