Hydrological change during the Pleistocene-Holocene transition associated with the Last Glacial Maximum-Altithermal in the eastern border of northern Puna

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ABSTRACT. The environment of the Andean Puna Plateau is mostly characterized by the dominance of evaporative processes due to aridity. Since the intermittent runoff lacks the morphodynamic competence to generate the present day landscape, authors have usually considered that the Puna landscape is a remnant feature of the Miocene arid-climate persistence. Then, a Quaternary-*sensu lato*-age was assigned to salars, alluvial fans and other geomorphologies. We present evidences from the endorheic depression of Guayatayoc-Salinas Grandes (GSG) located at 3,400 m a.s.l. in the eastern border of northen Puna. The basin includes a saline playa domain in the north (Guayatayoc Playa Lake) and a salt pan in the southern part (Salinas Grandes). We have identified two dissimilar processes originating the subdivision of the GSG depression. The characterization of those processes included sedimentological and geomorphological observations, as well as chronologies using luminescence and radiocarbon. Evidences reveal the development of a saline-lacustrine water body that is associated with the Last Glacial Maximum. During the Late Pleistocene and until ~13.8 cal kyr BP, lake shores were modelled in the front of distal-alluvial fans, the sedimentary aggradation was widespread, and associated with kaolinitic-clay accumulation, inyoite, and the formation of peat-deposits. An environmental change towards aridity occurred after 13.8 cal kyr BP, and wetter conditions returned during the early to middle Holocene, around 9 cal kyr BP. Then, incisive river dynamics accompanied the establishment of a playa lake, with montmorillonitic-fine sediments and ulexite generation during later Holocene. The subdivision of the GSG depression onset by the two following processes: **1.** the topographic decoupling, that is associated with Las Burras's alluvial fan aggradation during Pleistocene; **2.** the lacustrine regression phase at 13.8 cal kyr BP. Therefore, Guayatayoc and Salinas Grandes are saline systems functioning as a playa lake and a salt pan, respectively, since the Holocene, due to environmental constraints.

Keywords: Andes, Quaternary, Playa lake, Salar.

RESUMEN. Cambio hidrológico asociado al Último Máximo Glacial-Altitermal durante la transición Pleistoceno-Holoceno en el borde oriental de Puna Norte. Las condiciones ambientales de la Puna andina se caracterizan por la aridez y el dominio de procesos evaporativos. Debido a que las escorrentías intermitentes carecen de competencia morfodinámica para la generación del paisaje actual, los autores generalmente han considerado que el paisaje puneño es una característica remanente de la persistencia de la aridez miocena y asignaron una antigüedad cuaternaria *sensu lato* a los salares, abanicos aluviales y otras geoformas. Presentamos evidencias obtenidas en la depresión endorreica Guayatayoc-Salinas Grandes (GSG), situada a 3.400 m s.n.m., en el borde oriental de la Puna Norte de Argentina. La cuenca incluye un dominio de barreal salino al norte ('playa lake' Guayatayoc) y un salar al sur (Salinas Grandes), relacionados con procesos que generaron la subdivisión de la depresión GSG. La caracterización de tales procesos incluye observaciones sedimentológicas y geomorfológicas, así como cronologías mediante luminiscencia y radiocarbono. Las evidencias revelan la existencia de desarrollos lacustres asociados al Último Máximo Glacial. Durante la última parte del Pleistoceno y hasta hace unos 13,8 cal ka AP, las riberas lacustres se modelaron en los frentes distales de los abanicos aluviales y la agradación sedimentaria fue generalizada, asociada con la acumulación de arcillas caoliníticas, inyoita y depósitos turbosos. Un cambio ambiental hacia condiciones de aridez fue registrado después de 13,8 cal ka AP, pero las condiciones de humedad se establecieron nuevamente durante el Holoceno inferior a medio, desde 9 cal ka AP. La dinámica incisiva fluvial acompañó el establecimiento del ambiente de playa lake en el cual se generaron sedimentos montmorillóníticos y ulexita durante el Holoceno superior. La subdivisión de la depresión GSG se dio mediante dos procesos: **1.** la desvinculación topográfica, asociada a la agradación del abanico Las Burras durante el Pleistoceno; **2.** la retracción lacustre alrededor de 13,8 cal ka BP. En consecuencia, Guayatayoc y Salinas Grandes son sistemas salinos que funcionan como un 'playa lake' y un salar, respectivamente, desde el Holoceno y cuya génesis obedeció a condicionantes ambientales.

Palabras clave: Andes, Cuaternario, Playa lake, Salar.

1. Introduction

A Quaternary *sensu lato* age has been assigned to salars, alluvial fans and other geomorphological features in the Puna. It has been usually considered that the Puna landscape is a remnant feature of the arid climates established in the region since Miocene (Alonso, 2006). The aridity in the Puna is actually controlled by the orography that constitutes a physical barrier to the humid atmospheric circulation coming from the Atlantic. The arid and evaporative climate in the Andean Puna causes intermittent runoffs. These ephemeral runoffs lack the morphodynamic competence to generate the present day landscape, that includes un-incised fresh morphologies such as extensive alluvial fans as well as paleoshorelines modelled on the periphery of numerous salars (Abril and Amengual, 1999).

The study area involves an endorheic system located at 3,400 m a.s.l., in the eastern border of northern Puna, Argentina (Fig. 1A). The altitude determines temperatures with daily amplitude (18 °C) larger than annual (annual mean 8 °C). Annual rainfall concentrates in summer (300 to 400 mm) and defines a negative hydrological balance more than 10 month per year, and a relative humidity of 47% (Bianchi, 1981; Buitrago and Larran, 1994).

The lacustrine system (GSG) includes a saline playa domain in the north (Guayatayoc playa lake) and a salt pan in the southern part (Salinas Grandes) separated by Las Burras alluvial fan (LB). The GSG is the end point for the hydrological discharges of this endorheic system (Fig. 1A).

The present contribution characterizes environmental processes in the GSG during the late Quaternary. Environmental processes related to the basin evolution led to the establishment of the two present day sub-basins, Salinas Grandes as a salt pan (chemical-agradative domain) and Guayatayoc as a playa lake (clastic-agradative domain). Our study also contributes in a more regional scale, to better understand the variability of the upper Quaternary climate and its geomorphic influence under arid settings.

2. The Pleistocene-Holocene transition in the Andes

During last decades, multiples studies have analyzed Quaternary formations in the Andean high plateau (Ballivián *et al.*, 1978; Servant and Fontes, 1978; Servant Vildary, 1978; Veit, 1994; Argollo and Murguiart, 1995; Argollo, 1996; Abbott *et al.,* 1997; Argollo, 2000; Zreda *et al.,* 2001; Cross *et al.,* 2001; Paduano *et al.,* 2003; Servant and Servant-Vildary, 2003; Fritz *et al.,* 2004; Mayewski *et al.,* 2004; Grosjean *et al.*, 2007; Zech *et al.*, 2009b). The paleohydrological evolution of basins located in the NW Argentine Andes has been evaluated by
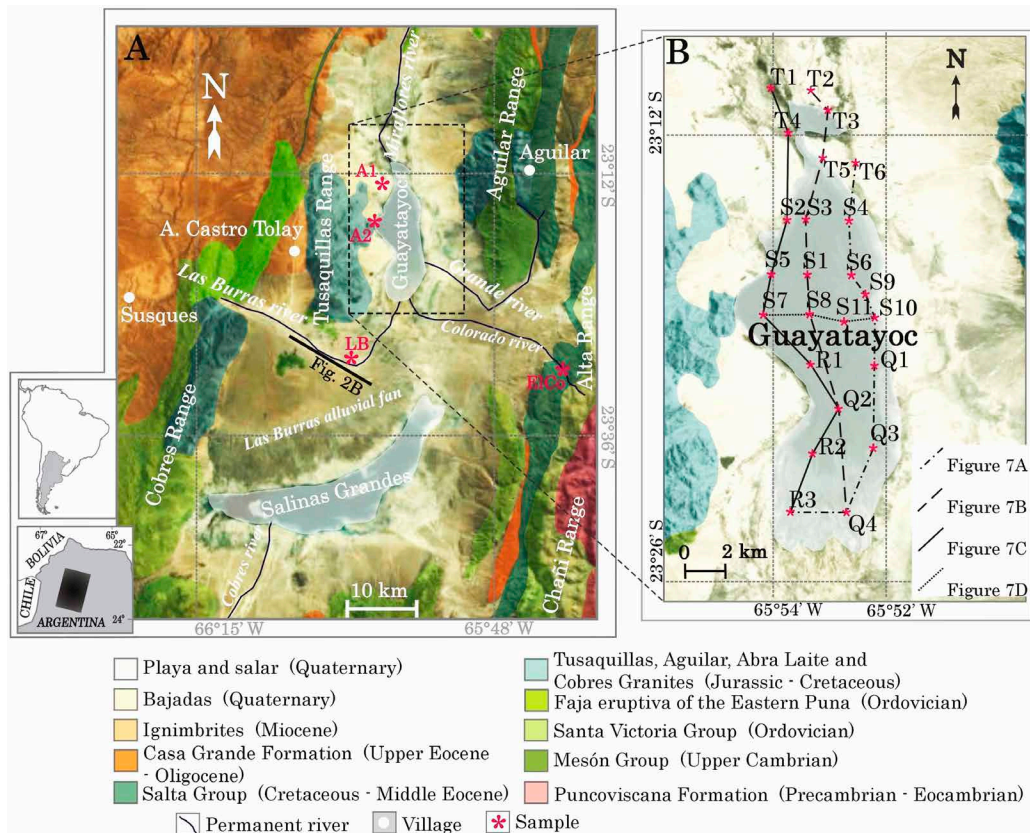
FIG. 1. Location map of the GSG area and the sampled sites. **A.** The studied area includes the Guayatayoc playa lake and the Salinas Grandes which are separate by Las Burras alluvial fan; **B.** Pits location for the playa lake-sampling in Guayatayoc.

