Late-Quaternary lowstands of Lake Titicaca: Evidence from high-resolution seismic data

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Abstract
Approximately 600 km of high-resolution seismic reflection data were collected to investigate the late-Quaternary stratigraphic development of Lake Titicaca. The focus of this report is on two seismic sequence boundaries, which are interpreted as erosional surfaces formed at times of low lake level. The younger erosional surface occurs as much as 90 m below the present lake level and up to 8 m below the present sediment–water interface. This erosional surface is interpreted to be coeval with a well-documented early- to mid-Holocene lowstand, dated between ~8,000 and 3,600 cal yr BP. An earlier and previously unknown erosional surface occurs at a sub-bottom depth of approximately 30 m, and as much as 240 m below the present lake level, which implies a major late-Pleistocene lowstand of Lake Titicaca. By extrapolation of sedimentation rates from the upper ~14 m of sediment, we estimate the age of this older lowstand at >90,000 cal yr BP. Both lowstands of Lake Titicaca indicated by the seismic data are likely to have been a response to climatic change in the region.

Keywords: Andes, Lake Titicaca, lake level change, seismic reflection data, tropical paleoclimate

1. Introduction

Lake Titicaca is an important site for paleoclimatic research in the South American tropics because of the evidence for major lake level changes in the late Quaternary (*e.g.*, Newell, 1949; Kessler, 1985; Wirrman, 1992; Abbott *et al.*, 1997; Binford *et al.*, 1997; Seltzer *et al.*, 1998; Cross *et al.*, 2000; and Baker *et al.*, 2001a). Despite having an outlet, the

Río Desaguadero (Figure 1), most of the water loss from Lake Titicaca today is by evaporation (Roche *et al.*, 1992), making the lake a nearly closed basin and increasing the sensitivity of the hydrologic mass balance of the lake to climate change. Lake level changes and related geochemical evolution of the basin have had a profound impact on sedimentary carbon, carbonates, and diatoms (Cross *et al.*, 2000; Baker *et al.*, 2001a). Furthermore, the
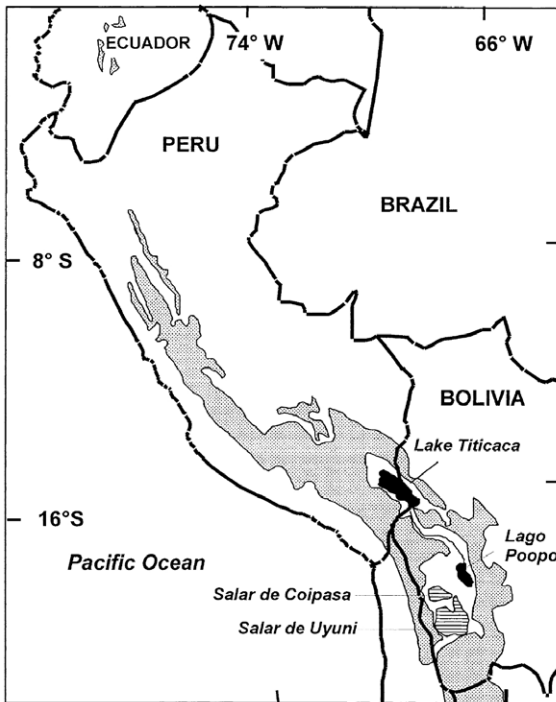
Figure 1. Location map for Lake Titicaca. Shaded area is >4,000 m a.s.l.

presence of nearby alpine glaciers makes the detrital flux of sediments to the lake a sensitive recorder of tropical glaciation (*e.g.*, Mercer, 1984; Seltzer, 1992; and Seltzer, 1994). Besides the impact of climatic change, the lake and the surrounding Altiplano are also affected by neotectonic activity associated with uplift and extension of the central Andes (Newell, 1949; Sebrier *et al.*, 1985; and Lavenu, 1992). Here we use the first seismic reflection data obtained from the lake (*e.g.*, Seltzer *et al.*, 1998) to investigate the recent stratigraphic development of Lake Titicaca and therefore the record of late-Quaternary climatic and tectonic change in the tropical Andes.

2. Study area

The Altiplano is a high-altitude, endorheic basin, 200,000 km^2 in area, that occupies the inter-cordilleran region of Bolivia and southern Peru (Figure 1). The northern Altiplano is occupied by Lake

Titicaca (3,809 m a.s.l.). During high lake stands, Lake Titicaca drains via the Río Desaguadero to the shallow and saline Lago Poopó. In turn, during past wet periods, Lago Poopó was hydrologically connected with the presently dry *salares* (salt pans) of Uyuni and Coipasa (Figure 1). Recently, 15,000–25,000 cal yr BP (calendar years before present), the latter three basins were joined to form paleolake Tauca on the southern Altiplano (Servant *et al.*, 1995; Baker *et al.*, 2001b). The hydrologic system reflects a strong modern precipitation gradient from the wet northern Altiplano (~800 mm/yr mean precipitation) to the arid central and southern Altiplano (<100 mm/yr mean precipitation).

The Strait of Tiquina connects the two modern sub-basins of Lake Titicaca, the larger and deeper (up to 285 m) Lago Grande (or Lago Chucuito), and the smaller and shallower (up to 40 m) Lago Menor (or Lago Huiñaimarca) (Figure 2). At its current level, the surface of the lake covers ~8,500 km^2 (Boulangé and Aquize Jean, 1981). Five tributary rivers (Ríos Ramis, Huancané, Suchez, Ilave and Coata) drain most of the 57,000 km^2 watershed of Lake Titicaca. The outflow of Lake Titicaca is controlled by a number of hydrologic sills. The outlet from Lago Menor at the Río Desaguadero has a sill at 3804 m a.s.l. A second sill is located at an elevation of 3,788 m a.s.l. in the Strait of Tiquina. When lake level drops below this elevation, hydrologic exchange between Lago Menor and Lago Grande ceases (Wirrman, 1992).

