Depositional environments of Quaternary lacustrine travertines and stromatolites from high-altitude Andean lakes, northwestern Argentina

Blas L. Valero-Garcés, Concha Arenas, and Antonio Delgado-Huertas

Abstract: Four distinctive depositional subenvironments of fossil travertines and stromatolites are identified in three high-altitude (3500–4000 m above sea level) lacustrine basins: El Peinado, San Francisco (Las Coladas Salar subbasin), and Las Peladas (southern Andean Altiplano, northwestern Argentina). These late Quaternary occurrences are characterized using geomorphological, sedimentological, petrographic, and stable isotopic data. Stromatolites of cyanobacterial origin only develop in shallow lacustrine margins of El Peinado basin. In the same basin, macrophytic travertines occur both near thermal spring seepage areas along the lake margin as in situ facies and in littoral lacustrine environments up to water depths of several metres as phytoclastic travertine facies. The stromatolites and macrophytic travertines have relatively heavy $\delta^{18}O$ compositions, suggesting initial ^{16}O-depleted waters and (or) evaporation effects through time. Their high $\delta^{13}C$ compositions are interpreted as a reflection of intense CO_2 evasion from the thermal groundwaters feeding the lakes. Similar laminated travertine facies, with no petrographic evidence for biotic origin, occur in both Las Coladas and Las Peladas basins. Neither petrographic nor isotopic data alone can differentiate between these two cases. Besides, diagenetic overprint in Las Peladas facies precludes the use of isotopic values as original isotopic signatures. However, the depositional environmental conditions defined by the geomorphological and sedimentological features are different. Laminated aragonitic crusts in Las Coladas basin formed in a shallow, saline lake and are associated with shoreline and terrace deposits cemented by aragonite. These travertine crusts represent periods of spring, ^{16}O-rich discharge to the lake, as suggested by the lighter oxygen isotopic compositions. In contrast, travertines from Las Peladas occur as laminated calcitic and aragonitic units intercalated at the top of fining-upward sequences composed of conglomerates, sandstones, and intraclastic limestones. Sedimentological data suggest that these travertines originated in fluvial-influenced lake margins during low lake-level episodes.

Résumé : Quatre sous-environnements distincts de déposition de travertins et de stromatolithes fossilifères sont identifiés dans trois bassins lacustres de haute altitude (3500–4000 mètres au-dessus du niveau de la mer), soit les bassins El Peinado, Lad Coladas et Las Peladas (Altiplano andain sud, au nord-ouest de l’Argentine). Ces occurrences du Quaternaire tardif sont caractérisées au moyen de données géomorphologiques, sédimentologiques, pétrographiques et d’isotopes stables. Les stromatolithes d’origine cyanobactérienne ne se développent que dans les marges lacustres peu profondes du bassin El Peinado. Dans ce même bassin, les travertins macrophytiques se retrouvent près de régions de sources d’infiltration thermales le long de la bordure du lac, en tant que faciès in situ, et dans des environnements lacustres littoraux jusqu’à des profondeurs de plusieurs mètres, en tant que faciès de travertins phytoclastiques. Les stromatolithes et les travertins macrophytiques ont des compositions relativement élevées en $\delta^{18}O$, suggérant des eaux initialement pauvres en ^{16}O et (ou) des effets de l’évaporation dans le temps. Leurs compositions élevées en $\delta^{13}C$ sont interprétées comme le reflet d’un échappement intense de CO_2 des eaux souterraines thermales qui alimentent les lacs. Des faciès semblables de travertins laminés, sans évidence pétrographique d’une origine biotique, se retrouvent dans les bassins de Las Coladas et de Las Peladas. Ni les données pétrographiques ni les données isotopiques ne peuvent seules faire la différence entre ces deux cas. De plus, la surimpression diagénétique dans le faciès Las Peladas empêche l’utilisation de valeurs isotopiques en tant que signatures isotopiques d’origine. Toutefois, les conditions environnementales de déposition définies par les caractéristiques géomorphologiques et sédimentologiques sont différentes. Des croûtes laminées d’aragonite dans le bassin de Las Coladas forment un lac salé peu profond et elles sont associées aux dépôts de rivage et de terrasse cimentés par l’aragonite. Ces croûtes de travertin représentent les périodes de printemps, de décharge riche en ^{16}O vers le lac, tel que suggéré par les compositions isotopiques d’oxygène plus léger. Par contre, les travertins de Las Peladas se présentent comme des unités calcitiques et aragonitiques laminées intercalées au

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sommet de séquences à affinement vertical ascendant composées de conglomérats, de grès et de calcaires intraclastiques. Les données sédimentologiques suggèrent que ces travertins proviennent de bordures des lacs influencés par les cours d'eau au cours d'épisodes où le niveau du lac est bas.

[Traduit par la Rédaction]

Introduction

Travertines are common deposits in many recent and modern carbonate systems, specifically springs, but also rivers and lakes (e.g., Chafetz and Folk 1984; Pentecost 1995; Ford and Pedley 1996; Sancho et al. 1997; Andrews et al. 1994, 1997). A great variety of deposits are produced depending on the many variables involved. These include physical (water temperature, CO_2 degassing rates, and geomorphology and topography of the depositional areas), chemical (water properties, such as Ca/Mg ratio and Sr content), and biological (presence of macroorganisms and (or) microorganisms that in some way influence carbonate precipitation) processes and factors. Travertines are nonlaminated or coarsely laminated deposits containing plant and (or) animal remains, frequently with carbonate coatings or encrustations (macrophytic travertines or tufas). On the other hand, many travertines lack in situ macrophytes (Ford and Pedley 1996), and the resulting deposits are commonly laminated, independent of their biotic or abiotic origin. In the geological record, laminated travertines have been described in a variety of continental environments of deposition (lakes, rivers, springs, soils, caves; Love and Chafetz 1990; Guo and Riding 1994; Renaut and Jones 2000). In this paper the term travertine is used as a general name to designate continental carbonate rocks that are the result of precipitation of calcium carbonate from cool and thermal surface waters, either by biotic or abiotic processes, but excluding those precipitated in caves. In this sensu latu, travertines include a wide range of surface deposits, from massive facies with carbonate-encrusted plant remains to laminated facies without any evidence of biological activity. The term stromatolite is only used for deposits characterized by fine lamination and with clear evidence of carbonate precipitation related to biological activity. Stromatolites can form in travertine depositional environments (Ordóñez and García del Cura 1983; Casanova 1984; Chafetz et al. 1990), but can also be present in lacustrine or fluvial systems that lack travertines (Anadón and Zamarreño 1981; Freytet and Verrecchia 1989; Arenas et al. 1993; Casanova 1994).

Due to the variety of surface environments where travertine and stromatolite facies occur, their ascription to particular environmental conditions of formation is not always straightforward. In this paper, we describe several travertine and stromatolite occurrences in three Quaternary lacustrine basins from the Andean Altiplano. Geomorphologic, sedimentological, petrographic, mineralogical, and isotopic data are used to characterize these facies. The proposed depositional models provide sedimentological criteria to identify environments of formation of stromatolites and of biotic and abiotic travertines in the geological record.

Geological setting

The three Quaternary basins described in this paper (El Peinado, San Francisco, and Las Peladas) are located in the southernmost Andean Altiplano (Catamarca Province, northwestern Argentina) and were formed by tectonic and volcanic activity during the Plio-Pleistocene (Fig. 1A). The area lies in the Ojos del Salado volcanic region, in the Central Andean Volcanic Province, straddling the border between Chile and Argentina at ~27°05′S, and coincides with a major morphological, seismic, and volcanic discontinuity (Baker et al. 1987). The Ojos del Salado area is characterized by major volcanic structures, including calderas, stratovolcanoes, ignimbrite sheets, compound volcanoes, and calc-alkaline volcanic rocks. The Central Andes consists of several north–south mountain ranges and intermontane basins that resulted from the subduction of the Pacific Nazca plate from the Permian to the present (Ramos 1994). The Central Andes include a high fore-arc region, an active magmatic arc (the Western Cordillera and the Altiplano), and a retro-arc belt (Eastern Cordillera, and the Chaco Foreland Basin; Börgel Olivares 1983). The Altiplano is a high ignimbrite plateau of ~ 100 000 km^2 in area that extends from ~15°S to 28°S at an average altitude of 3800 m, with many active volcanoes and intermontane lacustrine basins. The three Quaternary basins belong to a chain of tectonic depressions bounded by north–south to NNE–SSW faults (Fig. 1B). North of the San Buenaventura Cordillera, the large Antofalla Salar extends for hundreds of kilometres (Martínez 1995). The El Peinado Lake basin constitutes the southern end of the Antofalla Salar. South of the San Buenaventura Cordillera, a large north–south tectonic valley bounded by Carboniferous to Permian continental and marine siliciclastic rocks and Ordovician dacites, is filled mainly with Quaternary alluvial and aeolian sediments. Several topographic depressions in this tectonic basin contain Quaternary lacustrine sediments. They include the San Francisco, Las Peladas, Las Lozas, Cazadero Grande, and Chaschuil basins.

Methodology

Sediment cores were retrieved in several playa lakes in the San Francisco and El Peinado basins. Samples from modern surface sediments and peripheral lacustrine terraces were also collected. Former lacustrine terraces and a stratigraphic section were measured and sampled in Quaternary outcrops in Las Peladas. Thin sections were studied by petrographic and cathodoluminiscence microscopy. Scanning electron microscope (SEM) observations were carried out with a JEOL JSM 6400 scanning electron microscope at the University of Zaragoza, Zaragoza, Spain. Textures of allochthonous carbonate rocks are described following the classification of Dunham (1962), with modifications by Embry and Klovan (1971). The classification of Folk (1962) was used to describe the components and their relative proportions in thin section. Mineralogy was determined using a Siemens X-ray diffractometer. The $\delta^{18}O$ and $\delta^{2}H$ isotopic values for lake waters were determined for El Peinado and the largest playa lake in the San Francisco basin. Oxygen

Fig. 1. (A) Geographical location of the Quaternary basins in northwestern Argentina. (B) Geological map of the study area. The basins studied in this paper are El Peinado, San Francisco, and Las Peladas. (C) Location of Las Coladas Salar within the San Francisco basin. (D) Geomorphological map of the Las Peladas basin and location of the measured Lampallita stratigraphic section.

