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Holocene intramontane lake development: A new model in the Jáchal River Valley, Andean Precordillera, San Juan, Argentina

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ABSTRACT

The Jáchal River Valley displays a number of significant Holocene sedimentary accumulations made up of fine-grained materials. These deposits are interpreted as the sedimentary infill of shallow temporary lakes that were generated by slow growing episodes of alluvial fans that obstructed the Jáchal River Valley. The association of fossil remains through the Holocene sedimentary sequence suggests that the accumulation of lacustrine sediments was affected by climate variations. The predominant aridity was punctuated by very few humid episodes characterised by fresh-water gastropoda and the intercalations of muddy sediments. The high proportion of charcoal particles in some samples indicates periodic forest fires. Abundant non-pollen forest remains suggest that an open zone dominated by several types of grasses underwent a dry season during part of the year. The palynomorph associations found in the Jáchal River Valley Holocene lacustrine sediments suggest that the humid conditions were less intense than those in the San Juan River Valley located more than one hundred kilometres southwards. Our study suggests that lake formation could have been controlled by climate oscillation probably related to the ENSO variation at 30° south latitude.

1. Introduction

The Jáchal River is one of the few permanent rivers that flow eastward and cut the Argentinean Precordillera in a transverse direction at 30°S (Fig. 1). This river has been deeply incised because of the uplift of the Precordillera since the upper Miocene, and yields considerable evidence of the geological processes associated with the development of Andean Ranges. The upper Miocene and Pliocene fluvial sequences show substantial changes in sediment composition that could be related to several deformation processes during the history of the Andean orogeny in the region (Ramos, 1999).

In this context, coarse-grained sediments (gravels, boulders, gravely sands and coarse sands) predominate along the Jáchal River from the headwater in the Rodeo Valley to its mouth in the large intermontane Bermejo Valley. Despite the predominance of these materials, the occurrence of fine-grained deposits composed of silts, clays, and very fine sands is noteworthy. These sediments appear as horizontally bedded sequences (up to 30 m thick) characterised by a greenish-white colour, abrupt shift in grain size, the presence of log remains and gastropod-rich levels. The best outcrops appear along the road between the villages of Rodeo and San José de Jáchal in the upper section of the Jáchal River Valley. These fine-grained sediments fill topographic depressions produced by old fluvial valleys.

This work deals with the mud-sand-silt sequences. In particular, it seeks to establish the origin of the fine-grained sections and to ascertain whether climatic or tectonic processes played a role in the formation of this kind of accumulation. Moreover, the age of the fine-grained sections is discussed as well as their probable relationship to similar Holocene sequences reported in other places of the Precordillera (Colombo et al., 2000). Given that the materials are always siliciclastic and that they are very well washed, the preservation of the paleontological record is poor.

2. Setting

There are a number of outcrops that are dominated by fine-grained poorly consolidated sediments along the Jáchal River Valley (Fig. 2). They are mainly composed of clear silt, clay and very fine sand in tabular horizontal beds, showing planar stratification

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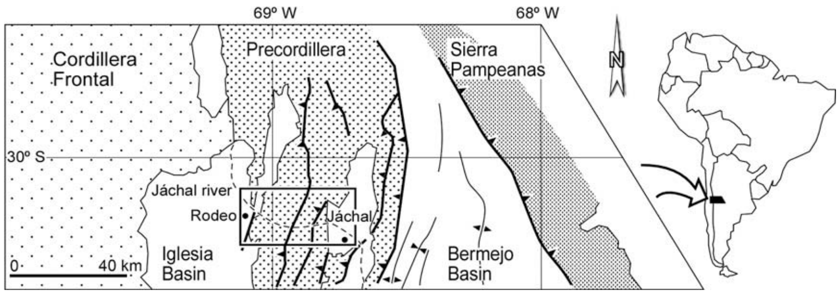

Fig. 1. Location of the studied area in relation to the main geological provinces of the Central Andes sector. The main faults, overthrusts, anticlines and synclines are displayed. The studied area is located along the Jáchal River Valley.

