Lake-level and salinity reconstruction from diatom analyses in Quillagua formation (late Neogene, Central Andean forearc, northern Chile)

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Abstract

A sedimentary and micropaleontological study of the Quillagua Formation provides a detailed paleohydrological reconstruction of the lacustrine system which occupied the present-day hyperarid Quillagua–Llamara fore-arc Basin (Northern Chile) from lattermost Miocene (5.8±0.4 Ma) to Early Pliocene times. Diatom and lithofacies analyses were carried out in two correlated stratigraphic sections of the lacustrine system. The Quebrada Temblor section is located at the southern margin of the ancient lake and is directly influenced by the freshwater inputs of a northward flowing fluvial system draining the Precordillera and Calama regions. The Cerro Mogote section occupies a western marginal location in the northern zone sheltered from direct fluvial inputs from the south but subjected to the activity of the alluvial fan systems of the Coastal Range. A mostly shallow oligosaline waterbody occupied the basin during the interval studied, though with fluctuations in salinity and the extent of the inner, open waters. The southern margin sector — represented by Quebrada Temblor — had, in general terms, a palustrine oligosaline character with almost freshwater conditions during certain periods, which favoured the establishment of semi-permanent to permanent freshwater plumes overlying a saline waterbody. Development of shoreline facies subjected to desiccation events was also characteristic at the top of this section. The innermost shallow lacustrine areas — represented by Cerro Mogote — maintained more homogeneous oligosaline characteristics and more persistent open waters. They were also subjected to freshwater pulses mediated in this case by the activity of the terminal alluvial fan zones. Paleohydrological evolution of the basin was strongly conditioned not only by shifts in the climatic–tectonic system but by variations in the local hydrological parameters. Four hierarchical orders of variability in the lake level of the basin were distinguished both by stratigraphic analysis of lithofacies and from changes undergone by the diatom record. Strong intrasample mixing of diatoms of incompatible salinity spectra and the presence of fine laminated lacustrine facies in some terms define the highest order short-term intra- or inter-annual pulses experienced by the lacustrine system (higher than 6th order). Diatom-based punctuated interruptions of the minor order bathymetrical trends highlight the high frequency variability in the basin (probably 6th order, 0.001–0.01 Ma), while the deepening/shallowing facies defined by the arrangement of the decimetre thick lithological sequences revealed a lower order of variability (5th order, 0.01–0.1 Ma). Combined lithofacies and diatom analyses delineate the lowest order of variability (4th order, 0.1–1 Ma) allowing the reconstruction of two well-established highstand and lowstand situations which implied the existence of a regressive trend between two transgressive trends. This order of variability is related to the interplay of tectonic events in the Calama Basin, and the regional climatic evolution during late Neogene to Pliocene times.

Keywords: Central Andes; Northern Chile; Neogene; Lacustrine; Diatoms; Paleohydrology

1. Introduction

Analysis of the lacustrine stratigraphic and sedimentological record in arid or semiarid areas of the world can provide crucial information on allogenic (climatic or tectonic) forcing of hydrological changes experienced by large lacustrine systems. Basic information on the expansion, stability conditions and on the high frequency water level oscillations of these paleolakes can be obtained from the analysis of lithofacies and their sequential arrangement.

Besides lithofacies analysis, microfossil biostratigraphy may be decisive for the interpretation of the paleolimnological conditions of the studied basins. Diatoms preserved in the sediments of these lake systems constitute powerful biological paleoenvironmental indicators due to their rapid response to hydrochemical changes, their diversity and their wide cosmopolitan distribution (e.g. Gasse *et al.*, 1987 ; Gasse *et al.*, 1997; Bradbury, 1988; Fritz et al., 1993). Due to their sensitivity to changes in water level and salinity, diatoms can be used as indicators of the precipitation–evaporation balance in an arid basin due to climatic factors or as tracers of local hydrological changes not directly related to climate (Bradbury, 1989; Gasse et al., 1997). In spite of this, few studies have dealt with the use of diatoms as proxies of past environmental conditions in the pre-Quaternary lacustrine sedimentary record of South America (Hustedt, 1927; Frenguelli, 1929 ; Frenguelli, 1936; Servant-Vildary and Blanco, 1984).