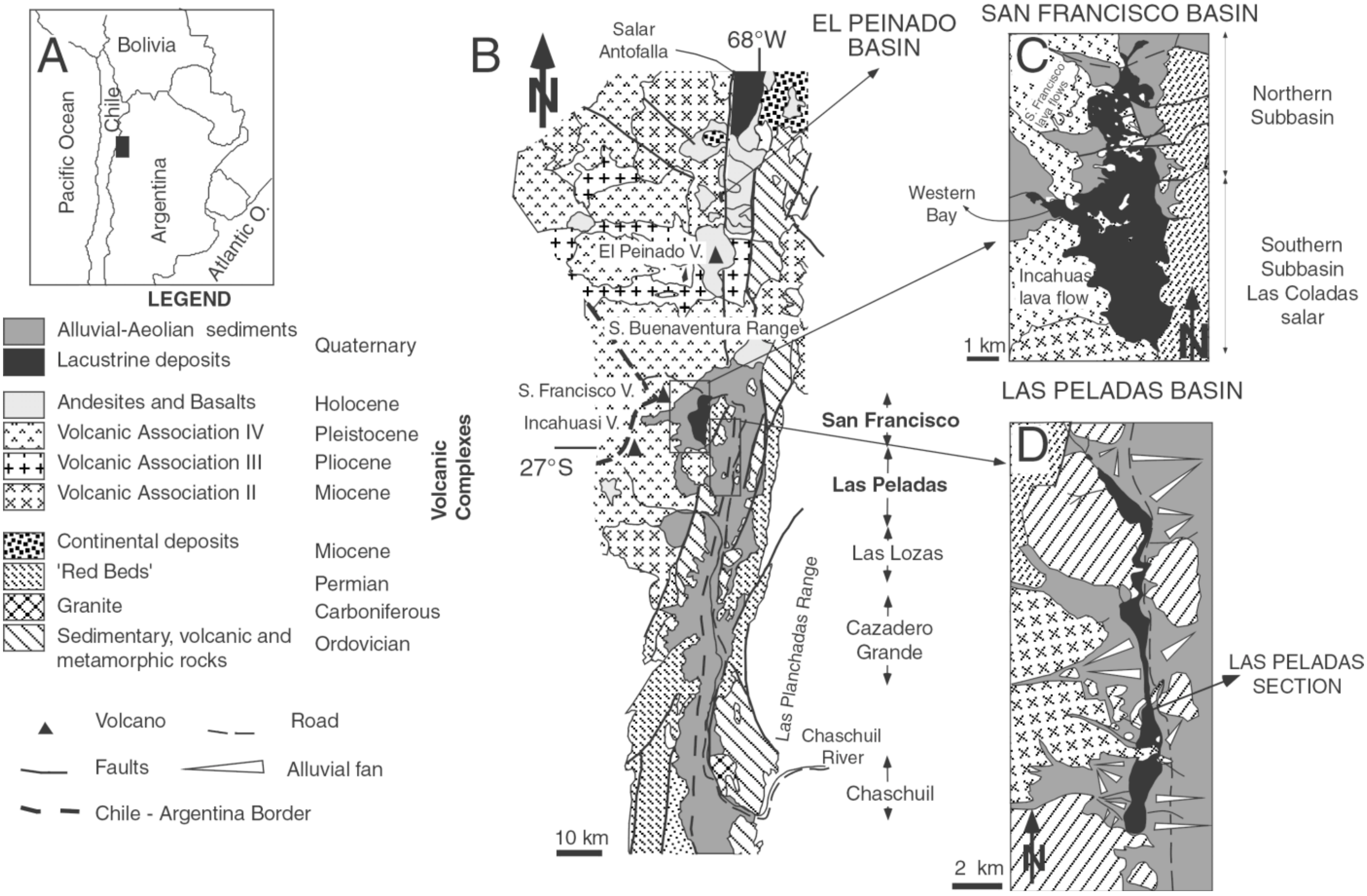


Table 1. Stable isotope (δ^{13}C and δ^{18}O) and mineralogical composition of the different facies from Las Peladas, San Francisco (Las Coladas subbasin), and El Peinado basins.

Facies[a]	Depth (cm)	Sample No.	δ^{13}C (‰ PDB)	δ^{18}O (‰ PDB)	Mineralogy[b]
Las Peladas					
Intraclastic limestone		LP-1-1	2.4	–2.2	Cal, Qtz, Pl
Intraclastic limestone		LP-1-2	2.4	–2.8	Cal, Qtz, Pl
Intraclastic limestone		LP-3-1	2.4	–2.1	Cal (<Arg)
Intraclastic limestone		LP-3-2	2.2	2.2	Cal (<Arg)
Intraclastic limestone		LP-3-3	1.8	–2.4	Cal (<Arg)
Intraclastic limestone + aragonite		LP-4-2	4.3	–1.5	Cal:Arg = 50:50
Intraclastic limestone + aragonite		LP-4-3	3.8	–3.2	Cal:Arg = 50:50
Intraclastic limestone + aragonite		LP-5-2	4.4	–1.6	Arg, Cal, Qtz, Pl
Travertine		LP-7-1	3.7	–1.9	Arg (<Cal)
Travertine		LP-7-2	3.7	–0.9	Arg (<Cal)
Travertine		LP-7-3	5.3	–1.1	Arg (<Cal)
Intraclastic limestone + aragonite		LP-8	3.7	–2.6	Cal (<Arg)
Travertine		LP-9-1	2.1	–3.5	Cal
Travertine		LP-9-3	4.6	–1.0	Cal
Travertine		LP-10-2	5.2	–2.7	Cal Qtz, Pl
Travertine		LP-10-3	4.0	–3.5	Cal Qtz, Pl
Biomicrite		LPN-T-1	1.9	–2.1	Cal (Qtz, Pl)
Biomicrite		LPN-T-2-1	1.2	–3.6	Cal (<Qtz)
Biomicrite		LPN-T-2-3	1.7	–2.6	Cal (<Qtz)
Biomicrite		LPN-2-4	1.4	–2.4	Cal (<Qtz)
Las Coladas Salar (north)					
Aragonite mud			10.2	3.1	Arg (<Cal)
Aragonite mud			9.5	2.9	Arg (<Cal)
Aragonite mud			9.5	3.1	Arg (<Cal)
Aragonite mud			9.8	2.5	Arg (<Cal)
Aragonite mud			9.8	2.4	Arg (<Cal)
Aragonite mud			9.7	2.7	Arg (<Cal)
Las Coladas Salar (creek)					
Aragonite mud			8.8	1.1	Arg (<Cal)
Aragonite mud			8.6	0.9	Arg (<Cal)
Aragonite mud			8.4	0.8	Arg (<Cal)
Aragonite mud			8.3	0.0	Arg (<Cal)
Aragonite mud			9.1	1.8	Arg (<Cal)
Las Coladas Salar (center)					
Aragonite mud			11.5	5.3	Arg (<Cal)
Las Coladas Salar (travertine)					
Travertine crust			9.7	–1.6	Arg
Travertine crust			10.7	–1.0	Arg
Travertine crust			8.4	–5.6	Arg
Travertine crust			10.9	–1.4	Arg
El Peinado					
2c	1		9.2	6.6	Cal
1a	5		9.5	7.0	Cal
1a	6		9.6	7.7	Cal
1a	7		8.7	4.6	Cal
1b	10		9.6	7.0	Cal
1b	15		9.4	7.0	Cal
2b	20		9.0	6.2	Cal
2b	23		8.7	4.7	Cal
2a	30		9.9	6.1	Cal
2c	33		11.4	7.0	Cal
2b	38		10.2	6.8	Cal
2a	45		9.5	5.8	Cal
2b	50		9.7	6.1	Cal
2a	55		10.0	6.4	Cal

Table 1. (*concluded*).

Facies[a]	Depth (cm)	Sample No.	δ^{13}C (‰ PDB)	δ^{18}O (‰ PDB)	Mineralogy[b]
2c	60		11.2	7.4	Cal
2a	65		9.4	6.8	Cal
2a	74		9.1	7.5	Cal
2c	79		8.8	6.5	Cal
2b	81		10.8	7.2	Cal
2b	87		9.4	6.8	Cal
2b	101		13.1	6.9	Cal
2a	105		9.7	7.1	Cal
3	110		9.2	6.8	Cal
3	111		9.6	7.0	Cal
2c	115		9.2	7.1	Cal
2b	120		9.4	6.5	Cal
2a	125		9.5	6.7	Cal
2a	128		9.0	6.7	Cal
3	135		8.6	6.0	Cal
3	135		8.5	5.7	Cal
3	145		8.7	5.3	Cal
3	155		8.7	5.5	Cal
2a	160		8.8	6.2	Cal
2b	167		8.2	6.1	Cal
2c	170		10.1	7.8	Cal
3	175		9.5	8.9	Cal
3	181		8.4	5.1	Cal
3	187		8.3	5.1	Cal
3	199		8.5	5.4	Cal
Stromatolite			9.2	5.3	Cal
Macrophytic travertine			8.2	3.3	Cal

[a] See legend in Fig. 8 for facies from El Peinado basin.

[b] Arg, aragonite (<Arg, minor aragonite); Cal, calcite; Pl, plagioclase; Qtz, quartz.

and carbon isotope analyses were performed on bulk sediment and rock samples using standard techniques (McCrea 1950). Powder for isotope analyses was obtained from rock slabs with a microdrilling tool to collect homogeneous samples. The isotopic ratios were measured with a Finnigan MAT 251 mass spectrometer at the Estación Experimental de El Zaidín, Granada, Spain. Analytical precision was better than 0.1‰ for δ^{18}O and δ^{13}C in carbonates and waters and better than 2‰ for δ^{2}H in water. Results are expressed in δ notation against the Pee Dee Belemnite (PDB) standard for carbonates and the Vienna standard mean ocean water (V-SMOW) standard for waters (Table 1).

Travertine and stromatolite depositional subenvironments

Las Peladas basin

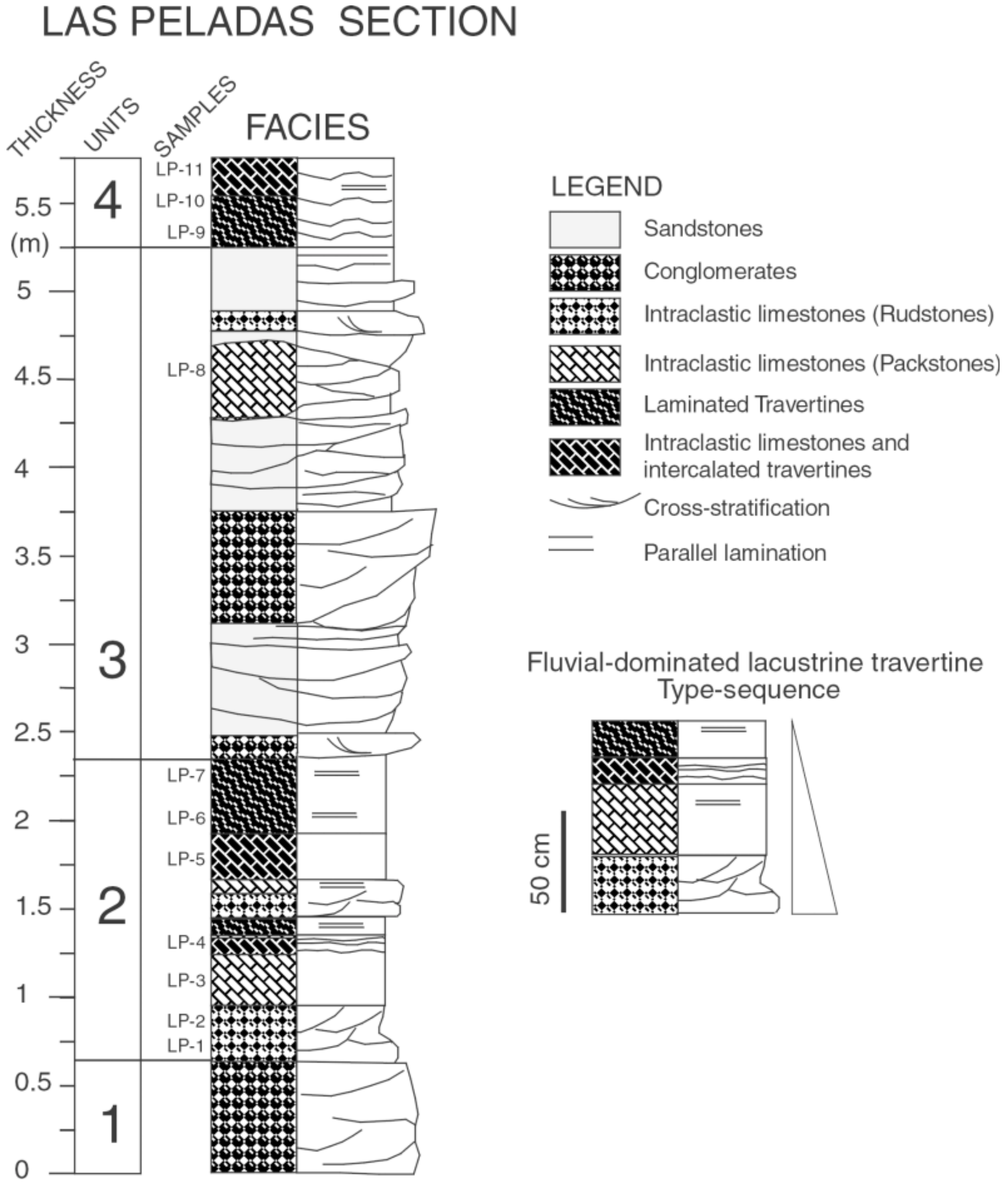
Las Peladas paleolake

South of the Buenaventura Range, a north–south-elongated tectonic valley, ~120 km long and <10 km wide, is filled with Quaternary alluvial, eolian, and lacustrine sediments. The valley is bounded to the east by the Sierra de Las Planchadas and to the west by Paleozoic outcrops and Cenozoic volcanic rocks (Fig. 1D). In the northern part, a structural high composed of Paleozoic rocks and Miocene volcanic rocks separates the San Francisco (west) and Las Peladas (east and south) basins. At present, there is no permanent surface hydrological connection between Las Peladas and Las Lozas to the south and San Francisco to the north. Several topographic highs define two small depressions that are connected by the Las Peladas stream: Las Peladas North and Lampallita. Several terraces composed of finely laminated limestones and sandstones are present along the margins of the northern subbasin. South of a narrow gorge carved in Ordovician rocks, the Las Peladas stream enters a southern depression. A 6 m-thick sequence, composed of fluvial and lacustrine sedimentary rocks, crops out along the western side of the gorge (Fig. 2). Garleff et al. (1992) dated the highest lacustrine terraces of the Las Peladas basin at 32 000 ± 520 and 29 380 ± 410 BP and the lowest terraces at 15 000 ± 100 BP. These dates suggest that Las Peladas paleolake developed during the full and late glacial periods in the Andes.