Godfrey *et al.* (1997), Trauth and Strecker (1999); Valero Garcés *et al.* (2000); Godfrey *et al.* (2003); Trauth *et al.* (2003) and McGlue *et al.* (2012).

In northern Puna, arid conditions would have been persistent during most of the Pleistocene (Abril and Amengual, 1999) until 150 cal kyr BP (Fritz *et al.*, 2004). Since 150 cal kyr BP environmental conditions changed with the occurrence of some cooler and more humid phases accompanied by glacial (Zipprich *et al.*, 1999; Zech *et al.*; 2009a) and lacustrine (McGlue *et al.*, 2013) activity in the eastern border of northern Puna.

Cold-humid conditions characterizing the Upper Pleistocene would persist during the Early and even middle Holocene, and the present-arid environment could have developed by middle to upper Holocene (Sayago and Collantes, 1990; Lupo, 1998; Kulemeyer,

2005; Yacobaccio and Morales, 2005; Tchilinguirian *et al.*, 2012).

The morphodynamic sequences in the GSG depression were previously associated with middle-upper Pleistocene climate conditions (Abril and Amengual, 1999). Sedimentological studies of the playa deposits in Guayatayoc (Reverberi, 1968[1]) documented the presence of lacustrine facies in the area.

3. Methods

The measured and described sedimentological profiles includes: **1.** Las Burras alluvial fan deposits; **2.** the shorelines deposits in the distal part of the Tusaquillas alluvial fan; and **3.** the terraces in valleys located in the southeastern margin of the basin (Fig. 1A). 24 pits were dug in the Guayatayoc playa

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[1]   Reverberi, O.V. 1968. Contribución al estudio de los yacimientos de boratos de Argentina. Laguna Guayatayoc. Departamentos Cochinoca y Tumbaya. Provincia de Jujuy. Reporte técnico (Unpublished), Instituto Nacional de Geología y Minería, Subsecretaría de Minería y Combustibles: 70 p. Jujuy.

lake (Fig. 1B) up to a depth limited by the brine-water table. Sections were described, sampled and collected in the pits.

Mineralogical compositions were analyzed using optic microscopy, scanning electron microscopy, diffraction and fluorescence of X-rays. Microfossils were observed under optic and scanning electron microscopy, and taxonomies were identified by comparison with local references using published taxonomic keys (Seeligmann *et al.*, 2008).

In order to estimate the basal age of the LB deposit, we have considered a sedimentation rate (mm/yr) based on **1.** two Optically Stimulated Luminescence (OSL) dates, **2.** thickness of the alluvial fan using a 2D migrated seismic reflection line. For the LB profile location, the static seismic correction procedure erased the weathered seismic-sequences until 350 DTS (Double Time Seconds). These weathered seismic-sequences were assimilated to the upper Quaternary deposits of the LB alluvial fan (López Steinmetz, 2013).

Chronologies (Table 1) were established using two different dating techniques. Optically stimulated luminescence: samples were collected using PVC cylinders with 50 mm in diameter and 30 cm in length that were push-hammered into the freshly cleaned vertical section and immediately covered with a lid. In laboratory (Laboratorio de Luminiscencia, Universidad de la República, Uruguay), the two ends of the samples in the cylinders were first removed and collected for estimation of environmental dose rate. Quartzitic sand-sized grains and polymineral fine fractions were isolated by chemical, magnetic and heavy liquid-flotation. Reading was performed using the thermoluminescence multiple-aliquot protocol (MAA), and monitoring feldspars by the infrared stimulated luminescence (IRSL). Radiocarbon ages: peat and carbonate samples pretreatment and dating were performed at the LATYR Laboratory of the Universidad de La Plata, followed by conversion of carbon-14 dates (^{14}C yr BP) to calendar ages (cal yr BP) using CALIB 6.0.1 (Southern Hemisphere calibration curve SHCal04) (McCormac *et al.*, 2004; Stuiver *et al.*, 1998). Considerations about reservoir effects for radiocarbon dates are set forth in the discussion.

4. Results

4.1. Las Burras alluvial fan

Las Burras alluvial fan is an un-incised geo-morphological unit. The access to its sedimentary deposits is restricted to a few quarries. The exposure Las Burras (LB, 23°30'59.2"S, 66°00'00"W, Fig. 1A) is a 6 m thick deposit formed by polimictic sandy conglomerates, with subrounded Ordovician quartzitic clasts, up to 60 cm wide. The quartzitic sandy matrix was sampled (LB$_1$ y LB$_2$), at 6 m and 4 m from the top of the alluvial fan surface for OSL dating. The age results are 76,335±7,000 yr BP and 32,022±3,000 yr BP (Table 1).

According to these chronological results, the range of the weathered seismic-sequence (erased from seismic data by the static correction procedure) and the altitude of both, the seismic data and the LB profile, we considered that the thickness of the alluvial fan could reach ~170 m in the position of the LB section (Fig. 2).

4.2. Tusaquillas alluvial fan

The distal deposits in the Tusaquillas alluvial fan (Fig. 1A) were sampled in hand-dug trenches. A1 (2.3 m thick) and A2 (1.60 m thick) are located in the northwestern side of the Guayatayoc playa lake (23°14'47"S, 65°57'13.1"W and 23°13'11.7"S, 65°55'46"W, respectively).

TABLE 1. DETAIL OF THE ^{14}C AND OSL DATED SAMPLES.

| Sample	Laboratory	Lab Code	Method	Material	Age
LB$_1$	Laboratorio de Datación por Luminiscencia, Universidad de la República, Uruguay	LB - TLD-UNCIEP-UY-00100	OSL	quartz	32,022±3,000 yr
LB$_2$		LB1 - TLD-UNCIEP-UY-00101		quartz	76,335±7,000 yr
ElCo	LaTyR, Universidad Nacional de La Plata, Argentina	ElCo M2 DAT	^{14}C	peat	9,050±80 *cal* yr BP
SS$_6$		SS6M6		carbonatic crust	13,840±180 *cal* yr BP
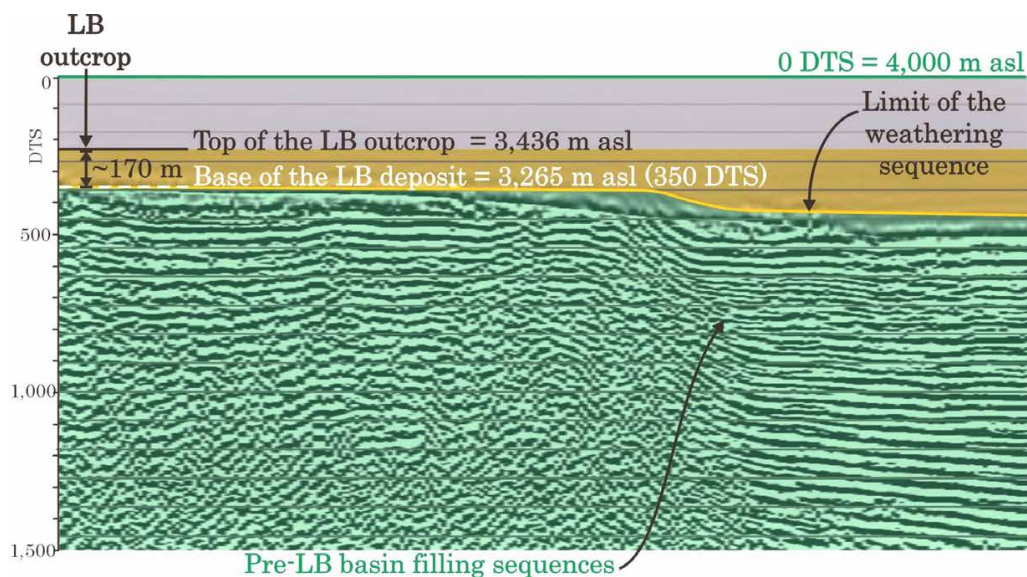
FIG. 2. Correlation between the top of Las Burras alluvial fan deposit, in the LB fill-cut position, and the 267 DTS reflector in the seismic line. The weightiness of the deposit could reach ~170 m in the position of LB.