Low order expansive–retractive lacustrine sequences are related to the climatic and tectonic induced hydrological balance of the basins; analysis of changes taking place in these systems necessitates a combined sedimentological and paleontological approach. Although cyclical paleoenvironmental changes registered in ancient lacustrine records of arid zones can be interpreted as climatically controlled, it has been emphasized that in most situations environmental changes in closed basins are primarily driven by local topographical and hydrological factors at time scales of 10^2 years and less (Gasse et al., 1987). It is therefore important to know the role of local and regional changes in the hydrological parameters as forcing factors in the evolution of the lacustrine systems of arid zones at higher time scales. This approach requires, the correct selection of sections for analysis in the framework of a regional basin model. It is of primary importance for reliable paleogeographic basin reconstruction that a thorough understanding of the sedimentary data is obtained.

In this paper we aim to establish the hydrological pattern of evolution of the Quillagua Formation lacustrine system, by focusing principally on its bathymetric and salinity trends. We will discuss the hierarchical order of variability during Late Miocene–Pliocene times based on the lithofacies and micropaleontological analysis of two contrasting sections selected according to a previously designed regional geological model (Sáez *et al*., 1994; Sáez *et al*., 1995 ; Sáez *et al*., 1999).

2. The Quillagua–Llamara Basin: geological and paleoclimatic setting

Alluvial-lacustrine deposits of the Quillagua Formation constitute a part of the Cenozoic infilling of the Quillagua–Llamara Basin located between 21°00′ and 23°00′S in the Longitudinal Valley (Central Andean region of Northern Chile; Fig. 1A). This fore-arc basin with an average height of 1000 m a.s.l. extends in a N–S direction and is bounded by the major N–S-trending fault systems which separate it to the east from the Precordillera Range (4500 m of altitude) and to the west from the Coastal Range (2800 m of altitude; Reutter et al., 1988). The basin includes a relatively wide northern sector split from a narrower southward extension by a basement threshold located at 21°45′S latitude (Fig. 1A). The northern basin sector, focus of this study, records ca. 900 m thick Oligocene?–late Neogene basin infill, whereas the southern sector records a significantly thinner sedimentary infill. In the northern sector, the sedimentary sequence extends about 3000 km^2 and comprises two alluvial- lacustrine units separated by a widespread unconformity (Fig. 1B; Sáez et al., 1999).

The lower unit has a maximum thickness of 900 m in the central part of the basin although only the upper 150 m crop out. These outcropping sequences are Late Miocene (5.8±0.4 Ma)–Pliocene in age and they include alluvial fan, fluvial, fluvial-lacustrine and lacustrine facies (Jensen, 1992; Cabrera et al., 1995; Sáez et al., 1999). Most of these fluvial-lacustrine terrigenous, diatomaceous, carbonate and epiclastic facies assemblages are included in the Quillagua Formation (Fig. 1B).

The upper unit is dominated by halite and anhydrite deposited in ephemeral playas and playa-lakes (Soledad Formation). This unit is most probably Pliocene in age, it is up to 100 m thick and overlays unconformably the lower unit, which was affected by gentle block tilting.

Paleocurrents and facies distribution indicate that, from the Late Miocene to Pliocene, the lacustrine areas of Quillagua Formation were mainly fed from the south by a longitudinal fluvial system, which drained a broad sector of the Precordillera Range and the Calama Basin, and to a lesser extent by the alluvial fan systems attached to the eastern and western slope margins which drained minor areas from the Precordillera and the Coastal Range, respectively. The main waterbody, with a more perennial, deeper and larger character was formed in the northern sector of the basin. More reduced and isolated lacustrine zones were developed in the southern sector, occupying interchannel flood plain areas (Fig. 2). In the southern margin area of this main lake (Quebrada Temblor area), ahead of the terminal zones of the longitudinal fluvial system, a lacustrine deltaic system developed (Sáez et al., 1999). The remaining marginal areas (including Cerro Mogote) had a gentler gradient corresponding to terminal distal fan delta zones (Fig. 2). The innermost lacustrine areas of the system do not crop out.