3. Methods

Approximately 600 km of high-resolution, seismic reflection data were obtained in 1996 on board the RV *Yakuza* (Figure 3). The data were collected using an Edge-Tech X-Star sub-bottom profiler, with a pulse-band width of 2–12 kHz. Assuming a velocity of 1500 m/s of sound in water and in the uppermost sediments, the expected maximum vertical resolution for this frequency band is about 0.15 m. Maximum acoustic penetration was ~50 m of sediment, although on average only the upper 30 m were imaged. Most of the seismic lines were located in the shallower re-
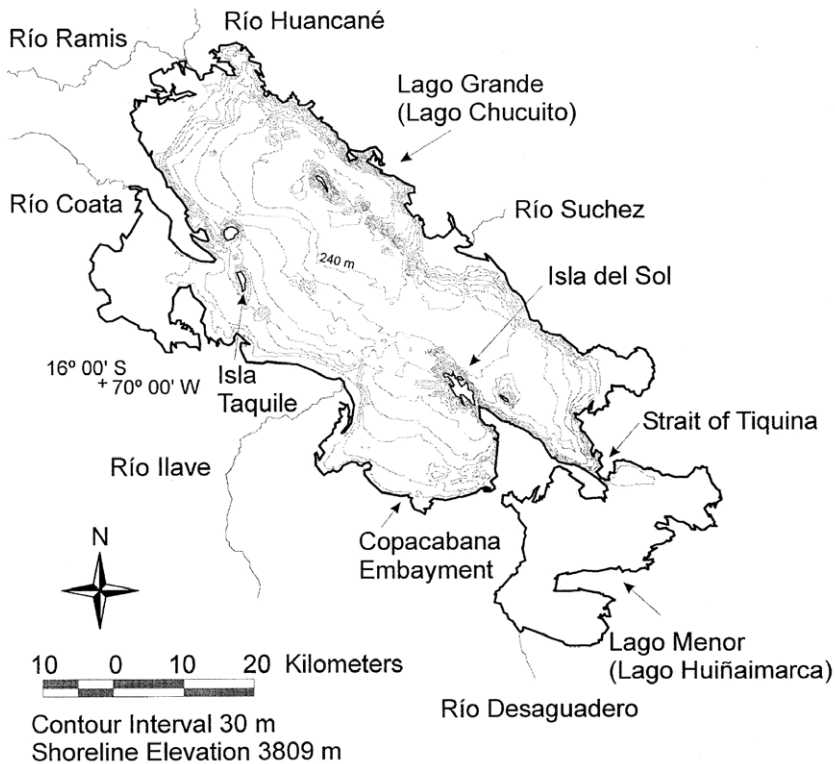
Figure 2. Bathymetry of Lake Titicaca. This map was created using approximately 5,000 depth soundings from five nautical joint Peruvian–Bolivian maps with a 1:100,000 scale. The data were entered into ARC/INFO in order to generate a triangulated irregular network and were then contoured.

gions of the lake, with a few crossing lines obtained in deeper regions to provide correlation of basinwide events and to examine deeper water sequence stratigraphy. A handheld global positioning satellite receiver operating in autonomous mode was interfaced with the seismic system providing positional accuracy of <100 m.

The interpretation of the seismic data followed procedures outlined by Vail *et al.* (1977) and Vail (1987). Sequence boundaries were defined by reflection terminations, such as convergence and truncation. Once the seismic sequences were defined and the bounding horizons mapped, the thickness of each sequence was measured by converting two-way travel time into sub-bottom depths, assuming a velocity of 1500 m/s (D'Agostino, 1998). Because of the low density of seismic lines, traditional seismic stratigraphic analysis, including mapping of seismic

facies and seismic reflection geometries, is not possible with this data set. Furthermore, although sequence boundaries were traced throughout the basin, isopach maps were not produced because of the sparseness of data.

Most of the published analyses of the sediments of Lake Titicaca (*e.g.*, Boulangé *et al.,* 1981; Wirrman and De Olivera Almeida, 1987; Abbott *et al.,* 1997; and Cross *et al.,* 2000) focus on the mid- to late-Holocene sedimentation of the lake. More recently, Baker *et al.* (2001a) analyzed the sedimentology and stratigraphy of several piston cores up to 14 m in length from locations throughout Lago Grande. Baker *et al.* identified detrital glacial sediments deposited in deep water between 30,000 and ~20,000 cal yr BP indicative of the last glacial maximum. Deep water sediments also accumulated from 20,000 to ~15,000 cal yr BP, 13,000 to ~11,500 cal yr BP, 10,000 to 8,000
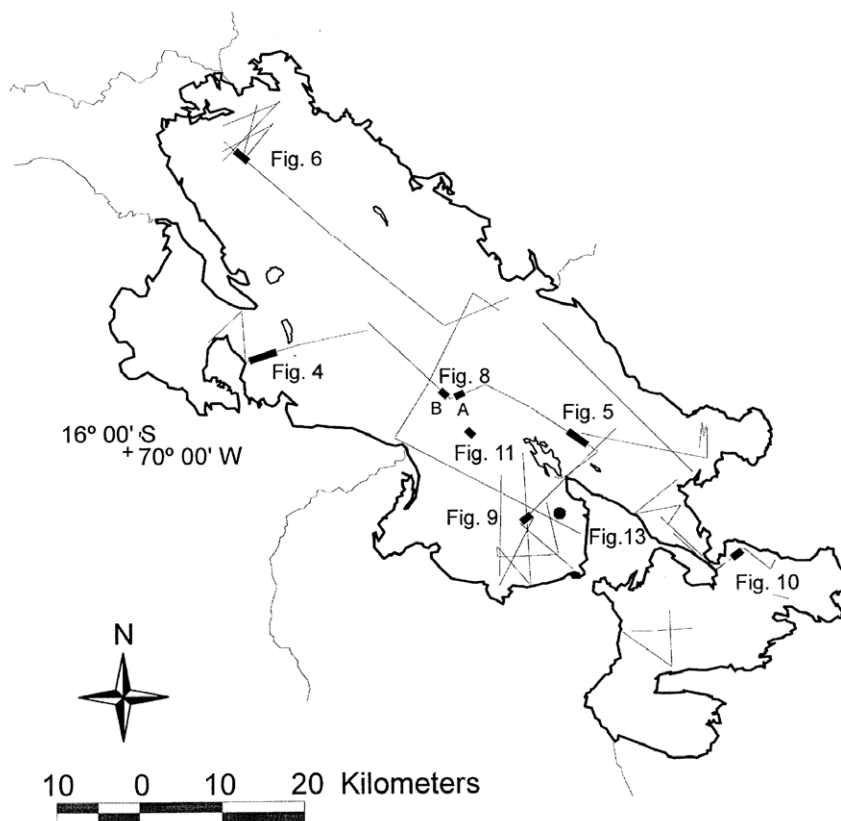
Figure 3. Location of seismic lines in Lake Titicaca. Locations of seismic data depicted in Figure 4, Figure 5, Figure 6, Figure 8, Figure 9, Figure 10 and Figure 11 are indicated by thick lines and the location of sediment core NE981PC and associated seismic data in Figure 13 is depicted by the solid circle.

cal yr BP, and 2,000 cal yr BP to the present. Interspersed with the periods of deep water sedimentation in the lake are relatively saline lake intervals characterized by the deposition of benthic diatoms and carbonates. The relatively saline lake intervals are interpreted as periods of time when the level of the lake dropped below its outlet and the sill at the Strait of Tiquina.

4. Results

4.1. Lago Grande

Within the upper 30 m of sediment penetrated by the acoustic signal, three seismic sequences can be defined (Figure 4). We refer to this group of three seismic sequences as the Taquile Sequence Set,

named for Isla Taquile, which is near the seismic line where these sequences are best identified (Figure 2 and Figure 4). This designation helps to distinguish this group of seismic sequences from subsequent sequences that might be identified using a more powerful acquisition system with greater penetration.

