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# Late Neogene lacustrine record and palaeogeography in the Quillagua–Llamara basin, Central Andean fore-arc (northern Chile)

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**Abstract**

The Cenozoic Quillagua–Llamara basin (northern Chile, Central Andes) is an asymmetrical, intramassif fore-arc basin with a relatively wide northern sector separated from a narrower southward extension by a basement threshold. The northern sector was characterised by a noticeable Oligocene?–late Neogene alluvial-fan and lacustrine dominated deposition which resulted in sequences up to 900 m thick, whereas the southern sector was often a bypass zone with thinner fluvial and lacustrine sediment accumulation. The basin infill includes two third-order alluvial–lacustrine unconformity-bounded units which include other higher-frequency (4th to 5th order) sequences. The evolution of the Late Miocene–Pliocene lacustrine episodes in the Quillagua–Llamara basin was not only controlled by the regional variations from arid to hyperarid palaeoclimate conditions, due to the combined influence of the Pacific high pressure cell, the rain shadow effect exerted by the rising Andes and the northward flowing cold oceanic currents, but also by: (a) the extensional tectonics and evolution and uplift of the fore-arc region which defined the location and size of the depocentres; (b) the resulting basement palaeorelief which affected sediment thickness and facies distribution during the late basin-infill episodes; and (c) the tectonic modifications of watersheds, water divides and drainage networks in the Precordillera which caused considerable changes of water income in the lacustrine systems. Understanding of this regional tectonosedimentary evolution is a necessary first step before analysing of the low- to high-order lacustrine sequence changes in the region. Lacustrine water supply was very sensitive to tectonics; even gentle tectonic tilting and uplifting in critical water-divide zones could result in changes in water balance in the lacustrine basins and trigger variations in the depositional record. The very conspicuous, lacustrine regime changes recorded in the Quillagua–Llamara basin infill cannot be considered in themselves conclusive proof of an exclusive climatic forcing, since they took place close to either major regional drainage changes or to gentle but noticeable tectonic reactivation in the fore-arc region. 

*Keywords:* lacustrine sequences; Central Andes; northern Chile; late Neogene; intra-massif fore-arc basins

## 1. Introduction

The fore-arc region of the Central Andes in northern Chile is located in one of the most arid to hyperarid regions in the world. General agreement exists that this current extreme aridity is because the region is under a high atmospheric pressure cell, the rain-shadow effect of the high Andes cuts off Atlantic moisture contributions, and the northward-flowing cold oceanic waters affected by upwelling

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prevent moisture from the Pacific Ocean penetrating onshore. But how and when these factors affected climatic evolution in the Miocene to Recent is still debatable (Alpers and Brimhall, 1988; Ortlieb, 1995).

Non-marine intramassif fore-arc basins have been evolving from Tertiary time in northern Chile in a fringe which extends from the present volcanic arc (Western Cordillera) as far as the Coastal Range (Chong, 1988). The Quillagua–Llamara basin is one of these basins where regional tectonic and palaeoclimatic evolution affected lacustrine systems. Recent and ancient lacustrine records have often been cited as substantial sources of pristine data for analysing regional and global environmental changes (Kelts and Talbot, 1990; Anadón et al., 1991; Gierlowski and Kelts, 1994). Nevertheless, the differentiation of the relative influence of diverse driving forces on lacustrine evolution is not always obvious, due either to the absence of high-resolution records or to poor understanding of the tectonic and morphological setting of the lacustrine systems.

This paper deals with the stratigraphy, main sedimentological features and palaeogeographic evolution of the ancient lacustrine systems which developed in the Quillagua–Llamara basin. It also proposes a tectonic and morphological framework for them. The late Neogene lacustrine sequences of the Quillagua–Llamara basin were deposited in a scenario of ongoing regional to global climatic events, but these were also coeval to critical structural and morphological changes in the southern Central Andean region. A good grasp of regional tectonosedimentary evolution is needed before interpretation of the low- to high-order sequential changes. This is also a pre-requisite of analysis of the potentially key high-resolution sedimentological, geochemical and palaeobiological records in lacustrine sequences, in order to detect higher-order, climatically forced periodical changes.

## 2. Geological setting — the Quillagua–Llamara basin

The southern Central Andes is a typical orogenic belt segment which rises between the oceanic Nazca plate and the western margin of South America since the Cretaceous (Fig. 1). The convergent margin of the Central Andes is characterised by a high- to moderate-altitude western fore-arc region, an extensive high plateau area with Cenozoic volcanic activity increasing to the east (volcanic arc), and an easternmost retro-arc fold and thrust belt. Thick Tertiary continental sedimentary successions characterise the tectonosedimentary evolution in this part of the Andes (Schmitz, 1994; Lamb et al., 1997).

In northern Chile, between 18º and 23ºS, the onshore fore-arc zone of the Central Andes has three main N–S-oriented morphostructural units: the Coastal Range, the Longitudinal Valley (Central Depression) and the Precordillera Range. Several Cenozoic alluvial–lacustrine and volcanoclastic basins developed in each of these domains (Reutter et al., 1988, 1991; Cabrera et al., 1995; Chong et al., 1999; May et al., 1999 and Gaupp et al., 1999).

The Longitudinal Valley includes several of N–S-oriented, elongated, asymmetrical fault-bounded basins and heights. Normal faulting has been put forward as the main process in the formation of this basin zone (Mortimer, 1973). These extensional faults have been related either to general regional extensional regimes developed in the intramassif fore-arc zones (Arabasz, 1971; Reutter et al., 1988, 1991; Hartley et al., 1988; Flint et al., 1991; Scheuber et al., 1995; Hartley and Jolley, 1995; Santanach et al., 1996), or to the local to regional extensional resolution of lateral motions along major regional strike-slip faults (Flint et al., 1991; Cabrera et al., 1995; Jensen et al., 1995).

The Quillagua–Llamara basin extends from 21º to 23º00′S and is a non-marine basin of 150 km in length. Its eastern margin is bounded by the western Precordillera Range which mainly consists of Precambrian basement rocks, Mesozoic terrigenous and carbonate sequences, and Cenozoic intrusive and extrusive rocks. The Precordillera Range slopes from 4000 m to 1000 m high in a region mantled by Miocene rhyolitic ignimbrites. The western edge of the basin extends along the foot of the Coastal Range and consists of a Palaeozoic metamorphic basement and Mesozoic igneous rocks, which rise to 1800 m. The Atacama Fault System to the west and the Precordillera Fault System to the east are two major N–S-oriented ancient fault systems (Mesozoic to Palaeogene) which are close to the boundaries of the basin (Fig. 1). The Tertiary Quillagua–Llamara basin

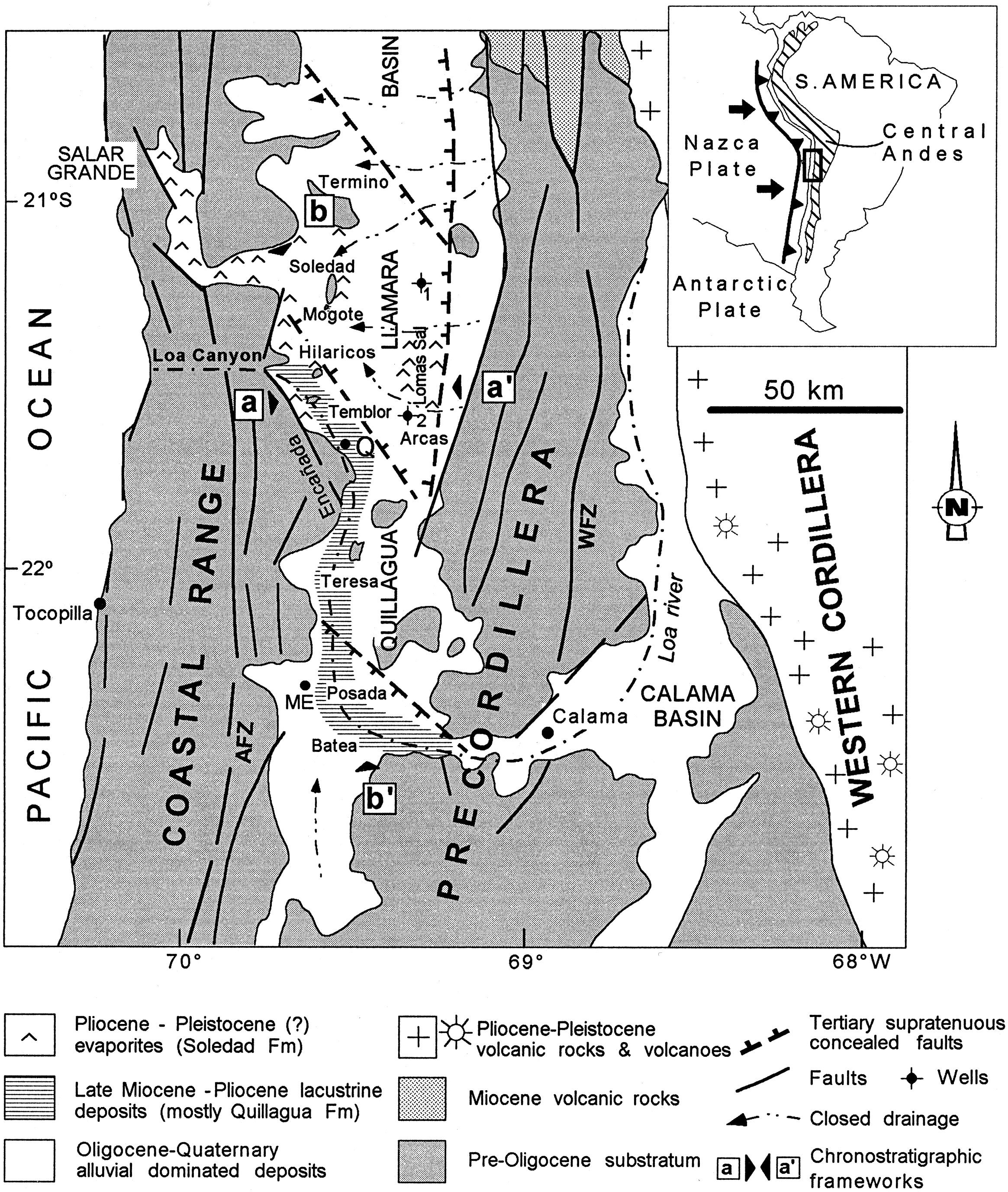


Fig. 1. Regional geological setting of the Quillagua–Llamara basin in the Central Andes and geological sketch of the Quillagua–Llamara basin (Longitudinal Valley–Central Depression) and surrounding Coastal Range, Precordillera Range, Central Andean Depression (including Calama basin) and Western Cordillera zones. *AFZ* = Atacama fault zone. *WFZ* = Western fault zone. Note location of studied sections, significant basin zones and of the chronostratigraphic frameworks *a–a′* and *b–b′* in Fig. 2. *ME.* = Maria Elena, *Q.* = Quillagua Village. Oil wells: *1* = Lomas de la Sal, *2* = Hilaricos.

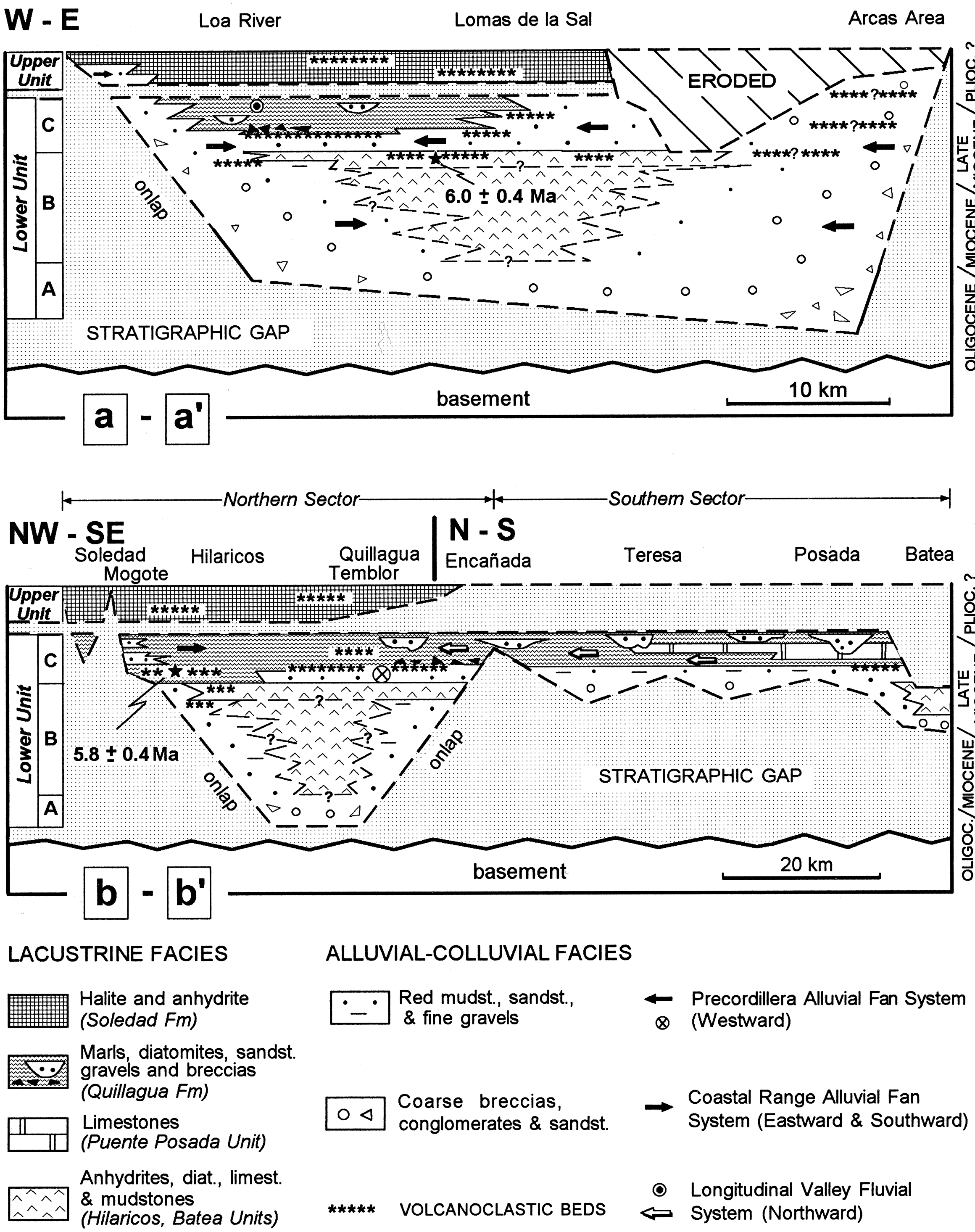


Fig. 2. General longitudinal and transverse chronostratigraphic frameworks of the Cenozoic basin infill of the Quillagua–Llamara basin. Topographic and structural features are not represented. See Fig. 1 for location.

was formed by the combined activity of N–S- and NW–SE-oriented faults, which in most cases were concealed by basin infill and became supratenuous faults. The subsurface data on the basement depth (Rieu, 1975; Dörr et al., 1995) and the basement outcrop distribution (Fig. 1) suggest that the NW–SE faults split the basin into several sub-basins and structural highs, and define two sub-basins (northern and southern) characterised by different structural, stratigraphic and palaeogeographic features and bounded by a basement threshold (Encañada high, Figs. 1 and 2). The northern sub-basin is 75 km wide and 75 km long and has a rhomb-shaped pattern which has been interpreted as the result of a pull-apart, strike-slip-related evolution (Jensen et al., 1995). Data from two oil exploration wells in the Lomas de la Sal area (20 km east of the Loa River, see Fig. 1) indicate that the pre-Cenozoic substratum depth ranges from 603 to 930 m deep, with the maximum located in the southern part of the northern sub-basin (Rieu, 1975). These subsurface data show that the basin bottom is asymmetrical with a gentle western margin and a steeper eastern one. The southern sub-basin was a narrower zone (30 km wide and 75 km long). The frequent occurrence of substratum highs in this zone points to the fact that the maximum basin substratum depth is not as deep as in the northern sector. In consequence, the stratigraphic successions of the northern and southern basin sectors are different, with the northern sector characterised by thicker, continuous deposition, whereas the southern sector was often merely a bypass zone with less accumulation (Fig. 2). In addition, the lower basin infill units, which are well represented in the northern areas, are lacking or thinner in the southern ones (Jensen, 1992).