Arid to hyperarid paleoclimatic conditions with minor changes have occurred in the arc and fore-arc northern Chile region since the Miocene to the present day (Alpers and Brimhall, 1988). Three main factors are responsible for these extreme climatic conditions (Ortlieb, 1995): (1) the influence of steady high-pressure cells; (2) the rain shadow effect on precipitation from the Amazon Basin caused by the increasing elevation on the Andean Orogen; and (3) the influence exerted by cold oceanic currents in the eastern Pacific in preventing precipitation in the coastal regions. Lack of palynological or other proxy data does not allow us to know in detail the minor climatic variations which occurred in the area during the late Neogene nor to determine their possible relationship with significant hydrological changes occurring in the lacustrine basin. Nevertheless, the present-day hydrological conditions of the Longitudinal Valley point to regular surface and phreatic water inputs feeding from the Precordillera and Cordillera areas where precipitations are significantly more abundant than in the Longitudinal Valley.

During the Miocene, the most important catchment areas for the Quillagua–Llamara Basin were located in extensive sectors of the Precordillera. Source areas belonging to the Coastal Range were minor and supplied lower water volumes. Late Neogene tectonic activity in the Precordillera, besides volcanic activity in the Western Cordillera, strongly modified the relief provoking water retention in the endorrheic lacustrine systems of the Calama Basin (May et al., 1999; Sáez et al., 1999). During the Late Miocene–Pliocene when the Calama Basin became partially or totally open, the longitudinal fluvial system developed giving rise, ahead of its terminal zones, to an extensive and permanent lacustrine system in the northern sector of the Quillagua Basin. When this system was closed, lake level variations could be primarily driven by restrictions of the hydrological system of the Calama Basin and, secondarily, by potential climatic variability.