The base of Sequence I is below the penetration of the acoustic signal and therefore the thickness of Sequence I is unknown at this time. The upper boundary of Sequence I is an erosional unconformity marked by truncation of reflections. Along the western shoreline, erosion along this boundary is found at depths as much as ~130 m below the present lake level. In the Copacabana embayment, erosion along the boundary is found 175 m below the present lake level. East of Isla del Sol, several locations show an angular uncon-
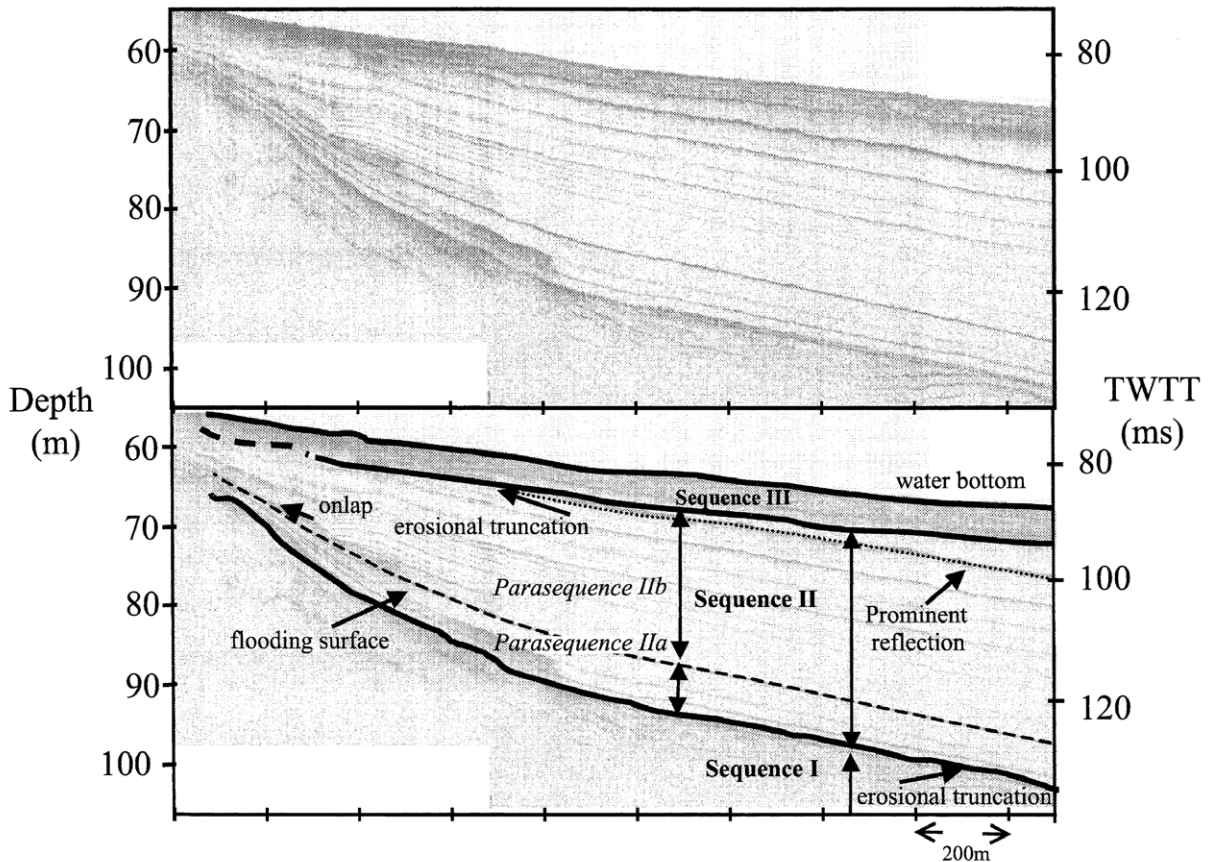
Figure 4. Seismic profile showing sequence boundaries in the Taquile Sequence Set. Seismic sequence boundaries are defined by erosional truncation of seismic reflections at the base of Sequences II and III.

formity at the upper boundary of Sequence I, as much as 240 m below the modern lake surface (Figure 5). Only in the deepest areas of the lake (from 200 m to 285 m modern water depth) do the sediments above this boundary appear to be conformable with Sequence I.

Sequence II is divided into two parasequences separated by a flooding surface. Roughly 5 m above the base of Sequence II there is a strong reflection with no evidence of erosion below, but onlap above (Figure 4). This reflection is interpreted as a flooding surface that represents lake level rise. The top of Sequence II is defined by an erosional unconformity found at two locations in the basin. In the nearshore area north of the Ilave delta, the top of Sequence II is eroded in depths as great as 90 m below modern lake level. In the Huancané

delta, erosion truncates an antiform of Sequence II sediments, at approximately 90 m below lake level (Figure 6).

The seismic signature of Parasequence IIa within Sequence II is characterized by an approximately 2-m-thick package of closely spaced high-amplitude reflections. The acoustic stratigraphy in Parasequence IIb consists of evenly spaced low- to medium-amplitude reflections. The upper 7 m of Sequence II contain a number of high-amplitude reflections, which are most apparent in the deeper regions of the lake.

Near the top of Sequence II is a prominent basinwide reflection at an average sub-bottom depth of 10 m (Figure 4 and Figure 5). Seismic reflection data do not indicate a sequence boundary along this reflection, as there is no evidence of
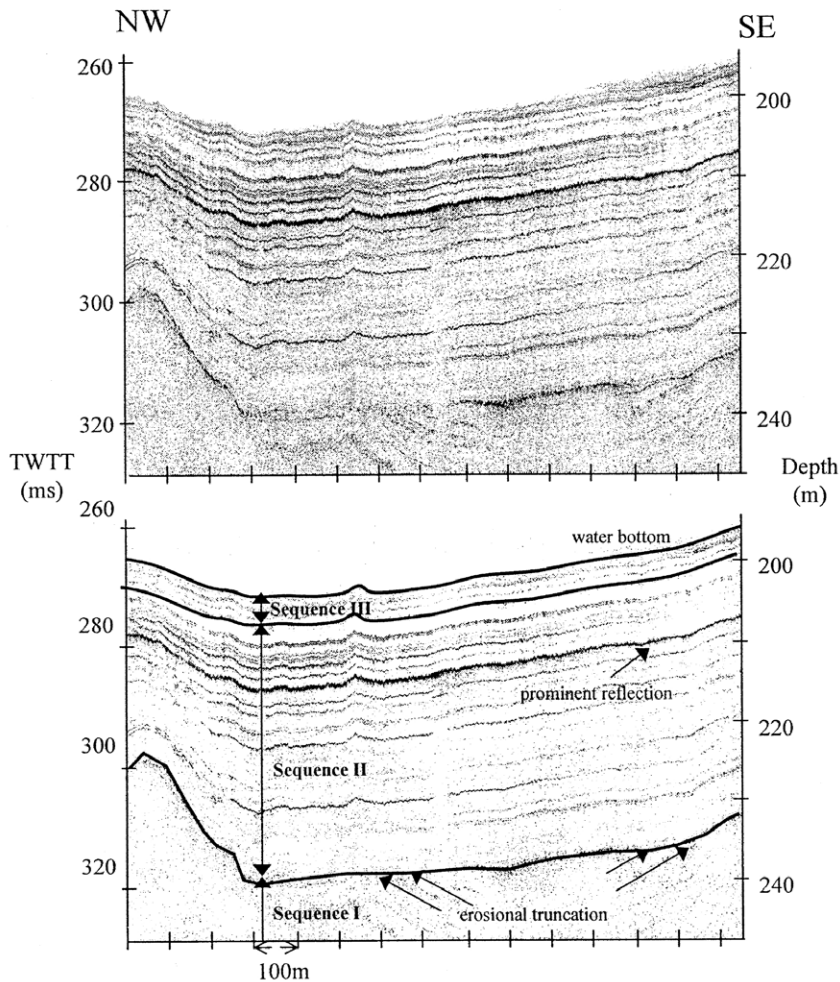
Figure 5. Seismic profile showing erosional truncation at the top of Sequence I in 200 m water depth.