The lower part of the hand-exposed fill-cut starts with bioturbated green clays and it is followed by brown-yellow sands and white-gray silt. The upper part contains peat deposits mixed with silty-clays, and 10 cm long inyoite ($Ca_2B_6O_{11} . 13 H_2O$) crystals. The top of the sequence is composed by interstratified alluvial sands and gravels (Fig. 3).

Coarse A1 and A2 sediment contain clastic grains: spherical-detrital fragments are abundant as well as quartz, biotites and plagioclase (Fig. 4A); however, the matrix is a fine, diatomaceous silty-clay (Fig. 4B). Morphologically identified taxa include *Anomoeoneis sphaerophora fa. costata Kützing*, *Planothidium* sp., *Surirella angusta Kützing* (Fig. 4C) and *Surirella* sp. (Fig. 4D), possibly *Surirella chilensis Janish* (Seeligmann *et al.*, 2008).

4.3. Guayatayoc Playa Lake

The Guayatayoc playa (Fig. 5A) is covered by a light brown salty crust due to the mixture of the evaporative halite in the surface and the underlying brown silty-clays (Fig. 5B). Below, green clays reached an unknown thickness that is at least greater than 1.7 meters.

Sediments are composed by clastic fragments, including tabular biotites, subangular plagioclases (Fig. 5C and D), fresh pumice, glass shards (Fig. 5E)

and a brown-green diatomaceous matrix. The following species have been identified in the matrix: *Surirella* sp. (Fig. 5F), *Surirella wetzelii Hustedt* (Seeligmann *et al.*, 2008), *Surirella chilensis Janish* (Fig. 5G; Seeligmann *et al.*, 2008), *Surirela angusta Kützing* (Fig. 5H) (Fig. 6A and B).

These clay deposits include illitic aluminous silicates and aluminous-kaolinitic mixtures (Fig. 6E, F and G). Montmorillonitic aluminous silicates rich in Na over Mg, possibly saponite (Mg, Al, Na) or montmorillonite *sensu stricto* (Al, Mg, Na), seems to be restricted to the brown silts.

The transition between the upper brown silts and the green clays occurs in a 10 cm interval accompanied by a carbonate crust and associated with ulexite cotton balls (Fig. 5B). The carbonate has provided a ^{14}C radiometric age of 13,840±180 yr cal BP. Carbonate crusts occur in the northwest to southeast margins, and the presence of borates is restricted to the southeast sector whereas brown silt thickness increases from the central areas toward the edges (Fig. 7).

4.4. El Colorado terraces

Fill-cut terraces of the El Colorado (ElCo) River (Fig. 1A) are located in the southeastern part of the Guayatayoc playa lake. The considered outcrop
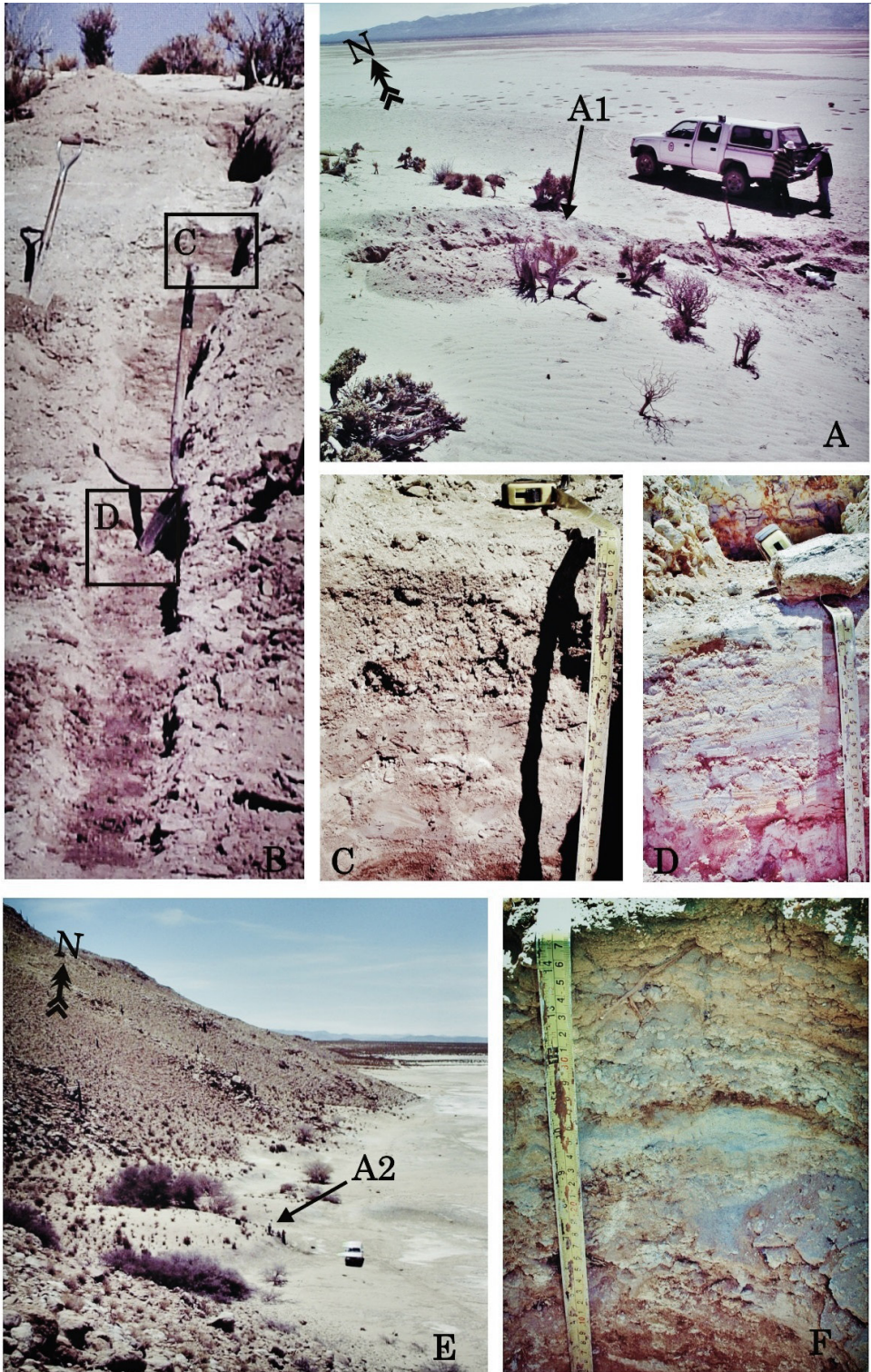
FIG. 3. The A1 and A2 fill-cuts are located in the distal parts of the Tusaquillas alluvial fan. In the A1 fill-cut (**A**) there are brown sands (**B**) and layered silts (**D**). In A2 fill-cut (**E**), the lower part includes brown-yellow peaty sand (**F**).
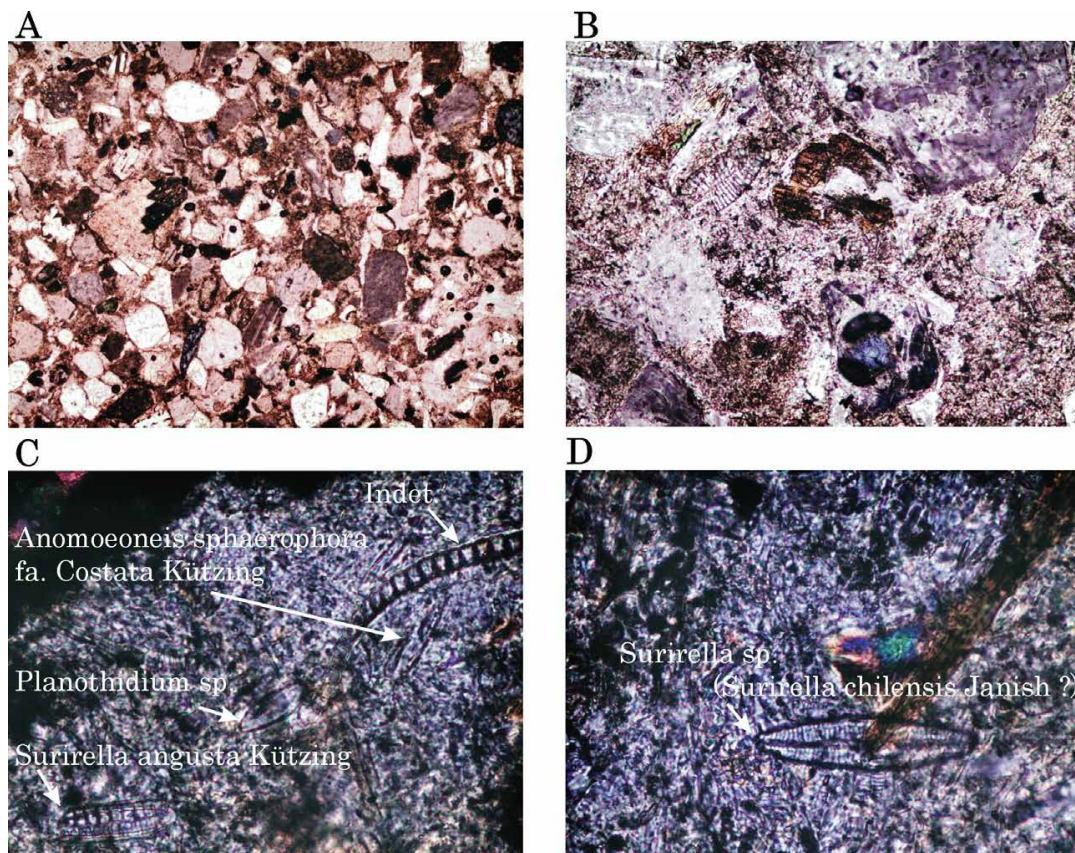
FIG. 4. Photomicrographs of the A1 (**A, B**) and A2 (**C, D**) fill-cut samples. Sediments are characterized by sandy textures with detrital fragments (A, 2X) in which the matrix is fully diatomaceous (B, 10X). Siliceous matrix contains many diatom valves (C and D, 40X).