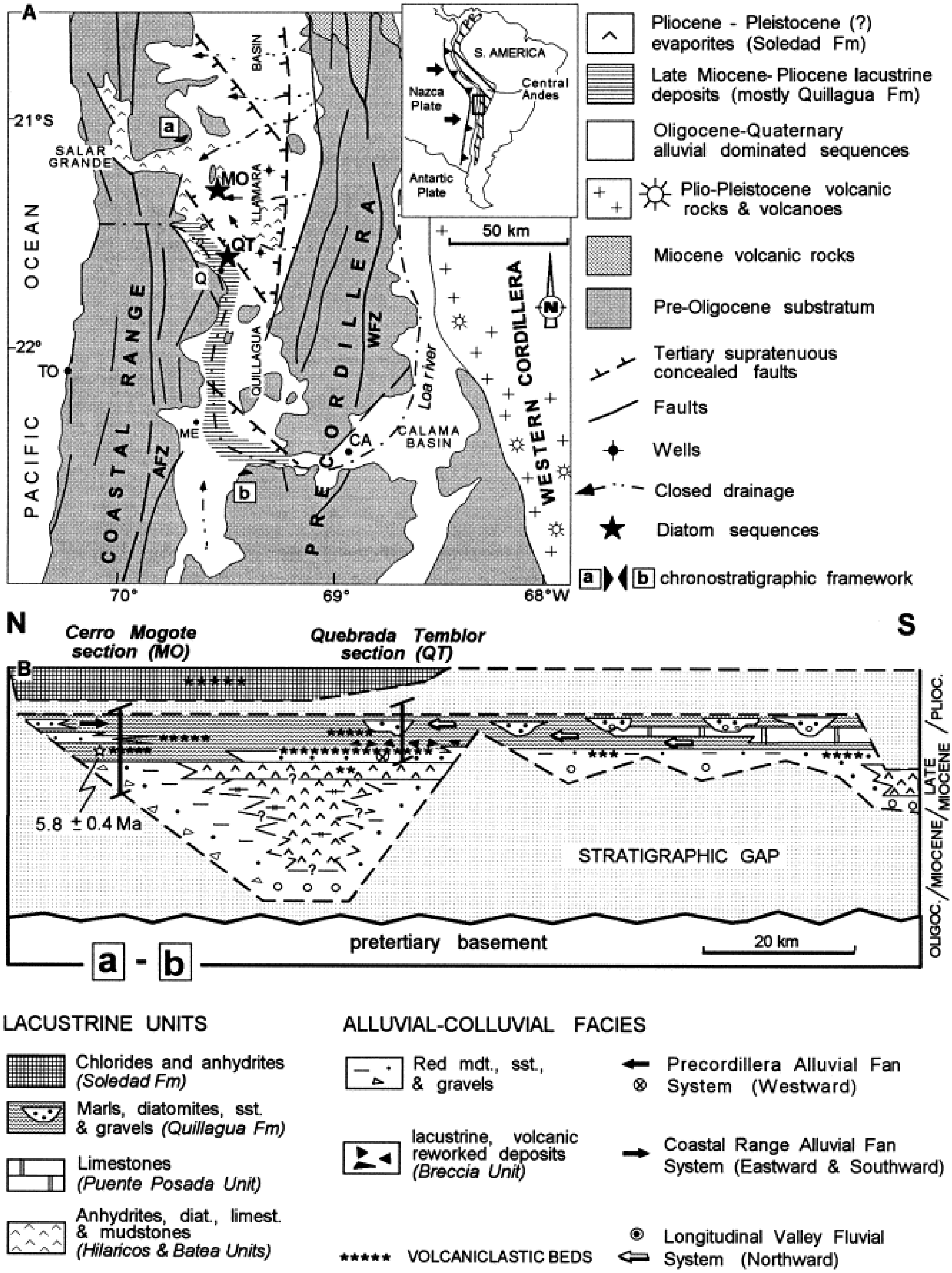

Fig. 1.(A) Regional geological setting of the Quillagua–Llamara Basin in the Central Andes and geological sketch of the Quillagua–Llamara Basin, Longitudinal Valley–Central Depression and surrounding Coastal Range, Precordillera Range and Central Andean Depression zones including the Calama Basin. Note location of studied sections and of the chronostratigraphic section *a–b* in (B). *AFZ* = Atacama Fault Zone; *WFZ* = West Fault Zone; *QT* = Quebrada Temblor section; *MO* = Cerro Mogote section; *CA* = Calama; *Q* = Quillagua Village; *TO* = Tocopilla. (B) General longitudinal chronostratigraphic framework of the Cenozoic basin infill of the Quillagua–Llamara Basin. Topographic and structural features are not represented. See (A) for location.