Therefore, the overall geometric features of the Quillagua–Llamara basin infill is clearly a consequence of the fault activity which affected the fore-arc region, but the upper basin infill occurred when fault activity was much less. Therefore, the Upper Neogene basin fill successions onlap a substratum palaeorelief which was carved during earlier erosive phases. The main sedimentary infill ranges probably from Oligocene (Jensen et al., 1995) to Pliocene–Pleistocene. Terraced alluvial-fan, fluvial and lacustrine deposits ranging from Pleistocene to Recent overlie unconformably the Late Miocene–Pliocene sequences. Neogene exposures crop out mainly along the N–S-oriented Loa river valley trenches (Fig. 4), which extend across the western basin zones, and also along ephemeral creeks (the so-called 'quebradas'). The 'quebradas' flow westward from the Precordillera Range and contribute to the Loa River or end in closed drainage zones (Fig. 1). The entrenched Precordillera 'quebradas' reach the pre-Cenozoic substratum in several areas and mostly expose the successions closer to the western basin margin which range from 100 to 300 m in thickness. Extensive exposures of Cenozoic successions are lacking in the northern and central basin zones where the quebradas have not cut so deeply.

## 3. Stratigraphy

### *3.1. Methodology and techniques*

The study of the basin infill has been focused on its stratigraphy and major sedimentological features. This has been the subject of previous work (Rieu, 1975; Naranjo and Paskoff, 1982; Marinovic and Lahsen, 1984; Jensen, 1992). Field mapping was carried out, supplemented by satellite images and aerial photography analysis of the laterally extensive exposures along the Loa valley and near the basin margins. Some oil exploration well data were also available (Rieu, 1975) and were used to establish the maximum recorded thickness and the lateral extent of the subsurface successions. Stratigraphical–sedimentological logging provided the framework for selective sampling of petrological, sedimentological and palaeobiological (diatomites, palynomorphs) analyses. More than 150 samples from diverse sedimentary and volcanic facies were taken for further mineralogical (XRD) and petrological analysis both by optic microscopy and SEM (Jensen, 1992). Biotite crystals from various pyroclastic deposits interbedded in the alluvial–lacustrine sequences were K/Ar-dated. The sedimentological and palaeoenvironmental interpretations of the sequences studied were integrated into the regional tectonic setting and were the basis of palaeogeographic basin reconstructions.

The depositional record in the basin includes Tertiary and Quaternary deposits. The stratigraphic subdivision adopted here for the Tertiary basin fill builds on previous proposals (Jensen, 1992; Cabrera et al., 1995) and consists of two low-order unconformity-bounded units (Lower and Upper), whereas the expansive–retractive relationships between the alluvial and lacustrine sequences enable three genetic subunits (A to C) in the Lower Unit to be distinguished.

### 3.2. Lower Unit

The Lower Unit includes the alluvial, lacustrine and volcanogenic sequences deposited between the basement-Tertiary unconformity and the unconformably overlying evaporite-dominated sequences of the Upper Unit. It ranges from 500 to 800 m thick in the northern basin sector and is lacking or is very thin in the southern zones (Figs. 1 and 2).

Subunit A includes the alluvial successions deposited between the basement-Tertiary unconformity and the lowermost lacustrine deposits which define the base of Subunit B (Fig. 2). The area distribution and lithological features of the sequences of this subunit are poorly known since it only occurs in the subsurface. Nevertheless it has to be restricted to the northern basin sector where well-log data (Hilaricos and Soledad wells) show that Subunit A includes red-bed-dominated, coarse-grained alluvial assemblages, which were deposited on proximal to middle alluvial fan fringes. The alluvial fan systems spread mainly from the Precordillera, although minor contributions could also reach the basin from the Coastal Cordillera, and the northern and southern ends of the northern sub-basin.

Subunit B includes alluvial–lacustrine sequences deposited between the lowermost lacustrine deposits overlaying Subunit A and those which underlie Subunit C. These sequences are only found in the northern basin sector. Outcrop and well-log data show that in this zone Subunit B consists of alluvial red beds containing conglomerates, sandstones and mudstones which were deposited on proximal to distal alluvial fan fringes. Moreover shallow lacustrine, playa and playa-lake sequences up to 450 m thick and consisting of diatomites, carbonates and sulphate evaporites also occur. Most of these deposits have been reported in the subsurface and only the uppermost lacustrine evaporite episode crops out in some zones of the northern sub-basin (Hilaricos anhydrite, Figs. 2, 4 and 6). In the linking zone between the Quillagua–Llamara and Calama basins the sub-unit B deposits are not so well developed but a slight increase in the substratum depth allowed the deposition of a terrigenous and evaporite alluvial and playa lake sequence, up to 100 m thick, which is broadly equivalent to the middle-upper part of the Lower Unit (Batea Formation; Jensen, 1992). Preliminary radiometric K/Ar analysis performed on biotites with 7.621% of K content, 1.782 nl/g of radiogenic Ar and 63% of atmospherical Ar indicate an age of $6.0 \pm 0.4$ Ma for volcanic layers interbedded in the lower part of Hilaricos anhydrite, which dates the upper part of the Lower Unit as Late Miocene (Fig. 2).

Subunit C includes the sequences deposited between the settling and early spreading of the lowermost lacustrine deposits which overlie subunit B and the development of the bounding unconformity between the Lower and Upper Unit. A variety of laterally related alluvial fan, fluvial, fluvial–lacustrine, lacustrine and volcanoclastic facies occur in this unit (Figs. 2–5 and Figs. 6–9). Most of these terrigenous, diatomitic, carbonate and epiclastic facies assemblages are included in the previously defined Quillagua Formation (Rieu, 1975; Jensen, 1992) and in the Puente Posada limestones (Figs. 2 and 3). Some of the alluvial deposits included in this subunit have been described as depositional units (Arcas alluvial fan, Dörr, 1996). The lacustrine diatomite, carbonate and terrigenous deposits extend through the northern and southern basin sectors (Figs. 1–3). The sequences of this subunit also thin towards the western and southern basin margin sectors where they onlap the regional basement (Figs. 2–4). The Puente Posada carbonate unit is assumed to be laterally equivalent to the carbonate-dominated sequences which crop out extensively in the linking zone between the Quillagua–Llamara and Calama basin (El Loa limestone, May et al., 1999). Preliminary radiometric K/Ar analysis carried out on biotites with 7.215% of K content, 1.617 nl/g of radiogenic Ar and 44% of atmospherical Ar indicates an age of $5.8 \pm 0.4$ Ma for volcanic layers interbedded in the lower part of the Quillagua Formation in the Cerro Mogote section, which dates the lower part of the Upper Unit as Late Miocene. Other preliminary magnetostratigraphic data suggest that the upper part of this unit could be Pliocene (Garcés et al., 1994).

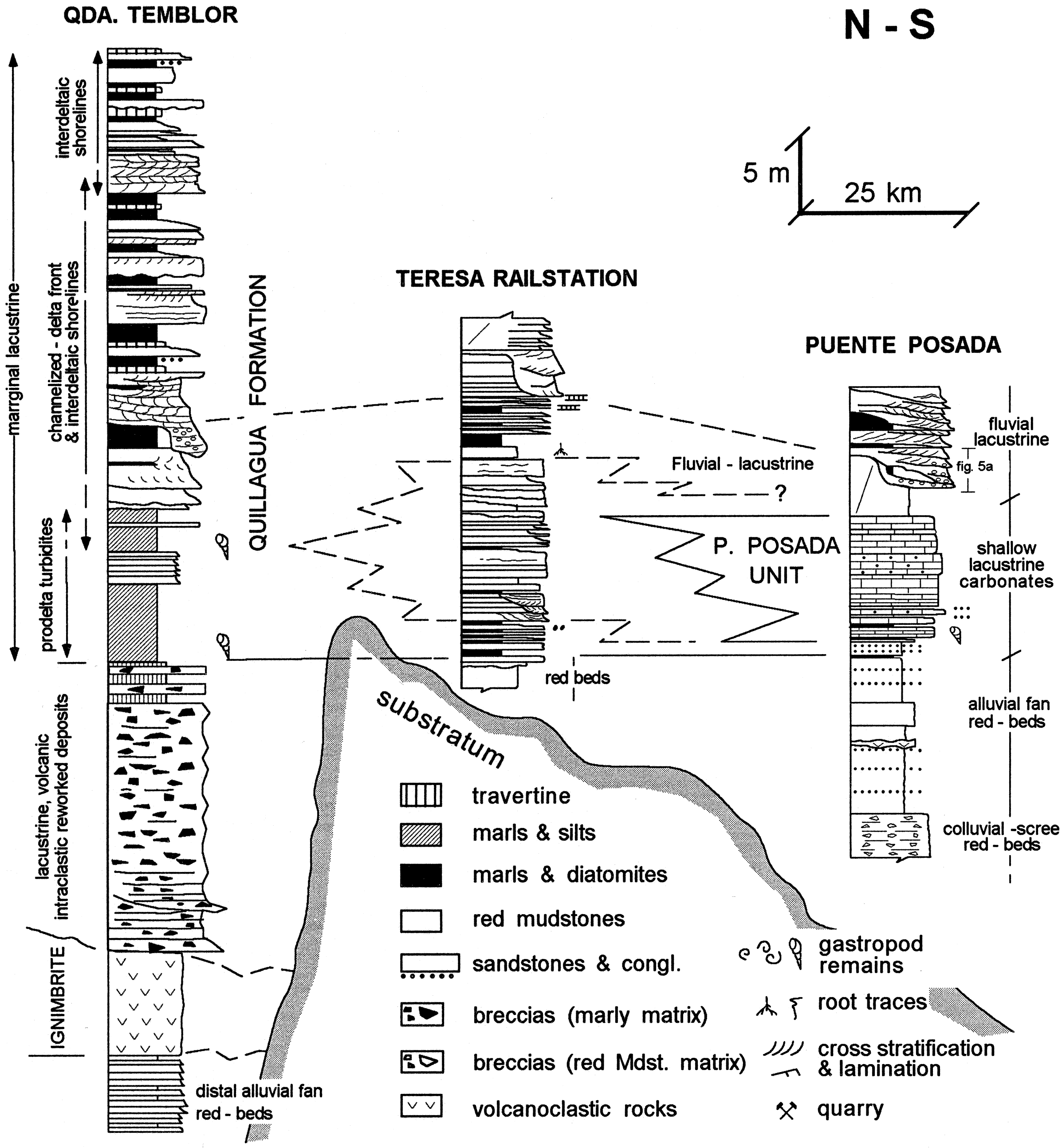


Fig. 3. Stratigraphic correlation between the lithological–sedimentological logs of the late Neogene (Late Miocene–Pliocene) successions in the southern sub-basin of the Quillagua–Llamara basin. See Figs. 1 and 2 for location.

### 3.3. Upper Unit

This unit is up to 100 m thick and overlies unconformably the Late Miocene–Early Pliocene sequences of the Lower Unit, which are affected by gentle tectonic deformation (Figs. 1 and 2). The mostly evaporitic Soledad Formation (Bobenrieth, 1979) is included in this unit and in the north-

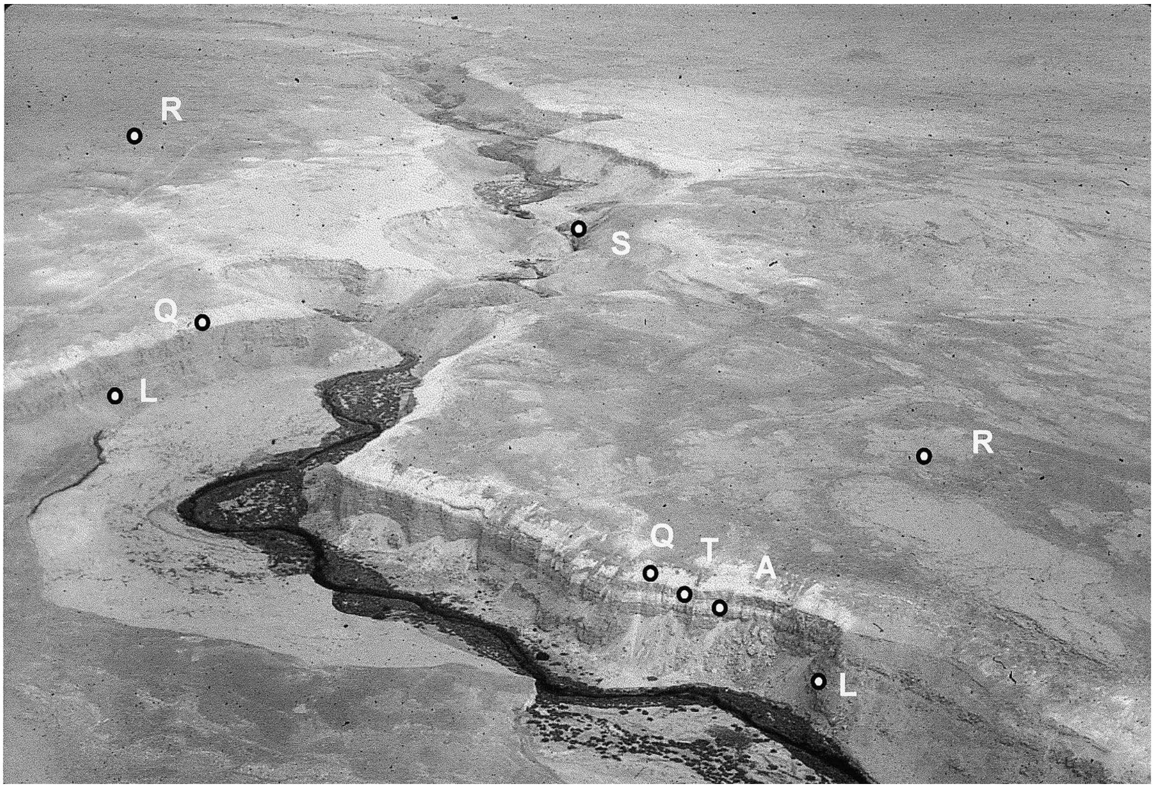


Fig. 4. Oblique aerial view of the Loa River crossing Longitudinal Valley in the northern sub-basin from 21º35′ (bottom) to 21º15′S (top). The north is located at the top of the photograph. *S.* = pre-Tertiary substratum; *L.* = Loa Canyon breccias (mainly scree and alluvial fan coarse deposits); *A.* = Hilaricos Unit (ephemeral playa-lake anhydritic deposits); *L.* = distal Precordillera alluvial fan red-bed facies. Note as this unit wedges out to the north. *Q.* = Quillagua Formation (mainly lacustrine marls, diatomites and travertines), *R.* = Quaternary red alluvial fan deposits.

ern Quillagua–Llamara sub-basin it overlies unconformably different Late Miocene–Pliocene units, which are gently tilted or folded. Thus, in Cerro Hilaricos, the Soledad Unit overlies the distal Precordillera alluvial fan successions, whereas in Lomas de la Sal it overlies the Hilaricos anhydrite. The deposits of this unit also onlap the basement on the northern and western basin margins (i.e. in Cerro Soledad and Cerro Término, Figs. 1 and 2). The upper boundary of this unit is the erosive surface related to the earlier lowering of the regional base level and the subsequent entrenchment of the drainage network. Its relative stratigraphic position and the available radiometric–magnetostratigraphic dating of the underlying sequences suggest the age of the Soledad Formation deposits as Pliocene–Pleistocene (?). Although this unit is clearly dominated by halite and anhydrite deposited in ephemeral playas and in playa-lake environments, minor alluvial fan terrigenous facies and pyroclastic and epiclastic beds occur as well (Fig. 10).