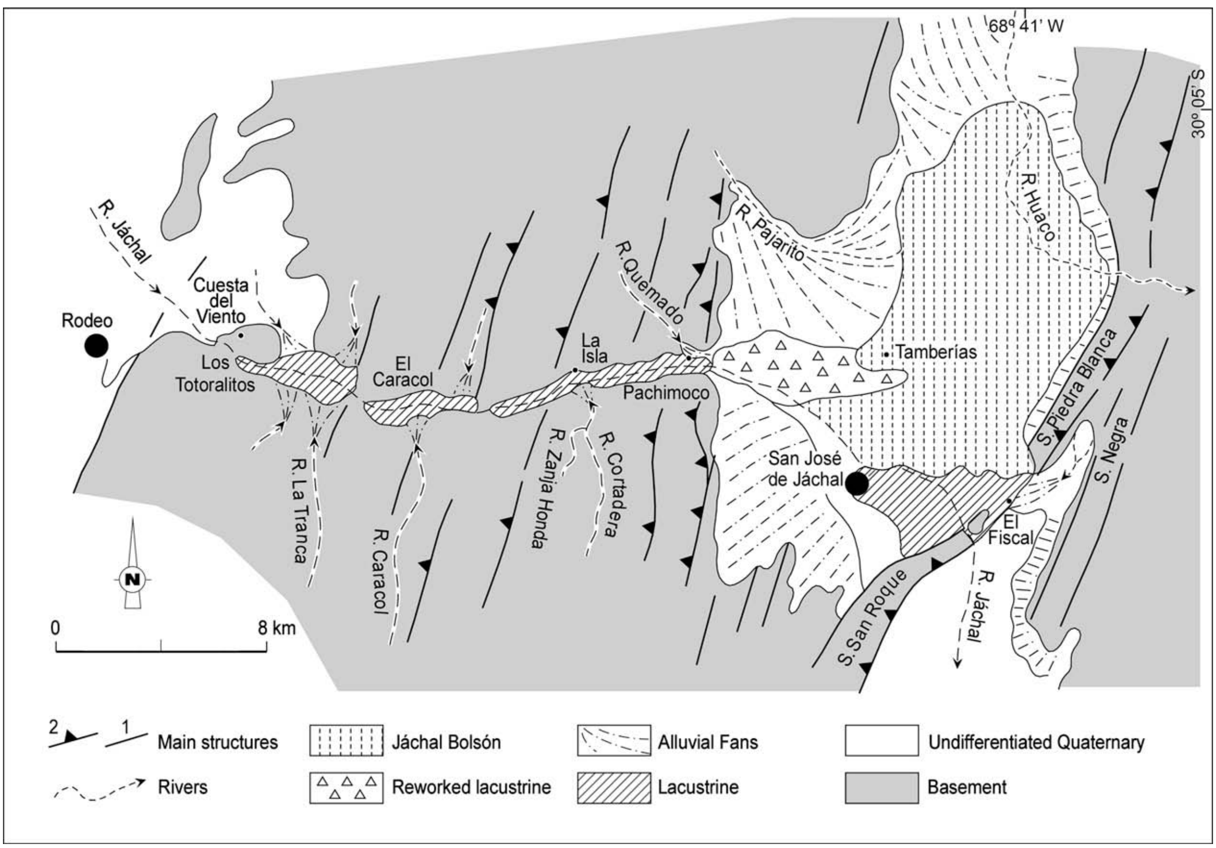

Fig. 2. Sketch of the Jáchal River area between the villages of San José de Jáchal and Rodeo. The main structures are placed in relation to the Jáchal River Valley. The areas with lacustrine sediments are enhanced.

and some small lamination commonly affected by intensive vertical bioturbation.

These sediments occupy relatively large areas when the Jáchal River flows through the transversal intermontane valleys (Pachimoco) but in other cases, these fine-grained materials occur in narrow and small depressions in the Jáchal Valley. The deposits cover unconformably the underlying Lower Paleozoic or Tertiary rocks and show some interfingering with coarse-grained gravels of local provenance.

The outcrops of fine-grained sediments occur for more than 40 km along the Jáchal Valley and are situated at different altitudes with a maximum topographic difference of approximately 300 m. Five major outcrops of fine-grained sediments were identified and located from east to west at Fiscal, Pachimoco, Isla, Caracol and Totoralitos (Fig. 3). To the east, between Pachimoco and Tamberías fine-grained sediments are displayed in an elongated and irregular outcrop.

All of these features were present in a regional context during which the Jáchal River cut into the previously accumulated fine-grained sediments. Thus, the river tends towards its local base level, which has not yet been reached, with the result that the river is in disequilibrium.

The Jáchal is an allochthonous (exotic) river because the waters are transported over a long distance without major tributaries in the studied area. At present, the whole region is characterised by semi-arid climatic conditions punctuated by episodic and locally large thunderstorms. The area is partially covered by scarce grasses and small amount of trees and shrubs.

3. Sedimentary characteristics

The most complete and representative sequence of fine-grained, poorly consolidated sediments along the Jáchal River is exhibited

Fig. 3. General disposition of lacustrine sediments (white) at Totoralitos, in the Jáchal River Valley.

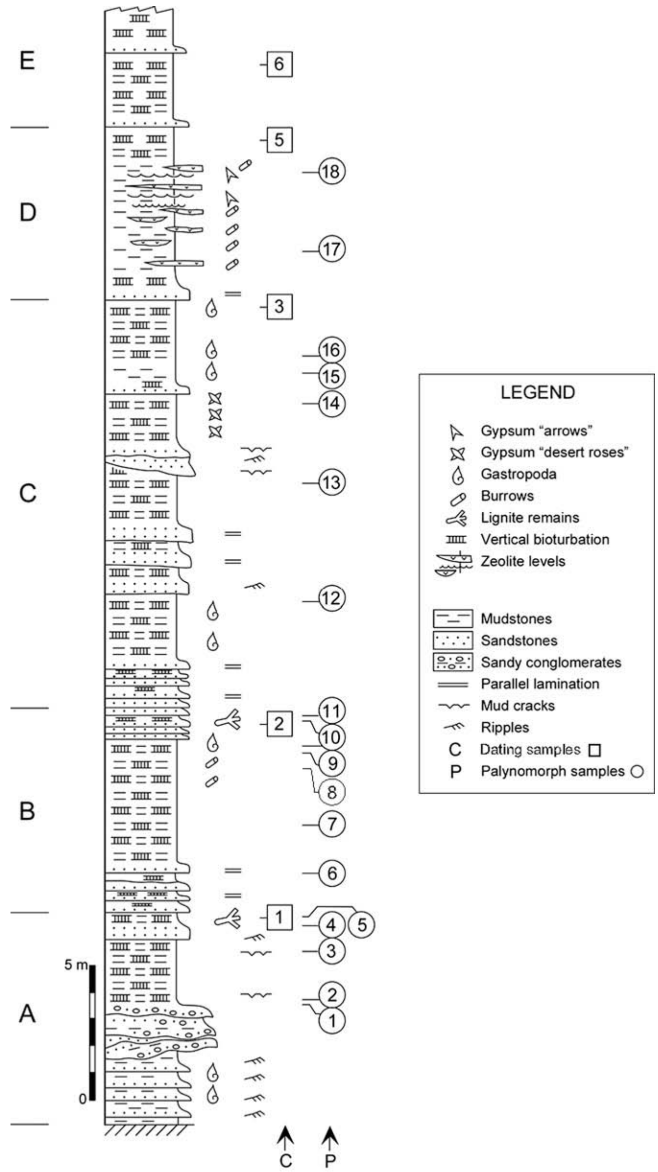

Fig. 4. Detailed stratigraphic section of the Totoralitos lacustrine sediments. (A–E) Main stratigraphic intervals. More explanations in the text.

in the Totoralitos outcrop (Fig. 4). These deposits consist of silts, fine and very fine-grained sands and clayey silt together with few intercalations of gravels and gravely sands. The Totoralitos sequence comprises five intervals from bottom to top: A, B, C, D and E. Interval A is composed of a number of beds of gravely coarse-grained sands up 2 m thick. Interval B is almost entirely constituted by silt and very fine sands. Interval C is predominantly made up of silts and very fine sands with some levels characterised by fresh-water gastropoda, whereas other levels display some gypsum crystals such as small desert roses. Interval D is composed of several beds of grey laminated mudstones containing some zeolitic levels. Finally, interval E is almost entirely formed by silts and few intercalations of fine sands.