Sedimentary facies

Description: The Las Peladas stratigraphic section (27°05.837′S, 68°04.850′W; 3860 m above sea level (asl)) is composed of lacustrine and fluvial rocks (Fig. 2). The sedimentary units show a slight southward dip that is interpreted to be a primary depositional slope toward the basin. Six different facies have been described and four main units have been identified (Figs. 2, 3). The *conglomerates* in the basal unit 1 (Figs. 3A, 3B) crop out as tabular deposits, up Most conglomerates are clast-supported, and they show

Fig. 2. The Upper Pleistocene Las Peladas stratigraphic section.



trough cross-stratification, in sets of several decimetres high. Clasts are composed of limestone and volcanic rocks; their size varies from 1 to 25 cm, and they are angular to subrounded. The *laminated sandstones* from unit 3 represent channel-shaped bodies up to 4 m wide and 60 cm thick. They have fining-upward textures with a basal conglomeratic lag deposit composed of reworked travertine clasts. A 1 m thick and 4 m wide lens of intramicritic limestone intercalates in the upper part. The *intraclastic limestones* (packstones, grainstones, and rudstones) constitute tabular bodies, 25–50 cm thick and decametres in lateral continuity, and internally show trough cross-stratification, with sets of about 10 cm high and parallel lamination towards the top. Rudstones are composed of carbonate clasts, up to several centimetres long. Several massive limestone lenses are also intercalated (Fig. 3B). Microscopically, the limestones consist of intramicrites and intrasparites (Figs. 4A, 4B). Coated grains are rare, and up to 1 mm in diameter. Several alternating concentric dark micrite and light-coloured microspar calcite laminae are present. No microbial-shaped remains were found in them during SEM observations. The *intraclastic limestones with planar voids* parallel to the stratification and cemented with aragonite and calcite constitute the transition between the travertines and the underlying limestones (Fig. 3C). Aragonite is present as acicular crystals cementing grains and filling cavities. Very irregular, thin laminae composed of aragonite fill cavities subparallel to the stratification. Acicular crystals grow from all sides of the cavities (toward the center; Fig. 4B). In some cases, aragonite grows within spar calcite laminae. These features reflect the later origin of these aragonite laminae with respect to the intramicrite formation.

The *laminated travertine facies* are white to light grey, dense tabular deposits up to 40 cm thick that overlie limestone facies (intramicrites–intrasparites; Figs. 3D, 3E). These deposits are typically laminated; laminae are parallel, with

Fig. 3. Las Peladas section. (A) Field view of unit 2 and lower part of unit 3. (B) Field view of units 2 and 3, showing conglomerates and sandstones (unit 3) associated with lacustrine laminated carbonates (unit 2). (C) Hand specimen of intraclastic limestones with subparallel laminae consisting of aragonite. Dark grains are volcanic extraclasts. (D) Field view of laminated travertines intercalated within intraclastic limestones. (E) Hand specimen of laminated travertines. In C and E, squares in the grid pattern are 1 cm × 1 cm.

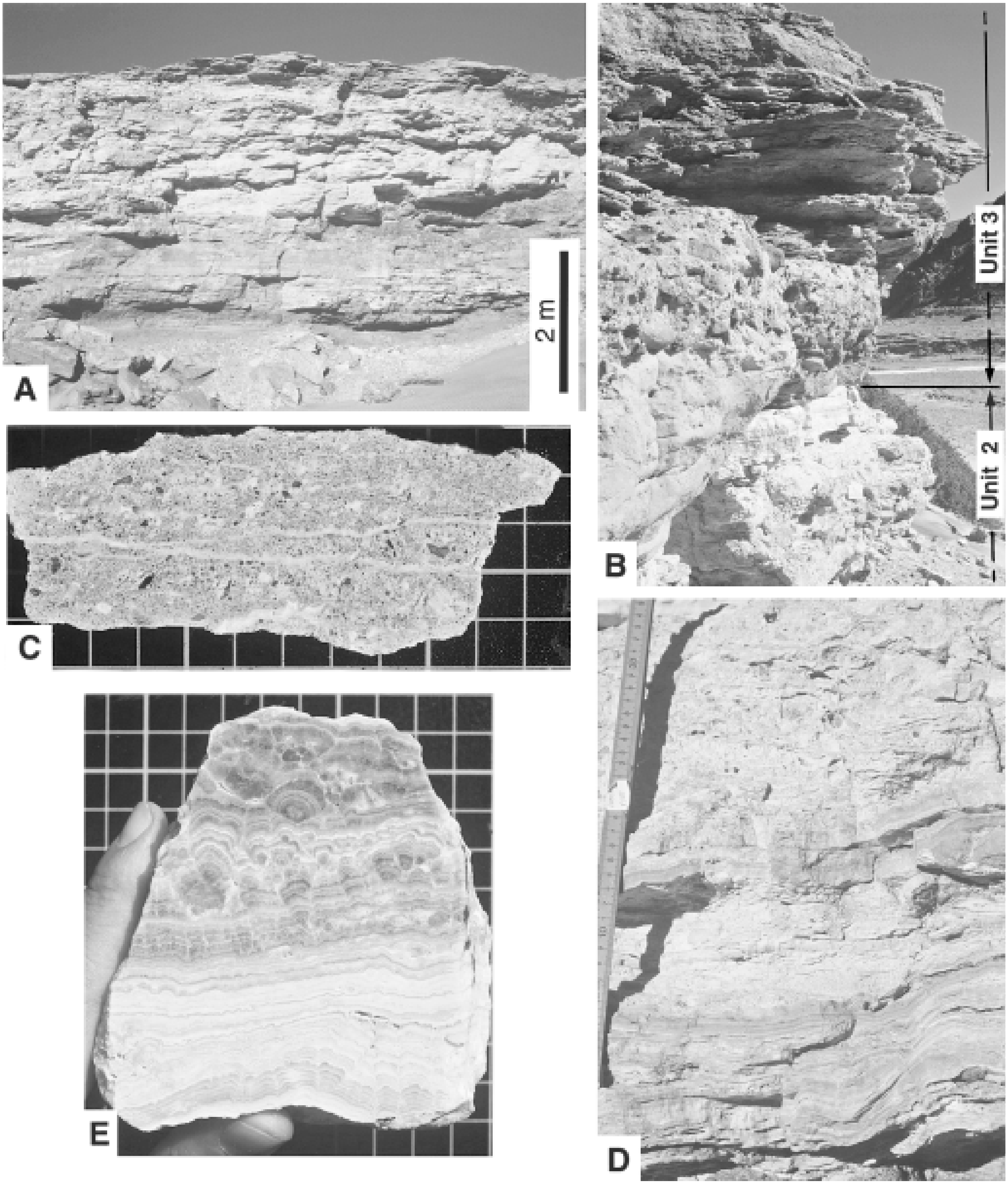
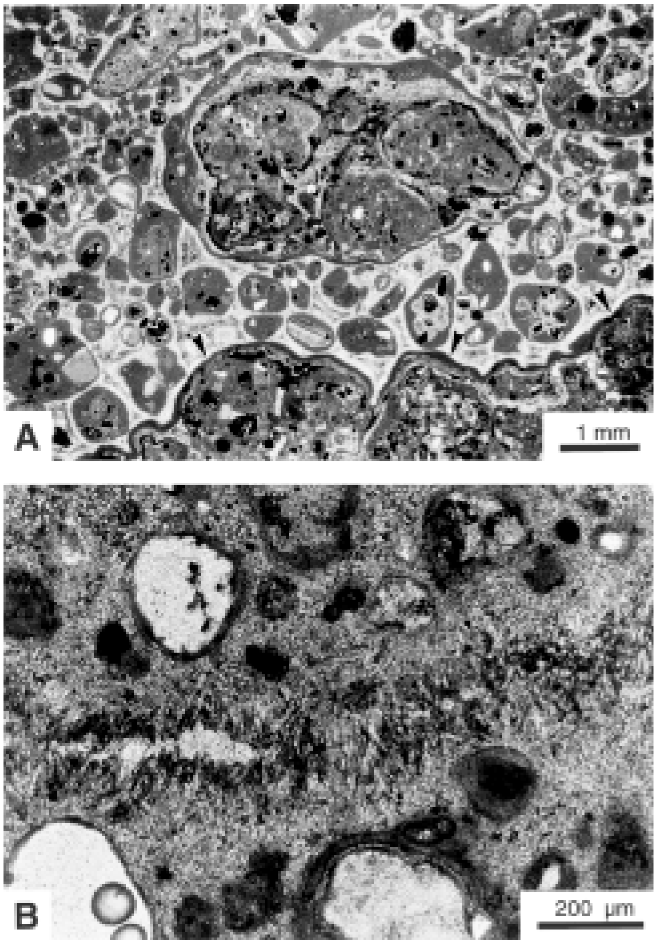


Fig. 4. Photomicrographs of Las Peladas samples. (A) Intraclastic limestones. In the lower part, note the presence of a thin carbonate coating (arrowheads), which represents a nonreworking period. (B) Detail of aragonite cements in intraclastic limestones.



horizontal or, more commonly, gently undulatory profiles. Domed morphologies up to 5 cm thick are also present (Fig. 3E). Some planar voids parallel to the lamination also occur. Individual lamina thickness ranges from micrometres to 1–2 mm thick. They are composed of aragonite in the lower part (unit 2) and calcite in the upper part (unit 4).

Microscopically, the finely laminated facies consist of a succession of (*i*) light-coloured laminae, each 0.1–2.3 mm thick, made of elongated calcite or aragonite crystals; and (*ii*) dark-coloured calcite laminae (50 µm to 0.5 mm thick) made of smaller anhedral crystals (Fig. 5). The laminae show horizontal, undulating or knobbed–domed profiles. They do not contain visible organic material. Lamination is produced by the alternation or succession of different crystal-size laminae. In some cases, lamination is enhanced or marked by the presence of dark, thin laminae rich in Fe–Mn oxides. Two cases are present: (*i*) laminae made of columnar, fanlike, and acicular crystals of calcite (0.1–3.3 mm long), predominant in travertines of the upper part of Las Peladas section (unit 4; Figs. 5A, 5B); and (*ii*) laminae composed of columnar and acicular crystals of aragonite (0.1–1 mm long), in some cases with a radial arrangement, and forming fanlike morphologies, limited to the travertines of unit 2 (Figs. 5C–5F). In both cases, the elongated, up to 3.3 mm long crystals are subperpendicular to the lamination and may pass through it (Fig. 5B). Anhedral calcite crystals (5–30 µm across) form patches within or between the long crystals, and also irregular laminae parallel to the structure between long crystal laminae (Fig. 5F). Several laminae of long crystals that are grouped into sets follow an upward-thickening pattern and are sharply separated from the following group by a thin lamina of anhedral calcite crystals (Fig. 5E). Cathodoluminescence observations show that some of these micrite and microspar layers are composed of dull red luminescent calcite.