The Soledad Formation has been extensively dissolved and eroded in widespread basin zones, but the sequences of this unit can be observed in several hill ranges (Lomas de la Sal, Cerro Soledad, Cerro Hilaricos, Cerro Término) where this unit is up to 100 m thick. The westward decrease of the altitude in the summits of these ranges (Lomas de la Sal 1097 m a.s.l., Cerro Soledad 1095 m, Cerros Hilaricos 1060 m, and Cerro Término 1048 m) indicates a very gentle westward dip in this part of the basin.

### *3.4. Quaternary deposits*

The Pliocene–Pleistocene? lacustrine evaporites of the Soledad Formation were affected by ero-

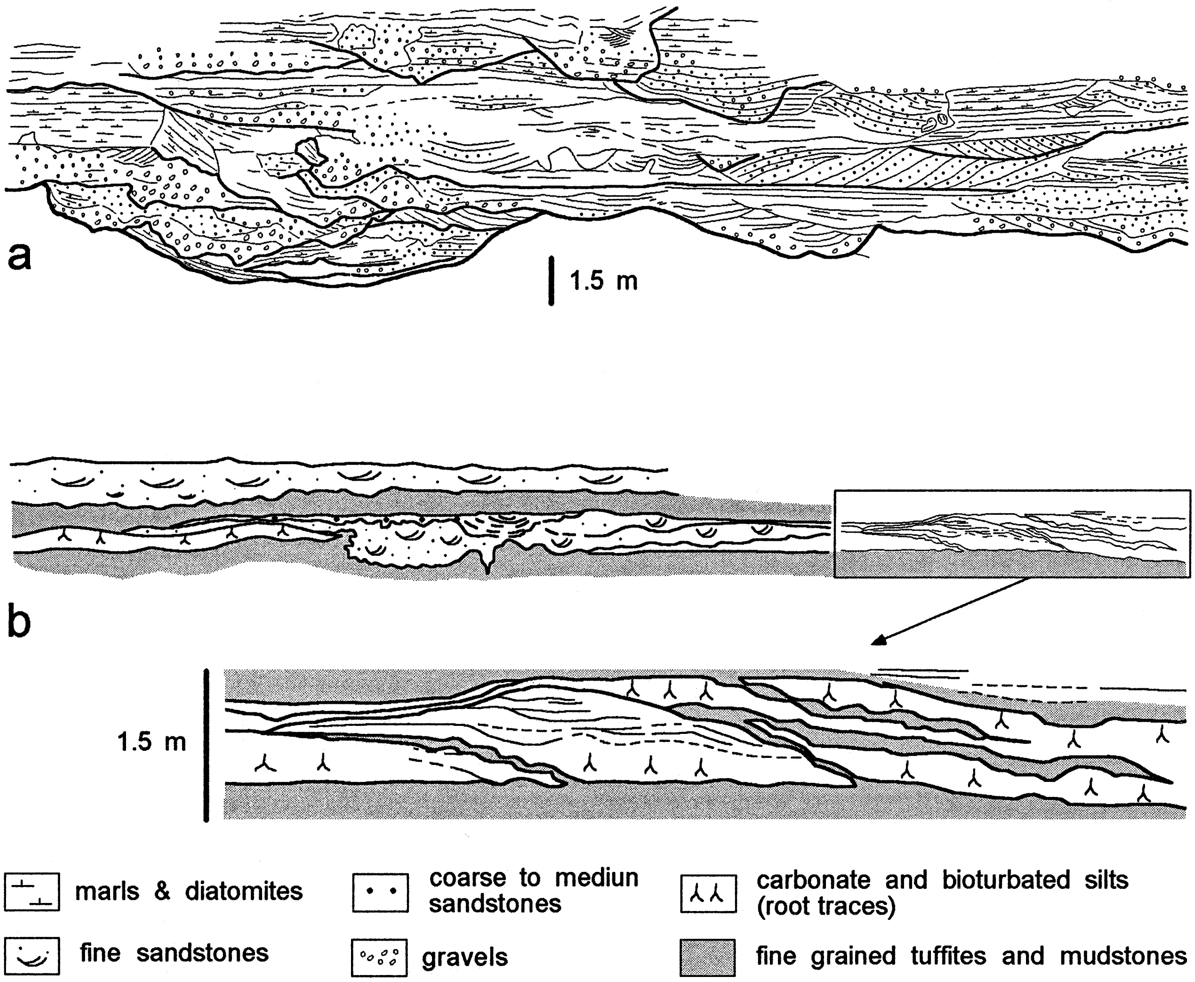


Fig. 5. General depositional styles of the channels in the fluvial and fluvial–lacustrine facies of the Quillagua Formation (Lower Unit, Subunit B). (a) Multistorey ribbon-like channel infills in the Puente Posada area (see stratigraphic location in Fig. 3). (b) Minor multi-storey, ribbon-like channel infills affecting underlying, abandoned laterally accreted point bar bodies which show pervasive root colonization in Encañada (see location in Fig. 1).

sion during the transition from internal to external drainage conditions in extensive basin zones. This change meant the end of the extensive evaporite sedimentation (nowadays limited to some minor karstic collapse ponds), the deep entrenchment of the Loa River and some of its tributaries, and the onset of a process of degradation of the formerly developed evaporites by dissolution and karstic collapse (Rieu, 1975; Cabrera et al., 1995). Minor Pleistocene-to-Holocene terraced deposits, which are mostly restricted to the neighbouring Loa valley, overlie unconformably the Neogene successions of the Quillagua–Llamara zone. Here several fluvial and fluvial–lacustrine terrace levels, with a wide clast compositional spectrum occur (Rieu, 1975). The thickness of the terraces and their clast lithology vary depending on: (a) the pre-Tertiary and Tertiary substratum composition in close drainage areas of local tributaries; (b) changes in river profile. In the older continuous terrace (San Salvador Unit, Rieu, 1975), local deposition of macrophyte travertines, domal stromatolites, oncoids, diatomite marls and pure diatomites took place; these record the development of fluvial–lacustrine environments in some

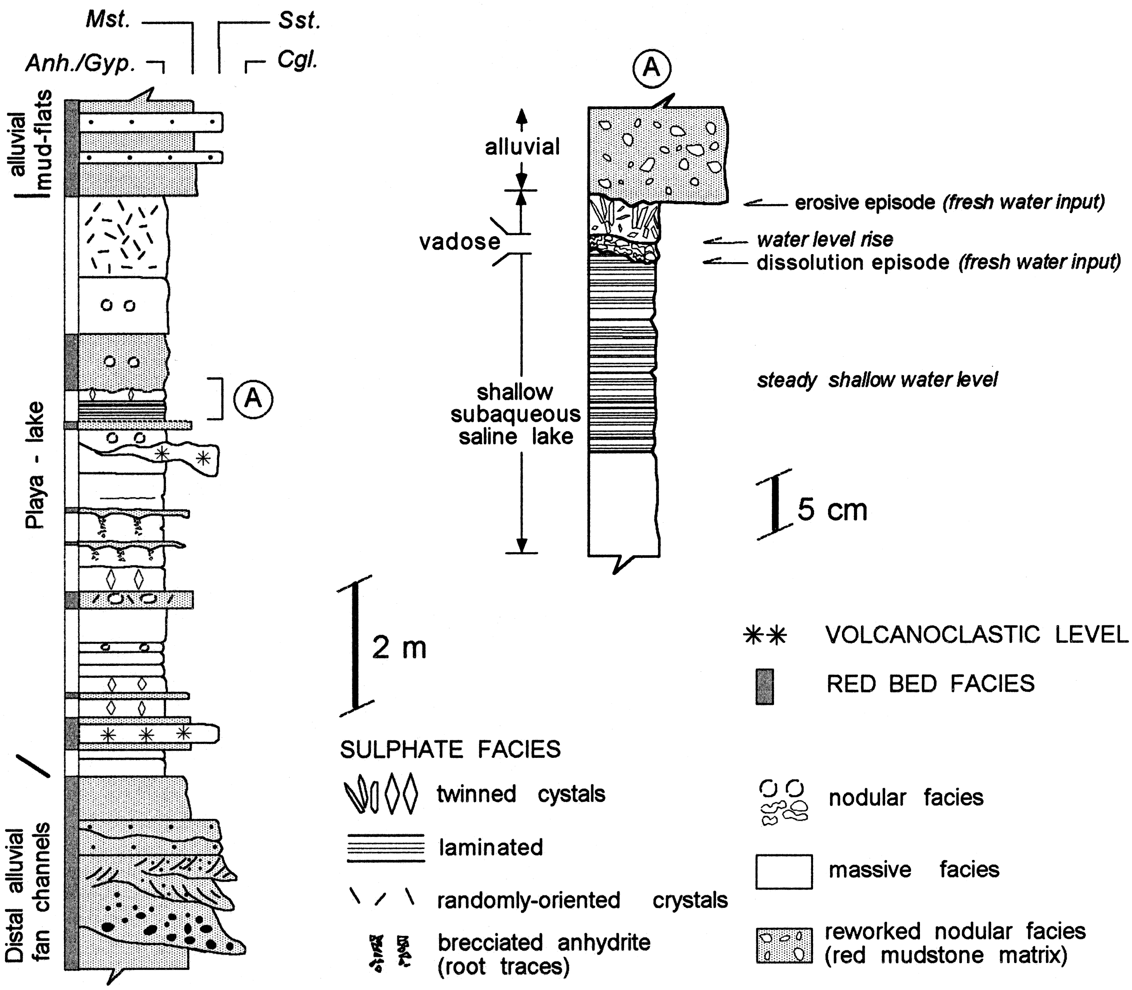


Fig. 6. Sedimentological log of Hilaricos Unit in Lomas de la Sal. Northern sector of Quillagua–Llamara basin. See Fig. 1 for location.

ancient river transects. The younger lower terrace levels (Las Vegas Unit, Rieu, 1975) are mainly terrigenous and more continuous laterally: they are present throughout the entire Loa valley and the Loa Canyon, including the outlet area where marine influence is recorded.

## 4. Depositional framework

The most significant lacustrine successions in the Lower and Upper Units of the Quillagua–Llamara basin were fed by alluvial and fluvial systems and developed ahead of their terminal zones (Fig. 11). Moreover, occasional volcanic events, which generated widespread pyroclastic and epiclastic deposits, were also significant and noticeably affected the final composition of the detrital and/or biogenic alluvial and lacustrine facies. A regional overview of the alluvial and volcanic frameworks is now given as a prerequisite to understanding the evolution of the lacustrine record.

### 4.1. Alluvial fan and fluvial systems

Changing sediment and water contributions from the alluvial systems were some of the most important features which either triggered or hampered the evolution of lacustrine systems in the fore-arc basins. Alluvial fan contributions spread into the Quillagua–Llamara basin directly from the neighbouring Precordillera and Coastal ranges. The Precordillera alluvial-fan watersheds were more extended than those in the Coastal Range (i.e. Arcas fan watershed up to 750 $km^2$). Other water and sediment incomes were contributed by a northward-draining fluvial system fed by wider, higher Precordillera catchment areas located to the east of the southern end of the Quillagua–Llamara basin.

The major alluvial fan systems were restricted mostly to the Northern Basin sector where thick, significant red-bed successions were sedimented, whereas thinner colluvial scree deposits, alluvial fan and fluvial successions were deposited in the southern basin sector (Figs. 2 and 3). Alluvial fan deposition in the northern basin sector was the result of the erosion of the Precordillera and Coastal Range relief caused by extensional faulting which gave rise to a set of basins and ranges (Santanach et al., 1996). Some gentle, minor internal progressive unconformities occur in the upper alluvial fan sequences which crop out along the Precordillera and Coastal Range basin margins. This suggests that minor reactivation of the structures previously generated took place during the sedimentation of the upper alluvial fan sequences which finally concealed the faults.

The Coastal Range alluvial fan systems gave rise to red and grey coarse-grained facies assemblages up to 300 m thick (Loa Canyon breccias), with extensive exposures visible in the Loa Canyon. These sequences consist of interbedded coarse-grained, poorly to well sorted and matrix- to clast-supported breccias and conglomeratic breccias. These deposits show a rather changing arkose- to slate-dominated clast composition, depending on whether the local source areas are igneous intrusive or metamorphic in composition. These facies assemblages were deposited by mass and stream flows in low-efficiency small alluvial fans radiating out a few km. The large thick exposures observed in the Loa Canyon show that the alluvial fan sequences are arranged into three fining upwards sequences which range from 20 to 80 m in thickness and which record successive stages of fault scarp generation and degradation.

The Precordillera alluvial fan sequences include thick (up to several hundreds metres), coarse- to fine-grained red bed sequences the upper part of which (up to 300 m) has been observed along the eastern marginal basin zones and the Loa river valley. They have been also reported in the two available oil well logs, where they are up to 400 m thick (Rieu, 1975). A striking feature of the depositional record of this alluvial fan assemblage is that one of its single genetic units seems to preserve its nearly final fan-shaped depositional surface long after becoming inactive (i.e. Arcas alluvial fan, Jensen et al., 1995; Dörr et al., 1995; Dörr, 1996). The Precordillera alluvial fan systems were more efficient than those of the Coastal Range and their contributions were widely spread over nearly the entire northern sector of the Quillagua–Llamara basin. The largest Arcas alluvial fan reached the foot of the Coastal Range during its maximum spread and radiating out to 40 km from apical to fan-toe zones (Figs. 2 and 11).

The Precordillera proximal alluvial fan facies assemblages consist of coarse-grained, boulder- to gravel-dominated conglomerate sequences with minor interbedded sandstones and red mudstones. Interbedded lenticular dune-like aeolian sands occur frequently in the upper part of the sequences. Three to four discontinuous but noticeably spread volcanic layers are also interbedded in the upper successions of these proximal alluvial sequences, where also some internal unconformities occur (Fig. 2). These marginal unconformities are spatially restricted and cannot be traced basinward. The proximal alluvial fan sequences grade laterally into medial to distal, poorly sorted fine-grained conglomerate channels, sheet sandstones and mudstones. This facies assemblage crops out extensively in the Quillagua zone where it reaches a thickness of 40 m and rapidly thins southward and westward, onlapping the basin substratum in the Coastal Range and the La Encañada threshold and interfingering with the lacustrine successions (Figs. 2 and 4).