Although sands commonly show small-scale and high-angle cross-laminated sets generated by climbing ripples, the beds are occasionally massive or horizontally laminated (Fig. 5). Mud cracks and intensive vertical bioturbation probably caused by fresh-water flora (bulrush, reed) are common in sandy silt beds (Fig. 6). This type of bioturbation is much more evident in the lower part of the section. Fine-grained deposits form decimetric to centimetric fining upward sequences which are bounded by a sharp and plane surface at the bottom and show a transitional upper contact. The sand/mud rate is widely variable along the sequence from equal sand/mud rate (=1) to sections clearly dominated by mud (sand/mud rate <0.2). Sandy layers vary in thickness between very few and more than 60 cm.

4. Palynomorph and charcoal remains

The Totoralitos (Fig. 7) deposits yielded palynological assemblages mainly related to shrubs and herbs but poorly preserved. The studied samples contain some organic remains that are more or less randomly distributed. Moreover, samples 2, 10, 17 and 18 have no palynomorphs but do have many charcoal particles. By contrast, samples 1 and 15 contain a large number of palynomorphs.

The relatively poor palynological assemblage suggests scant vegetation. Furthermore, the presence of charcoal particles suggests periodical burning of this scarce vegetation cover. Thus, the relatively low proportion of Palynomorpha could have been increased by the presence of the large number of charcoal grains in the samples.

Pteridophyta are present in the lower part of the section and Cyatheaceae are only found in the upper part and are thinly distributed. Tree pollen is present along the whole section but in a low proportion. Thus, Podocarpus is found in seven different samples but in a small number of specimens. It is possible that they may have been transported by winds from other areas (Fig. 8).

A large group is formed by shrubs and herbs where the Chenopodiaceae are the most abundant. Of these, *Salicornia* is present in the whole stratigraphic section, suggesting semi-arid climatic conditions. Large numbers of Chenopodiaceae remains are found as small pellets together with other taxa suggesting that they were affected by the biological activity (food digestion?) of different organisms living in the area during the sedimentary accumulation. The pellets could have been produced by zooplankton that was able to ingest the floating pollen (Robbins et al., 1996). Asteraceae, Poaceae and the rest of the taxa are present and randomly distributed along the stratigraphic log. There are also some well-preserved remains of Dinoflagellata.

The palynological assemblage studied in the stratigraphic section of the Jáchal River is constituted by a variety of palynomorphs subjected to three main controls, i.e., temperature, topography and

Fig. 5. Laminated lacustrine deposits in the Totoralitos area. Geological hammer for scale.

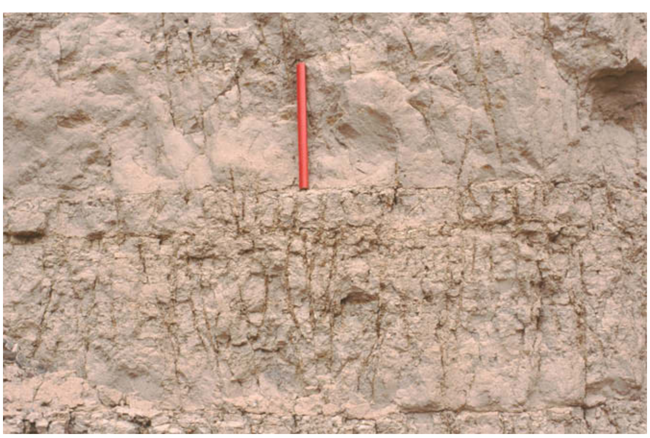

Fig. 6. Close-up view of the lacustrine levels affected by vertical bioturbation. Pencil (10 cm long) for scale.

samples														palynomorphs
1	3	4	5	6	7	8	9	11	12	13	14	15	16	
									●			●		Cyatheaceae
●					●		●							Hymenophyllum
●														Lophosoria
●	●	●					●							Polypodiaceae
●														Selaginella
●			●											Araucariaceae
●					●					●				Nothofagus
●	●	●			●		●		●			●		Podocarpus
					●							●		Ephedra
●	●						●	●	●			●		Ephedra frustillata
						●								Acantaceae
●						●	●					●		Apocynaceae
												●		Boraginaceae
●		●		●	●									Caprifoliceae
●	●	●	●		●		●					●		Asteraceae
●														Mutisieae
●														Mutisia
●														Convolvulus
●														Cruciferae
●				●	●		●			●		●		Chenopodiaceae
●														Atriplex
	●						●					●		Chenopodium
●	●	●	●			●				●	●	●	●	Salicornia
●												●		Euphorbiaceae
●														Geraniceae
●		●			●							●		Poaceae
												●		Laguminosae
										●		●	●	Mimosoideae
												●		Papilionatae
							●	●						Acacia
●														Cassia
●		●			●							●		Malpighiaceae
●	●	●	●		●	●	●		●			●		Malvaceae
●														Onagraceae
●									●					Polygonum
												●		Rosaceae
●														Rubiaceae
												●		Saxifragaceae
●														Scrophulariaceae
●					●									Solnaceae
											●			Urticaceae
												●		Umbelliferae
●											●			Verbena
											●			Dinoflagellate

Fig. 7. Vertical distribution of the fossil species present in the samples of the Totoralitos stratigraphic section.

precipitation (D'Antoni and Schabitz, 1990). These palynomorphs were carried mainly by eolian currents in a way similar to the present ones (D'Antoni, 1991). The absence of the vegetal remains of the specimens living in a water-dominated sedimentary environments should be noted (Fig. 9).