(23°34'42.4"S, 65°41'25.1"O) exposes a river paleowetland deposit from a non-glacial valley. It includes a 3 km long and 12 m high exposure which base levels are unexposed (Fig. 8A). The basal set comprises 4 m of laminated fine sediments, greenish clays and brown silts, intercalated with black peat layers. A ^{14}C date in the peat layer located at 1.15 m from the exposed base levels yielded a ^{14}C age of 9,050±80 yr cal BP. In the top, deposits are characterized by upward coarsening gravel-sands. The sub-rounded clasts are predominantly fragments of the Ordovician quartzites (Fig. 8B).

4.5. Present-day morphology of the GSG depression

Three altitudinal domains have been recognized in the GSG endorheic depression: **1.** the Guayatayoc playa lake is located below 3,410 m; **2.** the Salinas Grandes salar is positioned between 3,410 and 3,415 m,

and **3.** bordering alluvial fans are above 3,415 m (Fig. 9A). In the alluvial fans surrounding the GSG, it have been identified at least four different paleoshore lines (Fig. 9B and C).

5. Discussion

5.1. Paleoenvironmental implications for the GSG data

The sedimentary dynamic that produced the decoupling of the GSG basin is related to geomorphological processes generated under climatic conditions which are not currently taking place. As a preliminary approach, if we use the LB Profile sedimentation rate (~0.05 mm/year) and apply it to the total thickness of the alluvial fan, the basal age for this formation would reach the middle Pliocene (about 3.7 Ma).
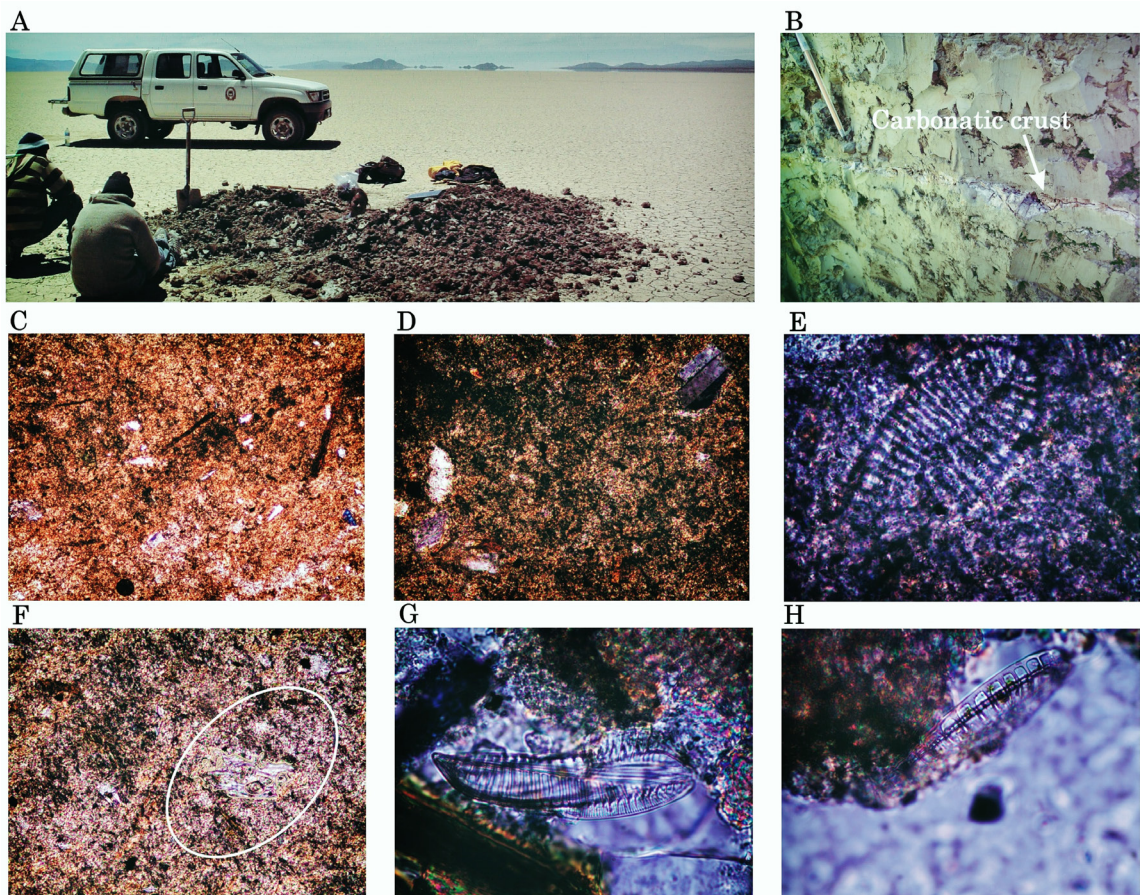
FIG. 5. The surface of the Guayatayoc playa lake contains a light-brown salty crust due to the mixture between evaporative halite and the underlying brown silt-clays (**A**). The contact between the brown silts and the green clays involves 10 cm and usually shows carbonatic crusts (**B**). Photomicrographs of samples taken from pit S6 (**C, D, E, G, H**) and Q1 (**F**); detrital green clays, tabular brown biotites and subangular plagioclases (C, 2X and D, 4X); valves of *Surirella* sp. (*Surirella wetzelii Hustedt*?) (E, 40X); fresh pumice and glass shards (F, 4X); a complete taxon of *Surirella chilensis Janish* (G, 40X); valve of *Surirela angusta Kützing* (H, 40X).

The southward predominant development of Las Burras alluvial fan indicates that the alluvial system mainly flowed towards Salinas Grandes (3,410 m a.s.l.) during Pleistocene. The river channel later turned north, then Guayatayoc (3,405 m) became the final receiver of the basin runoff. The northward changing course of Las Burras River has determined the development of the evaporative environment in the southern part of the depression and the beginning of the chemical salty accumulation. Conversely, the northern subbasin became permanently saturated due to Las Burras input, then Guayatayoc changed into a playa lake domain.

The northward shifting channel of Las Burras River may be prima facie linked to the progressive change in the topography outcome of the alluvial fan aggradation. Nevertheless, the turn north of the river channel could be also related to a hydrological regime modification. The widespread aggradation necessary for the formation of the LB alluvial fan is consistent only with more erosive capacities than the present day conditions. Then, the deposition of the alluvial fan should occur prior to the modern conditions lacking of geomorphic dynamic.