The overall sedimentological features of the Coastal Range alluvial fan sequences suggest the dominance of flash flood deposits probably laid down during storms. Some of the depositional features in the Precordillera alluvial fan systems also suggest ephemeral water contributions, which were not so flashy as in the western alluvial fan systems. Moreover, the larger radial spread of the Precordillera alluvial fans suggests that water and

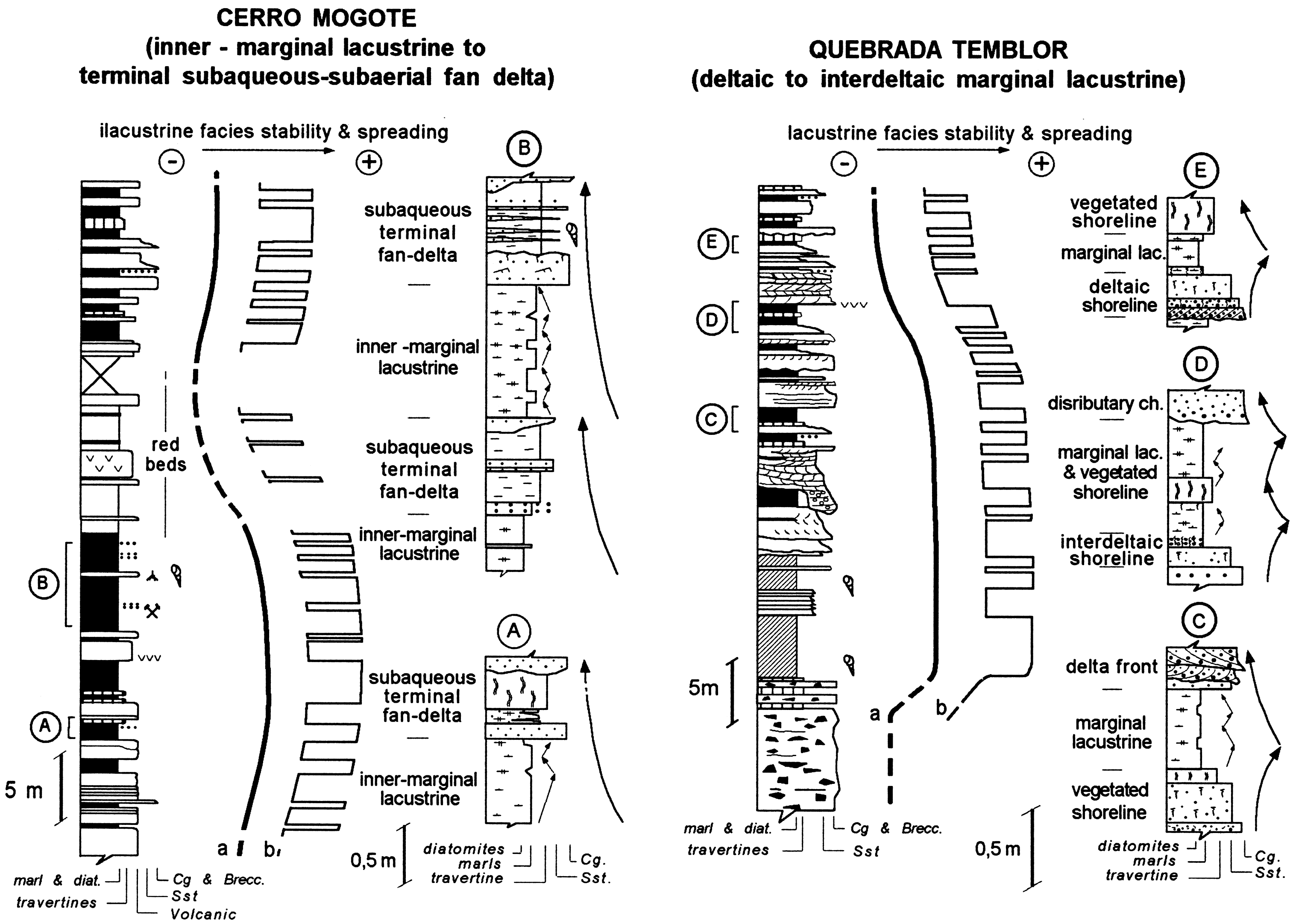


Fig. 7. Stratigraphic–sedimentological logs of the Cerro Mogote and of Quebrada Temblor sections showing low- to high-frequency sequence trends of the Quillagua Formation. Curve *a* represents 4th-order cycles of increasing–decreasing of persistence of the lacustrine conditions. Curve *b* represents the recorded transgressive–regressive 5th-order lacustrine cycles. See Figs. 1 and 2 for location and Fig. 3 for legend.

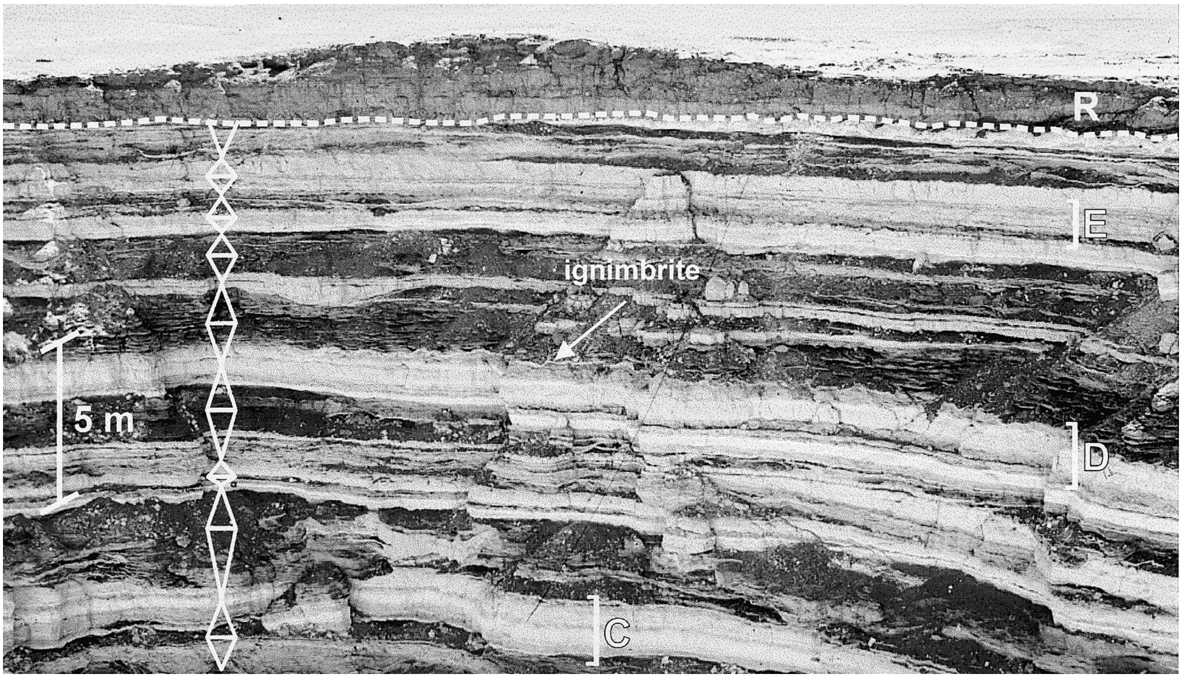


Fig. 8. Upper part of the Quillagua Formation in the Quebrada Temblor section. White area corresponds to marl, diatomites and travertine lacustrine facies. Dark dark corresponds to detritic deltaic facies. Triangles indicate 5th-order sequences. Locations in Figs. 1 and 2. Notice the rapid lateral changes of the high-frequency sequences and the stratigraphic position of sequences C, D and E in Fig. 7. *R*. = Quaternary red alluvial fan deposits.

sediment contributions from the eastern source areas were significatively larger. The position of the Precordillera Range, its greater height and larger catchment areas would have resulted in greater surface and groundwater water supply into the lacustrine zones.

The late Neogene fluvial facies are mostly related to the Quillagua Formation and crop out all along the western margin of a narrow zone which stretches from the southern end of the Quillagua–Llamara basin (i.e. Maria Elena–Puente Posada area) to the northernmost outcrops located nearby the La Encañada threshold (Figs. 1–3). The most proximal sandy and coarse-conglomerate fluvial facies related to these axial, northward-directed fluvial contributions are up to several dozen metres thick and occur along the southern basin zones (Puente Posada section, Figs. 3 and 5). The remaining middle to distal fluvial facies of this system are distributed more widely and crop out extensively. The distal–terminal fluvial assemblages grade northwards into the marginal lacustrine zones where diatomitic and carbonate marginal assemblages developed. Lateral transition into the inner lacustrine sequences of the Quillagua Formation occurs near the boundary between the southern and the northern sub-basins (Quebrada Temblor section, Fig. 3).

Both facies distribution and palaeocurrent trends of the fluvial sequences in the Quillagua Formation suggest that most of their deposits came from northward-flowing semi-perennial to ephemeral channel systems. The axial northward-spreading trend of fluvial facies along the southern basin sector suggests that water and sediment contributions were fed from extensive, higher Precordillera catchment areas (Intermediate Basin), which would have fed a larger water supply into the lacustrine systems developed in the northern sub-basin.

### 4.2. The volcanic influence

There are several laterally continuous (up to some km) tabular, stratiform volcanic and volcano-sedimentary deposits interbedded in the Quillagua–

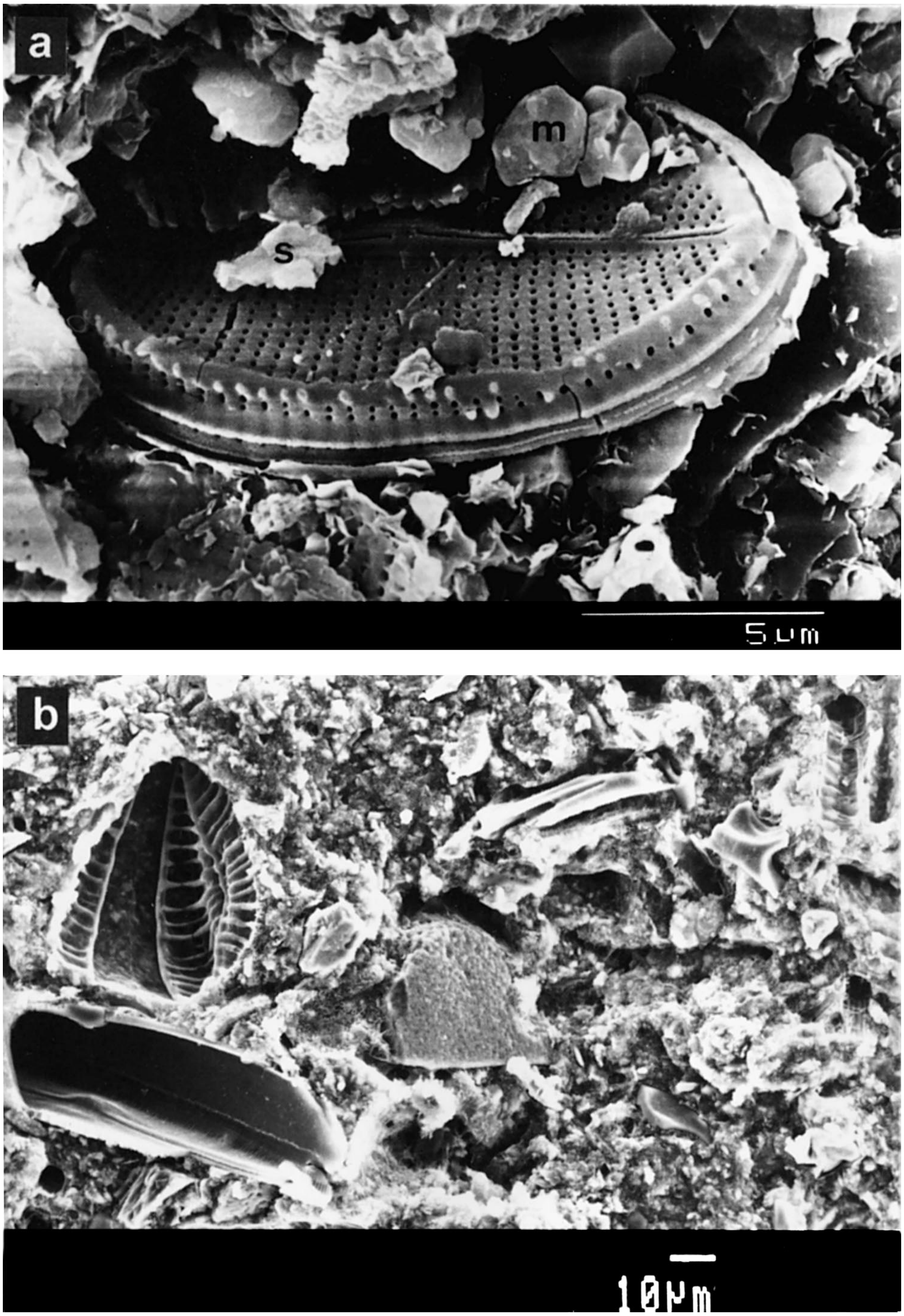


Fig. 9. (a) Smectite (*s*) and micritic calcite (*m*) crystals in diatomite facies of the Quillagua Formation. (b) Vitric volcanic shards in the diatomitic lacustrine facies of the Quillagua Formation.

Llamara successions, which are good local to regional key beds. These deposits are the product of pyroclastic flows (ignimbrites) and falls and their equivalents reworked in the lacustrine environment. The pyroclastic falls are coarse to fine ash tuffs that can be classified as vitric tuffs and ashes and, since they are fragmentary, as vitric-crystal tuffs and ashes. The degree of weathering is low to null, and therefore most of these lithofacies are friable and can be considered in a broad sense as tephra. In spite of this, the pristine characteristics of the deposits were frequently modified, leading to bentonitization or carbonation of the glass fragments; often, too, interstitial cement hardened the rock.

Clear pyroclastic and epiclastic textures can be observed under the microscope (selective concentration of crystal fragments, cross-lamination, etc.). The glass fragments are mainly minute shards, sometimes tightly packed and with delicate gradations in grain size. These textures look like pristine fall ones, and are interpreted as such. The pumice fragments are less abundant, and generally below lapilli size (coarse ash). These fragments are mostly vesiculated, showing sometimes some degree of flattening of the vesicles (and of the fragments themselves). The arrangement of pumice clasts enables hot, insitu deformation to be excluded. Quartz, plagioclase, biotite and, to a lesser extent, amphibole and alkali feldspar occur between the crystal fragments in most lithofacies. Therefore, the mineral composition suggests that some of those deposits are dacitic to quartz-andesitic. Nevertheless, it must be kept in mind that most of the rock consist of glassy fragments and can be noticeably more silicic than the crystal content (e.g. rhyolitic in composition). The origin and meaning of these ignimbrite layers should be seen in the context of the Late Miocene evolution of the Central Volcanic Zone of the Andes, which extends from 14º to 28ºS and has been active since the Late Miocene (10.4 Ma) up to the Recent (De Silva, 1989; De Silva and Francis, 1989). The spread of ignimbrites from their original volcanic focuses was conditioned by the pre-existing topography (Guest, 1969). In Miocene–Pliocene times the reliefs of the Precordillera normally acted as barriers to the pyroclastic flows coming from the east. Nevertheless, some of these flowed over the Precordillera Range and reached the eastern parts of the Quillagua–Llamara basin. Volcanic processes in the volcanic arc region are often recorded in the fore-arc depositional record with the development of widespread pyroclastic and epiclastic deposits which in some cases attain large areal spreading even from very distant volcanic focuses. Some punctual pyroclastic episodes may be significant as potential keys to establish a correlation between arc and fore-arc evolution but they do not seem to have resulted in dramatic modifications of the fore-arc depositional framework.

### *4.3. The lacustrine episodes*

Three major late Neogene (Miocene–Pliocene) lacustrine episodes can be distinguished in the Quillagua–Llamara region.

(1) The Lower Unit–Subunit B lacustrine episode which includes among others the ephemeral, saline playa-lake sequences of the Hilaricos anhydrite, and evaporite- and diatomite-bearing subsurface successions. The whole lacustrine episode was provably Miocene and developed between the early settling and spreading of the lacustrine zones in the northern basin sector and the widespread progradation of the Precordillera alluvial fans, which caused the obliteration of the evaporite zones (Figs. 2 and 11b).