The spore associations found in similar facies along the San Juan River Valley differ from those identified in the Jáchal River Valley (Busquets et al., 2002). This suggests greater humidity in the San Juan River Valley, which is corroborated by evidence of human settlements dating to 6500 yr BP (Uliarte et al., 1990) around the largest lakes.

5. Lacustrine system

The locally intense sedimentary activity of tributary streams could have generated different types of relatively small fans (natural dams), that partially blocked the Jáchal River Valley, thereby playing a role in the development of the temporary lakes (Colombo et al., 2000). The alluvial fan progradation could have resulted from significant changes in the rainfall regime, which increased the debris supply in the Jáchal River Valley.

The regional distribution of the lacustrine outcrops suggests the existence of a number of small and unconnected temporary lakes which formed deposits of varying size and thickness (40–55 m). These deposits were mainly controlled by the Jáchal River discharge.

The origin of the lakes could be attributed to two different possibilities: (1) random events or (2) an important regional control over sedimentation sufficient to produce significant local sedimentary responses. The presence of lake sediments with a thickness of

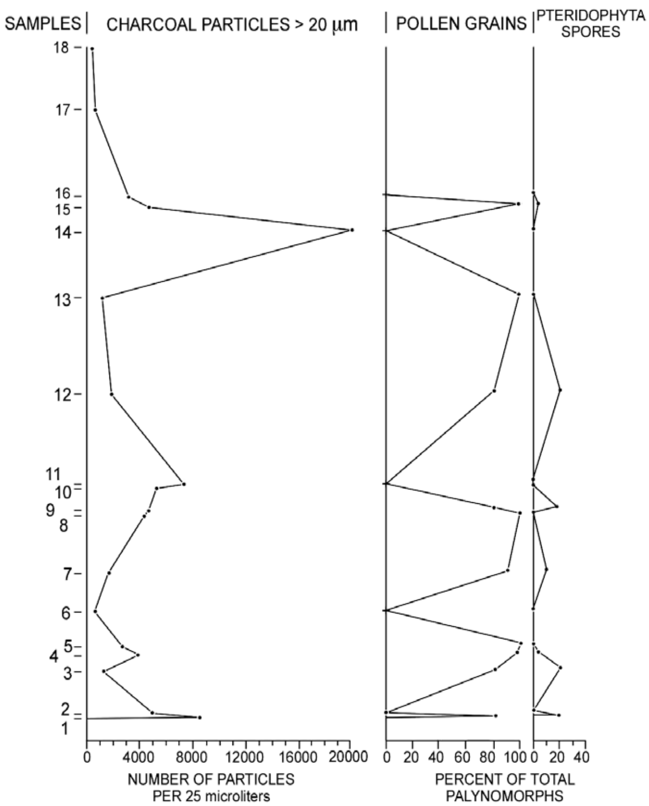

Fig. 8. Vertical distribution of the charcoal particles found in a volume of 25 µl of sediment for each sample of the Totoralitos lake stratigraphic section compared with the percentage of total palynomorphs (pollen grains and Pteridophyta spores).

up to 50 m does not necessarily imply that the lakes had this original depth given that the facies characteristics (mud cracks, root casts, desert roses, etc.) indicate that the sediments were deposited in shallow water. By contrast, the natural dams probably formed gradually, controlling the accommodation space whilst maintaining the shallow characteristics during sedimentary accumulation (Fig. 10).

The area of the lacustrine outcrops is directly related to the size of each lake. Thus, the lake formed near the village of San José de Jáchal occupied an area of 16–18 km^2, and a dam probably located at Fiscal controlled the growing events of the water body. Thus, the course of the Jáchal River was situated slightly to the east of the present course that crosses the Sierra de San Roque. The temporary dam was probably generated by the growth of a large alluvial fan in the intermontane valley located between the Sierra de la Piedra Blanca and the Sierra Negra. The lack of fine-grained lacustrine sediments in higher altitudes suggests that the top of the dam was 1225–1230 m above sea level (MASL) approximately. Other lake deposits occur in the Pachimoco locality, reaching about 3.5 km^2. In this case, the maximum elevation of the dam was 1300 MASL and was probably generated by the accumulation of coarse-grained sediments deposited by the Quemado River. The Isla lake (about 3 km^2) is placed where a fan deposited by the Zanja Honda and Cortadera rivers could have originated the dam with a maximum elevation of 1300 MASL. The next lacustrine section corresponds to Caracol where the Jáchal River undergoes a considerable increase in width owing to a supply from the Caracol River. This last river formed a large fan that partially obstructed the Jáchal River, resulting in a temporary lake that covered about 3.5–4 km^2 with a maximum altitude of 1420 MASL. The Caracol lake occupied not only the Jáchal Valley but also parts of other small lateral valleys.

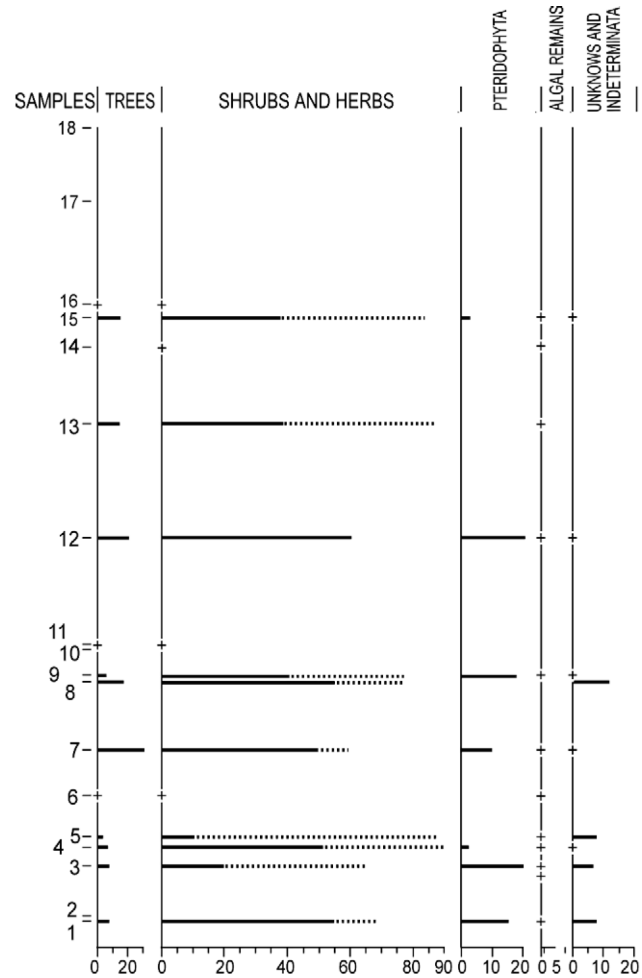

Fig. 9. Vertical distribution (%) of the particles from trees, shrubs and other herbs, Pteridophyta and algal remains. The Chenopodiaceae specimens and other indeterminate taxa are also represented by discontinuous lines. Totoralitos lake stratigraphic section.