Interpretation: The sedimentary facies in the Las Peladas section represent deposition in the littoral area of the Las Peladas paleolake during periods of higher lake level and increased river discharge. The section records several episodes of progradation of fan-delta facies into the lake followed by shallowing lacustrine episodes that include travertine formation. Conglomerates and sandstones formed in shallow, low-sinuosity channels that entered the littoral carbonate lacustrine area. These subaqueous channels were filled with extraclasts and littoral lacustrine material that was reworked by the river currents entering the lake. Intraclastic limestone lenses represent quieter deposition in the interchannel areas of the lacustrine margin. Early lithification of the mud and erosion by fluvial action and lacustrine littoral reworking caused intraclast formation. Extraclasts were carried by the Las Peladas stream. Recurrence of this process generated composite intraclasts.

The sequences composed of intraclastic limestones followed by travertine limestones are interpreted as being representative of deposition in a shallow, lacustrine margin. The facies association represents the transition from relatively deeper, fluvial-dominated and high-energy deposition (intraclastic limestones) to a very shallow and low-energy depositional environment (travertines). Travertines were formed by calcite and aragonite precipitation on the Las Peladas paleolake shores during periods of low lake levels. Increased chemical concentration during these lowstands resulting from evaporative concentration and precipitation of calcite led to increasing Mg concentration in the lake and pore waters that favoured aragonite precipitation. These waters also caused replacement and recrystallization fabrics, as well as void fillings, within previous intraclastic limestones and laminated travertines. Changes in chemical composition, temperature of the source waters, and hydrochemical evolution of the lake waters could have caused the selective aragonite or calcite precipitation.

Diagenesis of travertine deposits, which commonly takes place soon after deposition, usually results in a loss of porosity due to recrystallization and cementation (Assereto and Folk 1980; Turi 1986; Love and Chafetz 1988,1990). Love and Chafetz (1988) found that aggradational neomorphism (calcite to calcite recrystallization) of algal-laminated crusts resulted in dense laminated strata composed of coarse columnar crystals. The laminated pattern exhibited by both aragonite and calcite Las Peladas travertines suggests that neomorphism took place on initially laminated deposits. The presence of micrite and spar calcite remains

Fig. 5. Photomicrographs of laminated travertines of units 2 and 4 of Las Peladas section. (A, B) Calcite travertines (unit 4) consisting of light-coloured laminae of long columnar and fanlike crystals with intercalated thinner dark laminae of anhedral crystals. Note the presence in B of long fanlike crystals that pass through lamination. (C, D) Aragonite travertines (unit 2) made of light-coloured laminae of acicular, columnar and fanlike crystals, alternating with dark, generally micritic, irregular laminae. (E, F) SEM photographs of aragonitic travertines showing acicular and columnar crystal laminae, with intercalated irregular laminae of smaller, anhedral crystals. Note the presence in F of small anhedral crystals among long crystals.

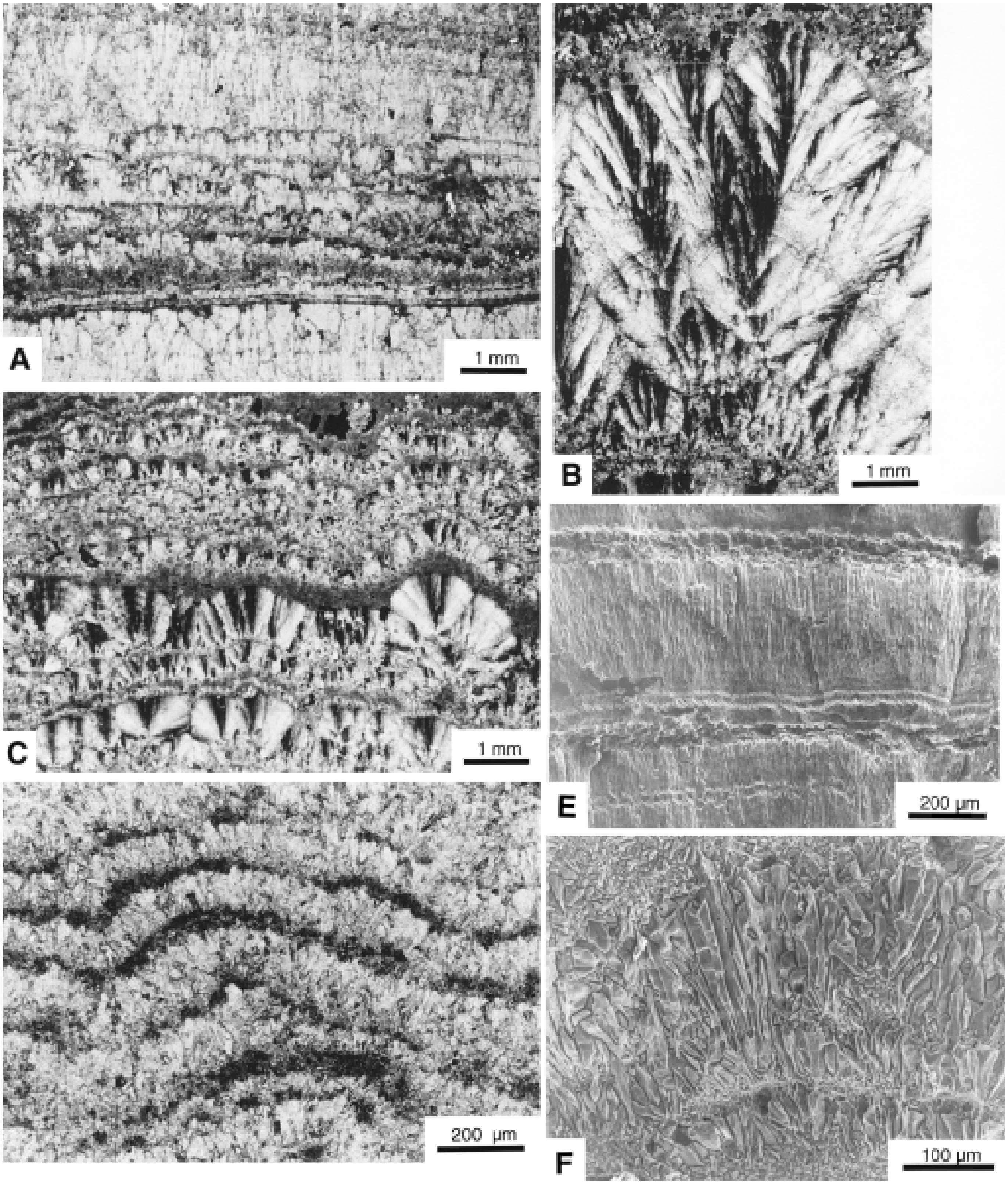
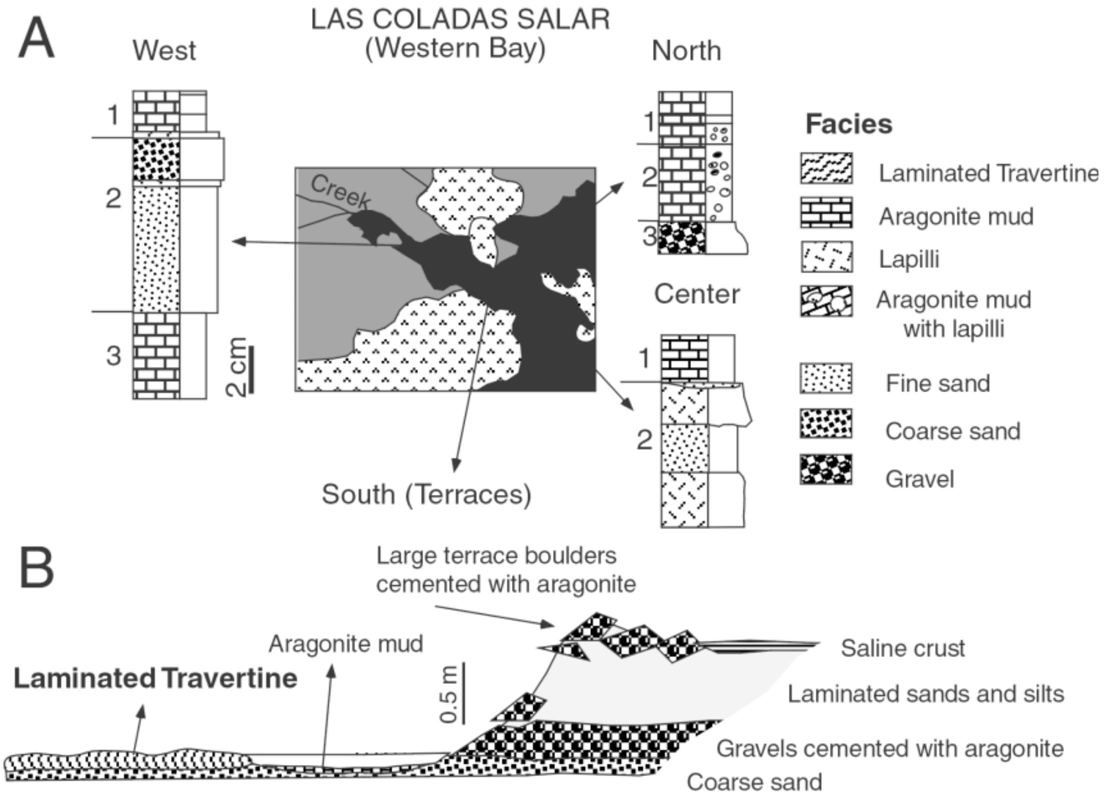


Fig. 6. (A) Stratigraphy of the western bay of Las Coladas Salar. (B) Geomorphological sketch of the carbonate-cemented lacustrine terraces, the travertine crusts, and the modern aragonite mud deposits in Las Coladas Salar.



among and within laminae of long crystals of aragonite and calcite and the existence of acicular crystals encased in prismatic carbonates indicate that the original composition could be microspar or anhedral spar calcite, acicular aragonite and calcite, and micrite calcite laminae.

Aragonite crystals in the laminated travertines were primary precipitates from a surface solution, but most of them were enlarged during the early diagenesis and, as a result, acicular carbonates were mostly replaced by columnar crystals, without a change in mineralogy (i.e., aragonite to aragonite). Similarly, calcite to calcite recrystallization could have occurred in the calcite travertines of unit 4, although there is no petrographic evidence to rule out inversion of aragonite to calcite processes. Thus it seems that the large aragonite and calcite crystals occurring in these travertines resulted from aggradational neomorphism (aragonite to aragonite and calcite–aragonite to calcite recrystallization). Replacement of micrite or anhedral calcite spar with acicular aragonite also occurred, but was probably a later process, as suggested by the presence of some micrite and spar calcite patches.

Although laminated travertines of Las Peladas resemble speleothem deposits because of the fine and regular lamination, their stratigraphic position, areal distribution, and generally horizontal morphology indicate that they formed in flat lacustrine areas with a shallow water depth. Both aragonitic and calcitic travertines seem to be mostly inorganic in origin, as no biological evidence is present (SEM observations), although possible biological remains might have been obliterated by aggrading neomorphism. Abiotic travertines have been described in freshwater environments that include springs and streams (Love and Chafetz 1988, 1990; Jones and Renaut 1996). In many hot springs, the most common crystal morphology assumed by aragonite seems to be needle-shaped crystals (Guo and Riding 1992; Jones and Renaut 1996), whereas calcite has a wider range of morphologies (Love and Chafetz 1990; Jones and Kahle 1993; Jones and Renaut 1995). There is no sedimentological or geomorphological evidence for thermal springs feeding the Las Peladas paleolake, and at present thermal springs are not present in the basin, although they exist in the two other basins studied (San Francisco and El Peinado).