The paleoshore lines evidence that highstands (Currey and Sack, 2009) have reached up to ~10 m
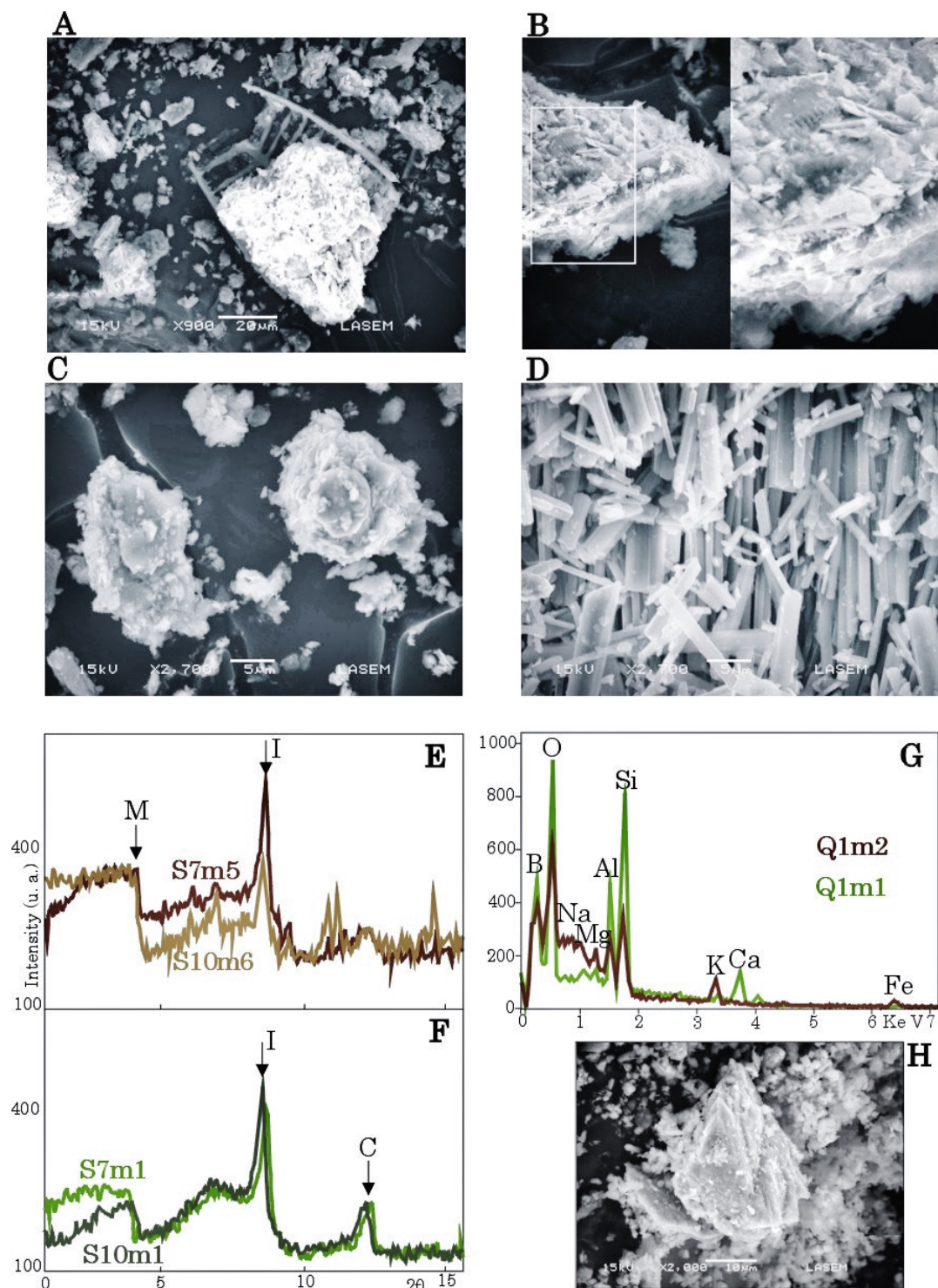
FIG. 6. Photomicrographs by scanning electron microscopy of samples from pits S1 (A, B, C), S6 (D) and Q1 (H); diatom valves in the green clays (**A-B**); rosettes of borates (**C**); triclinic crystals of ulexite (**D**). X-rays diffraction of brown silts (**E**) and green clays (**F**), **M:** montmorillonite, **I:** illite-smectite mixture, **C:** kaolinite. Scanning electron microscopy analyses of brown silts and green clays (**G**). Photomicrographs by scanning electron microscopy of illite (**H**).
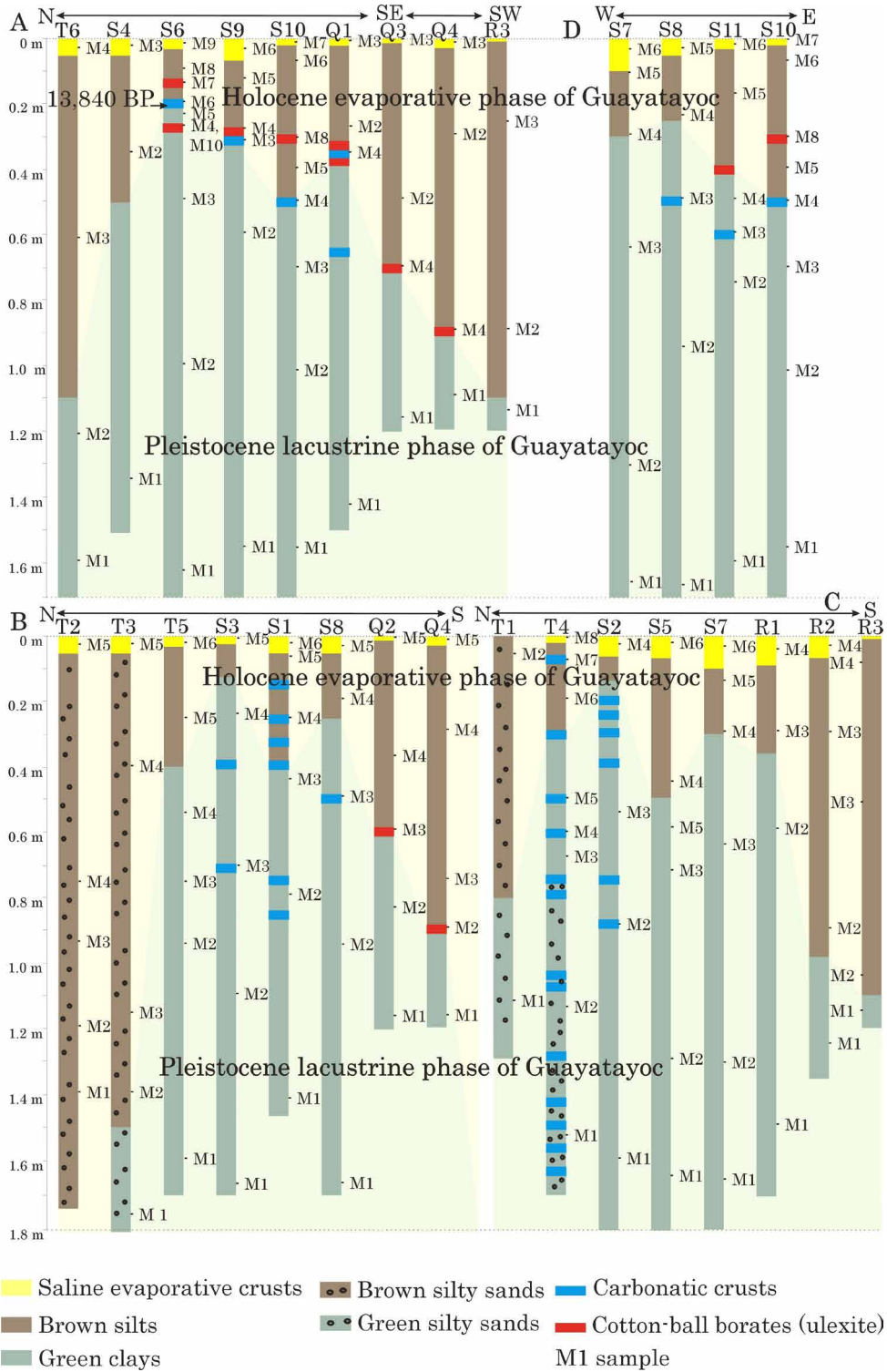
FIG. 7. East (**A**), central (**B**), west (**C**) and west-east (**D**) axes schemes, according to pits in the Guayatayoc playa lake. Data includes handy digged pit deeps, presence of carbonate crust, borates and position of the dated sample. Locations of axes schemes are shown in figure 1B.
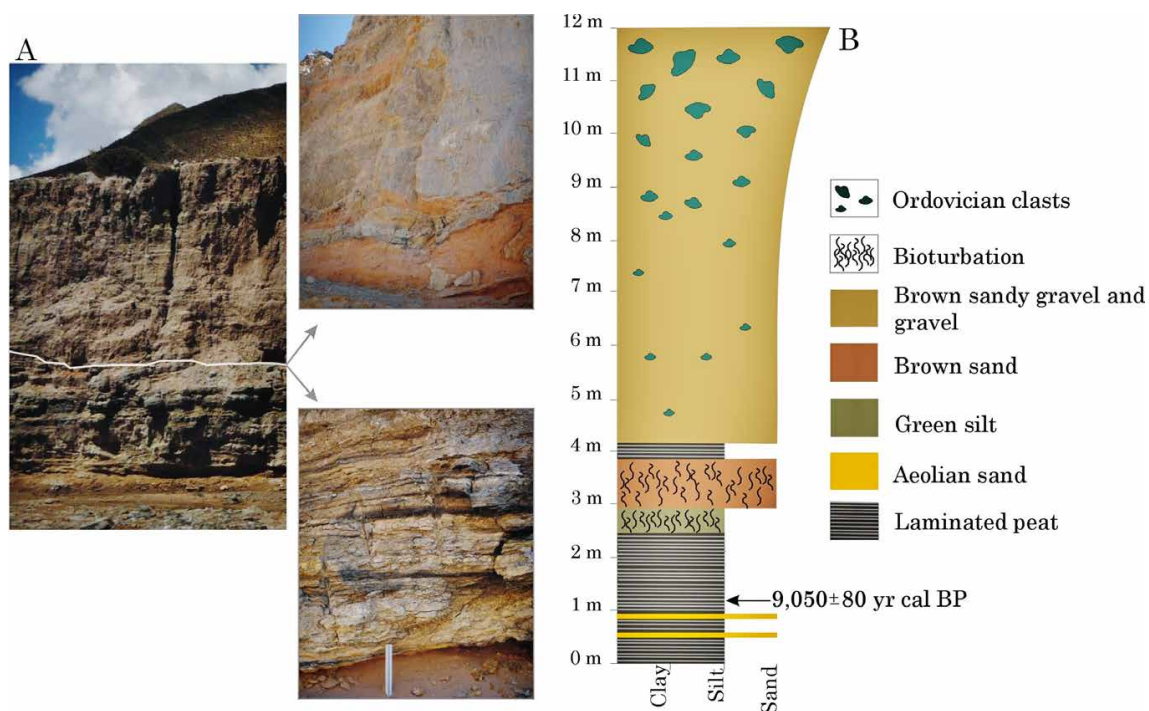
FIG. 8. ElCo profile in the terrace of El Colorado River (**A**). The stratigraphical section (**B**) shows Lower Holocene laminated fine sediments, greenish clays and brown silts, intercalated with black peats. The presence of an erosive surface indicates the existence of a different aggradative phase which is characterized by upward coarsening gravel-sands with Ordovician quartzites clasts.