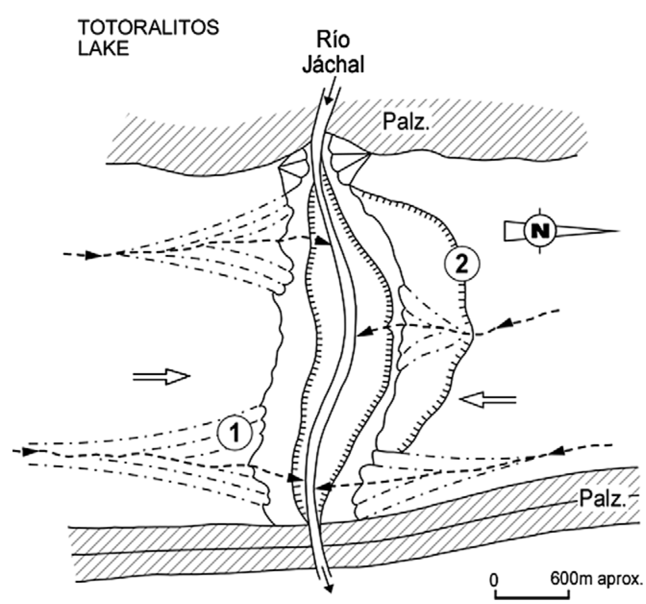

Fig. 10. Distribution of the lacustrine sediments infilling the Totoralitos lake. The main alluvial fans (1) and terraces (2) can be observed. The cross-section of Fig. 14 is depicted by open arrows.

Towards the top of the Totoralitos lacustrine sequence there are thin zeolitic levels displaying some log and root casts. Zeolite is identified as Heulandite (Queralt, personal communication, 2004). Despite the fact that the Heulandite genesis is often considered to be of hydrothermal origin (Pe-Piper, 2000), we cannot agree with this explanation given the stratigraphic position and sedimentary features of the zeolite-rich levels interfingered with mudstones in Totoralitos section. Moreover, heulandites formed in sedimentary continental environments (Teruggi and Andreis, 1963) have been described in closed alkaline lakes (DeWet and Hubert, 1989; Mertz and Hubert, 1990). A large amount of volcanic ash over the vegetation and the upper lacustrine deposits could be responsible for the zeolite generation. In the studied case, Heulandite occurred only in the upper part of the lacustrine sediments suggesting that these were accumulated coevally with the ash falls.

It may be inferred that the large lakes were randomly generated whereas the small ones such as Pachimoco, Isla and Caracol developed subsequently given that their natural dams formed on the lacustrine materials accumulated previously and upstream of the older lakes. The Totoralitos lake developed first, followed by the Pachimoco, Isla and Caracol lakes. The Pachimoco lake developed as a result of the natural dam made up of coarse-grained sediments deposited by the Quemado River. In the western sector of Pachimoco lake, the Zanja Honda and Cortadera rivers deposited boulders and gravels, generating another natural dam that controlled the evolution of the Isla lake. The Caracol lake was subsequently formed by the dam produced by the Caracol River.

5.1. Pachimoco–Tamberías sector

The lacustrine deposits with a thickness of 15 m (Furque, 1979) occurring downstream of Pachimoco are at about 1260 MASL. These deposits expanded eastwards as far as Tamberías (1175 MASL), occupying an area of about of 15.5–16 km^2 and attaining a volume of $120 \times 10^6\,m^3$. It is noteworthy that these sediments were located in an area with steep slopes. This is striking given that the primary lacustrine materials usually display a horizontal distribution. Thus, if these materials occurred in the same location as their original accumulation, they would also crop out at the Sierra Piedra Blanca and Sierra Negra at an altitude similar to that of the Pachimoco locality (1260 MASL), where the lake reached its maximum level (Fig. 2). It is not possible to attribute the origin of these materials to one large primary lake, given that they only crop out at Jáchal bolsón in the surroundings of Tamberías.

The lacustrine materials did not undergo a significant compaction because they were not overlain by any younger sedimentary accumulation. Thus, it may be assumed that the volume of the lakes was the following: Pachimoco $41.25 \times 10^6\,m^3$; Isla $33 \times 10^6\,m^3$; Caracol $50 \times 10^6\,m^3$ and Totoralitos $90 \times 10^6\,m^3$. The total volume attains $214.25 \times 10^6\,m^3$, which exceeds that calculated ($120 \times 10^6\,m^3$) for the Pachimoco–Tamberías sector. The difference of $94.25 \times 10^6\,m^3$ would correspond to the remnants of present lacustrine materials outcropping along the Jáchal River Valley given that an unknown but probably small amount of fine-grained materials could have been eroded by washing processes.

6. Dating

Randomly distributed charcoal remains in the studied fine-grained sequences have been utilized for some absolute dating. Moreover, there are some thin muddy levels with small freshwater gastropoda that also yield valuable data. The samples were collected for dating by means of (AMS) ^{14}C analysis carried out at the Van der Graaf Laboratorium of the Utrecht University.

Table 1
Totoralitos section dating.