San Francisco basin

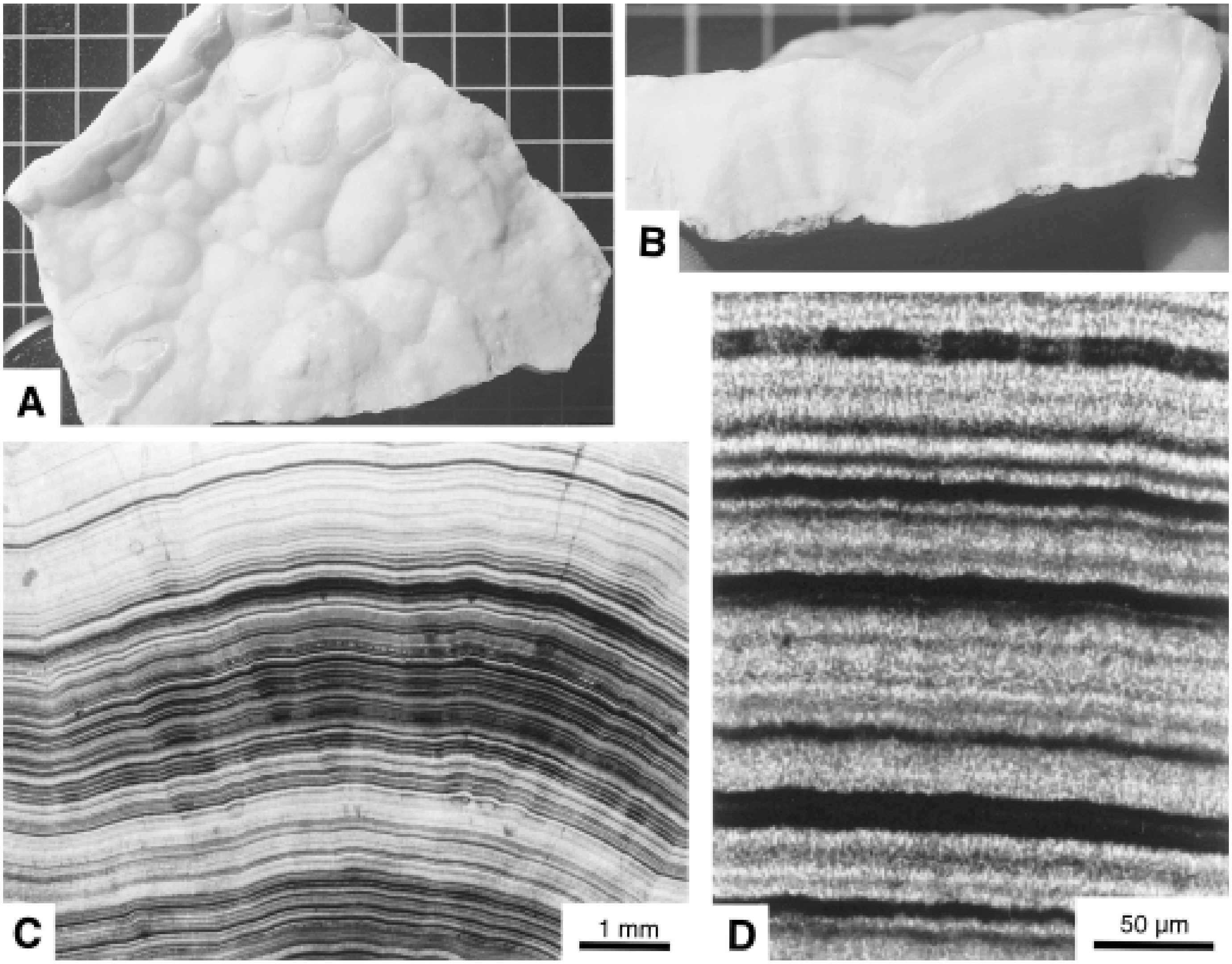
Las Coladas Salar

San Francisco basin can be subdivided into two subbasins (Fig. 6A). To the north, small hills and shallow depressions forms a landscape dotted with shallow, small playa lakes. To the south lies a larger playa lake (Las Coladas Salar). The Las Coladas Salar (26°57.789′S, 68°10.260′W, 4000 m asl) is bounded to the west by lava flows from the Incahuasi and San Francisco volcanoes. The salar has a large surface, flat bottom, and shallow water depth (up to 25 cm). Several small creeks, groundwater seepage areas, and thermal springs provide the main water input to the lake. The waters of Las Coladas are saline (electric conductivity 41 900 μS/cm), alkaline (pH 8.5), Ca poor (73 ppm), and have a high Mg/Ca ratio (11; Valero-Garcés et al. 1999*a*, 2000) and high water isotopic values ($\delta^{18}O$ = 7.3‰ SMOW, δD = 29‰ SMOW).

Sedimentary facies

Description: Several short cores (up to 30 cm) were re-

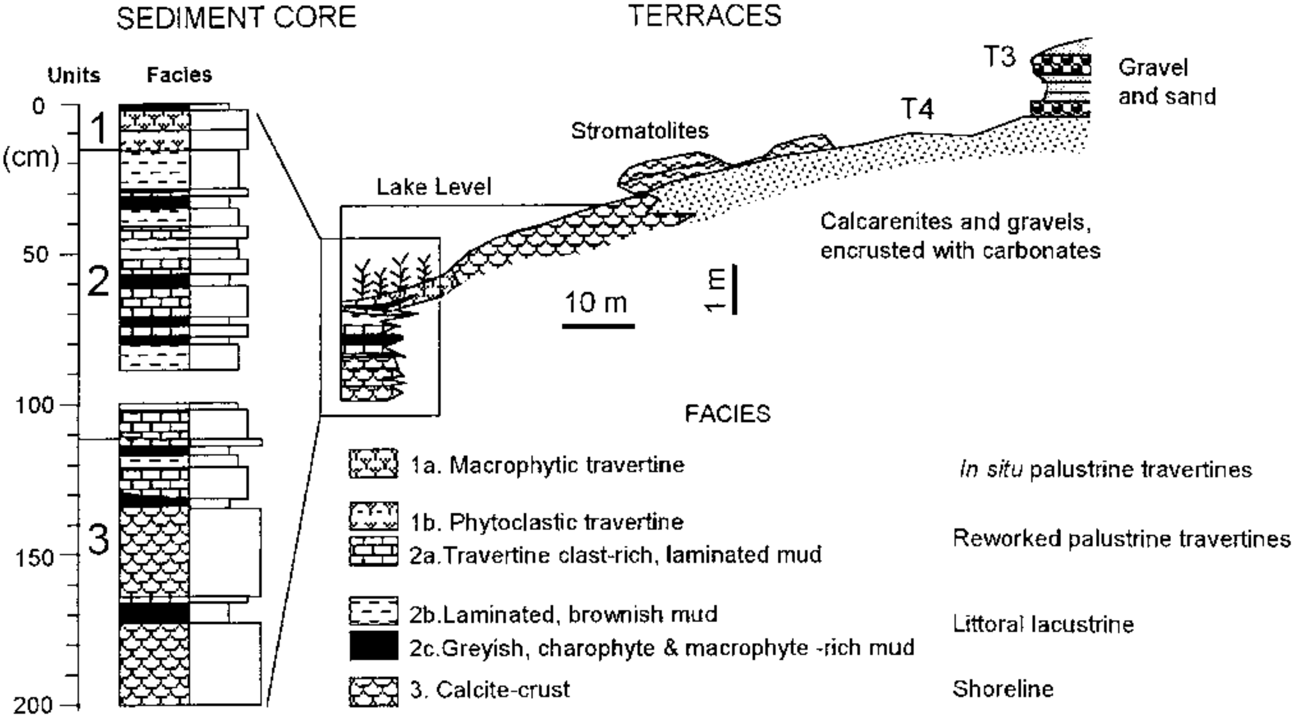
Fig. 7. Aragonite laminated travertines of Las Coladas. (A, B) Hand specimen in plan and cross sections. Note the fine laminations in B. Squares in the grid pattern are 1 cm × 1 cm. (C, D) Photomicrographs showing alternating light-coloured and dark laminae. Note the presence in D of very fine acicular crystals perpendicular to laminations.



trieved in the western bay of Las Coladas Salar. All showed the same stratigraphy from bottom to top (Fig. 6A): (*i*) *gravels* composed mostly of volcanic clasts, (*ii*) *volcanic lapilli*, and (*iii*) *carbonate lacustrine muds*. Current carbonate precipitation in Las Coladas Salar is dominated by aragonite, due to the high Mg/Ca ratio of the waters. In the western margin, where a small creek enters the lake, the alluvial gravel unit and the carbonate units are overlain by silts and sands deposited by the creek prograding into the salar (Fig. 6B). The laminated travertine facies occur as dense, tabular white crusts with small domes (Figs. 7A, 7B), up to 5 cm thick and decametres long, laterally associated with cemented shoreline and terrace clastic deposits (carbonate-cemented gravels). The carbonate-cemented gravels crop out around the western edge of the salar at less than 1 m above current lake level. In the south margin of the western bay, large blocks of the cemented gravels have been removed and piled up due to wave action. Some areas of the western bay show a patchy distribution of a travertine crust. All these features suggest a period of intense carbonate crust generation. Although U/Th series are not commonly used to date recent materials, the high U-238 content (55 ppm) of the carbonate allowed the use of this methodology, which provided an age of 1660 ± 82 BP for the travertine limestone development at Las Coladas Lake (Valero-Garcés et al. 2000).

The laminated travertines are composed entirely of aragonite and microscopically show a very regular and fine parallel lamination marked by alternating black and light-coloured (white and grey) laminae, each 5–50 μm thick, with the light-coloured laminae being the thickest (Figs. 7C, 7D). These thick, light-coloured laminae are composed of two or three individual laminae. Black and light-coloured laminae can be grouped into sets, 0.3–1 mm thick, in which one type is dominant. Most crystals are acicular and their length defines the thickness of the individual laminae. Dark laminae show no distinct crystals. Back-scattered electron images did not show any differences in composition between the different coloured laminae. No microbial-shaped remains are present. Curved cracks affecting several laminae are

Fig. 8. The sediment core sequence and lacustrine terraces in El Peinado basin.



common. No diagenetic modifications seem to be present in the studied samples, so they represent the original aragonite precipitates.

Interpretation: The core sediment sequence illustrates recent changes in the salar hydrology and depositional subenvironments. Deposition of aragonite-rich muds overlying the gravel unit represents a raise in groundwater level and more frequent flooded episodes in the salar. On the other hand, the cemented gravels and the laminated crusts in the shoreline indicate very different hydrology and environmental conditions in the salar in the past (around 1600 BP). In this and other Andean salars the laminated travertine facies resulted from aragonite precipitation from saline waters with a high Mg/Ca ratio and (or) high temperature. The abundant thermal springs and seepage areas around the salar suggest that they represent a large fraction of the water input to the lake. Acicular aragonite is a very common precipitate in many hot springs that give rise to travertine deposits (Friedman 1970; Pentecost 1990; Guo and Riding 1992). The differently coloured laminae could correspond to variable content in organic matter and (or) could be related to cyclic changes in chemical, physical, or environmental conditions. There are no discrete organic remains. As shown by several authors, aragonite precipitation from hot springs seems to be episodic and rapid, with growth dependent on changes in the physicochemical characteristics of the spring waters (Jones and Renaut 1996). As pointed out by Pentecost (1995), rapid degassing and cooling of waters at active thermogene sites leads to a high precipitation rate.