(2) The Lower Unit–Subunit C lacustrine record including the fluvial and perennial lacustrine sequences of the Quillagua Formation and the Puente Posada Unit (Late Miocene–Early Pliocene?). This lacustrine episode took place after significant pyroclastic layers were deposited in the basin. This is the best known lacustrine episode in the region with the largest facies variety and a lot of outcropping sequences (Figs. 2 and 11c,d).

(3) The Upper Unit playa and playa-lake record of the Soledad Formation (Pliocene–Pleistocene?). The lacustrine sequences related to this episode overlie a tectonic unconformity which records changing depositional gradients and regional drainage. The evolution of this lacustrine stage was characterized by a spreading of the depositional zones and the clear connection between the Quillagua–Llamara basin and other neighbouring depocentres (e.g. Salar Grande, Figs. 2 and 11e).

The amount of information available on these well-distinguished lacustrine stages is diverse, due to the changing quality and extent of the exposures and the variety of facies in the lacustrine zones. However, it is possible to define their most significant general features and establish some comparison between the ephemeral, saline–evaporitic systems and the perennial oligohaline systems.

## 5. The evaporite lacustrine record

### *5.1. Lower Unit lacustrine evaporites (Subunit B)*

The outcrops of the evaporite lacustrine sequences deposited during the early evolutionary stages of the basin (Subunit B) are only found in the upper part of the succession and near the Hilaricos anhydrite. Nevertheless the available oil well data (Hilaricos, Fig. 1) show that up to 450 m thick evaporite-bearing sequences occur in this unit (Rieu, 1975) and suggest that the main depocentre of lacustrine evaporites during the earlier basin evolutionary stages was located around the Lomas de la Sal area (Figs. 2 and 11b). Thus, during the lacustrine episodes linked to Subunit B, evaporite-dominated facies were deposited mainly in the southern part of the southern subbasin, in the marginal, peripheral evaporitic fringes of a perennial, likely saline lake located more to the north and where carbonate and diatomite sedimentation took place (Fig. 11c,d). Sulphate evaporites became dominant and more widespread in the upper part of this Subunit B, leading to the deposition of the Hilaricos anhydrite.

The Hilaricos anhydrite crops out in the northern basin sector in the Loa valley exposures and to a lesser extent, in Cerro Hilaricos and Lomas de la Sal, with a thickness ranging from 11 up to 20 m. From these northern basin areas, the anhydrite successions thin westward and southward, onlap the regional basement along the western basin margin in the Coastal Range (Figs. 2 and 4) and may reach the La Encañada threshold (Figs. 2 and 3). This unit is often detected in the subsurface thanks to the collapsed dolines which affect the overlying Quillagua Formation sequences.

This unit is composed mainly of laterally extensive anhydrite beds interbedded with red mudstones and pyroclastic and epiclastic beds which are more frequent in the eastern basin sectors closer to the Precordillera (Fig. 6). The interbedded red mudstones and lithic, epiclastic wackes and sandstones indicate rapid and repeated progradation of the terminal alluvial fan zones fed from the Precordillera and Coastal Range and which surrounded the playa and playa-lake zones. That interbedded volcanoclastic beds were more frequent in the anhydrite successions than in the coeval alluvial-dominated assemblages suggests that volcanoclastic deposits were preserved better in lacustrine–palustrine zones sheltered from terrigenous contributions. In the Quillagua village area near the Loa valley (Figs. 1 and 2) the anhydrite beds are predominantly white and display diagenetic massive and nodular (chicken-wire) facies. However, some decimetres-thick, shallowing-upward playa-lake sequences occur in the Hilaricos zone (Fig. 6). The most simple of these sequences consists of anhydrite beds topped by desiccation cracks and vertical, root-like traces filled by anhydrite intraclasts in a red mudstone matrix. More complex playa-lake sequences display four main lithological terms: (a) laminated anhydrite, (b) selenitic in-situ growing crystals, (c) nodular anhydrite supported in red mudstone matrix, and (d) red mudstones. Some of these anhydrite sequences show their tops partially brecciated or affected by dissolution caused probably by later influence of diluted flows (Fig. 6).

Anhydrite sequences of the Hilaricos unit record the sedimentation in playa-lake environments ranging from subaqueous to vadose and subaerial zones. These lacustrine assemblages were deposited between the terminal fringes of the alluvial fan systems rooted in the Precordillera and in the Coastal Range and record the development of sulphate-dominated playas and playa-lakes. The recorded lateral facies relationships between the alluvial fan successions and the lacustrine evaporites suggest that the water and solute feeding of the ephemeral–saline lakes were largely dependent on these surrounding Precordillera and Coastal Cordillera fan systems. No traces of significant water and sediment contributions from other catchment areas have been detected. (Fig. 11b).

The smaller-scale sequence arrangement of the lacustrine record in the Hilaricos anhydrite (Fig. 6) shows the spreading and retreat of the subaqueous ephemeral lacustrine zones, and the influence exerted by the terminal alluvial fan facies. The sequences observed could be the result either of shallow lake level changes or of autogenic evolution (i.e. sediment infill, progradation–retrogradation and lateral shifts of the terminal fan zones which spread into the lacustrine zones). Some especially noticeable erosive surfaces related to entrenched channels or dissolution could be due to incisions forced by lacustrine water-level drops and changes in the water solute concentration.

### *5.2. Upper Unit lacustrine evaporites (Soledad Formation)*

Saline deposits of the Soledad Formation (Bobenrieth, 1979) are the uppermost, non-terraced Neogene lacustrine sediments recorded in the Quillagua–Llamara Basin (Fig. 2). The halite- and sulphate-dominated sequences of this unit only occur in the northern basin sector, which also includes the uppermost saline deposits in the Salar Grande area (Chong et al., 1999). Pyroclastic and epiclastic, volcanic lithofacies also occur in the sequences studied in the Quillagua–Llamara basin (Figs. 2 and 10). The thickest sections of the Soledad Formation were formed in Cerro Soledad and in Lomas de la Sal, where they reach at least 100 m. A low halite member (about 80 m thick) and an upper, much more extensive sulphate–halite member can be distinguished. The lower halite member crops out widely in Lomas de la Sal where it has been intermittently mined. The upper sulphate–halite member crops out along the western and northern basin margins, reaching the Salar Grande basin margins (Figs. 1 and 11e). All the evaporite successions of the Soledad Formation in the Quillagua–Llamara Basin display early diagenetic textures which show that these deposits were intensively diagenised under vadose conditions. This caused massive displacive playa halite facies, whereas subaqueously generated facies did not form (Fig. 10). Only in the neighbouring Salar Grande basin do chevron-like crystals and other features of outcropping upper halite deposits prove subaqueous sedimentation in very shallow saline lakes (Cabrera et al., 1995; Chong et al., 1999).

According to Brüggen (1950), the saline lacustrine sequences of the Soledad Formation (i.e. the evaporite sequences in the Quillagua–Llamara zone and in the Salar Grande halite-dominated sequence)

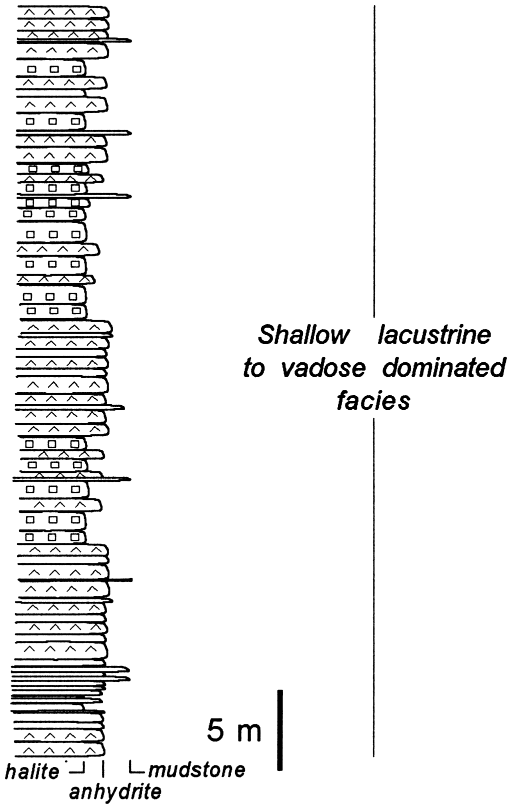


Fig. 10. Sedimentological log of Soledad Formation in the Cerro Soledad area (northern sector of Quillagua–Llamara basin). Detailed facies observation is prevented by recent dissolution processes. See Figs. 1 and 2 for locations.

mark the existence during the early Quaternary of a deep, perennial saline palaeolake. On the basis of some stepped lineaments recorded in the Cerro Soledad zone and which involve the Soledad Formation deposits, Brüggen (1950) also suggested the existence of abandoned lacustrine shorelines which would have developed during successive water level drops of the perennial saline lake, which would have attained a water depth of up to 80 m. Other authors (Hollingworth, 1964; Stoertz and Ericksen, 1974) accepted this idea and even increased the estimated depth to 200 m. Later contributions (Rieu, 1975) nuanced that the stepped arrangement could have been caused by the activity of normal faults. Moreover, the sedimentological and early diagenetic features of the facies which make up the evaporite sequences in the Soledad Formation do not support the hypothesis of a deep, perennial saline lake. Any interpretation of the observed morphological features has to take into account the persistently shallow, ephemeral character of the lacustrine zones. Thus, tectonic stepping (Rieu, 1975) and/or erosive terracing of the previously deposited Soledad evaporites during the late erosive stages of the basin are the most likely explanation for the morphologies observed. In any case, the highest topographical position of the evaporite deposits of the Soledad Formation records the highest infill level attained in the basin during the closed-drainage evolutionary stages of the basin.

The large area reached by the Soledad Formation sequences (Fig. 11e) in the Quillagua–Llamara and Salar Grande basins culminates the spreading trend of sedimentation in this fore-arc region, since lacustrine depositional zones were more extensive than in previous episodes (Fig. 11b–d). The halite–anhydrite dominated sequences record sedimentation in shallow playa-lake environments ranging from subaqueous to vadose and subaerial zones. In the Quillagua–Llamara basin these lacustrine assemblages were deposited in a belt between the terminal fringes of alluvial fans draining the Precordillera and Coastal ranges. The water and solute feeding of these lacustrine systems seems to have been again dependent mostly on these surrounding fan systems; there is no evidence of water and sediment contributions from the southern basin. In the Salar Grande basin the playa and playa-lake successions received surface water and solutes from the Quillagua–Llamara zone (Chong Diaz et al., 1999).

### *5.3. Meaning of the evaporite lacustrine assemblages*

The distribution of the evaporite lacustrine facies assemblages in the Quillagua–Llamara zone during the sedimentation of the Lower and Upper Units shows that, although the area distribution of the ephemeral playas and playa-lakes clearly increased, the lacustrine zones were always restricted to the northern subbasin (Fig. 11b,e). The Late Miocene Hilaricos anhydrite and the Pliocene–Pleistocene (?) Soledad Formation were deposited in extensive (up to 1300 and 2000 $km^2$, respectively) shallow playa and playa-lake systems (Fig. 11b,e) which only occasionally included steady, shallow open water. This considerable area correlates well with both the westward increase of the depositional zones and the coeval Precordillera alluvial fan shrinkage.

Among other late Neogene lacustrine units the evaporite assemblages of the Hilaricos anhydrite and the Soledad Formation are clear examples of the widespread ancient ephemeral, saline–evaporitic lakes in the region. They clearly show negative water balances over an extensive region whose hydrology was probably determined by a low to very low local surface runoff which was not compensated by surface or groundwater inflow from neighbouring or more distant high zones. If it is so, it must be emphasised that the expansion of the evaporite lacustrine zones was coeval to the retrogradation of the Precordillera alluvial fans.

The widespread dominance of shallow subaqueous to vadose facies in the evaporite deposits of the ephemeral–saline lakes in this region has important consequences, since it means that the water input and accumulation in the Quillagua–Llamara basin during long time spans of the late Neogene was just enough to keep place with subsidence. Thus for the Pliocene–Pleistocene (?), when the Soledad Formation was deposited, this water income was significantly lower than previously hypothesized (Brüggen, 1950; Hollingworth, 1964).

## 6. Perennial lacustrine record

Well developed perennial lacustrine facies assemblages occur in the Lower Unit (Subunits B and C, Figs. 2 and 11c,d), as is shown by subsurface data and the successions recorded in the Quillagua Formation and Puente Posada Unit (Figs. 2 and 3). The N–S-oriented Loa river valley provides over more than 100 km near-continuous exposures of the Quillagua Formation sequences (Figs. 1 and 4). Moreover, in the Cerro Mogote section (northern sector) the lacustrine successions reach up to 65 m in preserved thickness. In the southern basin zones, the Quillagua Formation becomes fluvial-dominated and passes laterally to the Puente Posada Limestone Unit (Figs. 2 and 3). The area of the carbonate-dominated sequences of the Puente Posada Unit in the study zone is not precisely known, but their exposures are restricted to the southernmost end of the basin (Figs. 1–3). Six major facies assemblages have been distinguished in the deposits interpreted as lacustrine and fluvial–lacustrine on the basis of their lithological features, thickness, geometry, sequential arrangement and floral and faunal contents.

### *6.1. Shallow lacustrine–palustrine carbonate assemblage*

This carbonate-dominated assemblage of the Puente Posada Unit overlies the lowermost red scree and alluvial fan deposits which onlap the basement in the southern basin sector and pass laterally northward into the diatomite-bearing facies of the lower Quillagua Formation (Figs. 2 and 3). This limestone-dominated assemblage is laterally spreading westward and interfingering with the Quillagua Formation sequences of the carbonate-dominated El Loa Formation which was deposited in the neighbouring Calama Basin (Naranjo and Paskoff, 1981; May et al., 1999), but no physical continuity has been established to date between the two units. The succession studied is up to 12 m thick and made up mainly of cm to dm thick limestone and minor interbedded sandstones and green-grey mudstones (Fig. 3). Limestone is mostly sandy biomicrites (mudstones–packstones) with minor bioclastic gastropod shell accumulation. They show typical shallow lacustrine and palustrine sedimentary and early diagenetic features. The top of this unit is partially incised by fluvial palaeochannel sandstones of the Quillagua Formation. The upper part of the limestone packet is irregularly brecciated and karstified, and shows dissolution porosity ranging from small vugs to larger caverns filled by green mudstone. This facies assemblage records deposition in shallow, carbonate-dominated lacustrine–palustrine zones, in floodplains sheltered from active channel zones. The sequential relationships observed between this carbonate-dominated unit and the overlying channel-dominated facies record the shift or spreading of these fluvial active channel zones into the lacustrine–palustrine floodplains (Fig. 3).

### *6.2. Intraclastic lacustrine breccia assemblage*

A widespread breccia-dominated facies assemblage occurs in the northern basin sector along the eastern Loa riverside in the lower part of the Quillagua Formation (Fig. 3). The breccias are whitish, very poorly cemented and make up lenticular bodies several kilometres wide and up to 15 m thick. They range from massive to well-stratified and show large internal erosional surfaces. Single beds in the stratified breccia bodies are sheet-like to lenticular with their thickness ranging from a few centimetres to 0.5 m. The breccias are poorly sorted, polymodal, range from clast- to matrix-supported and include boulder- to gravel-sized, angular to sub-angular clasts composed of volcanics, lacustrine marls and diatomites which vary from centimetres to decimetres in size and are often silicified. The matrix is marly with variable amounts of volcanic epiclastic particles and includes a mixed diatomite assemblage, which comes from the reworking of the lacustrine materials. No significant terrigenous, extrabasinal contributions are recorded in these deposits, but some clastic contributions from the neighbouring ranges cannot be ruled out.