Sample	Lab. Symbol	Material age (yr BP)	Cal. (yr BP)	OSL (yr)
Jáchal-6	GdTL 689			525 ± 32
Jáchal-5	GdTL 690			1050 ± 200
Jáchal-3	UtC Nr 8639	6213 ± 35	7169–7096	
Jáchal-2	UtC Nr 7436	6497 ± 45	7433–7319	
Jáchal-1	UtC Nr 7437	8930 ± 50	9804–9728 10,030–9887	

The values of samples 1, 2 and 3 are the AMS ^{14}C results from the Van der Graaf Laboratorium of the Utrecht University, Netherlands. The material age is corrected to "Present = 2000". The calibrated values (^{14}C) are corrected using the Calibration Table for Radiocarbon Ages (Roberts, 1998). The values of samples 5 and 6 are the OSL results from the Institute of Physics. Silesian University of Technology, Gliwice, Poland. These values are expressed as years before AD 2000.

In the Totoralitos sequence if it is assumed that the sedimentation was produced more or less continuously, the development of a natural dam would be generated episodically mainly during the Holocene (Table 1). It should be pointed out that there are some periods during which the natural dam undergoes high rates of growth, i.e., in the lower interval (B) when the sedimentation rate reaches 30 cm each 100 years (30 cm/100 yr). This is followed by another interval (C) with the highest rate of sedimentation reaching the 645 cm/100 yr. The intermediate interval (D) has a medium rate of sedimentation of the order of 10 cm/100 yr whereas the upper interval (E) attains high sedimentation rates of the order of 50 cm/100 yr. These data suggest that natural dams grew episodically with different accumulation rates.

Furthermore, some samples of the other lacustrine outcrops were also studied. Thus, the Fiscal lake was generated at 1805 yr BP and the Isla lake developed at 2790 yr BP, whereas the reworking of the lacustrine materials (Pachimoco–Tamberías sector) occurred at 2262 yr BP.

7. Discussion and concluding remarks

Fine-grained sequences along the Jáchal River Valley are interpreted as the infill of temporary lakes during episodes of damming due to the obstruction of the valley by coarse-grained alluvial fans.

The random dispersion of charcoal remains in the sand-silt beds and their good preservation suggest that they were deposited along the lacustrine basin filling episodes. The varying degrees of vertical bioturbation (mainly root casts) indicate shallow lakes periodically colonized by herbaceous vegetation in their marginal areas. The incision of natural dams subsequently occurred, resulting in the cessation of the lacustrine sedimentation. Given the difference in elevation of the lacustrine sections (about 300 m), all the lacustrine deposits cannot be attributed to a single large lake. Rather they belonged to different and coeval lacustrine basins located along the Jáchal River Valley.

In the Totoralitos succession, the lower conglomeratic levels were deposited by braided river episodes. This interval is covered by silts and sands that predominate in the lacustrine deposits. This rapid shift indicates a sudden change from high-energy fluvial conditions to a low energy sheet-like deposition that progressively extended over the whole sedimentary environment. Both the horizontal stratification and the lateral continuity of the beds suggest that the sediments transported by turbulent flows accumulated rapidly owing to the loss of stream confinement and sudden lateral expansion. This led to the formation of a temporary lake, which was caused by a natural dam that controlled the evolution of the lacustrine sedimentation. The evidence of mud cracks, desert roses, and vertical bioturbation (root casts), distributed along different sedimentary events characterised by the interfingering of sandy and silty levels suggests that the lakes were usually shallow.

The lakes no longer exist today, which indicates a recent regional fall in base level. Thus, three major phases with different dominant processes marked the Holocene evolution of the Jáchal River sedimentary sequence: (1) an initial erosive phase during which the river channels excavated the valley floor; (2) an aggradational phase characterised by fine-grained lacustrine sedimentation and (3) a base level fall, resulting in the erosion of the natural dam and a new episode of channel incision.

All the temporary lakes were formed when the Jáchal River was partially blocked by natural dams (alluvial fans) largely constituted by Paleozoic basement-derived coarse-grained clasts. The geometry and stratification of these clasts that show a progressive decrease in dip of individual deposits (transversal to the river valley) indicate that alluvial fans developed as the lake water level rose (Figs. 11 and 12). The absence of large-scale clinoforms suggests that depositional processes were dominated by tractive flows that periodically flooded the stable water bodies. The lack of evidence of progradational sequences also indicates that sedimentation occurred in a shallow context as the water depth underwent a gradual increase. Given the sediment accumulation, the presence of shallow lacustrine facies and the friable character of the sediments that suggest insufficient compaction, the thickness of depositional units could reflect the approximate depth of each lake. Bearing in mind the thickness of the small sequences, a maximum depth of 3–5 m can be estimated for at least part of the lake development.

Of the lakes, the San José de Jáchal one was the largest containing about $131.25 \times 10^6\ m^3$ of sediments. The Totoralitos lake was the second in size and Caracol the third. The Isla and Pachimoco lakes correspond to secondary water bodies and were limited to the sedimentary infill of the Jáchal River Valley. The existence of other small lakes between Pachimoco (1300 MASL) and Isla (1350 MASL) may be assumed given the presence of several coarse-grained minor accumulations probably related to other natural dams.

The damming of heavy discharges generates an accommodation space that is sufficient to be filled by lacustrine sediments. These conditions could have prevailed during high discharge periods caused by heavy precipitations in the neighboring Andean Cordillera region where the drainage systems had their source areas.

In the Pachimoco–Tamberías sector, the sediments correspond to fine-grained sands with some intercalations of silt and clay levels. They commonly display plane beds with some irregularly distributed clasts varying in size and density. The facies characteristics indicate that these sands had accumulated by means of high-energy hydraulic processes, and the poor sorting suggests that the flows were also rapid and highly concentrated, such as flash floods. This accumulation of fine-grained sediments interfingered with coarse-grained ones was deposited by a sudden high-energy hydraulic process, which could be an event such as an outburst flood or a huge wave produced by the sudden failure of the natural dam (Costa, 1988; Costa and Schuster, 1988; Clague and Evans, 2000), resulting in the subsequent reworking of previous lacustrine deposits. Thus, it is possible to account for the Pachimoco outcrop of lacustrine materials and their irregular distribution in the Pajarito River alluvial fan without any lateral equivalence with similar deposits in the eastern sector of Jáchal bolsón. The dam failure probably started in the Totoralitos lake when the water overflowed the natural dam because of a large water discharge of the Jáchal River. After the dam failure, a huge water avalanche would have resulted in the destruction of other natural dams located downstream along the Jáchal River Valley, and in the subsequent erosion of their lacustrine deposits. After the destruction of the Pachimoco dam, a violent and rapid loss of the stream confinement occurred, resulting in a rapid expansion and in a marked fall in the flow transport capacity. This led to the rapid accumulation of a large amount of reworked lacustrine sediments downstream of Pachimoco (Fig. 13).