high in Guayatayoc (paleoshoreline 3,415 m a.s.l.). At the time of formation of the highest paleoshoreline, the Guayatayoc lake level surpassed the distal fan area of Las Burras and flooded Salinas Grandes (Fig. 9C)**.** Consequently, the surface-separation between the two basins was *sensu stricto* established only after this post-lacustrine phase.

During the Upper Pleistocene, wet conditions determined that the glacier activity (Messerly, 1967; Rodbell *et al.*, 2009) became widespread through the region (Zipprich *et al.*, 1999; Zreda *et al.*, 2001; Zech *et al.*, 2009b). Glacier meltwater must have been a determining factor in regulating lake levels, so that deglaciations furnished necessary water volumes to increased lake levels. The beginning of the deglaciation in the Sierra de Santa Victoria occurred at ~17 cal kyr BP (Zech *et al.*, 2009a) after the Last Glacial Maximum (Shakun and Carlson, 2010). In Guayatayoc, this event could be represented by the highest paleoshoreline (3,415 m) and its associated highstand (Fig. 9 D). The remaining paleoshorelines

at lower elevations would correspond to successive stages of melting glaciers with decreasing lake levels. Even though glacial activity requires wetter climates than present-day (Messerly, 1967; Rodbell *et al.*, 2009), these lake levels could be a response to rising temperatures and melting glaciers without higher rainfall regimes (Ochsenius, 1986).

The formation of peat deposits in El Colorado Terrace at around 9 cal kyr BP demonstrates the persistence of high humid conditions during the early Holocene. Non-stormy precipitations were recorded by the fine-organic sedimentation of the river paleowetland deposits in the non-glacial valley of the El Colorado. The development of an upward coarsening sequence in the top of the El Colorado terrace suggests a later phase of increased erosive capacities of the hydrological network, which could reflect the gradual establishment of the seasonal monsoonal regime. The 12 m high fill-cutting of the El Colorado terrace indicates that erosive incision processes were dominant during the Late Holocene (Fig. 8).
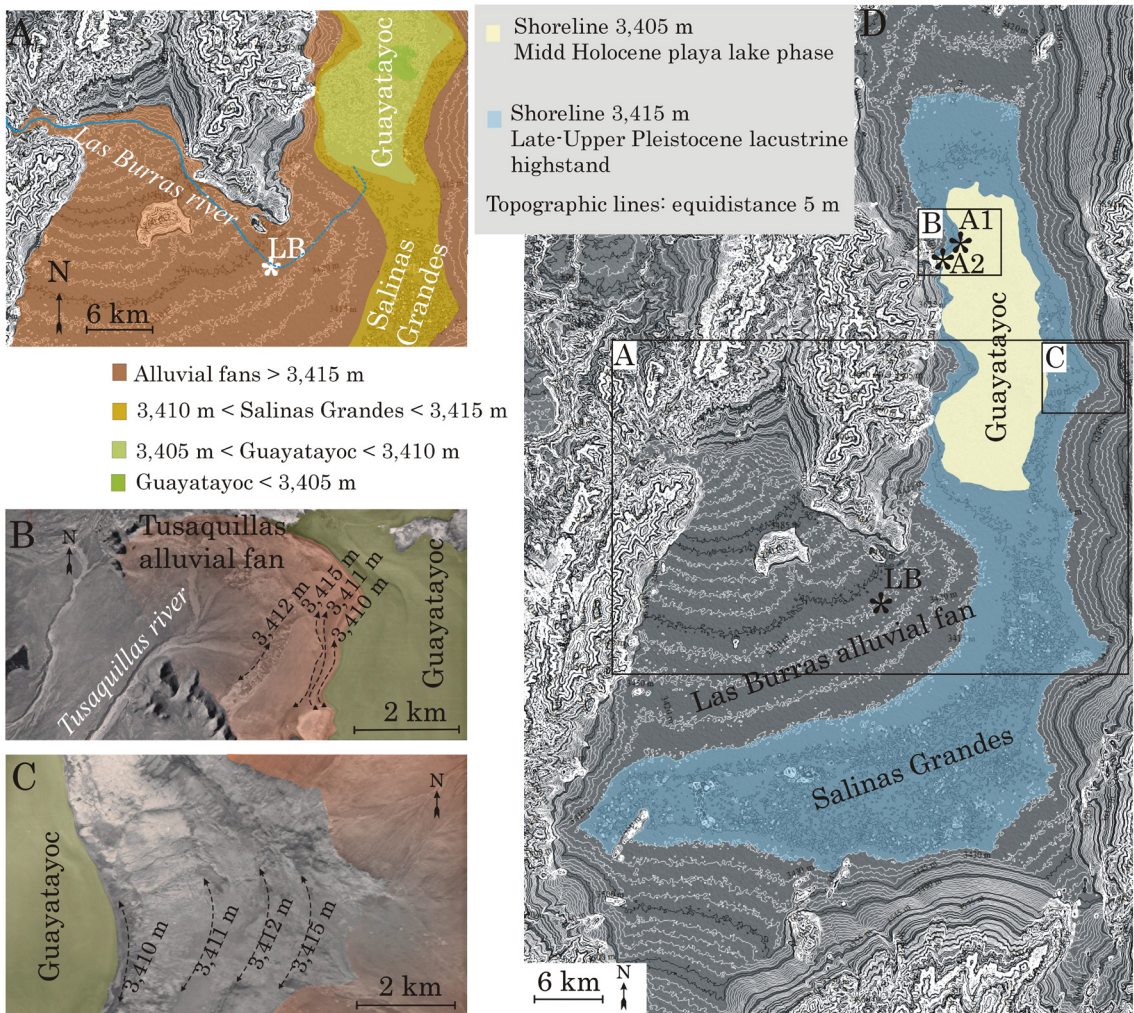
FIG. 9. Altitudinal domains of the Guayatayoc-Salinas Grandes depression. The playa lake is located below 3,410 m, the salar is positioned between 3,410 and 3,415 m and distal areas of alluvial fans reach 3,415 m (**A**). Lacustrine paleo-shore lines in the Tusaquillas alluvial fan (**B**) and in the eastern-border of Guayatayoc (**C**). During the highstand a 10 m deep lacustrine water body occupied Guayatayoc and Salinas Grandes (**D**). Figure captions were edited over digital elevation models (A and D) and aerial photographs (B and C).

In the GSG depression, Pleistocene green clays represent an expansive stage of the lake. The presence of a meso-euhalophile diatom flora, characterized by many individuals with low diversity, and the occurrence of kaolinitic alumino-silicates with no evidence of bioturbation suggests a saline-basic pH water body under reductive conditions.