This breccia assemblage is the consequence of erosion and cannibalistic reworking by mass flows or highly concentrated flows of partly lithified pyroclastic, epiclastic and lacustrine deposits occurring in marginal lacustrine zones. This cannibalistic, intrabasinal reworking was subsequent to the prior accumulation and consolidation of pyroclastic and epiclastic deposits which entered the lacustrine system through major volcanic activity. The gradual upwards transition between these breccias and the overlying lacustrine sequences suggests that their deposition took place during the early stages of development of the Quillagua lacustrine depositional framework. They may reflect the reworking and redeposition of marginal lacustrine deposits in inner lake zones due to tectonic destabilization of the lake bottom floor or to storm-generated flood events.

### *6.3. Inner-marginal lacustrine facies assemblage*

The inner-marginal lacustrine facies consist of sequences up to 7 m thick of massive to poorly laminated, white to very pale brown marls, diatomaceous marls and diatomite beds. This assemblage is well recorded in the middle part of the Cerro Mogote section (Fig. 7).

Both marls and diatomaceous marls make up tabular to gently lenticular beds (tens to hundreds of metres in length) up to 0.5 m thick. These are massive or thinly laminated and are quite often connected to pure diatomite beds. Whitish to yellowish diatomitic marls often include thin, millimetre-thick lenses or pure diatomite. They often gradually grade upwards into purer white-diatomite beds which are up to a few decimetres thick. The optical microscope analysis shows pelloidal micritic aggregates (0.05 to 0.1 mm), rounded pumice grains (0.1 mm in diameter) often altered to smectite and scattered fragmented diatom frustules, charophytes, disarticulated ostracod valves and gastropod remains (Fig. 9a). Minor quartz, feldspar and volcanic vitric shards are also frequent components (Fig. 9b). The scanning microscope shows that most of the clay grains are associated with vesicular volcanic particles (20 mm), whereas the ostracods are sometimes micritized. Widespread microsparitic and micritic cements occur, forming euhedric–subeuhedric crystals of calcite reaching up to 6 mm at maximum.

Pure diatomites form lenticular and decimetre-thick tabular beds which attain at least a hectometre in lateral extension. They are white, soft and very porous although some of them are silicified and are associated with decimetre- to centimetre-scale chert nodules. Diatom frustules can be well-preserved but they are often rather fragmented. Microsparitic and micritic calcitic cements, together with minor quartz cement precipitation, are also found. Preliminary data from diatom assemblages found in these facies record widespread oligohaline–mesohaline conditions in lake waters. Nevertheless they also suggest rapid changes of bathimetry and salinity both in the single diatomite beds and in the whole vertical section (Servant Vildary in Jensen, 1992; Bao et al., work in progress). These diatomite-dominated facies record subaqueous, perennial, inner-marginal lacustrine conditions with terrigenous contributions ranging from negligible to noticeable. The overall taxonomical composition of the diatom flora and the absence of well-preserved lamination in these inner facies suggest that these lacustrine zones were rather shallow (no more than a few metres deep) and non-stratified, with holomictic conditions dominant.

### *6.4. Deltaic lacustrine facies*

A 40-m-thick sequence of deltaic marginal lacustrine facies occurs in the Quebrada Temblor section in the southern area of the Northern Basin sector (Figs. 3, 7 and 8). This assemblage is characterised by an interbedding of subaqueous marginal interdeltaic lacustrine facies (marls, diatomaceous marls, diatomites and travertines) and prodelta and delta front channelled facies, which alternate with a clear and marked sequential arrangement forming decimetre- to metre-thick sequences. The deltaic facies assemblage passes laterally northward into inner lacustrine facies dominated by finer-grained and diatomitic deposits.

Prodelta facies are characterized by well-laminated intervals of sub-millimetre- to millimetre-thick rhythmites consisting of a diatomite silty lamina with biotite grains which is overlain by a clay diatom-bearing episode. These deposits are turbidite-like and probably record sedimentation from underflow currents active during fluvial flood episodes. Diatom frustules may be well-preserved, but are often rather fragmented.

Lenticular coarse-grained conglomerate and sandstone channel infills are well recorded in the lacustrine delta front deposits. Channel infill bodies are up to several metres thick and several tens of metres wide in a transverse section, with a high width to height ratio. They are mainly shallow ribbon-like bodies with vertical monostorey to multistorey infill and erosional bottom surfaces which are from gently to deeply incised. The coarse-grained bodies mainly consist of gravelly sands and poorly cemented conglomerates. Each is bounded by erosional surfaces and usually has a fining-upwards trend. Laterally extensive trough-cross-bedding sets up to 10 cm high make up the upper infill of channel cores and lateral wings which display sigmoid cross-bedding. The coeval occurrence of several channel bodies at the same level, their vertical infilling and significant entrenchment suggest that the channel patterns were probably anastomosing. Cross-stratification data point to northward palaeocurrent trends and the scour directions observed at the channel bottoms are coherent. These palaeocurrent trends point to the fact that the deltaic facies were the result of the northward spread into the lacustrine zones of the fluvial system which parallels the basin axis.

Thin sheet-like sands and fine-gravel facies occur frequently in the Quebrada Temblor section and consist of dark grey to brown fine gravels and cross-laminated sands with a clast composition spectrum dominated by volcanic clasts and grains. Minor whitish silicified marl clasts also occur. These deposits are up to a few decimetres thick and are mainly sheet-like to gently lenticular in shape with a lateral range of tens to hundreds of metres. Root traces infilled by finer marly material occur at the tops of this coarse, sheet-like sandstone term. This facies records the deposition of subaerial to shallow subaqueous small-scale terrigenous lobes at the mouth of the fluvial channel. The shallow subaqueous conditions favoured their quite widespread colonization by marginal palustrine vegetation.

### 6.5. Littoral interdeltaic lacustrine facies

This facies assemblage is characterized by carbonate macrophyte travertines, sands, intraclastic microbreccias and epiclastic volcanic beds with minor thin interbedding of diatomites and diatomitic marls. These facies make up more or less symmetrical, deepening–shallowing-upwards lacustrine sequences. Upwards transitions from whitish to yellowish diatomitic and sandy marls to purer white diatomites are often observed. These pure diatomitic facies intervals may display sedimentary and palaeontological features similar to those of the inner lacustrine facies. Nevertheless, clastic coarse terrigenous and epiclastic volcanic contributions are more frequent in these subaqueous fine-grained and biogenic beds, which causes layers to be thinner (up to several decimetres thick) and narrower (up to some hundred metres) than in the inner marginal lacustrine assemblage. Moreover, frequent root traces at the top of the marl and marly diatomitic beds point to deposition in very shallow lacustrine zones (Fig. 7C–E, Fig. 8).

Travertine layers may be sometimes embedded in sandy, intraclastic marls (Fig. 7E, Fig. 8). They are grey, lenticular, up to a few decimetres thick and consist of small carbonate tubules up to 0.8 mm in diameter and a few centimetres long, which tend to occur in a vertical position and occasionally display bothrioidal textures and vug porosity. Only calcite is present in this facies which shows a very porous clotty microfacies. Some intraclasts can also be coated with calcite–micrite laminae. This travertine facies records the development of a marginal zone of vegetation which encroached on marginal lacustrine zones and probably suggests shallowing of the water column.

Intraclastic microbreccias also occur and consist of massive to nodular grey sandy and marly intraclastic beds, which display an upward increase in the fine-matrix percentage. Microbreccias are almost unconsolidated, forming gently lenticular layers, cm to dm thick and tens of metres wide. Marl intraclasts make up most of the microbreccia framework together with volcanic pumice and ash clasts. Gastropod bioclastic lenses and accumulations of fragmented travertine carbonate tubules are associated with this facies. Vertically arranged root traces, which often are infilled by marly sediment, also occur. This facies records the action of tractive currents which eroded and reworked marginal lacustrine zones, producing mixed intraclastic, bioclastic and clastic primary deposits later affected by plant rooting in shoreline or shallow marginal lacustrine–palustrine zones.

### 6.6. Terminal lacustrine fan-delta assemblage

Thin sheet-like to gently lenticular, up to a few decimetres thick, dark grey to brown fine gravels and ripple cross-laminated sands and silts occur in some of the sequences studied (e.g. A and B in the Cerro Mogote section, Fig. 7). The lateral extent of these layers ranges from tens to hundreds of metres. They were deposited in terminal fan–marginal lacustrine zones. These coarse-grained deposits are dominated by igneous terrigenous contributions and epiclastic clasts. Root traces infilled by overlying very fine marly material are often recorded at the top of these coarse-grained beds. This facies assemblage was deposited in subaerial to subaqueous small-scale terrigenous lobes developed in the terminal, frontal parts of alluvial fans. The top of some of these coarse-grained lobes was colonized by marginal palustrine vegetation, which suggests rather shallow environmental conditions for these deposits. Predominantly fine-grained red sandstones and mudstones usually overlie these thin subaqueous fan-delta assemblages and record the progradation of the terminal subaerial fan-delta zones over the shallow subaqueous lacustrine zones (Fig. 7B).

### 6.7. Meaning of the perennial lacustrine assemblages

The distribution during the sedimentation of Subunit C (Lower Unit) of the perennial lacustrine facies assemblages which can be seem in the Quillagua–Llamara zone, enables two major depositional zones to be distinguished (Fig. 11c,d).

(1) Zone of fluvial bypass and water and sediment transference all along the southern sub-basin. Fluvial and fluvial–lacustrine diatomite-bearing successions were deposited where the influence of fluvial contributions was dominant, whereas lacustrine–palustrine carbonate zones developed in zones sheltered from terrigenous contributions.

(2) Main, extensive lacustrine zones developed in the northern sub-basin. Deltas and fan-deltas developed at the head of the terminal fluvial and alluvial-fan systems, whereas interdeltaic and inner open lacustrine diatomite-dominated sequences developed in other marginal and central zones of the sub-basin.

The sequence arrangement of the lacustrine record in the Quillagua Formation enables the settling and pulsating expansion and retreat of the Late Miocene–Pliocene lacustrine system to be visualized. Two low-order (3rd order, see review by Einsele et al., 1991) expansive–retractive lacustrine alluvial sequences can be observed in the Cerro Mogote succession and illustrate the overall evolution of the palaeolake system (Fig. 7). These low-order sequences were, in this case, the consequence of interaction between the lacustrine depocentres and the areally restricted alluvial fans, which spread from the Coastal Range basin margin. They split into minor, higher-order (4th to 5th order) transgressive/regressive sequences which record minor progradations and retrogradations of the terminal fan delta and/or oscillations of the water level.

An overall trend of early lacustrine spreading and later retreat is also recorded in the deltaic-dominated Quebrada Temblor section (Figs. 3, 7 and 8). This overall trend can be again split into lower-order (4th to 5th order) transgressive–regressive sequences probably driven by processes similar to those described for the Cerro Mogote. Therefore, the observed sequences could result either from lake level changes or from the autogenic evolution (i.e. progradation–retrogradation and lateral shifting) of the deltaic system which impinged on the lacustrine zones. Some especially noticeable erosional surfaces related to deeply entrenched channels might be related to forced regressions linked to falls in lake water level, but no conclusive evidence has been found. Depending on sediment influx variations, some of the observed regressive progradational sequences could in fact develop under both highstand and lake-level fall conditions.

The lacustrine assemblages of the Quillagua Formation were deposited under perennial conditions which made them rather different from the more widespread ancient and recent ephemeral evaporitic systems in the region (Chong, 1988). Therefore this perennial lacustrine record is an interesting element of contrast with other ancient and recent, ephemeral, evaporitic lacustrine systems in the region. The Late Miocene–Early Pliocene (?) Quillagua system was an extensive (up to 2000 $km^2$), shallow (mostly a few metres deep), low- to intermediate-altitude holomictic lake (Fig. 11c,d). Unlike most former and later lacustrine systems in the region, the Quillagua lacustrine system included a steady open waterbody whose hydrology was determined by a low to very low local surface runoff which could be compensated by surface and groundwater inflow from neighbouring or more distant high-altitude zones. The clear predominance of oligohalobe to mesohalobe diatom species suggests that the lake waters were mainly fresh to moderately saline, and partially confirms evaporative water concentration though this did not attain high enough concentrations to lead to either the widespread development of diatom assemblages characteristic of high saline concentrations or the deposition of evaporites. It is not possible to establish for sure whether the perennial lacustrine zones were hydrologically closed systems. The non-occurrence of evaporite facies suggests either generally open conditions or a balance between water income and evaporation.

## 7. Sedimentary and palaeogeographic evolution in the Quillagua–Llamara basin

With the above-described tectonosedimentary features in the basin and the observed depositional changes taken into account, the following five major palaeogeographic evolutionary stages can be established in this Central Andes zone (Fig. 11).

### 7.1. Stage 1

The main phase of extensional fault activity in the region probably took place in the Oligocene–Early Miocene (?) and led to the activity of the N–S major normal faults (Precordillera fault system) and of other NW–SE-oriented faults. Normal movement along these faults defined the basin margins along the Precordillera and the Coastal Range, resulted in broad basin asymmetry and gave rise to two main sub-basins (northern and southern, Fig. 11a). A main depocentre developed in the northern sub-basin sector and lasted around the Lomas de la Sal Area during successive evolutionary stages. The resulting tectonic palaeorelief in the area includes several substratum inselbergs (e.g. Cerro Soledad, Cerro Mogote, Cerro Hilaricos, Encañada Range) that were onlapped by the basin infill. One of these highs (Encañada Range) acted as a threshold separating the southern and northern sub-basins. The erosion of the tectonic relief and the degradation of fault scarps led to the deposition of coarse scree breccias and of a first generation of alluvial systems in the northern sector of the basin (Lower Unit, Subunit A). No lacustrine deposits during this evolutionary stage have been found.

### 7.2. Stage 2

This stage was characterized by the progressive vanishing of the activity of the faults bounding the basin, which became supratenuated, and the resulting onlap of the earlier basin margins by the Lower Unit (i.e. Subunit B) deposits. Oil well data indicate that lacustrine sedimentation began with the development of both perennial saline lakes with diatomite deposition (northern parts of the northern subbasin; Fig. 11b) and ephemeral playas and playa-lakes (in the central zones of the northern basin sector and southern parts of the southern basin sector). These lacustrine zones were closed and received water and sediment contributions mostly from the Precordillera alluvial fans. After an early areally restricted development, these lacustrine zones expanded, as demonstrated in the eastern basin zones and in the western basin margins; Fig. 2). This spreading of the lacustrine zones culminated in the Late Miocene ($6.0 \pm 0.4$ Ma, Figs. 2 and 3) with the sedimentation of the uppermost playa-lake episode recorded in Subunit B (Hilaricos anhydrite, Fig. 2) which was coeval with a retrogradation of the Precordillera alluvial fans. The maximum area of the lacustrine system was about 1000 $km^2$. The lacustrine zones were bounded by the Precordilleran distal alluvial fan environments, and to the west and south by the colluvial and alluvial systems along the western basin margin and to the south of the Encañada Range. Although no major volcanoclastic influences have been recorded in this stage the volcanoclastic beds interbedded in the anhydrite-dominated successions outline the importance of the active Western Cordillera volcanic focuses.

At the end of stage 2, between $6.0 \pm 0.4$ and $5.8 \pm 0.4$ Ma, a major progradational episode of the Precordillera alluvial fans took place (Fig. 2). The evaporitic areas shrank dramatically or disappeared completely.