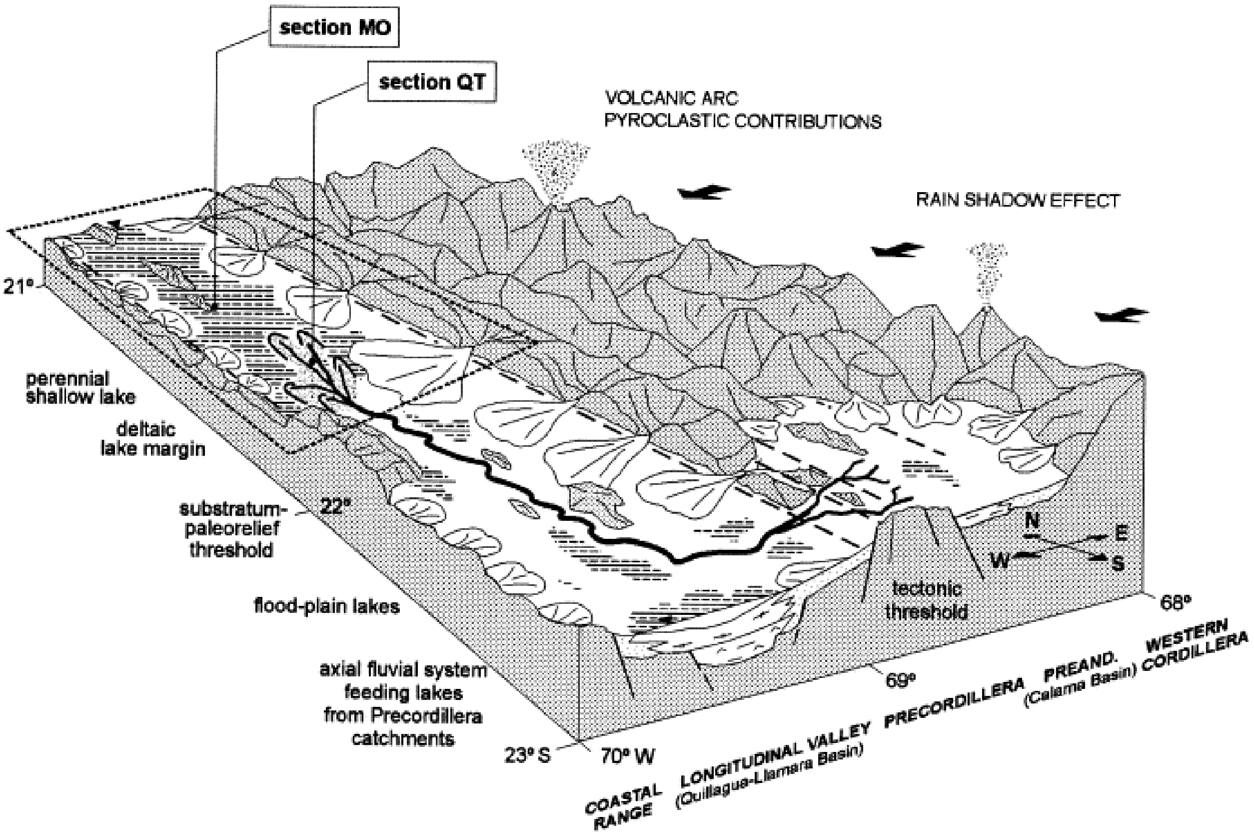

Fig. 2. Block diagram showing the overall relationships between the various fore-arc zones in the southern Central Andean region in northern Chile and the influence exerted by tectonic, volcanic and climatic driving features. Dashed rectangle indicates the perennial lacustrine environments where the studied diatom assemblages were deposited (modified from Sáez et al., 1999).

To further our understanding of the lake level changes and other hydrological features of the Quillagua lacustrine system, two sections were selected for study (Fig. 1 ; Fig. 2) from the northern sector of the Quillagua Formation where the main waterbody developed and the hydrological conditions for the whole basin can be considered as being more representative. The Quebrada Temblor section is located in the southern margin of the main lake in an area strongly influenced by direct water and coarse detrital inputs of the fluvial system which drained the Precordillera–Calama region. The Cerro Mogote section is located in the northern zone of the same ancient lake, in a western, relatively marginal zone sheltered from the southern coarse fluvial detrital inputs and subjected to scarce finer inflows from the Coastal Range alluvial.

The Cerro Mogote section is 31 km from the Quebrada Temblor section without any outcrop continuity. Nevertheless, preliminary paleomagnetic data (Garcés et al., 1994 and work in progress) point to the existence of a short normal magnetozone in a long reverse period, which can be used as a datum level for correlation of the two sections (Fig. 13). Given the average duration of the geomagnetic chrons during the Neogene of about 0.29 Ma, the Quillagua Formation deposits record a time span of about 1 Ma, pointing to an average sedimentation rate of about 0.85 m every 10,000 years.

3. Facies assemblages and sequential arrangement of Quillagua Formation

Five major lacustrine facies assemblages have been identified in the fluvial-lacustrine deposits of the Quillagua Formation, in the Quebrada Temblor and Cerro Mogote sections, on the basis of their lithological features, thickness, geometry, sequential arrangement and paleobiological contents (Fig. 3Fig. 4). These assemblages record the biogenic siliceous sedimentation developed from marginal, littoral lacustrine zones to inner but shallow lake zones.