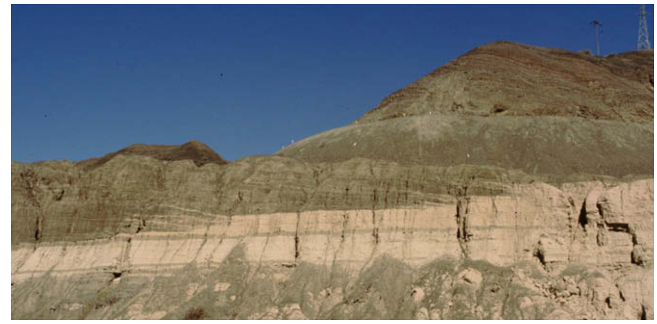

Fig. 12. Alluvial fan deposits interfingered with La Isla lacustrine sediments. The interfingering of alluvial fan sediments (dark) with the lacustrine (white) ones is noticeable. Right side of Fig. 11. The lacustrine deposits have a thickness of approximately 10 m.

7.1. Climate considerations

No evidence of deformed sediments and landslides coeval with the development of lacustrine deposits was found, suggesting that the development of these basins had not been controlled by tectonics (Trauth and Strecker, 1999; Wayne, 1999). The lacustrine basins that developed along the Jáchal River Valley during the Holocene could have been subjected to a climatic control. This is evidenced by the repeated variations in the water level of the lakes. This fact could have controlled the development of some alluvial fans produced by the tributaries of the main river (Figs. 14 and 15). For example, at the Isla section and in the Caracol area, well-exposed coarse and poorly-sorted monogenic clasts from the Paleozoic basement are interfingered with fine-grained sediments,

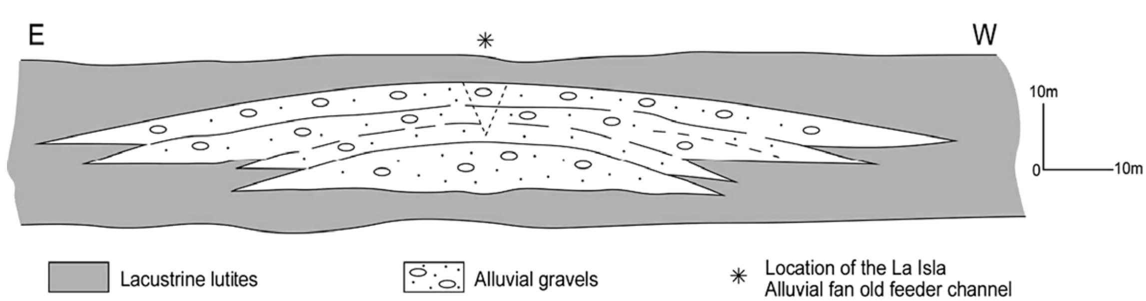

Fig. 11. Alluvial fan deposits interfingered with La Isla lacustrine sediments. The vertical variation in the sedimentary slope of the coarse-grained materials can be observed. All these data suggest that the development of this small alluvial fan was coeval with the gradual increase in the water depth controlling the accumulation of the lacustrine sediments.

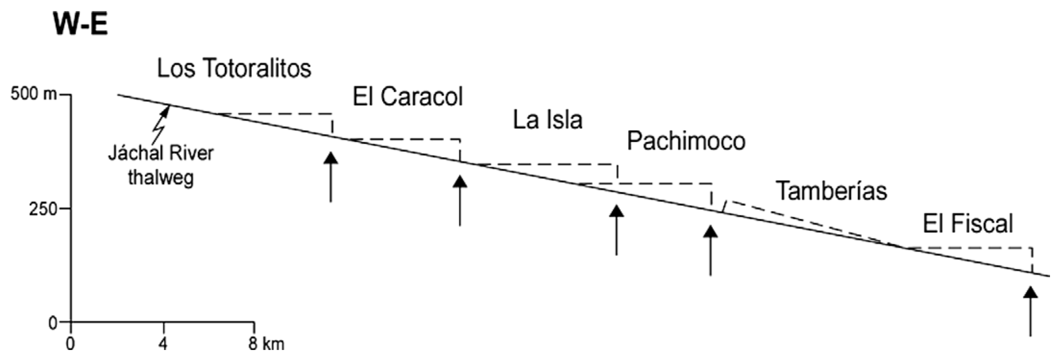

Fig. 13. Schematic arrangement of the main natural dams (arrows) along the Jáchal River Valley. The horizontal discontinuous lines correspond approximately to the maximum flooding surface of the lakes. In the surroundings of Tamberías there is an accumulation of lacustrine reworked materials.