El Peinado basin

El Peinado Lake

El Peinado Lake (26°29′59′′S, 68°05′32′′W, 3820 m asl) lies on an north–south-elongated, topographically closed basin north of El Peinado volcano (Fig. 1B). Waters are saline (electric conductivity 55 500 μS/cm), alkaline (pH 7.6), and dominated by SO_4^{2-}, Cl^-, Ca^{2+}, and Na^+, and have a relatively high content of strontium (58 ppm) and boron (135 ppm; Valero-Garcés et al. 1999*a*). The isotopic ratios of waters ($\delta^{18}O$ = 4.3‰, δD = –6.8‰) are also relatively high. There is no surface outflow to the Salar de Antofalla, although the lake could have overflowed to the north during former higher lake level periods. Four lacustrine terraces occur in the northern edge of the basin (Fig. 8).

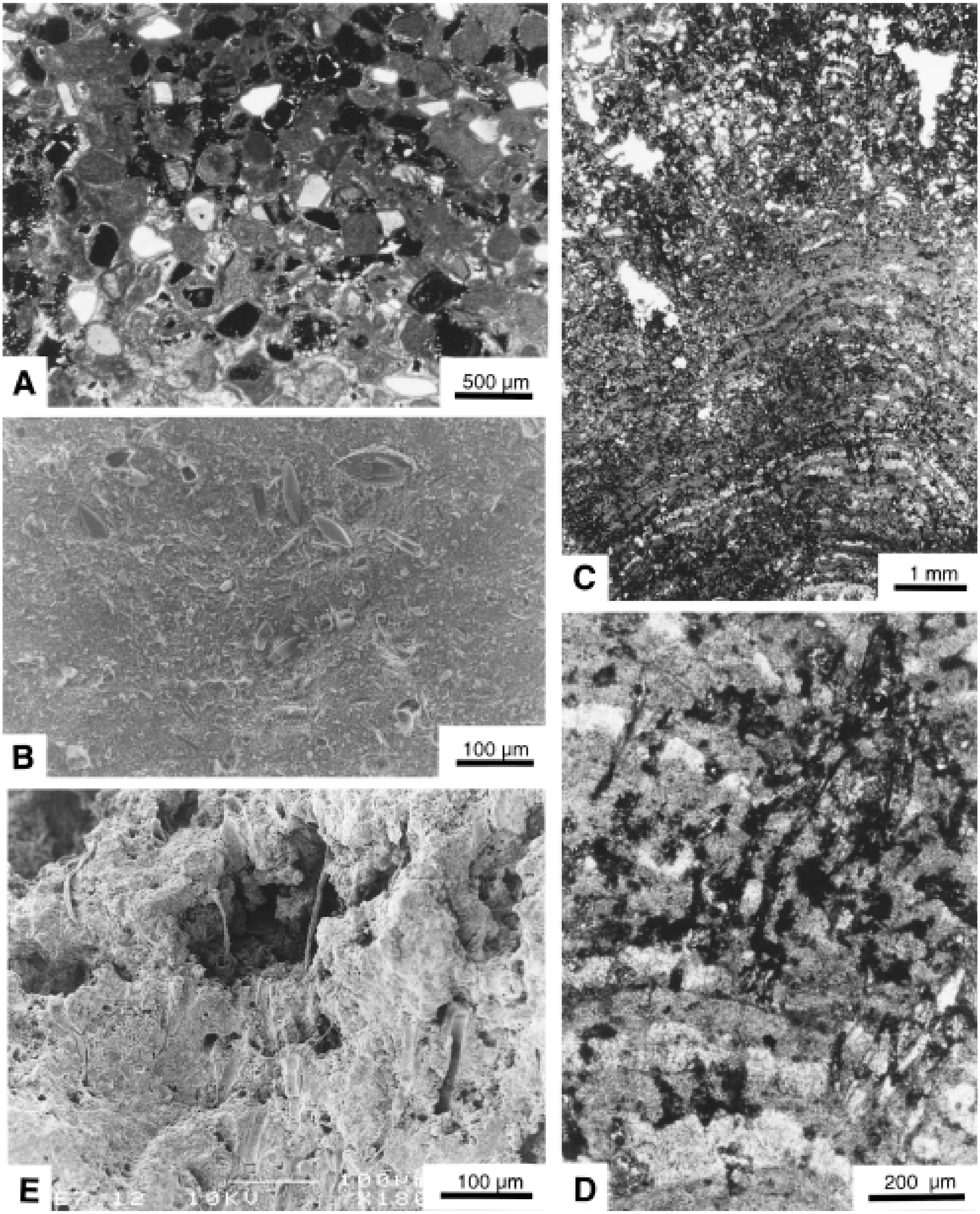
Sedimentary facies

Description: The lacustrine terraces form tabular sedimentary packages of about 30–40 cm thick and with 100 m of lateral continuity. Contrary to other lakes in the Altiplano, the older lacustrine terraces do not show any travertine facies. The highest terrace, T1 (up to 8 m high), is composed of conglomerates and sandstones with volcanic rock clasts and parallel stratification. Calcite cementation and coated grains of very different sizes (<1 mm to 1 cm across) and morphology occur. The intermediate terraces, T2 and T3, are composed of massive intraclastic and biomicritic limestones.

Intraclastic limestones are intramicrites with coated grains (packstones or, in some places, rudstones; Fig. 9A). Intraclasts are made of massive micrite grains. These components are not evenly distributed. *Biomicrites and biomicrosparites* are wackestones made of diatoms (pennate forms) and ostracods, trapped in a microspar or, in places, micrite–calcite matrix (Fig. 9B).

Stromatolites: Finely laminated facies are only found at the lower level of terraces (T4). They form small mounds up to 20 cm thick that have a patchy distribution along the emergent shore of El Peinado Lake (T4; Fig. 10A). The lamination shows variable morphological styles through the same

Fig. 9. Photomicrographs of different facies in El Peinado basin. (A) Intraclastic limestones of the middle terraces (T2 and T3). (B) Biomicritic facies of the middle terraces made of pennate diatoms (SEM photograph). (C) General view of a stromatolite sample showing gently domed to columnar growths from base to top. Note the existence of filamentous micritic bodies perpendicular to subperpendicular to lamination. (D) Detail of C. Isolated or loosely clustered filaments attributed to cyanobacteria similar to present-day *Calothrix* or *Dichothrix*. (E) SEM photograph of El Peinado stromatolites showing subvertical calcite filaments and their molds.



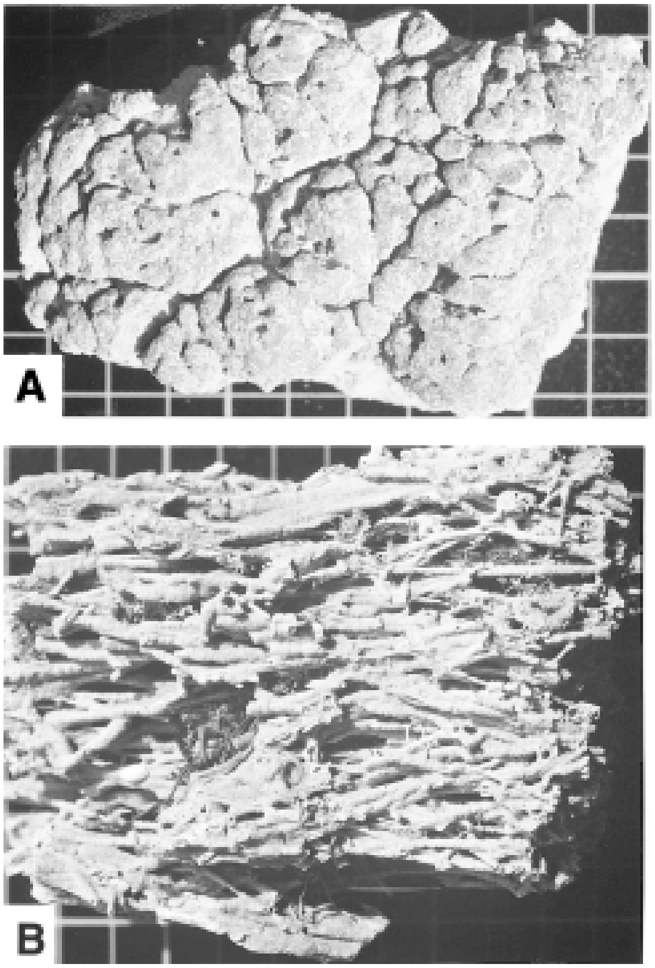


Fig. 10. (A) Plan view of stromatolites of El Peinado. (B) Emergent macrophytic travertines of El Peinado consisting of fine stalks encrusted with calcite. Squares in the grid pattern are 1 cm × 1 cm.

buildup. A section about 3 cm thick shows from the base to the top (Fig. 9C): (*i*) at the base, horizontal lamination, gentle undulating lamination, or discrete domes made of alternating laminae of calcite–micrite and microspar; microbial-shaped bodies (mostly micrite filaments) lie subperpendicular to lamination; (*ii*) light-coloured, porous micrite and dark, dense micrite laminae form small domes that contain dispersed, dark, clotted micrite grains; and (*iii*) at the top of the buildups are alternating light-coloured and dark micrite laminae, or dark micrite and light-coloured microspar–spar calcite laminae, that constitute fanlike growths that are grouped into columns up to 0.5 cm high. Abundant micrite filamentous bodies, 10–20 µm wide and 300–500 µm long, are isolated or loosely clustered. The filaments lie subperpendicular to lamination and pass through several laminae (Figs. 9D, 9E). They resemble present-day *Calothrix* and *Dichothrix* growths. Under SEM, abundant pennate diatoms are observed among the generally anhedral calcite crystals, but particularly in association with the filamentous cyanobacterial bodies.

Facies with encrusted plant remains (macrophytic travertine or tufa) occur only in the lower terrace and the littoral areas of El Peinado Lake. The macrophytic travertine facies appear (*i*) along the vegetated shorelines close to thermal seepage areas that feed the lake, and (*ii*) in the submerged littoral zones. The emergent travertines show an open meshwork of calcite-coated stems. Coated stems are very thin (around 1–2 mm in diameter) and lie with vertical orientation (Fig. 10B). A 2.5 m long core collected at 2 m water depth contained different facies: indurated calcitic crusts, laminated muds rich in travertine debris, and in situ and reworked travertine facies (phytoclastic travertines; Fig. 8; Valero-Garcés et al. 1999*a*, 2000). Subrecent travertine deposits at 2 m water depth (Fig. 8A; facies 1a) display an open vertical fabric of interlocking stems, <1 mm thick, coated with calcite and with little matrix. Although the vegetation is different from that in the emergent travertines, both show similar textures. Based upon the matrix content, the size of the travertine clasts, and the presence of organic matter remains, five reworked phytoclastic travertine facies have been distinguished (Fig. 8).

Interpretation: Stromatolite facies crop out on the shoreline a few decimetres above modern lake level. The presence of microbial filaments in this facies is clear evidence for a biological origin. The formation of these laminated facies is linked to the development of cyanobacteria, such as *Calothrix* and *Dichothrix* microorganisms that build stromatolites in many modern freshwater environments (e.g., Ferris et al. 1997; Freytet and Verrecchia 1998). Their association with diatoms suggests a permanently submerged environment.

The occurrence of macrophytic travertines only in the seepage areas of El Peinado and in the sediment deposited during the last 400 years (Valero-Garcés et al. 2000) suggests that current conditions conducive to travertine deposition were not common in the past. Macrophytic travertines are interpreted as having formed in emerged vegetated areas with thermal spring seepage. The core sequence represents littoral reworking of submerged macrophytic travertine deposits. Based upon the ^{210}Pb and U/Th chronologies, the El Peinado travertine core sequence spans only a few centuries (Valero-Garcés et al. 2000). Both facies are quite common in ancient and modern examples of fluvial and lacustrine environments (Ordóñez and García del Cura 1983; Pedley 1990; Arenas et al. 2000). The calcitic crusts at the base represent shoreline facies cemented and indurated with calcitic cement during low lake levels.