The carbonate crust in the green clays/brown silts interface in the playa of Guayatayoc indicates the occurrence of a hydrological change towards hydro-deficiencies. The lacustrine retraction is as-sociated with the beginning of the accumulation of montmorillonitic brown silts and the development of carbonatic crusts that in the pit S6 yielded an age of 13.8 cal kyr BP. However, this is a minimal age due to crusts seem to be more ancient in the rest of the playa lake (*e.g.,* pits R3, T6, etc.). High spatial facies variability is a common feature in the evolution from a lacustrine to a playa system (Velde, 1992). The playa domain appeared early in the northern part of Guayatayoc and it was influenced by the alluvial input of the Miraflores river. The playa developed

later in the southern part of Guayatayoc and finally covered the whole oriental margin. The final expression of the lacustrine body occupied the northern sector, coinciding with the present shallow lagoon formed by the Miraflores River mouth.

Inyoite were formed along the shoreline deposits during the lacustrine highstands. Following deglaciation the environment changed towards dry conditions (Lupo, 1998; Kulemeyer, 2005; Yacobaccio and Morales, 2005; Tchilinguirian *et al.*, 2012). Climate could have exerted the evaporative concentration of the water table. The playa lake deposits may have been then saturated in sodium-rich brines favouring the formation of the ulexite during the Holocene. The ulexite occurs selectively within montmorillonitic sediments in the transition between the distal alluvial fans and the Holocene playa lake domain. The intra-sedimentary formation of the ulexite is linked to subsurface evaporative processes whereas the inyoite crystallization would be related to a gradual mineral precipitation within cold standing waters. In the Guayatayoc context, the distinctive paragenetic sequence of the inyoite-ulexite and the calcium borate stability at lower temperatures than the sodium one (Ortí, 1996), could be used as a relative chronological tool.

The intensification of the summer monsoonal regime (Trauth *et al.*, 2003) causes seasonal flooding in the GSG. These regimes are in agreement with evidences from El Colorado terraces that indicate that the hydro availability during the Holocene was intermittent. Therefore, the establishment of the altithermal stage (Shakun and Carlson, 2010) and the dry postglacial conditions that have been characterizing this environment during the Middle to Upper Holocene until the present day seem to have taken place later than 9 cal kyr BP.

5.2. The GSG paleoenvironment in a regional context

The regional contextualization of the GSG paleoenvironment requires to assess the reliability of the ^{14}C chronology. The limits of this assessment are difficult to ascertain due to the lack of knowledge regarding the reservoir effect that could have the system on the radiocarbon dates. Radiocarbon dates may be significantly older than their true age of deposition due to the long residence time of water, the input of volcanic thermal springs and the weathering of carbonate lithologies in the drainage basin. For example, Grosjean *et al.* (2001) have considered very large ranges (between 1 and 10 kyr) for reservoir effects, in agreement with the findings of Geyh *et al.* (1998) and Geyh *et al.* (1999). However, some authors (*e.g.,* Baker *et al.*, 2001; Abbot *et al.*, 2003; Fritz *et al.*, 2004) have not corrected ages for reservoir effects: **1.** due to the reservoir effect for the different paleolake stages remained undefined; **2.** since a small reservoir effect was assumed, based on the little presence of carbonate rocks in the watershed; **3.** and according to the large volume of inflows supposed to feed lakes, that would have minimized the contribution of non-atmospheric carbon (Baker *et al.*, 2001; Sylvestre *et al.*, 1999).

Abbot *et al.* (1997) have considered that the contemporary reservoir effect of Lake Titicaca (250 yr) measured on aquatic gastropods, has been consistent through time for the past 3,500 yr. Nevertheless, Sylvestre *et al.* (1999) have observed that a modern reservoir correction cannot be applied throughout past time to paleolakes of lower levels than today. As well as for low lake level periods, a strong reservoir effect should be introduced in radiocarbon dates from groundwater-influenced systems. Conversely, radiocarbon ages are neither affected in fluvial environments nor lake systems during transgressive phases and highstands (Sylvestre *et al.*, 1999). The variable reservoir effect through time was considered by Argollo and Mourguiart (2000), as well as large reservoir effects related to groundwaters and volcanic contributions of geothermal fluids have been detected by Valero-Garcés *et al.* (2000).

An opposite reservoir effect, that is a radiocarbon date younger than their true age, was detected by Jenny *et al.* (2002). Authors proposed that this younger age is related to recrystallization during desiccation phases. They have also observed two differential reservoir effect cases in lacustrine systems: the inorganic carbon, having a reservoir effect (~1 kyr in the younger sense) and the organic carbon, with no reservoir effect. This observation is in agreement with Quade *et al.* (2008), who found no reservoir effects on fine-grained thin layers of pure carbon originated from terrestrial plant fragments.

The reservoir effect for the GSG Quaternary system remains unknown. According to Quade *et al.* (2008), we do not consider necessary a reservoir effect correction for the radiocarbon age of the peat sample ElCo (~9 cal kyr BP). Concerning

radiocarbon age of sample SS6, in the GSG system we have found neither evidences of fossil nor active carbonated hydrothermal discharges. Sources that could have potentially influenced the radiocarbon date of sample SS6 are related to: **1.** weathering of Mesozoic sedimentary formations located in the southeast areas of the basin (Fig. 1); **2.** old ground waters feeding the lake during dry phases.

The sample SS6, a carbonate crust that separates both the lacustrine and the playa facies, may represent a retractile lacustrine stage. Thus, it should be then necessary to consider a reservoir effect for the ^{14}C age of SS6. If the sample SS6 do represents decreasing lake levels, then, the retractile stage in the GSG basin would have started at ~13.8 cal kyr BP. This date must be contrasted 'vis à vis' the hydrological models proposed for the region (Fig. 10).

The last glaciation in the Altiplano (Argollo and Mourguiart, 2000; Tapia *et al.*, 2003), in northern Puna and in the Eastern Cordillera (Clayton and Clapperton, 1995; Smith, 2003; Zech *et al.*, 2009a) seems to have extended until ~17-16 cal kyr BP.

Melting glaciers linked to rising temperatures (Paduano *et al.*, 2003) led to lacustrine developments. The Tauca lacustrine phase in the Altiplano and the Bolivian Eastern Cordillera (Sylvestre *et al.*, 1996; Clapperton *et al.*, 1997; Sylvestre *et al.*, 1999; Argollo and Mourguiart, 2000; Fornari *et al.*, 2001; Zreda *et al.*, 2001; Paduano *et al.*, 2003) seem to have been synchronous with the Central Andes Pluvial Event (CAPE) registered in the Atacama region (15.9 to 13.8 cal kyr BP; Gayo *et al.*, 2012; Quade *et al.*, 2008). In northern Chile, this rainy period (Baker *et al.*, 2001) was also recorded by Geyh *et al.* (1999), Bobst *et al.* (2001), Grosjean *et al.* (2001) and Grosjean *et al.* (2003).

The Tauca phase reached the highstand (Sylvestre *et al.*, 1996, 1999; Zreda *et al.*, 2001; Blard *et al.*, 2009; Blard *et al.*, 2011) at ~15 cal kyr BP, just next to the major moraine-glacial advance in the Eastern Cordillera of northern Argentina (Smith, 2003; Zech *et al.*, 2009b), Bolivia (Clayton and Clapperton, 1995), and southern Altiplano (Clapperton *et al.*, 1997). However, Blard *et al.* (2009, 2011) proposed that the glacial maximum activity was synchronous with the Tauca lacustrine highstand between 17 and 15 kyr BP.

The retraction of the Tauca phase was controlled by hydrological shifts towards aridity. This brief dry period was registered between 14 and 12 cal kyr BP

in the Atacama region (Gosjean *et al.*, 2001) and in the southern Altiplano (Sylvestre *et al.*, 1996; Sylvestre *et al.*, 1999). Then, the Coipasa lacustrine stage have developed during the Lower Holocene (Sylvestre *et al.*, 1996; Sylvestre *et al.*, 1999; Zech *et al.*, 2007; Blard *et al.*, 2009; Blard *et al.*, 2011).

We consider that the lacustrine stage of the GSG basin could be synchronous with the Tauca lacustrine phase and the CAPE. We propose that the 3,415 m lacustrine paleoshoreline in Guayatayoc may corresponds to this regional Tauca highstand. In this context, the ^{14}C age of sample SS6 is in agreement with the beginning of the retraction of the Tauca phase. The carbonate crust of sample SS6 could be formed starting the dry period that took place between 14 and 12 cal kyr BP. Thus, the radiocarbon date of ~13,8 cal kyr BP results in good agreement with the regional hydrological context, and it becomes then unnecessary correcting it for reservoir effects.