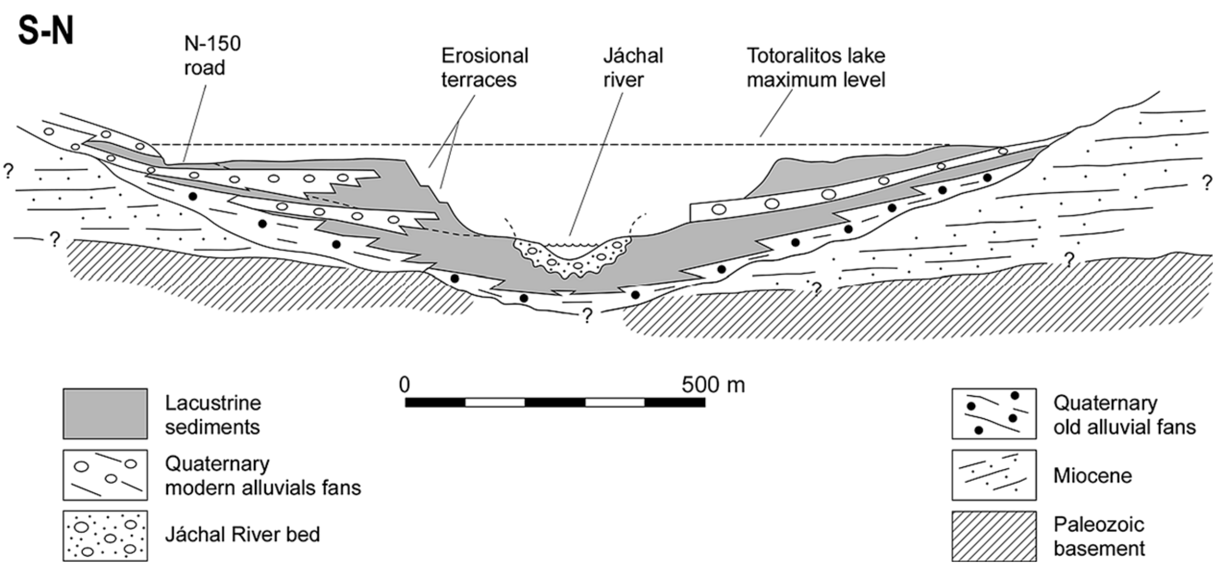

Fig. 14. Cross-section of the Totoralitos lacustrine sediments (maximum thickness of approximately 50 m) which infill the Jáchal River Valley. Its position is depicted by open arrows in Fig. 10.

Fig. 15. Distribution of Totoralitos lacustrine sediments in the southern part of the Jáchal River Valley. These are 40 m thick in the foreground. Left side of Fig. 14.

indicating that the clast supply originated from the lateral sides of the Jáchal River Valley.

Regional sedimentary activities with irregular distribution and a varying intensity can be clearly recognized in recent Quaternary materials of South America (Stager and Mayewski, 1997). These Holocene sedimentary accumulations, which are distributed over a wide region, could have been controlled by a specific climatic factor that was randomly distributed. The recent activity of the El Niño Southern Oscillation (ENSO) implies (Markgraf, 2001; Villa Martínez et al., 2003) that very intense and randomly distributed rainfall can cause floods that are locally very important. Although the specific causes and the precise mechanisms of the ENSO are still unclear, it is assumed that the main controls correspond to variations in sunshine associated with orbital conditions of the Earth (Berger, 1978), resulting in the destabilization of the meteorological regime over wide areas. In general, the ENSO activity is clearly evidenced in very recent sediments, becoming less evident in older sedimentary deposits.

The typical manifestations of the ENSO correspond to interannual periods. By contrast, similar situations are repeated in decadal periods ranging between 10 and 50 yr. These periods probably occurred in longer cycles (Dettinger et al., 2001) although the evidence is scant. It is possible to reconstruct the performance and rhythm of these periods (Enfield and Mestas-Núñez, 2001) in recent sedimentary accumulations younger than 5000 yr BP–6100 cal yr BP (Sandweiss et al., 1996, 1999) – where the evidence is very clear. However, records of the ENSO activity exist in alluvial materials dated approximately to 15,000 yr BP (Rodbell et al., 1999). For example, it is well known that the ENSO produced intense regional activity in the Central Argentinean Andes region between 1968 and 1975 AD (Ebbesmeyer et al., 1991). In the San Juan River Valley the detached parts of a road bridge (Fig. 16) which col-

Fig. 16. Terrace of a small tributary of San Juan River. A man-made (ashlar) block (hammer), the remnant of an old bridge of the N 20 national road, which collapsed between 1968 and 1972 AD due to heavy rain, can be observed. This could have been caused by the ENSO activity.

lapsed during 1968–1972 AD time span are included in the terrace of small tributary.

The ENSO activity produces an irregular distribution of the main regional rainfall, which would trigger significant episodes of clastic sediment transport. This could give rise to the generation of natural dams produced by alluvial fans due to the significant and irregular increase in rainfall, which would result in the formation of temporary lakes. This is consistent with the data provided by the analysis of the Holocene sediments located inter alia in the areas of the rivers San Juan (Colombo et al., 2000) and Jáchal. It may be assumed that the ENSO meteorological variations of high frequency (Dettinger et al., 2001) rather than climatic (low frequency) changes (Bull, 1991) account for the wide regional distribution of alluvial fans, giving rise to the formation of a number of temporary lakes along the main river valleys.

In the case of Totoralitos, the average sedimentation rate would be of the order of 185 cm/100 yr. This suggests a high erosion rate of the Precordillera and Andean Cordillera. Given that the tectonic activity is not coeval with the lacustrine sedimentary activity, another control should be proposed. This would correspond to specific and repetitive changes in erosion and sediment transport due to climatic variations. After the last cold events, the vegetal cover became impoverished (Clapperton, 1993) and as a result the topographic slopes were in disequilibrium, favoring the slumping and transference of large amounts of sediments during heavy rain episodes. In the Southern Hemisphere, the climatic maximum (Isla, 1989; Iriondo and García, 1993) occurred approximately at 10,000–8000 yr BP (11,500–8784 cal yr BP). During this time span, the lower lacustrine facies that accumulated along the Jáchal River Valley underwent periods of intense rain alternating with episodes of extreme aridity. Initially, the climatic context could have been warm as suggested by the pollen associations and by the intense vertical bioturbation produced by the grass and shrub cover of the lacustrine materials. Subsequently, the aridity would have increased as indicated by gypsum crystals (desert roses) dispersed in the sediments. In the upper part of the lacustrine sequence there are some centimetric zeolitic levels, suggesting that the area had been exposed to volcanic ash accumulations, favoring heulandite generation. The mud levels rich in fresh-water snails were accumulated during events of major humidity coevally with periods of major water lake stability.

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