Stable isotopes

Oxygen isotopes

The δ^{18}O of precipitating carbonates depends on the water temperature of formation, the isotopic composition of the water, and the fractionation between the waters and the mineral phase (Anderson and Arthur 1983; Talbot 1990). The oxygen isotopic composition of lake waters is controlled by (*i*) the isotopic composition of the rainfall, its seasonality, and the relative humidity; (*ii*) temperature at the time of precipitation; (*iii*) potential evaporation; and (*iv*) groundwater inflow. Most of the studied travertine and stromatolite facies are monomineralic: calcite for the El Peinado macrophyte travertines and stromatolites, aragonite for the Las Coladas laminated travertines, and calcite for the Las Peladas laminated travertines (unit 4). Only the lower travertines from

Las Peladas (unit 2) contain both calcite and aragonite. The initial water isotopic composition and the subsequent evaporative effects in these saline lakes are more influent factors than those due to the isotopic fractionation related to mineralogy; in general, aragonite is only about 0.6‰ more positive than calcite precipitated from the same waters (Anderson and Arthur 1983). There is no indication of diagenetic alteration in El Peinado and Las Coladas occurrences, so the mineral phases are considered to retain original isotopic signatures. Diagenetic alterations may have changed the isotopic compositions of Las Peladas samples to some degree. In this sense, the relatively large range of variability (3‰ for δ^{18}O) does not preclude a diagenetic imprint. On the other hand, all the stromatolites and travertines studied here are fossil occurrences, and consequently we lack the temperature and isotopic composition data for the formation waters.

The high δ^{18}O values in these high-altitude lake deposits most likely reflect the large evaporation rates in this arid environment. (Table 1; Fig. 11). In the case of Las Peladas, the diagenetic imprint prevents us from drawing conclusions on the environment of formation based on the isotopic signatures. In general, the oxygen isotopic composition of the lacustrine carbonates cannot be interpreted exclusively as salinity or evaporation ratio indicators. Valero Garcés et al. (1999*a*, 2000) found in the El Peinado core sediments a general positive correlation between δ^{18}O and salinity proxies (Na, Li, and B), but they concluded that the large data dispersion indicates that other factors besides evaporative effects control both chemical and isotope water concentration (e.g., water inputs with different δ^{18}O, redissolution of previously precipitated salts). The modern emergent macrophytic travertines developed on the shoreline of El Peinado Lake show lighter oxygen and carbon compositions than the sediment core samples and the stromatolites (Fig. 11). The higher isotope values of carbonates precipitated in the lake waters as submerged travertines and stromatolites suggest enrichment processes due to evaporation and a longer residence time of the waters.

The δ^{18}O compositions for modern aragonite sediments in Las Coladas display increasing values from the margin (–1.0‰ to +1.0‰ PDB; site closer to the creek) to the northern areas (+2.0‰ to +3.5‰ PDB) and to the center of the lake (+5.0‰ PDB). They also show a clear covariant trend between δ^{13}C and δ^{18}O (Fig. 11A). These patterns indicate increasing isotopic enrichment of the lake waters due to evaporative effects farther away from the surface inflow and a typical hydrologically closed behaviour (Talbot 1990; Talbot and Kelts 1990; Li and Ku 1997). Samples from the travertine crusts in Las Coladas show the lowest compositions (–6.0‰ to –1.0‰ PDB), suggesting less evolved waters. Geomorphological evidence indicates that the formation of the travertine crusts and the cementation of the terraces occurred during the same period of relative increase in lake level. The lower isotopic values of the travertines are in agreement with rapid precipitation of aragonite related to periods of higher discharge into the lake.

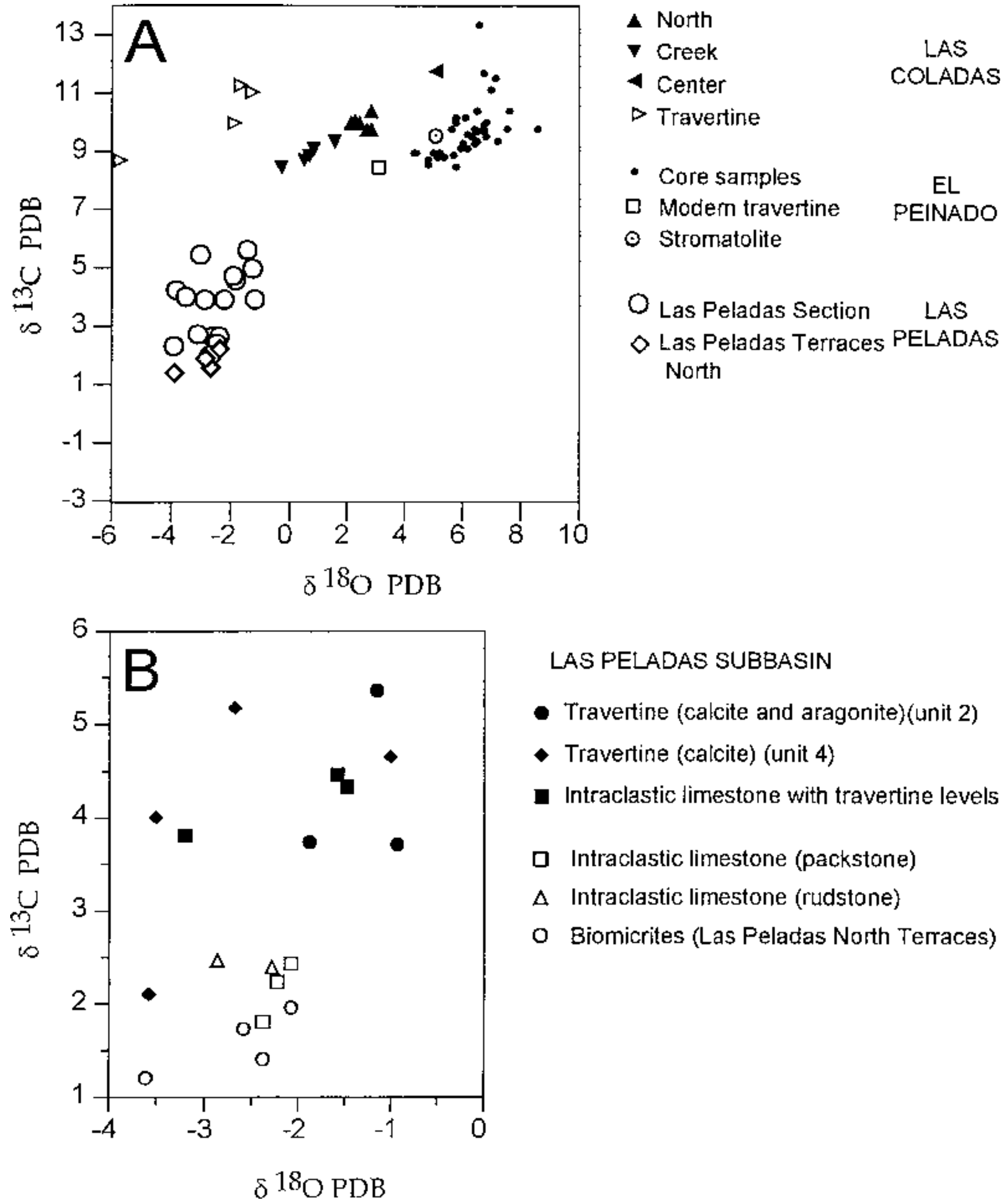
The Pleistocene Las Peladas samples show an isotopic range (–4.0‰ to –1.0‰ PDB; Fig. 11A) similar to that of the travertine crust in Las Coladas Salar. The Upper Pleistocene Las Peladas Lake was large and relatively deep (up to several tens of metres), in accordance with the altitude of the terraces and paleoshorelines. A scenario of large river inflow during these humid periods, and likely lower evaporation, agrees with the lower isotopic values of the primary carbonates precipitated in Upper Pleistocene Las Peladas when compared with the late Holocene El Peinado and Las Coladas lacustrine systems. For comparison, we also have plotted data from the associated carbonate facies. The Las Peladas biomicrites and intraclastic limestones lie in a narrower, lower δ^{18}O field than the travertines (Fig. 11B). Unlike Las Coladas Salar, where travertines show the lightest oxygen compositions, Las Peladas travertines show a large range and generally higher isotopic ratios than facies from the same sequences. The isotopically heaviest samples are from the aragonite travertines of unit 2, whereas intraclastic limestones from the same unit show lower values. These differences in isotopic compositions agree with the following sedimentological interpretation: relatively higher lake levels related to fluvial inputs during deposition of the intraclastic facies, and shallower, more concentrated waters during the formation of the travertines, although less concentrated in the case of calcitic travertines (unit 4). The biomicrites from the northern Las Peladas basin terraces that correspond to the highest lake level also show generally lower oxygen isotope ratios.

Although these environmental interpretations are coherent, caution should be used when considering diagenetic facies. The isotopic composition of Las Peladas travertines may have been modified during diagenesis, and thus such reconstructions cannot be considered as conclusive. In these lake basins, diagenetic waters that caused aragonite to aragonite recrystallization could have been more evaporated waters, with higher δ^{18}O values than the lake waters. This process can be a consequence of evaporative effects and the resulting aragonite travertines record ^{18}O enrichment with respect to their original isotopic composition. In the case of calcite to calcite or aragonite to calcite recrystallization, the isotopic composition of the diagenetic waters could have been lighter, heavier, or even the same as that of the primary precipitating lake waters. Thus conclusions on environmental conditions based exclusively on isotopic composition of travertines in Las Peladas basin cannot be established.

Carbon isotopes

Carbon isotopic ratios of authigenic lacustrine carbonates reflect isotopic variations in the dissolved inorganic carbon (DIC), controlled by input, biological processes (mainly respiration and photosynthesis), and physical processes (evaporation, residence time, CO_2 degassing; Talbot and Kelts 1990). Most samples show δ^{13}C > 1‰ PDB (Fig. 11) and are clearly distributed into two groups: (*i*) a group with values higher than 7.0‰ PDB (El Peinado and Las Coladas), and (*ii*) a group with values lower than 6.0‰ PDB (Las Peladas). Lacustrine carbonates with very high δ^{13}C values have been reported from very concentrated evaporating brines (Stiller et al. 1985; Mees et al. 1998), anoxic sediments (Talbot and Kelts 1990), fresh waters with methane input (Nissenbaum and Magaritz 1988), and travertines (Turi 1986). High δ^{13}C values for carbonates in the Andean Altiplano have been found in other saline lakes (Grosjean 1994; Grosjean et al. 1995; Schwalb et al. 1999) and fluvial

Fig. 11. Isotopic composition. (A) Cross-plot including carbonate facies from the three basins. (B) Isotopic composition of the carbonate facies from Las Peladas basin.