erosion below, or onlap or downlap above the reflection. Furthermore, the reflection does not appear to be the boundary between two distinct seismic facies. The characteristics of the reflection are unique and easily recognizable as the highest-amplitude and most continuous reflection on most seismic profiles. The amplitude of the reflection is consistent throughout the basin even in a variety of depositional environments. Diffractions are common along this reflection, indicating that in places it is an uneven or discontinuous surface.

The erosion surface at the top of Sequence II forms the base of Sequence III. The sediment–water interface defines the top of Sequence III. The

reflection geometry of Sequence III is relatively uniform throughout the basin. The vertical succession of seismic facies is characterized by two packages. In many areas, two equally spaced, relatively low-amplitude reflections are found immediately above the basal boundary and are themselves overlain by a high-amplitude reflection (Figure 4). This lower package of Sequence III is about 1–2 m thick. The stratigraphic section between the high-amplitude reflection and the sediment surface contains closely spaced, medium- to high-amplitude reflections, especially in shallower areas. Onlap occurs in a few locations within this uppermost package, especially around the Huan-
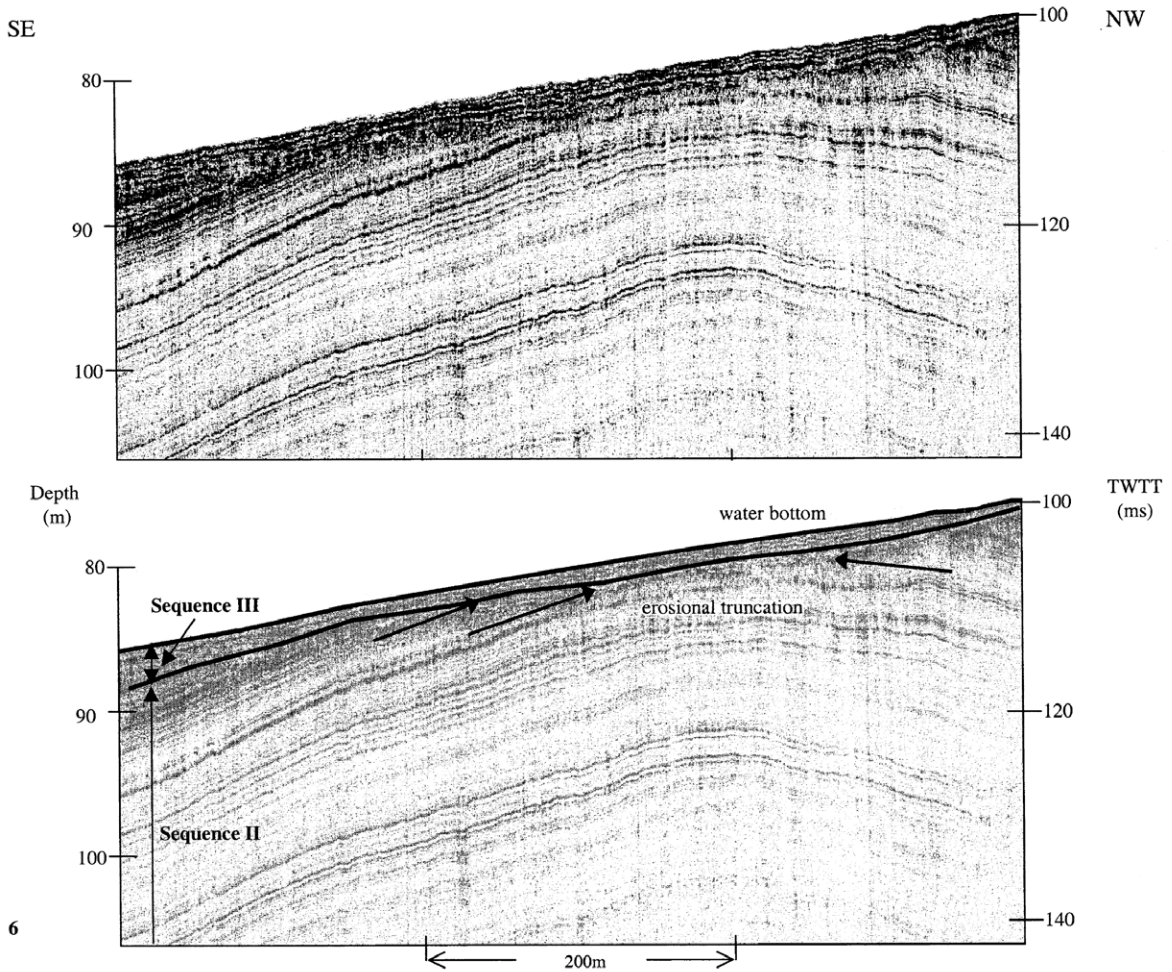
Figure 6. Seismic profile showing erosional truncation at the top of Sequence II in the Río Ramis-Huacané delta.

cané delta, suggesting relatively recent lake level variations.

The thickness of the seismic sequences consistently shows that the rate of sediment accumulation was lowest in the Copacabana embayment, most likely because no modern rivers feed directly into this section of the lake. Because the basal boundary of Sequence I was not imaged, the thickness of Sequence I cannot be determined. Although thinning in shallower regions, Sequence II has a uniform thickness of close to 30 m throughout the deeper sections of Lago Grande. The sub-bottom depth of the prominent reflection in Sequence II varies from 6 to 12 m. Sequence III is as

much as 8 m thick; highest accumulation rates occur close to the deltas (where data are available) and the average thickness is 4 m.