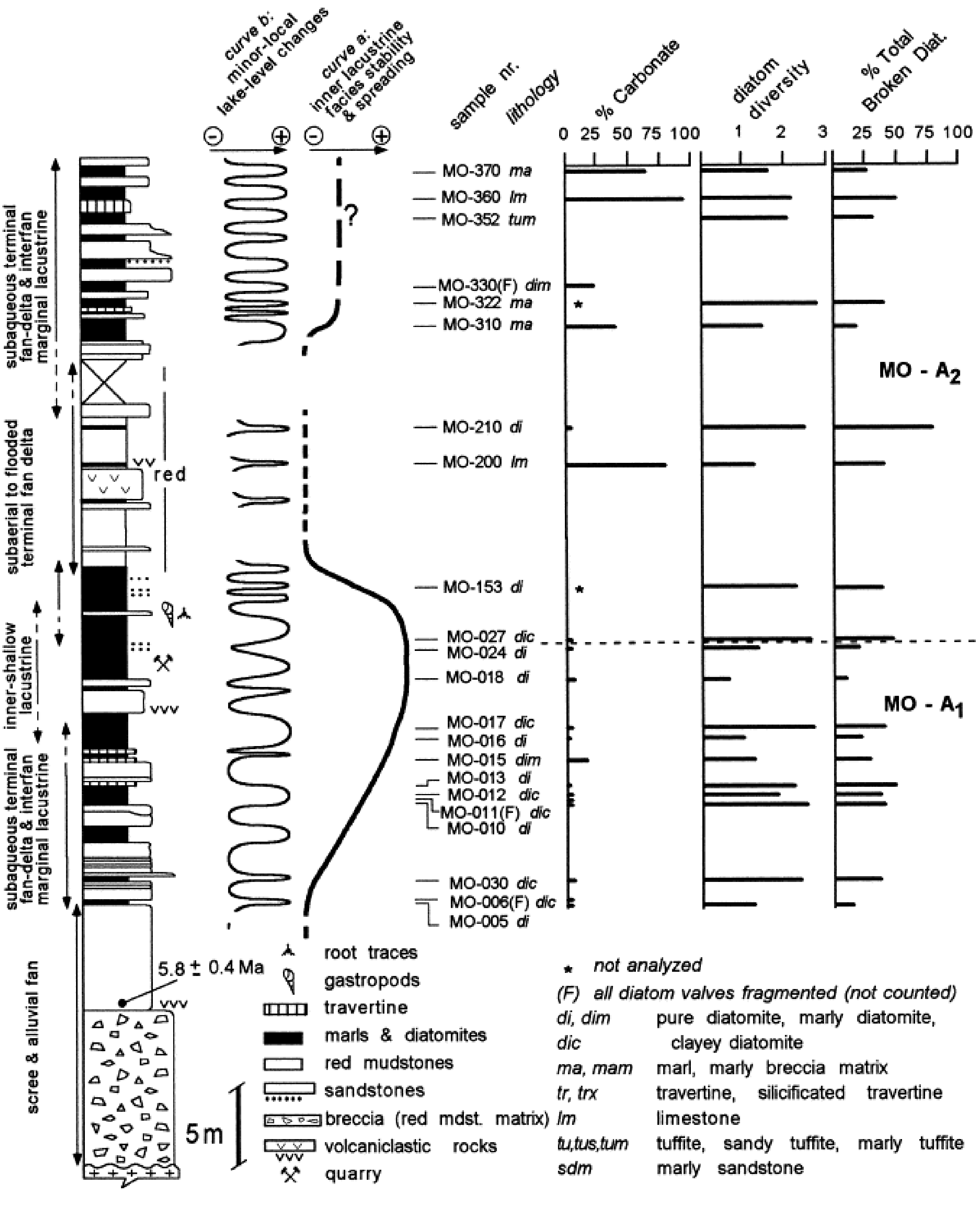

Fig. 3. Stratigraphic–sedimentological logs of the Cerro Mogote section showing the low- to high-order sequential arrangement of the Quillagua Formation. Curve `a' (low-order sequences) represents cycles of increasing–decreasing persistence of the lacustrine conditions in the area. Curve `b' (higher-order sequences) represents the recorded deepening/shallowing lacustrine cycles. Both curves are based on sedimentary facies analysis. Vertical changes variations of carbonates, diatom diversity and percentage of total broken valves in the section are also shown.