### 7.3. Stage 3

During the Late Miocene new lacustrine environments expanded southward to 23ºS from the northern basin depocentre. This major perennial lacustrine episode was preceded by the emplacement of an extensive ignimbrite layer and was characterized by early intrabasinal cannibalistic erosive episodes which resulted in the local to sectorial reworking of pyroclastic and lacustrine deposits. Interbedded volcanoclastic beds frequently occur in the overlying lacustrine sequences. All this suggests volcanic activity in the volcanic arc region before and during lacustrine sedimentation. Carbonate and siliceous biogenic deposits and terrigenous facies were deposited in this perennial, mostly fresh-to-oligohaline water system. The evolution of the area of the lacustrine zones, the relation of carbonate to biogenic siliceous facies, and the changing importance of the fluvial and deltaic lacustrine, led us to distinguish two successive palaeogeographic settings during this stage. During the earlier episodes shallow lacustrine carbonates (Puente Posada unit, Figs. 2, 3 and 11c) accumulated in the southernmost basin zones. These zones received water contributions and were crossed by a non-hierarchised fluvial system draining large areas of the Precordillera Range. This fluvial system flowed northward more or less parallel to the

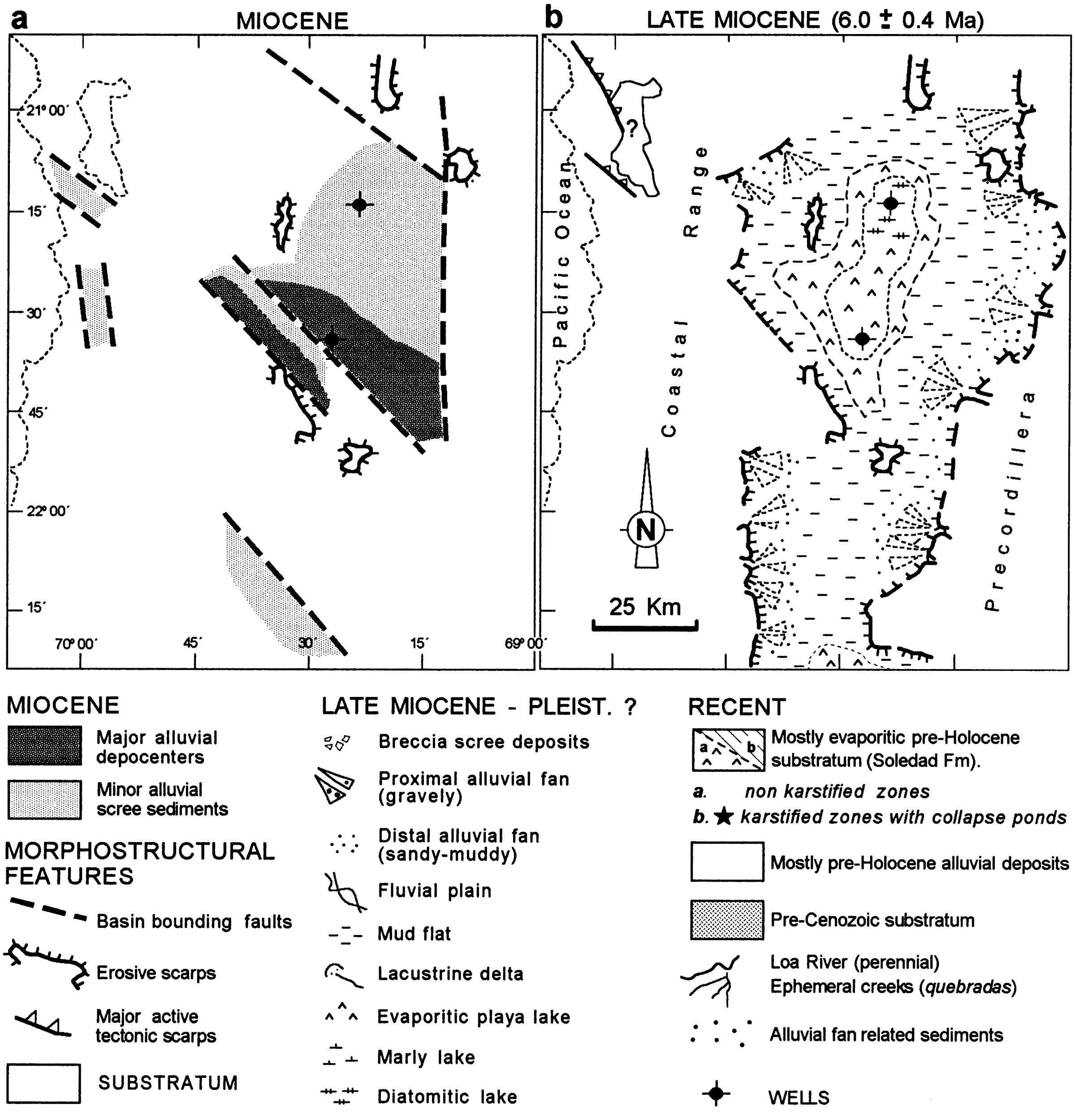


Fig. 11. Main late Neogene evolutionary stages of the Quillagua–Llamara basin area between 21°45′ and 22°15′S. Note the change from ephemeral playa-lake (recorded in Hilaricos anhydrite and Batea Formation evaporites, map b (stage 2)) to perennial, shallow lacustrine conditions (recorded by the Quillagua Formation diatomitic sequences, maps c and d (stage 3)) and from there again to ephemeral playa-lake and playa environments (recorded by Soledad Formation evaporites, map e (stage 4)). The current situation stage is shown in map f (stage 5). Note the important effects of the opening of the Loa River to the Pacific Ocean.

basin axis and the channelled parts graded laterally into flood-plain and lacustrine zones where biogenic silica accumulation was significant. Eventually the fluvial channels crossed the former Encañada threshold, bringing water and terrigenous input to the northern lacustrine basin and deposited fluvial-domi-

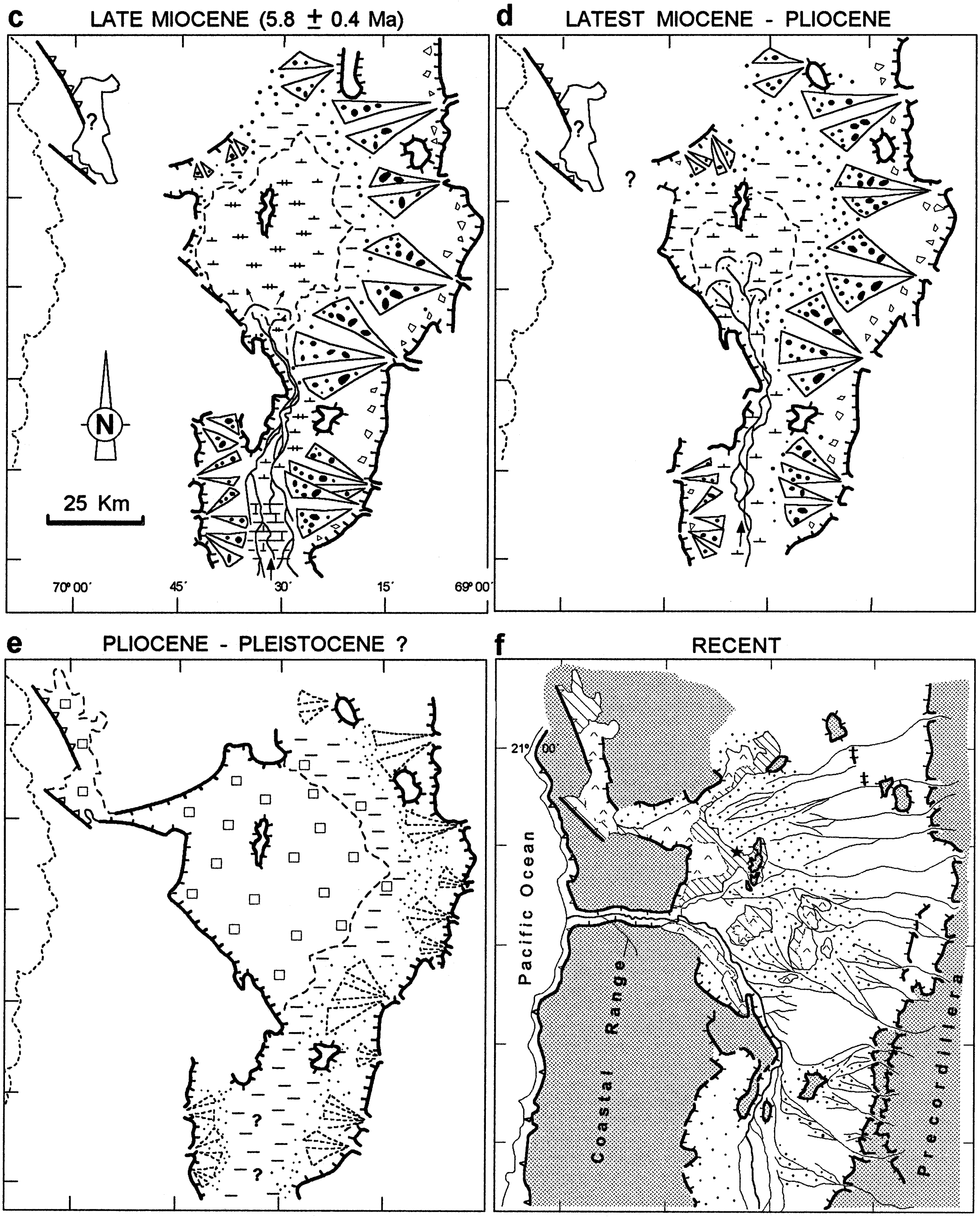


Fig. 11 (continued).

nated deltas. The passage from deltaic to inner lacustrine zones is recorded in the facies assemblages at the lower part of the Quillagua Formation. The lake was surrounded by the minor alluvial fan systems flowing from the Coastal Cordillera and by the larger Precordillera alluvial fans. During the later episodes of the third evolutionary stage, inner lacustrine environments persisted in the northern basin areas close to Cerro Soledad and Cerro Mogote. Deltaic sedimentation persisted in the Encañada and Quillagua zones, whereas fluvial channel, flood-plain and related lacustrine environments occupied areas of the basin more to the south (Fig. 11d).

Marly and diatomaceous deposition spread over some 2000 km$^2$ during the maximum extension of the lacustrine conditions. But this situation largely changed and the lake underwent expansions and retractions, as is recorded by the high-frequency sequential arrangement of marginal and inner lacustrine facies in the Quillagua Formation. Fresh to brackish, slightly saline conditions were dominant in this lacustrine system, where no very saline conditions have been found. If some palaeohydrological connection existed during this evolutionary stage between the Quillagua–Llamara basin and the Salar Grande zone (Figs. 1 and 11d), some of the subsurface deposits of halite in the Salar Grande could represent the development of chlorure-dominated playa-lake and playa facies, coeval with the diatomites sedimented in the perennial lacustrine zones of the Quillagua basin. Higher water-concentration brine evolving from Quillagua water contributions would have been attained in the Salar Grande basin.

The third stage ended rather sharply due to gentle tectonic movements, which probably changed watersheds in the region and led to the disappearance of the Quillagua lacustrine system disappearance. In the northern basin sectors these movements caused a gentle unconformity between the Lower and Upper Units (Fig. 2).

### 7.4. Stage 4

Ambiguous dating criteria prevent adequate dating of the erosive surface linked to the gentle tectonic unconformity which developed at the end of the third stage and is recorded in the northern basin. Subsequently, when lacustrine conditions recurred during the Pliocene (?), a highly saline, chlorure- to sulphate-dominated ephemeral system was established. This fourth evolutionary stage could range from Pliocene to Pleistocene in age. This depositional stage was characterised by a noticeable spreading of the lacustrine zones, with the upper basin units onlapping again the western basin margin. The new lacustrine zones occupied only the northern sub-basin and covered some 2500 km$^2$, i.e. more than the former Quillagua system. They were ephemeral playas and playa-lakes, which gave rise to the deposition of halite-dominated sequences with interbedded layers of anhydrite (Soledad Formation: no facies showing fresh or oligohaline conditions have been found; Fig. 11e). The ephemeral saline lacustrine zones of the northern basin sectors were connected with the Salar Grande basin and brine could be fed into this area from the Quillagua–Llamara zone.

The maximum height of the saline deposits in Cerro Soledad and other isolated neighbouring hills (e.g. Cerro Salar) shows the final base level during the final evolutionary stages of the basin. It was in relation to this base level that the Precordillera alluvial fans developed, which likely experienced a noticeable shrinkage and are considered here the only significant source of water, solutes and clastic sediments from the neighbouring Precordillera heights. No sedimentary record of this stage is preserved in the southern basin zones and there is no record of a northward-flowing fluvial system which could have supplied some water and sediment to the northern sub-basin.

### 7.5. Stage 5

After deposition of the Soledad Formation evaporites (Pliocene–Pleistocene?), the internal drainage of a few sectors of the Quillagua–Llamara basin remained closed, but very large zones were affected by the opening towards the Pacific Ocean of the deeply entrenched Loa Canyon (Fig. 11f). This canyon is up to 600 m deep and cuts at right angles through the N–S-oriented Coastal Range. As a consequence an extensive open, erosive drainage network (which takes as its lowest expansion point the eastern end of the canyon at 800 m a.s.l.) has been developing to date in the Quillagua basin. This change to open drainage conditions resulted in widespread erosion and dissolution of the ancient alluvial and lacustrine deposits. Since then sedimentation has occurred in rather restricted zones, giving rise to terraced alluvial-fan, fluvial and minor lacustrine deposits which developed at increasingly entrenched topographic levels.

Most dissolution which affects the evaporite rocks of the Soledad Formation is produced by ephemeral sheet flooding of Precordillera alluvial fans and the groundwaters which discharge in the basin from the Precordillera Range recharge zone (Fig. 11f). The entrenchment of the El Loa drainage is deeper in the central zone of the northern basin sector, i.e. in the areas where the evaporite Soledad Formation was probably thicker. In consequence, the entrenchment of the Precordillera network of alluvial fans (which depends on the base level defined by the Loa River incision) is relatively shallow in those zones located far away from this more deeply incised zone. This fact, together with the hyperaridity of the region, allowed the nearly final depositional surface of some of the Precordillera's Late Miocene alluvial fans (e.g. the Arcas fan, Dörr, 1996) to be well preserved. The successive entrenchments giving rise to the Loa River terraces were probably caused by several factors (e.g. vertical lithospheric rising, glacioeustatic sea level change, changing supply of water and terrigenous sediments), whose scale of importance has not been properly established (Ortlieb, 1995).

## 8. Discussion

The three major Miocene–Pliocene and Pliocene–Pleistocene (?) lacustrine episodes recorded in the Quillagua –Llamara basin were mainly affected by extensional tectonic evolution, volcanic activity and the changing climate affecting the water balance in the source and depositional areas of the fore-arc region. Considered as a whole, the Late Neogene lacustrine record in this basin is significant since it records the repeated alternation during Miocene–Pliocene times of extensive evaporitic (ephemeral and saline) and non-evaporitic (perennial and fresh to slightly saline) lakes in a climatically sensitive, arid zone which evolved to hyperarid conditions. But deeper understanding of the context within which where these lacustrine systems evolved is crucial in order to evaluate their palaeoclimatic and/or tectonic meaning.

### *8.1. Tectonic and volcanic influence*

Lacustrine evolution in the Tertiary Quillagua–Llamara was closely related to the development of fault-bounded basins along fault lines active since the Oligocene that progressively became inactive. This resulted both in changes in the subsidence–sedimentation rate (i.e. of the accommodation space) and in basin sizes and morphology which modified the extent and distribution of the alluvial and lacustrine environments. The location and north–south orientation of the basin depocentres and the alluvial–lacustrine depositional arrangement were clearly related to these faults.