The depth distribution of morphologic channels at the sediment–water interface where they cross the seismic profiles is approximately bimodal, at ~50 m and 210 m water depth (Figure 7). Most channels are located offshore from modern deltas. The channels in shallower areas likely formed by subaerial erosion of Sequence II during the late-Glacial to mid-Holocene lowstand (Seltzer *et al.*, 1998) and in places only contain a thin drape of Sequence III sediment. The deeper channels may be of sub-lacustrine origin as they are not clearly
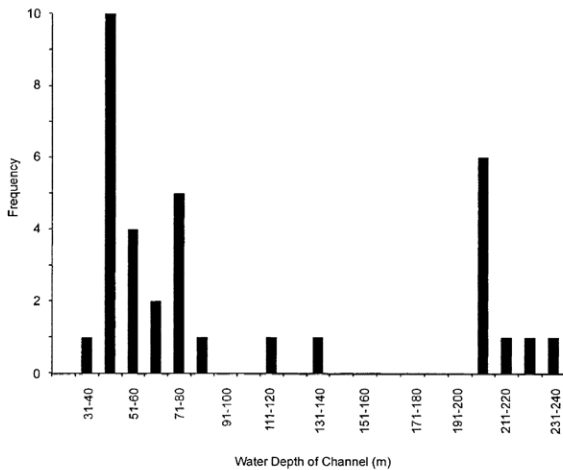
Figure 7. Histogram of channels at the sediment–water interface observed in the seismic data as a function of water depth ($n = 36$).

There is little evidence of structural deformation of the shallow sediments. Several antiforms are present (*e.g.*, Figure 6), but because of limited sub-bottom penetration, it is impossible to determine whether they are due to compression or are sediments simply draped over bedrock highs. The seismic data reveal faults in the shallow sediments, with a maximum offset of about 1 m (Figure 9). The throw of most faults decreases up section and sometimes disappears completely towards the lake floor. In limited areas, where bedrock is imaged, some faults are found near bedrock highs and might be part of the basin-scale tectonic framework. In most areas, however, the bedrock surface was not penetrated by the acoustic signal, leaving the relationship between faults and basin evolution unclear.

4.2. Lago Menor

related to other evidence for lake level lowering. The deeper channels have also incised Sequence II, but they contain a thicker drape of recent sediments that may constitute all of Sequence III (Figure 8). Thus, the channels found in deep water may predate the middle-Holocene lowstand of the lake. There is a notable absence of channels in water depths between 140 and 205 m.

The seismic coverage of Lago Menor is limited. Many areas of the basin lie in less than 5 m of water, with a maximum water depth of ~40 m. Because Lago Menor was mostly desiccated and was separated from Lago Grande during much of the early and mid Holocene (Wirrman *et al.,* 1992; Abbott *et al.,* 1997), its stratigraphic development
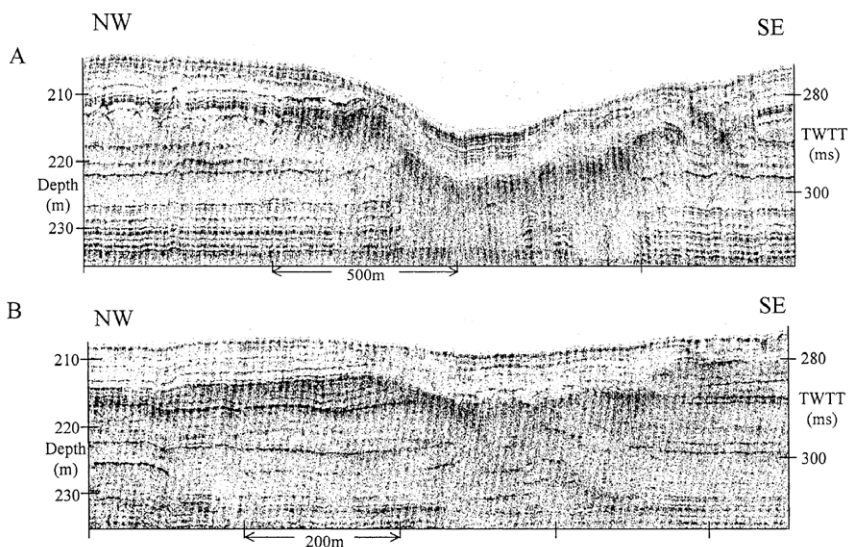

Figure 8. Seismic profiles showing channels west of the Ilave delta in ~200 m water depth. Both channels contain several meters of sediment that may constitute most of Sequence III. The channels are eroded into the top of Sequence II.
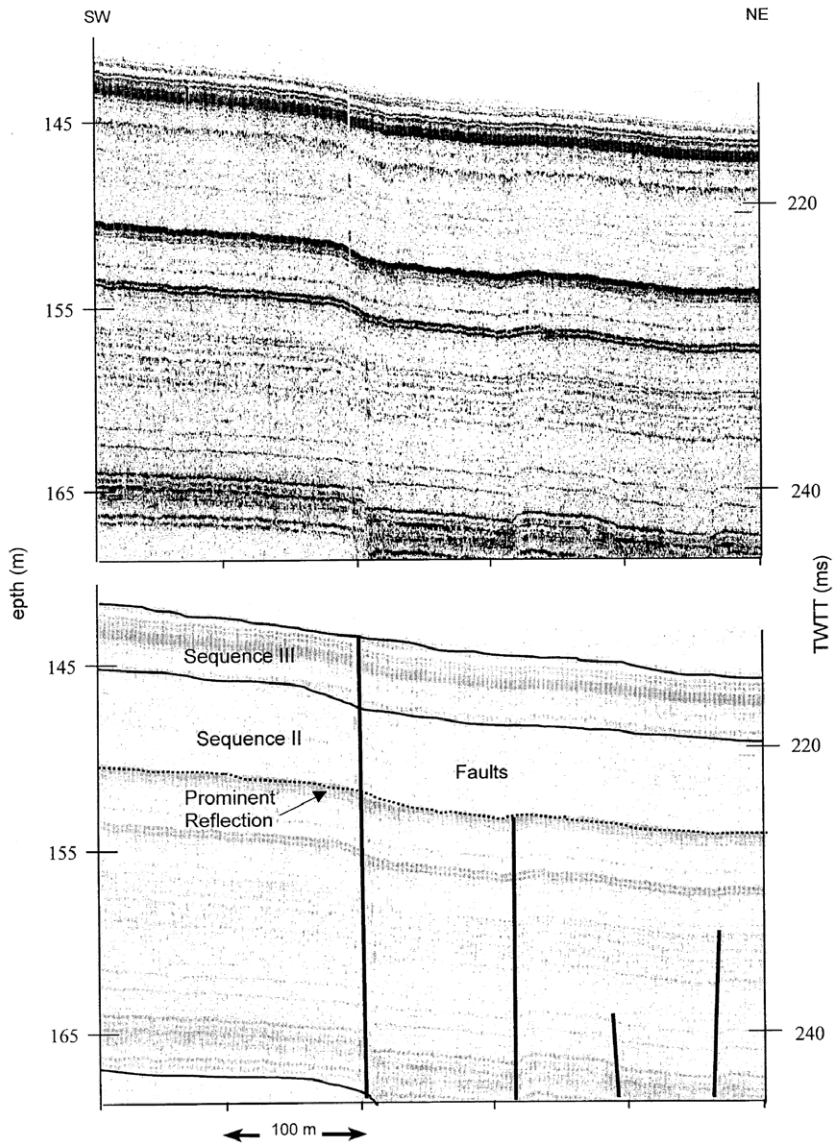
Figure 9. Seismic profile showing high-angle normal faults and sediment stratigraphy in the Copacabana embayment.

