Late Quaternary hydroclimate variability in the Colombian Andes and the potential for deep sediment core recovery at Lago de Tota revealed through CHIRP and airgun-sourced seismic reflection data

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Abstract

A geophysical investigation of lacustrine stratigraphy at Lago de Tota (Tota), Boyaca, Colombia provides evidence for significant lake level fluctuations during the late Quaternary from ~60 ka to the present. CHIRP data collected in 2015 from this large, high-elevation lake in the Eastern Cordillera of the Northern Hemisphere (NH) Colombian Andes reveal a series of off-lap and on-lap sequences in the upper ~20 m of the lake's sediment column that indicate large amplitude changes in lake level. These data, temporally constrained by 14C-dated sediment cores and extrapolated Holocene sedimentation rates, suggest that lake levels at Tota were lower than present during Marine Isotope Stage (MIS) 4 between 60 and 57 ka, relatively high during MIS 3 between 57 and 29 ka, fell to their lowest levels during MIS 2 between 29 and 14 ka, and gradually rose to the modern high-stand through a series of transgressions during MIS 1 and the Holocene from ~14 ka to the present. These fluctuations are broadly consistent with trends observed in other lake level reconstructions from the Northern (in phase) and Southern (out of phase) Hemisphere Andes, possibly supporting the idea that millennial-to-orbital-scale South American hydroclimate variability is linked to shifts in the mean latitude of the Intertropical Convergence Zone (ITCZ) due to the influence of insolation- and ocean circulation-driven hemispheric temperature gradients during glacial/stadial and interglacial/interstadial events. These results, as well as the presence of a thick (>300 m) sedimentary archive, indicate that Tota has significant potential to produce high-resolution, quantitative, paleo-hydroclimate data spanning much of the last 1 million years. Because geophysical surveys and long paleoclimate records from NH South America are exceedingly rare, these data provide critical insight into regional hydroclimate trends through the Late Quaternary.

Study Site: Lago de Tota

A large, high-altitude (3015 m above sea level) lake located in the Eastern Cordillera of the Colombian Andes (Fig. 1).

The largest high-altitude water body in Colombia with a surface area of 55.1 km^2, an average depth of 34 m, a maximum measured depth of 62 m.

Although Tota is generally considered a closed hydrologic system (i.e., lake volume is principially driven by local P/E balance, with negligible flux attributed to groundwater or surface streams), outflow from Tota during periods of very high lake levels flows into the Magdelena, Orinoco, and other smaller tributaries.

The bathymetry is characterized by a flat profundal zone that shallows gradually to the east and south, and descends very sharply along the structurally-controlled western and northern shores (Fig. 2),

Peninsulas and islands created by subsurface anticlines extend into the eastern side of the lake from the north and south, separating a smaller eastern bay (Aquitania Bay) from the main body of the lake.

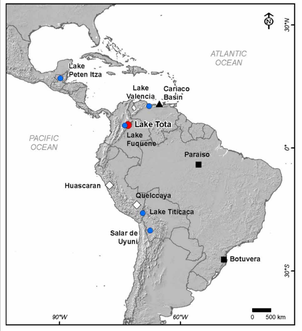

Fig. 1. Laguna de Tota in relation to other prominent SH paleoclimate records. Lacustrine records are represented by circles, speleothems by squares, and ice cores by diamonds.

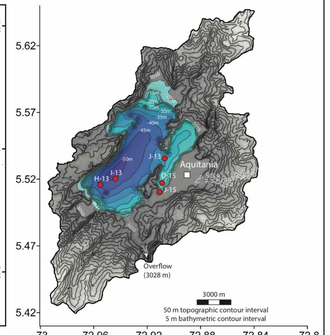

Fig. 2. Bathymetry and surrounding watershed topography of Lago de Tota

Methods

Tota's sedimentary archive was profiled using deep-penetrating airgun-sourced seismic reflection, towed across Tota's surface in a grid of intersecting transects (Fig. 7a). The thicknesses of the sedimentary units were determined by converting the two-way travel time (TWTT) of the energy from the airgun as it traveled from its source to each sedimentary reflector and back into a unit of distance. The speed of sound was estimated to be 1500 m/s through the water column and water-saturated lacustrine sediments. All analyses of the seismic data, including reflector tracing and interpretation, were conducted using the IHS Kingdom software suite.

Results

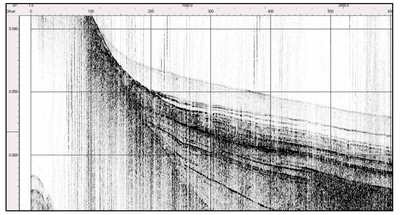

Fig. 3. CHIRP seismic data collected from near Tota's southwestern shore.