The onlap relationships observed between the basin substratum and the upper basin infill along the basin margins suggest that most of the tectonically generated topographical–depositional gradients in the fore-arc were generated before the final stages of the basin infill took place and that a vigorous palaeorelief was filled up by the alluvial and lacustrine sequences. Nevertheless, gentle tectonic activity still affected the Quillagua–Llamara basin during the later depositional stages causing minor intraformational unconformities such as the one between the Lower and Upper Units (Fig. 2).

Widespread development of biogenic, silica-rich diatomite facies is one of the most obvious influences of volcanism in the lacustrine record of this Central Andean fore-arc region. The extensive lixiviation processes which affected the huge volcanic formations after the Neogene igneous activity supplied large amounts of silica. The high solubility of the main vitric volcanoclastic deposits in the lacustrine zones together with the hydrothermal activity of the volcanic centres was also able to provide supplementary incoming silica, which enhanced diatom blooms.

The occurrence of significant pyroclastic ignimbrite deposits underlying one of the most important lacustrine episodes (i.e. Quillagua Formation lacustrine successions) and the frequent occurrence of pyroclastic and epiclastic volcanic deposits in the lacustrine deposits suggest a certain relationship between volcano-tectonic processes and the lacustrine record. However, although volcanism could have exerted a noticeable short-term influence on the regional sedimentary frameworks, it is difficult to establish clear causal relationships between major single volcanic episodes and potentially coeval depositional changes. Volcanic eruptions can modify the morphology of drainage areas, change in a nearly instantaneous way water contributions into depositional zones and obliterate extensive lacustrine zones. These rapid changes can however be rather quickly buffered or counter-balanced by regional drainage evolution and do not lead to long-lasting situations, which are likely to be easily recorded or recognized.

### *8.2. Climatically and tectonically driven water balance — drainage evolution*

Tectonic plate reconstructions (Smith and Briden, 1977; Smith et al., 1981; Parrish et al., 1982; Parrish and Curtis, 1982; Scotese et al., 1988) and palaeomagnetic data (Hartley et al., 1988) suggest that the fore-arc region of northern Chile was located during Neogene times under the influence of the steady high-pressure southeastern Pacific cell which causes arid to semiarid climatic conditions between 23º and 30ºS latitude. Parrish et al. (1982) and Parrish and Curtis (1982) suggested that arid palaeoclimatic conditions started in the Palaeogene, so times favouring widespread and large evaporite deposition (Chong, 1992). Further hyperaridity conditions were triggered by both the Andean rain-shadow effect and the influence of cold oceanic currents. The effect of the rain shadow on precipitation from the Amazon Basin was increased by the growth in height of the Andean orogen during the Oligocene and Early Miocene (Alpers and Brimhall, 1988). Recent evidence from ocean drillings point to huge increase of sediment flux into the western Atlantic at 8 Ma (Filippelli, 1997). This would suggest that in the Late Miocene renewed uplift in the Andes triggered more orographic precipitation from tradewinds from the Amazon basin and also reinforced the rain-shadow effect on the Late Miocene to Recent fore-arc regions, which became more arid. In its turn the thermal inversion related to cold oceanic currents (similar to the present Humboldt current) and coastal upwelling enhanced hyperaridity in the fore-arc regions. The existence since the Paleocene of a similar oceanic cold circulation pattern in the eastern Pacific has been suggested (Andel, 1979, in Kennet, 1982; Haq, 1981). However, its effect was enhanced especially from Middle Miocene to Recent times, as a result of glaciation in Antarctica (Keller and Barron, 1983). Several authors suggested that ice sheets in Antarctica expanded a lot during the latest Miocene, simultaneously with the first glacial spreading beyond the Andes (Mercer and Sutter, 1982). This Southern Hemisphere cooling process in high latitudes would have led to increased Antarctic Bottom Water (Hodell et al., 1986) and reinforced cold oceanic currents and upwelling processes, all of which is well-established thanks to Miocene phosphorite and diatomite marine deposits in northern Chile (Ferraris and Di Biase, 1978; Tsuchi et al., 1988; Martínez-Pardo, 1990).

Late Neogene climatic evolution in the Southern Hemisphere may have led to regional changes which enhanced the dominant arid to hyperarid situation in the region studied. Thus, some of the most conspicuous lacustrine changes recorded in the Quillagua–Llamara basin could be tentatively related with this global to regional palaeoclimatic evolution. One of the main problems in this analysis is that dating of the Late Neogene to Quaternary alluvial and lacustrine sequences is still inaccurate and discontinuous, although several points can be emphasised. Transition from ephemeral, evaporite-dominated lacustrine systems into perennial, non-evaporitic systems took place several times during the depositional evolution of the area, which implies that this transition was neither single nor exceptional (Fig. 2). One of these transitions took place between the Hilaricos anhydrite and the Quillagua Formation (Figs. 2 and 4). This transition was preceded by a widespread progradation of the Precordillera alluvial fans, which could imply an increase in water and sediment contributions. This transition was also characterized by the additional water supply from the northward-flowing fluvial system. Increased water and sediment contributions from the Precordillera would mean either enlargement of the catchment areas or more precipitation in the Precordillera source areas, i.e. a wetter climate, which would have hampered progradation, and a larger-than-average radial spread of the Precordillera alluvial fans (Figs. 2, 4 and 11c,d).

Even when alluvial fans retrograded due to lacustrine spreading and rising base level, they attained a rather larger radial extent than during the earlier evaporite-dominated stages.

However, the increase in water input caused by the system flowing northward means that not only climatic changes but modifications of watersheds and drainage divides in the region could have played a role in the evolution of water balance. Thus, water-sediment contributions to the diverse basin zones were also closely related to the tectono-sedimentary and drainage network evolution in the southern basin sector and in its linking zone with the Calama basin (Chong, 1992; May et al., 1999). The Calama basin zone underwent changing tectonic and palaeogeographic conditions, which resulted in evolutionary stages characterized in some cases by water barrage and storeying, whereas in others it acted as a bypass area, allowing a noticeable input of water and sediment into the Quillagua–Llamara basin (Figs. 1 and 12).

Other well-recognized lacustrine changes took place between the Lower and Upper Units, when the biogenic silica sedimentation in oligohaline to freshwater lakes which characterized the Quillagua lacustrine stage was replaced by evaporite-dominated playa and playa-lake deposits. The occurrence of this transition in the latest Miocene–Early Pliocene could give support to a causal relationship between the ongoing climatic and oceanic changes which affected by that time the Southern Hemisphere and the recorded depositional changes in the basin (i.e. Precordillera alluvial fan retractions suggesting smaller water contributions). However, it should be stressed that this evaporite lacustrine episode was not only coeval with a retraction of the surrounding alluvial fans but also with a regional gentle reactivation of tectonic activity, which caused regional unconformity. In consequence, tectonically induced changes in the regional drainage network and watersheds can be claimed as at least an additional reason for this change of lacustrine regime.

It can be concluded that when morphotectonic evolution in the fore-arc region triggered water barrage and spreading of lacustrine areas in watersheds to the south of the Quillagua–Llamara basin (i.e. the Calama basin zone), water input into the basin diminished drastically. This favoured the onset of a negative water balance and the development of sulphate–chloride-dominated saline playas and playa-lakes, especially when more arid–hyperarid regional climatic conditions were also occurring and less water was being fed from the neighbouring Precordillera and Cordillera source areas (Fig. 11, stages b and e and Fig. 12a). When water storeying in the Calama Basin decreased and larger water inputs flowed into the Quillagua–Llamara region, widespread fresh-to-oligohaline lacustrine zones with diatomite and marly deposits were able to develop, especially if this situation was coupled with relatively wetter conditions (Fig. 11, stages c and d and Fig. 12b).

The two low-order (3rd order) Lower and Upper unconformity-bounded units defined here include hierarchically arranged, higher-order alluvial–lacustrine successions, which resulted mainly from the inter-relationship between alluvial and lacustrine systems. These sequences recorded cyclically changing depositional conditions possibly triggered by palaeoclimatic evolution, i.e. alternation of arid–semiarid pulses in the Central Andean region from the Late Miocene to Recent (Alpers and Brimhall, 1988; Gaupp et al., 1999). The hierarchical sequence arrangement in the upper basin infill in the Quillagua–Llamara basin can be recognised in most of the lacustrine successions, but the marginal deltaic and fan-deltaic lacustrine sequences of the Quillagua Formation display especially clear, well developed high-frequency (4th–5th order) sequence trends, which suggest some climatic forcing, with possible interference from tectonic and volcanic–tectonic processes (Figs. 6 and 8). Despite this, no conclusive evidence is available for an exclusive allogenic climatic forcing on this sequence arrangement, since autogenic processes (progradation, retrogadation and shifting of the deltaic and fan-deltaic lobes) could have produced similar cyclical, though not necessarily periodical, patterns.

## 9. Concluding remarks

Some general concluding remarks can be established on the base of the overall major features of the Late Neogene tectono-sedimentary and lacustrine record in the northern Chile fore-arc zones (Fig. 12).

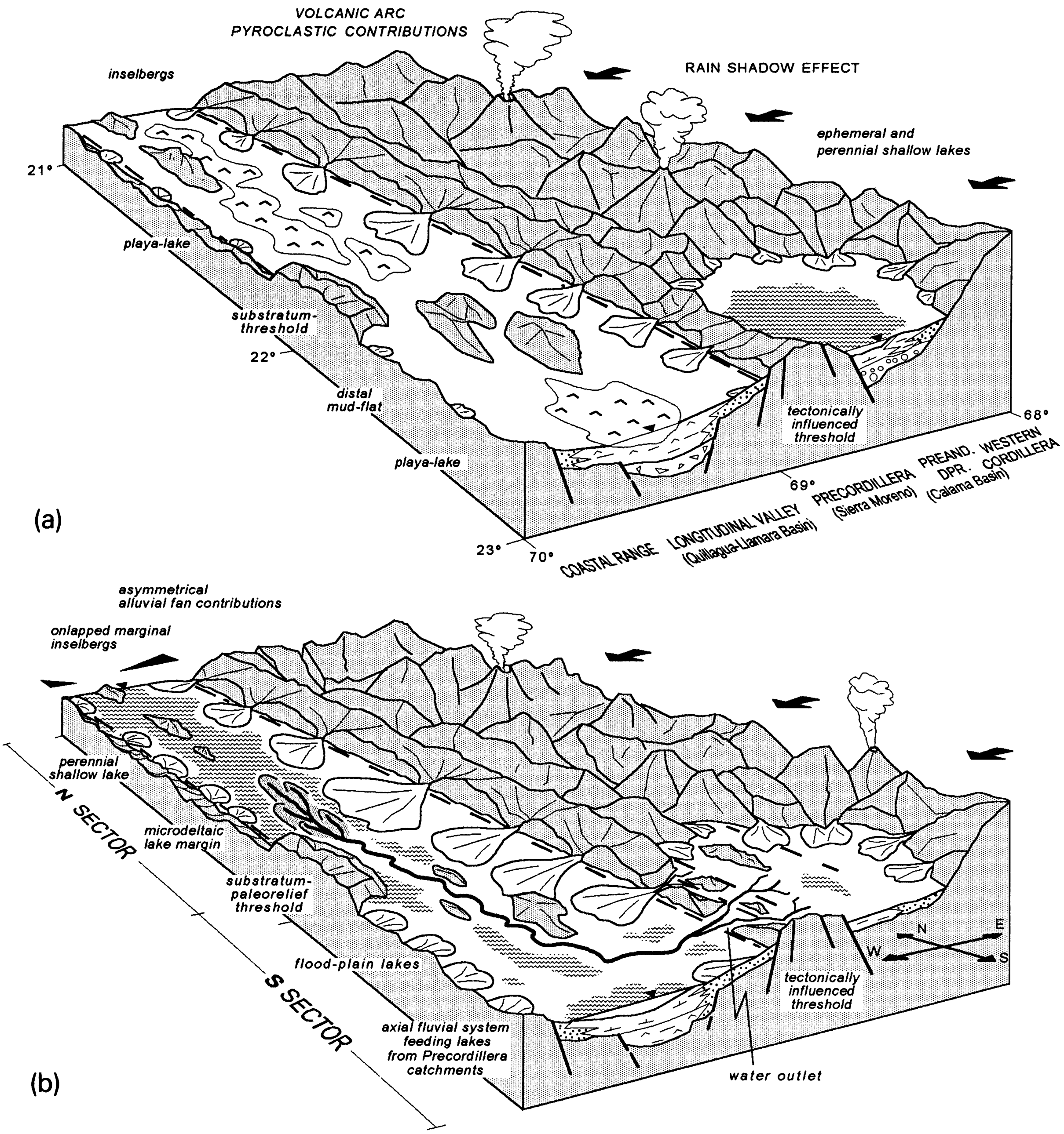


Fig. 12. Conceptual block diagrams showing the overall relationships between the diverse fore-arc zones in the southern Central Andean region in northern Chile and the influence exerted by tectonic, volcanic and climatic driving features on the lacustrine record. Two extreme situations are shown. (a) Negative water balance in the northern zone of Quillagua–Llamara basin, linked to drier climatic conditions (which resulted in playa-lake development and in retrogradation of surrounding alluvial fans and/or to water barrage in the Calama Basin because of the existence of a tectonic topographical threshold. (b) Clearly positive water balance in the same zone linked to wetter climatic conditions (which would enhance perennial lakes spreading and progradation of the alluvial fans) and to a very distinct regional drainage which results in no water retention in the Calama basin and the development of a northward flowing fluvial system.

(1) Fault activity in the non-marine, intramassif fore-arc regions studied played a major role in the early development of the basins and their pattern of deposition since it controlled the location of the early basin depocentres. Later sedimentary evolution of the basins was not so strongly dependent on active fault tectonics, but rather on the interaction between the evolving reliefs and the depositional systems. Relatively minor substratum palaeoreliefs of tectonic and erosive origin acted as topographic thresholds. These thresholds controlled accommodation space and water and sediment bypassing or accumulation, and gave rise to diverse sedimentary records in the diverse basin zones. Late basin aggradational stages preceding regional drainage entrenchment were characterized by spreading of the depositional zones and onlapping of the basin margins and topographic highs by sediments.

(2) The Precordillera catchment areas which fed the alluvial fan and river systems were larger than in the Coastal Range and in most cases contributed with larger water and sediment amounts, which led to clear depositional and hydrological asymmetry. The distance of some of the Precordillera watersheds from the lacustrine zones meant that local but significant tectonic modifications of drainage divides could become driving forces of the sedimentary evolution. Even gentle tectonic tilting and uplifting in critical water divide or bypass zones could bring about noticeable changes in the water income into the lacustrine basins and trigger variations in the depositional record.

(3) The Late Miocene to Pliocene global scenario in the Southern Hemisphere was characterized by an overall stepping trend of high-latitude cooling and variation in the intensity of cold oceanic currents affecting the ocean close to this Central Andean region. The alternating reinforcement and weakening of these cold oceanic currents could have caused oscillations in the arid–hyperarid conditions which in turn could have modified the regional water balance. Due to this, the coeval development of evaporite-dominated deposits and alluvial fan retrogradations, and the nearby deposition of perennial diatomite successions related to major alluvial fan progradations support the idea of low-frequency climatic forcing. However, these very conspicuous facies changes recorded in the Quillagua–Llamara basin infill (i.e. transition to Hilaricos anhydrite, to Quillagua Formation and its later change to Soledad Formation) are not on their own conclusive evidence for exclusive climatic forcing, especially when they are so close to either remarkable regional drainage changes and/or gentle but noticeable tectonic reactivation in the fore-arc region

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