differed from Lago Grande, making correlation of seismic sequences between the two basins difficult. High-amplitude, closely spaced reflections are observed in the upper few meters of the seismic sequence throughout much of the Lago Menor basin. Below the upper few meters, both the frequency of reflections and their amplitude decrease. An erosional surface, representing the late-Glacial to early-Holocene unconformity (*e.g.*, Abbott *et al.*, 1997) is found at 2–7 m sub-bottom (Figure 10). Desiccation in the middle Holocene produced

distinctive erosional surfaces that have been buried by relatively little sediment since flooding of Lago Menor (Seltzer *et al.*, 1998).

5. Discussion

Little can be inferred about the nature of Sequence I, because no sedimentologic data and limited acoustic data are available. The dynamics that caused the non-horizontal strata in the seismic data
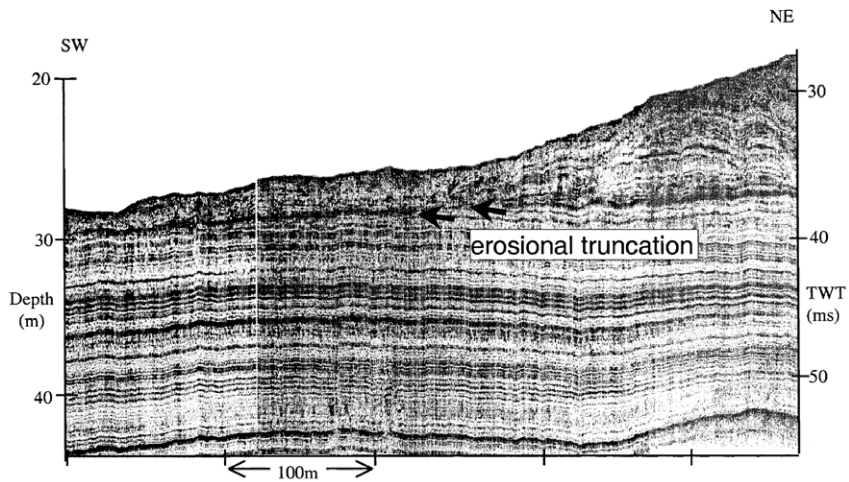
Figure 10. Seismic profile showing erosional truncation of seismic reflections in Lago Menor.

within Sequence I in many locations cannot be determined. Possible mechanisms include structural deformation or, more likely, sediment drape over structural highs. In the deeper areas of the basin (>200 m modern water depth), where Sequence I is present in the seismic profiles, the reflections appear to be continuous and conformable with the overlying strata, indicating relatively undisturbed deep water sedimentation.

The limits of acoustic penetration of the seismic data nearly coincide with the top boundary of Sequence I. This erosional boundary suggests a significant change in the depositional mode of the lake. Evidence of erosion along this boundary is
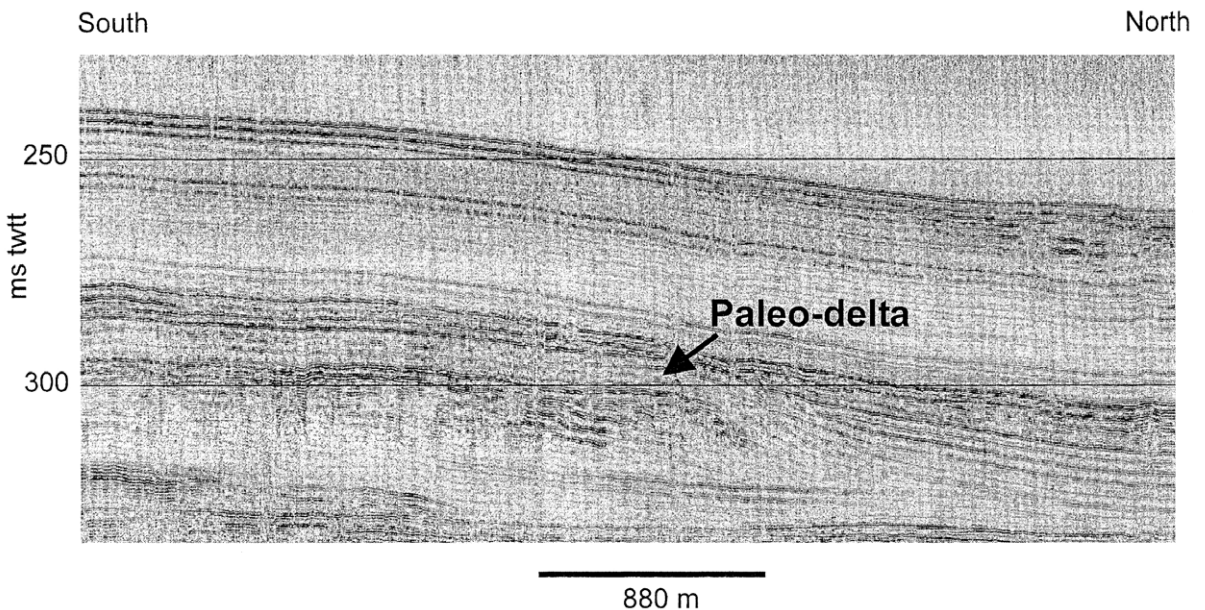

Figure 11. Seismic profile showing clinoforms interpreted as a paleo-delta at the Sequence I/II boundary. These data were acquired using a Huntec boomer system in 1998.
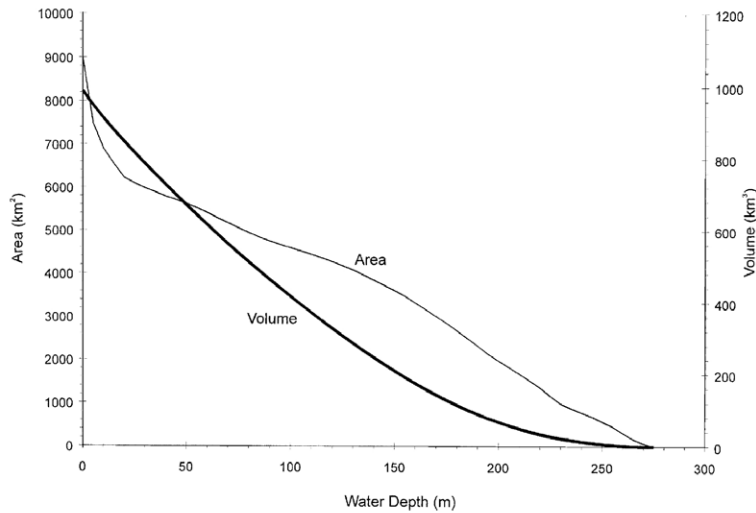
Figure 12. Lake area and volume as a function of water depth for Lake Titicaca.

found on a basinwide scale as much as 240 m below present lake level, implying that during this event only the deepest parts of the basin were accumulating sediment, while shallower areas were experiencing erosion or a depositional hiatus. We interpret the erosion surface to have formed near the lake surface, which is further substantiated by the presence of clinoforms interpreted as deltaic sequences that have been identified along this sequence boundary using a more powerful seismic source (Figure 11; Seltzer *et al.*, 1999). If the lake level indeed dropped ~240 m, then its volume was decreased by ~80% and its surface area was reduced from 8,600 to ~2,000 km^2 (Figure 12).