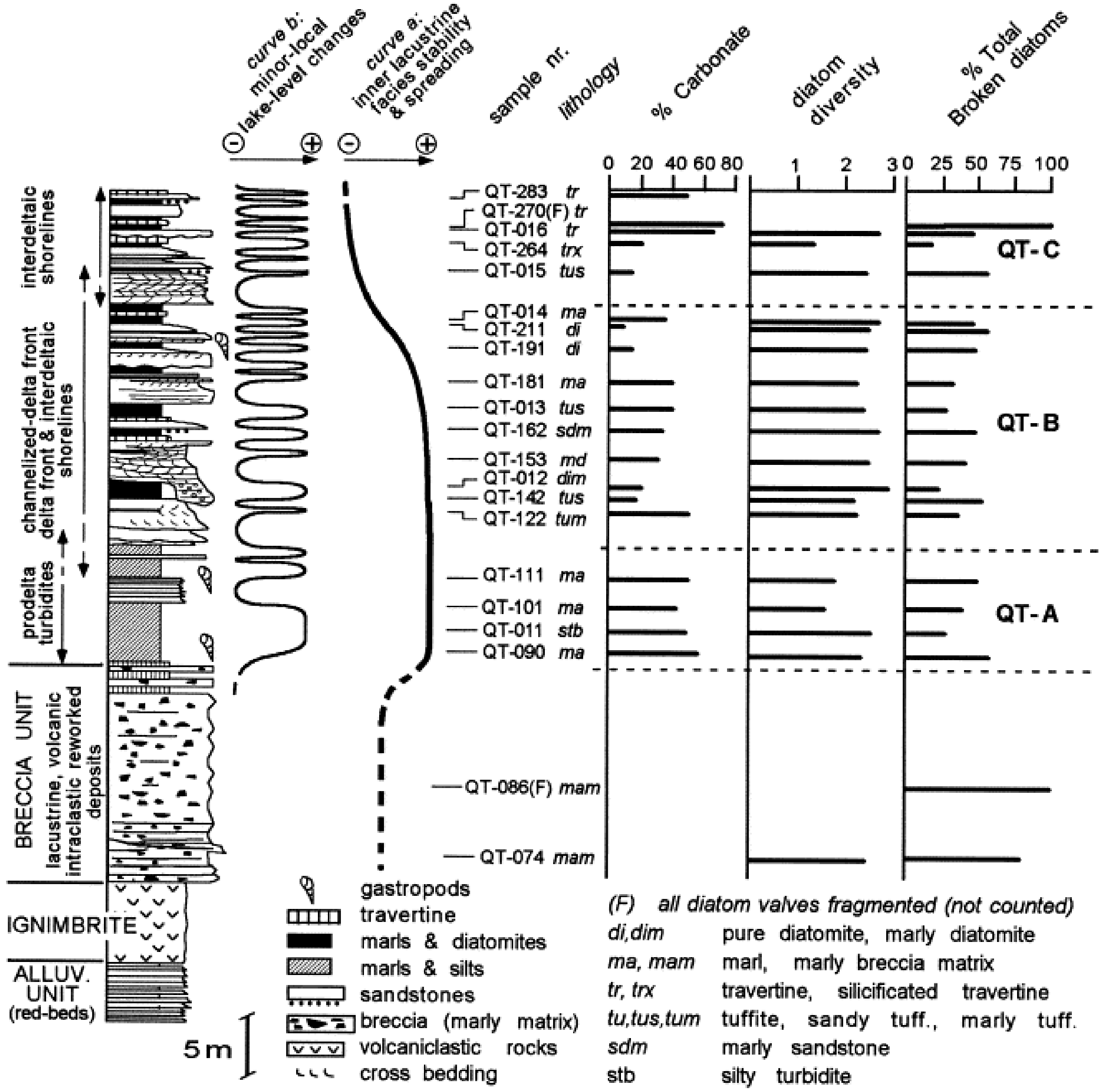

Fig. 4. Stratigraphic-sedimentological logs of the Quebrada Temblor section showing the low- to high-order sequential arrangement of the Quillagua Formation. Curve `a' (low order sequences) represents cycles of increasing–decreasing persistence of the lacustrine conditions in the area. Curve `b' (higher order sequences) represents the recorded deepening/shallowing lacustrine cycles. Both curves are based on sedimentary facies analysis. Vertical distribution of carbonates, diatom diversity and percentage of total broken valves in Quebrada Temblor.