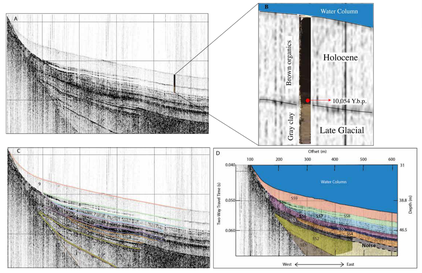

Fig. 5. **A** Raw seismic data from the southwestern littoral zone at Tota. **B** Livingstone cores taken from near the southwestern transect shows the lithological contrast between the upper two seismic sequences. A radiocarbon date taken from near the transition suggests that this lithology change marks the boundary between the Holocene and Late Glacial periods. **C** Raw seismic image with traced onlapping reflectors. **D** Annotated seismic image, separated into the 9 interpreted seismic sequences visible in the CHIRP data.

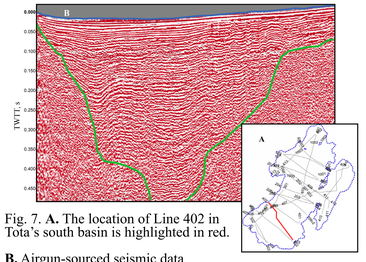

Fig. 7. **A.** The location of Line 402 in Tota's south basin is highlighted in red.

B. Airgun-sourced seismic data collected along Line 402 displays the thick sedimentary archive characteristic of this section of the lake.

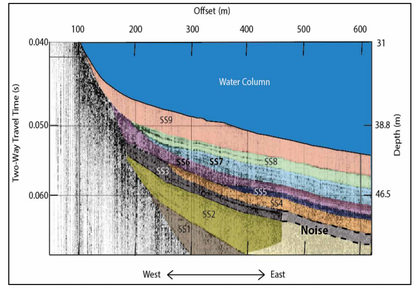

Fig. 4. The 9 sediment sequences recorded in the seismic survey collected from Lago de Tota, designated SS1 (oldest)-SS9 (youngest).

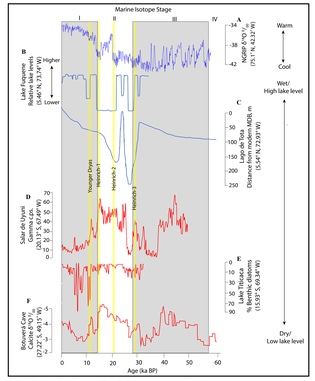

Fig. 6. **A.** NGRIP $\delta^{18}O$ data. **B.** 35 ka record of relative lake levels from NH Lake Fuquene (van der Hammen 1974). **C.** 57 ka record of transgressions and regressions at NH Lago de Tota. **D** 50 ka record of lake sediment gamma radiation from SH Salar de Uyuni (Baker et al. 2001a). **E.** 32 ka record of %benthic diatom species from SH Lake Titicaca (Tapia et al. 2003). **F.** 60 ka record of calcite oxygen-18:oxygen-16 from SH Botuvera Cave in Southeastern Brazil (Wang et al. 2007).

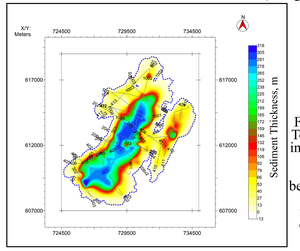

Fig 8. Isopachs of Tota's sedimentary infill, calculated by converting the seismic TWTT between source and bedrock into a measurement of depth/thickness.

Discussion

Geophysical evidence for significant lake level fluctuations during the late Quaternary at Lago de Tota on orbital and millennial timescales suggest that Tota's lake volume is sensitive to the impacts of climatic changes on the regional long-term P/E balance. Based on the timing and magnitude of lake level changes at Tota and other South American lakes, we propose that over these timescales the mean position of the ITCZ imparts the greatest influence on regional precipitation. The geophysical data support a southerly mean latitude of the ITCZ in response to a disproportionately cool Northern Hemisphere during the end of MIS 4, causing a subdued monsoon and generally low lake levels at Tota. Following MIS 4, a northern shift in ITCZ latitude resulted as global temperatures warmed through MIS 3, increasing precipitation delivery to the Northern Hemisphere and resulting in rising lake levels at Tota. The ITCZ returned to a southerly latitude as Northern Hemisphere ice sheets expanded during MIS 2 and through the LGM, driving lake levels at Tota to their lowest point in our recorded data. Lake levels rose steadily post-LGM, with the exception of a brief, but significant, reduction of volume during H1. After H1, through MIS 1 and the Holocene, a northern migration of the ITCZ has increased Northern Hemisphere precipitation delivery and caused lake levels to rise to their current level.

Tota offers a rare opportunity for deep sediment core recovery. The total thickness of the sediment sequences preserved in the south sub-basin of the lake is between 320 and 350 m, which have remained largely undisturbed by faulting or mass wasting. Based on the Holocene sedimentation rate of 1 m of accumulation per 3000 years, this thick sedimentary archive has the potential to represent more than 1 million years of sediment deposition. Since Tota has retained water through the duration of its existence, deep cores from Tota would provide one of the longest continuous lacustrine-based climate records ever collected from the NH.