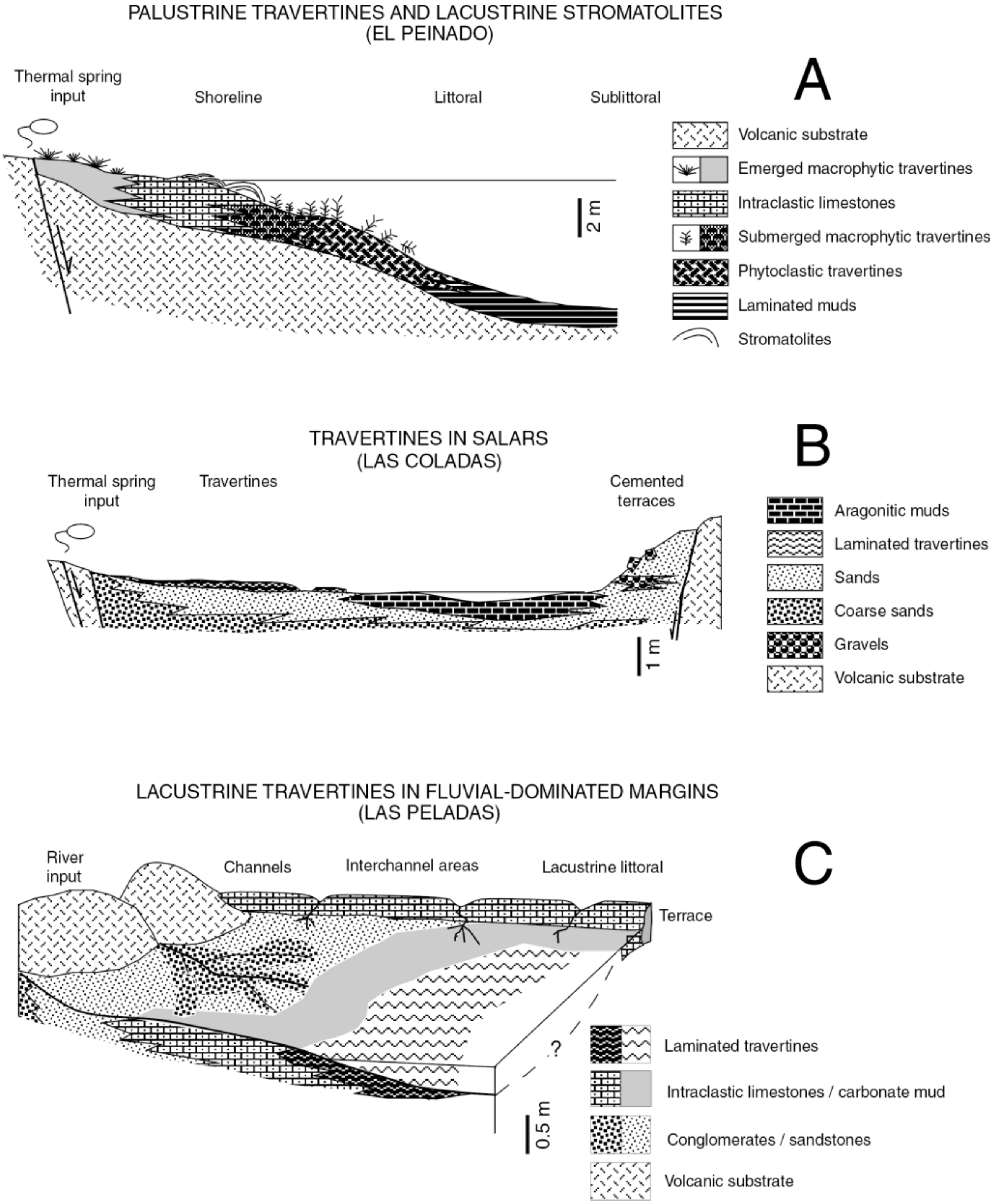


travertine deposits (Aravena and Suzuki 1990). These authors have suggested that there is a significant contribution of volcanic-hydrothermal CO_2 in the Altiplano area.

The mechanisms that can generate ^{13}C enrichment in Andean lakes over values in equilibrium with atmospheric CO_2, including evaporation processes and CO_2 degassing, have been discussed elsewhere (Valero-Garcés et al. 1999*a*). The similar, heavy $\delta^{13}C$ values for the modern aragonite mud samples at Las Coladas and other facies in the El Peinado terraces (biomicrites, intramicrites) show that heavy carbon isotopic compositions are not restricted to travertine facies. The large reservoir effect indicated by the accelerator mass spectrometry (AMS) ^{14}C dates from El Peinado core sediments (Valero-Garcés et al. 1999*a*, 2000) indicates a significant input of ^{14}C-free volcanic and geothermal CO_2 into El Peinado. In a volcanic region devoid of carbonate rocks, contamination of the sediments by older carbonates can be rejected; consequently, the most likely reason for the reservoir effect is the large input of ^{14}C-free volcanic and geothermal CO_2 from the numerous thermal springs in the area. An intense CO_2 evasion from the volcanic and geothermal springs would preferentially enrich the waters in ^{13}C. This mechanism provides a coherent explanation for the heavy carbon isotope compositions of lacustrine carbonates in active volcanic areas. Large enrichments may result from the nonequilibrium gas-transfer isotope fractionation during CO_2 degassing from thermal springs and groundwater discharge. Further degassing of carbon dioxide during lake water evaporation also contributes to increasing $\delta^{13}C$ and $\delta^{18}O$ trends. These data also indicate that physical rather than biological processes are controlling the ^{13}C enrichment in El Peinado and Las Coladas lakes.

The Las Peladas samples have $\delta^{13}C$ values between +1‰ and +5.5‰ PDB (Table 1; Figs. 11A, 11B). Intramicrite and

Fig. 12. Sedimentary facies models for the different basins studied: (A) El Peinado, (B) San Francisco (Las Coladas subbasin), and (C) Las Peladas. In C, the sketch corresponds to a low lake level period (travertine formation).



biomicrite facies display lower values (+1‰ to +2.5‰ PDB), and travertine facies show higher values (+3.5‰ to +5.5‰ PDB). High $\delta^{13}C$ values in the travertine facies can be explained by a combination of several processes: (*i*) increased evaporation effects in the Las Peladas paleolake during periods of lower lake level, when the lake did not overflow into Las Lozas subbasin, and decreased input of biogenic CO_2; (*ii*) CO_2 degassing processes related to travertine formation (Turi 1986); and (*iii*) increased input from heavier thermal-spring waters or ^{13}C-enriched

Table 2. Classification of Andean travertine and stromatolite occurrences in northwestern Argentina and summary of the physical, chemical, biological, and isotopic characteristics of the different depositional environments.

Type	Main water source	Hydrology	Hydrochemistry	Mineralogy	Basin morphology	Organisms	Carbonate precipitation	Diagenetic processes	$\delta^{18}O$ (‰ PDB)	$\delta^{13}C$ (‰ PDB)
Macrophytic travertine	Thermal springs	No surface outlet	High salinity; low Mg/Ca ratios	Calcite	Topographically closed; low sdr	Emerged plants Aquatic macrophytes	Biomediated	None	Emerged: 3.3 Submerged: 4.5–7.8 (*n* = 39)	Emerged: 8.2 Submerged: 8.2–11.4 (*n* = 39)
Lacustrine stromatolites	Thermal springs	No surface outlet	High salinity (?); low Mg/Ca ratios	Calcite	Topographically closed; low sdr	Cyanobacteria; diatoms	Biomediated	None	5.3	9.2
Salar travertine	Thermal springs	No surface outlet	High salinity; high Mg/Ca ratios	Aragonite	Topographically closed; high sdr	None	Physicochemically induced	None	–5.6 to –1.0 (*n* = 4)	8.3–10.9 (*n* = 4)
Fluvial-influenced travertine	River inflow (springs?)	Surface outlet	Fluctuating salinity and Mg/Ca ratios	Aragonite and calcite	Topographically open; low sdr	None	Physicochemically induced	Recrystallization; replacement; cementation	Calcitic –3.5 to –1.0 (*n* = 4); aragonitic –1.8 to 0.9 (*n* = 3)	Calcitic 2–5.2 (*n* = 4); aragonitic 3.7–5.3 (*n* = 3)

Note: sdr, surface-to-depth ratio.

groundwaters from the San Francisco basin. The occurrence of ^{13}C-enriched carbonates in the San Francisco basin indicates the presence of ^{13}C-enriched surface and groundwaters that could be transported to the Las Peladas basin during hydrologically open periods. The lower $\delta^{13}C$ values of the intramicrites and biomicrites could reflect higher lake-level conditions when there was a shorter residence time, and increased input of organic-derived CO_2. A higher input of isotopically lighter carbon sources, like soil-derived CO_2, or proportionally lower recharge of ^{13}C-enriched spring waters could contribute to such lower values.

Sedimentary models for lacustrine travertines and stromatolites. Discussion and conclusions

Travertines and stromatolites are common deposits in many high-altitude Andean Quaternary lake basins (Grosjean 1994; Grosjean et al. 1995; Schwalb et al. 1999). Geomorphological and sedimentological studies and microscopic (cathodoluminescence, petrographic, and SEM) observations and stable isotopic analyses ($\delta^{13}C$, $\delta^{18}O$) have allowed reconstructions of the paleohydrological conditions of different depositional subenvironments for lacustrine travertine and stromatolite occurrences in some of the Andean late Quaternary lacustrine basins in northwestern Argentina. Such deposits formed under different geomorphological, hydrological, chemical, and biological conditions. They all occur in high-altitude basins (3500–4000 m asl) that originated by tectonic and volcanic activity during the late Quaternary. Both El Peinado and San Francisco (Las Coladas subasin) basins are located in active volcanic areas, with geothermal springs discharging in the lakes. Although today the region is one of the driest in the world, the three lake basins show geomorphological evidence (highstand terraces and shorelines) of large fluctuations in the water balance during the Holocene and Upper Pleistocene. The sedimentary facies models for the different basins are shown in Fig. 12. The geomorphological, hydrological, geological, and isotopic characteristics of these Andean travertines and stromatolites are summarized in Table 2.

Four travertine and stromatolite environments of formation in Andean lakes have been identified:

(1) Fossil stromatolites are only present in El Peinado basin. Thermal waters constitute a major component of the hydrological input of the lake. Petrographic and SEM observations indicate a cyanobacterial origin. The stromatolites were formed in the littoral zone during low lake levels, when conditions were more favourable to cyanobacterial than to macrophyte development.

(2) Macrophytic travertines (El Peinado Lake) occur in vegetated areas near thermal spring seepage along the lake margin and in littoral lacustrine environments up to waters depths of several metres. In both cases, in situ travertines consist of an open meshwork fabric of calcite-coated stems (~1–2 mm in diameter) that lie in a subvertical position. Most lake sediments in El Peinado are composed of reworked travertine facies (phytoclastic travertines).

(3) Laminated aragonitic travertines in salars (Las Coladas) lack morphological or microscopic evidence of a

biogenic origin and are interpreted as abiotic carbonate precipitates. The aragonite mineralogy reflects the high Mg/Ca ratio of the lake brine. Their isotopic signatures suggest lighter initial water compositions and, likely, less important evaporation processes than in El Peinado waters.

(4) Laminated calcitic and aragonitic travertines in fluvial-influenced lacustrine margins (Las Peladas) are found at the top of fining-upward sequences deposited in a fluvial-dominated lake margin. During periods of high river discharge, conglomerates and sandstones were deposited, whereas during lower river discharge and lower lake level, intraclastic limestones and travertine facies formed. Like Las Coladas Salar, there is no evidence of microbial activity in the Las Peladas travertines. Neomorphic processes in these Late Pleistocene travertines resulted in carbonate cementation, recrystallization, and replacement textures. Geomorphological, sedimentological, and isotopic data indicate that the main water input to the Las Peladas paleolake was from rivers, although there may have been some thermal recharge.

Sedimentological, isotopic, and petrographical data from these Andean lacustrine facies show how similar laminated facies correspond to different depositional environments. Such data provide criteria that may serve to describe and identify them and better define the paleoenvironmental setting of other travertine and stromatolite occurrences. Similar laminated travertine facies with no biotic evidence occur in both Las Coladas and Las Peladas, but they have two opposite hydrological interpretations. In relatively deep lake basins like Las Peladas, travertine forms in littoral areas during episodes of low lake level and low river discharge. In contrast, in shallow and flat basins, like Las Coladas Salar, travertines represent periods of higher spring discharge to the lake. Neither petrographic nor isotopic data alone can differentiate between these two cases.

In situ and reworked macrophytic travertines do not provide reliable indications of water depth during deposition. In El Peinado Lake, similar facies occur in both emergent settings related to spring seepage areas and in lake floors up to several metres depth. Encrusted charophyte facies occur in up to 9 m water depth in other Altiplano lakes (Valero-Garcés et al. 1996, 1999*b*). Phytoclastic travertine facies can reach even deeper areas in the sublittoral zones.

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