Between ~12,7 and 9 cal kyr BP the climate becomes wet. This shift defines a new lacustrine stage (the Coipasa phase) in the Altiplano (Clapperton *et al.*, 1997; Argollo and Mourguiart, 2000; Fornari *et al.*, 2001; Fritz *et al.*, 2007), and in the Eastern Cordillera (Smith, 2003; Zech *et al.*, 2007). This humid period was also registered in the Atacama region (Grosjean *et al.*, 1995; Núñez *et al.*, 1997; Geyh *et al.*, 1999; Bobst *et al.*, 2001; Núñez *et al.*, 2002; Jenny *et al.*, 2002; Grosjean *et al.*, 2003) and it was defined as the 12.7-9.7 cal kyr BP CAPE (Quade *et al.*, 2008).

Diatomaceous brown silts from the Guayatayoc playa lake could correspond to a local lacustrine stage, contemporaneous with the Coipasa phase. Sedimentary records are not conclusive, but if so, this lacustrine stage was less intense that the Tauca phase. In the other hand, these brown silts might formed in a playa environment during the Holocene *sensu lato*-humid phase, which accomplished at ~6 kyr BP with the end of the paleohydrological conditions that allowed aggradation in the GSG basin.

Around 9 to 8 cal kyr BP hydrological conditions seems to take different paths. Extremely arid conditions have dominated the lower Holocene in the Atacama region (Grosjean *et al.*, 1995; Núñez *et al.*, 1997; Grosjean *et al.*, 2001; Núñez *et al.*, 2002; Jenny *et al.*, 2002; Grosjean *et al.*, 2003), and in the Altiplano (Wirrman and De Oliveira Almeida, 1987; Wirrman *et al.*, 1988; Wirrman, 1995; Abbot
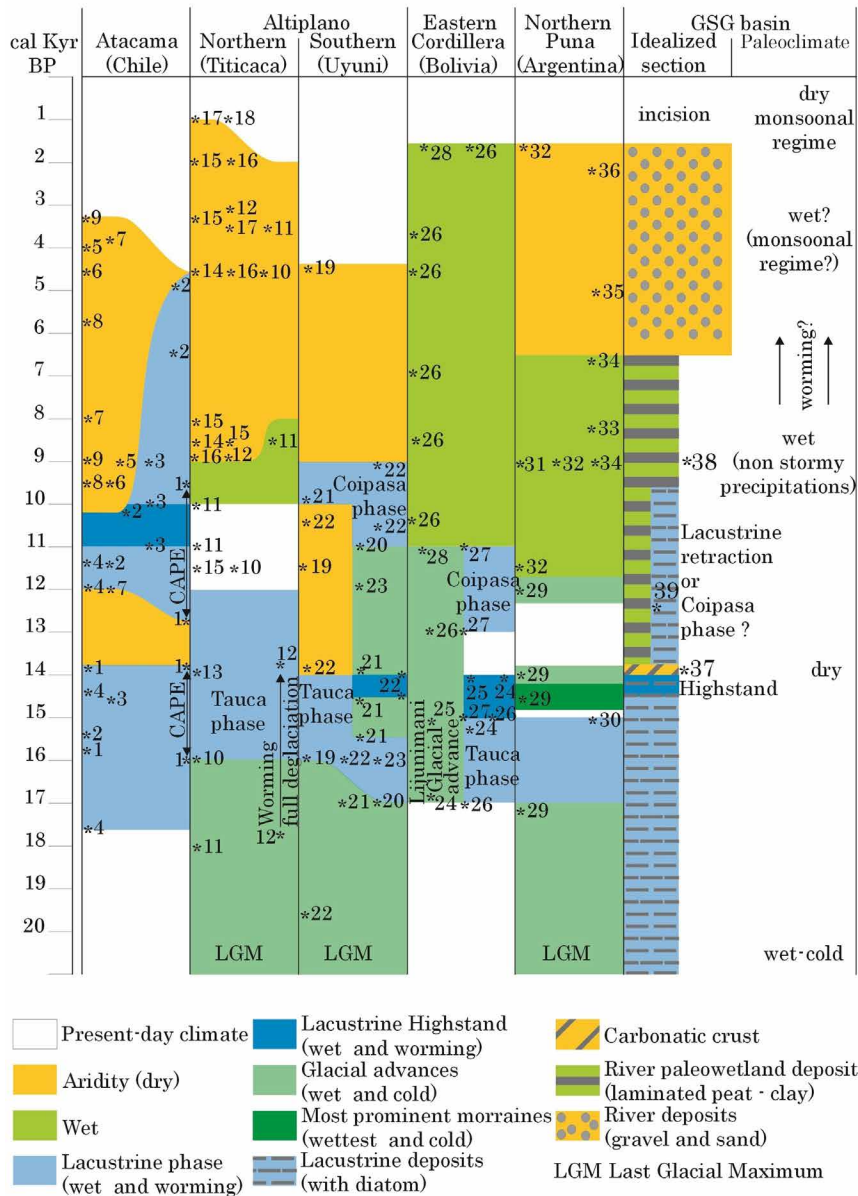
FIG. 10. Regional paleoenvironmental models for the last 20 cal kyr BP for the region of Atacama (Chile), the Altiplano and Eastern Cordillera of Bolivia, and for the northwestern region of Argentina (including the northern area of the Eastern Cordillera and the eastern border of northern Puna). The northern Altiplano climate model takes data mainly from Titicaca, while the southern Altiplano paleoenvironmental reconstruction was principally based on the available information from Uyuni. The paleoclimate reconstruction for the GSG is based on an idealized and simplified section. Referenced sources are: *1 Quade *et al.* (2008); *2 Bobst *et al.* (2001); *3 Geyh *et al.* (1999); *4 Gayo *et al.* (2012); *5 Grosjean *et al.* (2003); *6 Núñez *et al.* (2002); *7 Grosjean *et al.* (2001); *8 Jenny *et al.* (2002); *9 Grosjean *et al.* (1995) and Núñez *et al.* (1997); *10 Argollo and Mourguiart (2000); *11 Tapia *et al.* (2003); *12 Paduano *et al.* (2003); *13 Fritz *et al.* (2007); *14 Wirrman and De Oliveira Almeida (1987); *15 Wirrman *et al.* (1988); *16 Wirrman (1995); *17 Abbot *et al.* (1997); *18 Cross *et al.* (2001); *19 Argollo and Mourguiart (2000); *20 Sylvestre *et al.* (1996); *21 Clapperton *et al.* (1997); *22 Sylvestre *et al.* (1999); *23 Fornari *et al.* (2001); *24 Zreda *et al.* (2001); *25 Clayton and Clapperton (1995); *26 Smith (2003); *27 Zech *et al.* (2007); *28 Servant and Servant-Vildary (2003); *29 Zech *et al.* (2009a); *30 Baker *et al.* (2001); *31 Grossjean *et al.* (2007); *32 Kulemeyer (2005); *33 Markgraf (1985); *34 Yacobaccio and Morales (2005); *35 Trauth *et al.* (2003); *36 Valero-Garcés *et al.* (2000); *37 and *38 correspond to 13,8 and 9 *cal* kyr BP radiocarbon dates from the present contribution; *39 Blard *et al.* (2009, 2011).

et al., 1997; Argollo and Mourguiart, 2000; Paduano et al., 2003; Tapia et al., 2003). However, climate remains wet in the Eastern Cordillera of Bolivia (Servant and Servant-Vildary, 2003; Smith, 2003). Evidences of humid conditions were also mentioned in the northern part of the Argentine Andes. These humid conditions remained until 6,5 cal kyr BP in the Eastern Cordillera and northern Puna (Markgraf, 1985; Kulemeyer, 2005; Yacobaccio and Morales, 2005; Grosjean et al., 2007; Zech et al., 2009a). The pit-terraces from El Colorado in GSG (^{14}C age of ~9 cal kyr BP) should represent these wet times.

6. Conclusions

During the late Pleistocene and until middle Holocene the environmental and climate conditions in Guayatayoc-Salinas Grandes were conducive to the development of a 10 m deep saline-lacustrine water body. This humid phase occurred after the Last Glacial Maximum. During deglaciation and until 13.8 cal kyr BP, lake paleoshores were molded on the front of distal-alluvial fans, the sedimentary aggradation was widespread, and associated with kaolinitic-clay accumulation, inyoite precipitation, and the formation of peat-deposits. An environmental change towards aridity occurred after 13.8 cal kyr BP, and wetter conditions returned during the early to middle Holocene, around 9 cal kyr BP. Then, incisive river dynamics accompanied the establishment of a playa lake, with montmorillonitic-fine sediments and ulexite generation during later Holocene. The subdivision of the GSG depression in two subbasins occurred by two processes, the topographic decoupling associated with Las Burras's alluvial fan aggradation during Pleistocene, and the lacustrine regression phase at 13.8 cal kyr BP. Therefore, Guayatayoc and Salinas Grandes are saline systems functioning as a playa lake and a salt pan respectively since the Holocene.

Acknowledgments

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