Sedimentation rates calculated from core data permit us to estimate the age of the lowstand event by extrapolation. The rate of sedimentation of dated glacial age sediments in deep water averaged about 0.8 mm/yr (Baker *et al.*, 2001a). Postglacial sediments accumulated at slower rates of ~0.2 mm/yr in the deep part of the lake. If time is equally divided between stadial and interstadial periods (sedimentation rates of 0.8 and 0.2 mm/yr, respectively), then an average Sequence I/II boundary depth of 30 m in the deeper areas of the lake, where sediment likely accumulated continuously, implies that the related lowstand occurred at least 90,000 cal yr BP.

The nature of the climatic or tectonic changes that led to the lowstand indicated by this widespread erosional event are unknown. A 240-m tectonic rise of the outlet or subsidence of the basin appears to require improbably high rates of tectonic activity. For example, Quaternary uplift rates in the Bolivian Andes are believed to have been only about 0.7 mm/yr (Benjamin *et al.*, 1987). High rates of relative subsidence would also be expected to cause extensive sediment disturbance such as slumps and turbidity flows. Instead, these are remarkably rare. On the contrary, sedimentation seems to have been mostly continuous and uniform after the deposition of Sequence I. Therefore we presume that lake level variation due to climatic change was the dominant factor in producing this lowstand.

Lake level fluctuations on the order of hundreds of meters caused by climatic change have been proposed for other lakes at similar latitudes. For example, Lake Malawi in the East African Rift Valley underwent a lake level drop of 200–300 m between >40,000 to 28,000 ^{14}C yr BP (Finney *et al.*, 1996) and 100–150 m during the early Holocene (Finney and Johnson, 1991). Owen *et al.* (1990) determined that a 30% decrease in precipitation was sufficient to account for such a large lake level drop in as little as 400 yr in the East
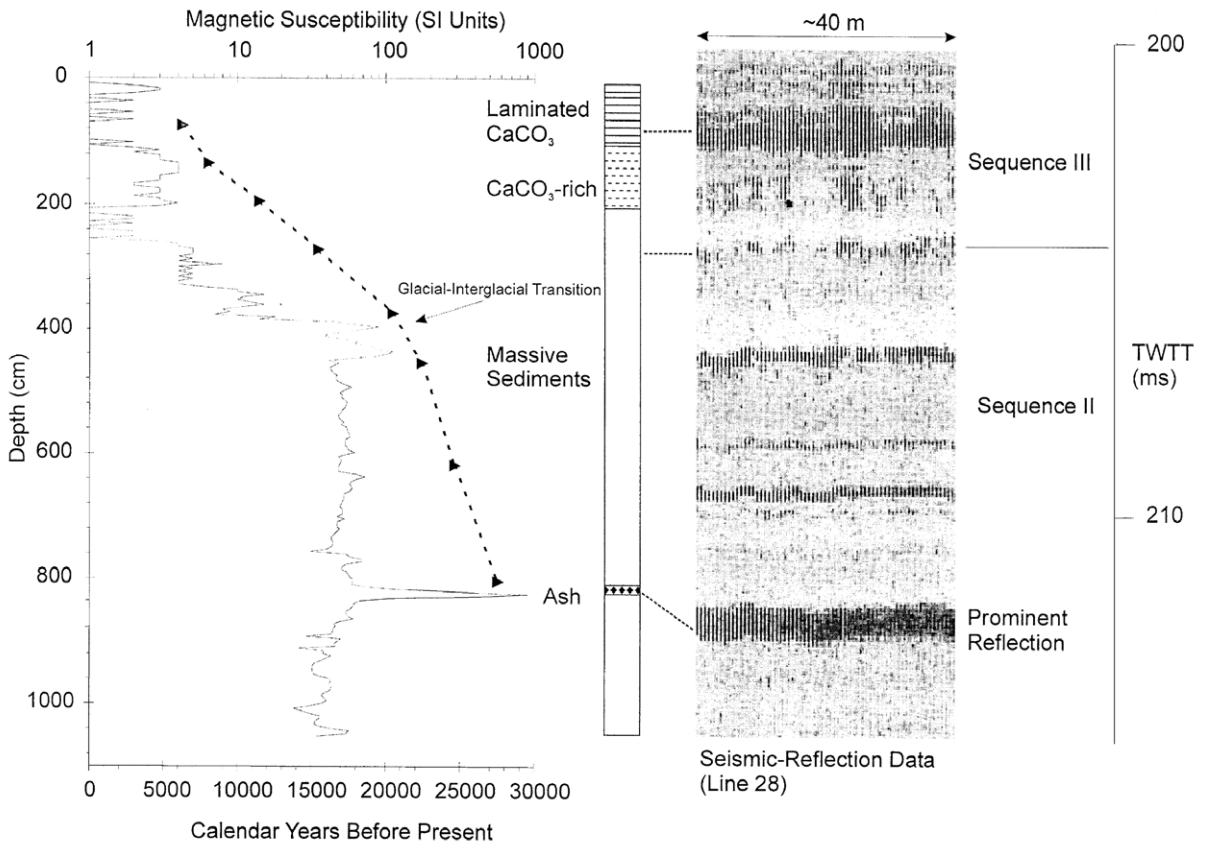
Figure 13. Visual and magnetic susceptibility stratigraphy of sediment core NE981PC in 152 m water depth correlated with seismic reflection data. The triangles represent AMS radiocarbon dates on bulk organic matter. The magnetic susceptibility spike near the base of the core correlates with an ash layer. This ash has been observed in a number of sediment cores in the basin, and we believe that it correlates with the prominent reflection that occurs at an average sub-bottom depth of 10 m in the deep areas of the lake. The order-of-magnitude drop in magnetic susceptibility at ~21,000 cal yr BP coincides with a drop in sedimentation rate and with what we believe is the glacial–interglacial transition in this region. At this time glaciers apparently pulled back from their maximum positions, and glacio-fluvial sediments were subsequently trapped in proglacial lakes, which formed in the neighboring cordillera. The carbonate-rich sediments near the top of the core correlate with the middle Holocene lowstand of the lake that is indicated by the sequence boundary at the bottom of Sequence III. At this time the lake was as much as 90 m below its modern level.

African Rift Valley. The 85–100 m drop of Lake Titicaca in the early to mid Holocene was probably produced by a sustained decrease in effective moisture of 30–40% compared to modern levels (Cross *et al.*, 2001). The steep-sided morphology of the basin suggests that similar, or slightly greater, moisture decreases could easily result in a greater decrease in lake level and thus in the formation of the deeper erosional surface.

Above Sequence I, the seismic stratigraphy indicates a lake level rise (Sequence II). Paleolake highstands on the southern Altiplano have been studied by Servant and Fontes (1978), Servant *et al.* (1995), Bills *et al.* (1994), and Sylvestre *et al.* (1999). The last two major paleolakes have now been dated in a drill core in the Salar de Uyuni at 15,000–25,000 cal yr BP ("Lago Tauca") and >40,000 cal yr BP ("Lago Minchin") (Baker *et al.*, 2001b). These ages coincide with past periods of maximum summer insolation and apparently more intense tropical convection (Baker *et al.*, 2001b). It is possible that the onlapping reflectors at the

base of Sequence II (Parasequence IIa) formed during a rise of Lake Titicaca at the same time as the formation of paleolake Minchin on the southern Altiplano. Above the flooding surface (Parasequence IIb), the reflections indicate no major lake level fluctuations, suggesting highstand conditions prevailed until the erosional event at the top of Sequence II.

Within Sequence II (and within Parasequence IIb) there is a prominent reflection. Its depth coincides with the lower limit of the sediment core data that we have available. We believe the prominent reflection is caused by a ~4-cm-thick ash layer that is present in most of the long cores throughout the basin (Figure 13). The combination of the seismic character of the reflection, the fact that it is not a sequence boundary, and its basinwide presence suggests that the ash layer may in fact be the prominent reflection. The ash layer was bracketed

by radiocarbon dates in several sediment cores that place it at 27,000 cal yr BP (Baker *et al.*, 2001a).

The lake level appears to have remained relatively steady until the erosional hiatus that defines the top of Sequence II. Erosion of Sequence II is found in water depths of as much as 90 m in a number of locations in the lake. Some erosional features, such as channels, associated with this boundary have been discussed previously (Seltzer *et al.*, 1998). These channels contain <1 m of sediment that has accumulated since the late-Holocene transgression of the lake level. The lowstands occurred between ~8,000 and 3,600 cal yr BP (Seltzer *et al.,* 1998; Cross *et al.,* 2000; and Baker *et al.,* 2001a).

The sequence boundaries at the tops of Sequences I and II are defined by erosional surfaces, indicating lake level lowstands. The top of Sequence I, in an average sub-bottom depth of 30 m,
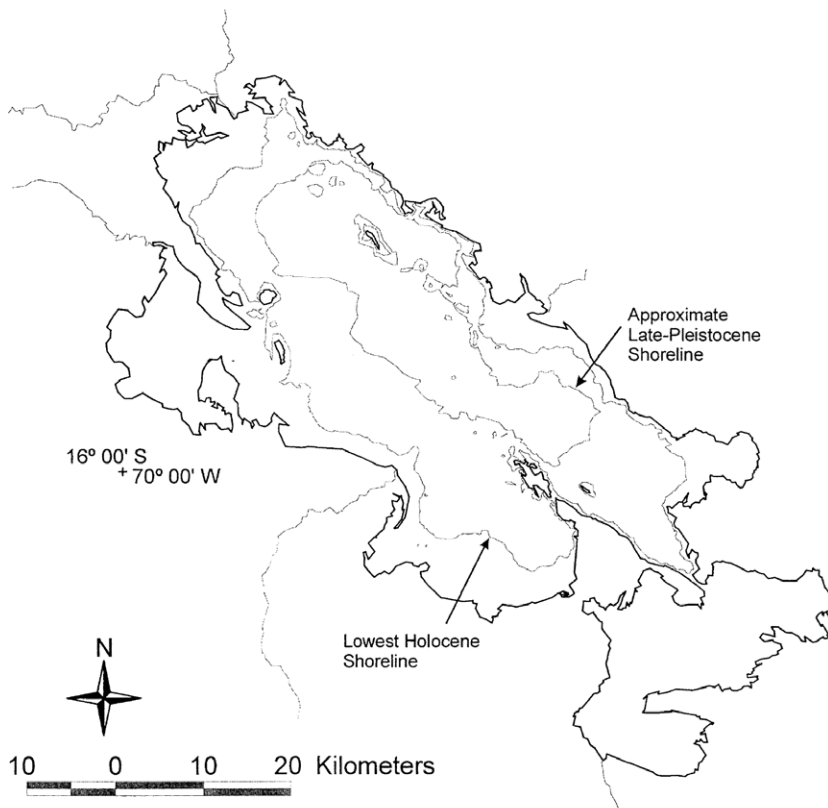

Figure 14. Shorelines at present, ~8,000–3,600 cal yr BP (−90 m), and >90,000 cal yr BP (−240 m) based on interpretation of the seismic reflection data.

indicates that the level of Lake Titicaca was more than 240 m lower than today (>90,000 cal yr BP). A drop in the lake level this large was previously unknown for Lake Titicaca and signals a major late-Pleistocene lowstand. The top of Sequence II, the second erosional boundary, is interpreted as a reflection of the well-documented early- to mid-Holocene aridity in Lake Titicaca and the tropical Andes (*e.g.*, Seltzer *et al.*, 2000). The seismic reflection profiles show erosional truncation at the base of Sequence III in present water depths as much as 90 m. The approximate aerial extent of both lowstands can be determined using the modern bathymetry of the lake (Figure 14).

Seismic Sequence III represents sediments that have accumulated during the Holocene. These are characterized by organic- and carbonate-rich silts that show a progressive freshening of the lake up to the present (Cross *et al.,* 2000; Baker *et al.,* 2001a). In shallower regions of the lake (<90 m) this seismic sequence is either missing or thinned because of selective erosion by bottom currents and erosion by subaerial processes in the early to mid Holocene.

6. Conclusions

The seismic stratigraphy of Lake Titicaca indicates that late-Quaternary lake levels have varied significantly, most likely because of climatic change. Seismic sequence boundaries dated to >90,000 and ~8,000–3,600 cal yr BP correspond to lake level drops from the modern level of about 240 and 90 m, respectively. Prominent erosional channels in <90 m water in the lake bottom are associated with the most recent lake level drop. The seismic data used in conjunction with sediment core data indicate that there is a basinwide stratigraphic marker, most likely volcanic ash, dated at ~27,000 cal yr BP. Small-scale neotectonic movement of the sediments is indicated by normal faults, some of which penetrate the sediment–water interface. However, evidence for slumping and deformation of the sediments associated with major tectonic activity is lacking in the seismic reflection data.

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