3.1. Reworked breccia assemblage

These breccia-dominated facies occur in the northern basin sector along the eastern Loa riverside in the lower part of the Quillagua Formation (Sáez et al., 1999). The breccias range from massive to well-stratified, show large internal erosive surfaces and constitute lenticular bodies up to 15 m thick, with a lateral extent of up to a few kilometres. They are polymodal, vary from clast to matrix supported and include clasts of volcanics, lacustrine marls and diatomites which vary from centimetres to decimetres in size. The matrix is marly and includes volcanic epiclastic particles. This breccia assemblage resulted from the reworking by mass flows or highly concentrated flows of pyroclastic, epiclastic and sedimentary lacustrine deposits.

3.2. Terminal lacustrine fan delta assemblage

Subaerial to subaqueous terminal lacustrine fan delta facies occur in the Cerro Mogote Section

(Fig. 3). Red mudstones with interbedded thin (up to 1 m), lenticular fine-grained sandstones record the deposition in the subaerial fan delta zones. Thin sheet-like to gently lenticular, up to a few decimetres thick, dark gray to brown fine gravels and ripple cross-laminated sands and silts, interbedded with green mudstones correspond to the subaqueous facies. The lateral extent of these layers ranges from tens to hundreds of metres and their coarse-grained deposits are dominated by igneous and epiclastic clasts. The occurrence of root traces at the top of these beds suggests rather shallow palustrine environmental conditions.

3.3. Deltaic lacustrine assemblage

The deltaic lacustrine facies assemblage occurs in the Quebrada Temblor section and is mainly characterized by dominant channelized clastic delta front facies with interbedded subaqueous marginal lacustrine facies (marls, diatomaceous marls, diatomites and travertines (Fig. 4). These facies alternate and make up sequences that range from a few decimetres to a few metres in thickness.

Lenticular-coarse grained conglomerate and sandstone delta front facies, which correspond to channel infills, are well represented in this facies assemblage. These channel infills are up to several metres thick and several tens of metres wide in their transverse section, showing a high width–height ratio. They are mainly ribbon-like bodies with vertical monostorey to multistorey infills and deeply to gently incised erosional bottom surfaces. The paleocurrent trends suggest that these delta front facies resulted from the spreading into the lacustrine zones of a northward flowing fluvial system.

Dark grey to brown fine gravels and cross-laminated sands with a composition dominated by volcanic clasts and grains frequently occur in Quebrada Temblor (Fig. 4). These deposits reach thicknesses of a few decimetres and display mainly sheet-like to gently lenticular shapes with lateral extent ranging from tens to hundreds of metres. This facies records the deposition of small-scale terrigenous lobes developed ahead of the fluvial channel mouths. Root traces infilled by fine marly material also occur at the top of these deposits.

In the lower part of the Quebrada Temblor section, marl dominated beds interbed well-laminated intervals of sub-millimetre to millimetre thick detrital dominated rhythmites. Each rhythm consists of a diatomite silty interval with biotite grains followed by a clayey diatomite interval. These are turbidite-like deposits accumulated in a prodelta environment by underflow currents.

3.4. Interdeltaic and interfan marginal lacustrine assemblages

These facies assemblages occur in uppermost parts of the Quebrada Temblor and Cerro Mogote sections and are characterized by a thin interbedding of diatomites and diatomaceous marls with minor macrophyte travertines, sands, intraclastic microbreccias and epiclastic volcanic beds (Fig. 3 ; Fig. 4). These subaqueous fine-grained and biogenic facies make up thinner (up to several decimetres thick) and less laterally extensive (up to some hundred metres thick) diatomite layers than those recorded in inner lacustrine assemblages. They make up roughly symmetrical, deepening-shallowing upwards sequences. The transition from whitish to yellowish diatomitic marls and sandy marls which grade upwards to more pure white diatomites often occurs. Although these more pure diatomite intervals may display sedimentological and paleontological features similar to those of inner-shallow facies, they show more frequent clastic coarse terrigenous and epiclastic volcanic contributions. Moreover, the frequent occurrence of root traces suggests the development of very shallow palustrine environments.

Thin sandy and marly carbonate travertine facies have also been observed overlying some of the marl and diatomite-dominated sequential terms (Fig. 3 ; Fig. 4). They are gray, lenticular, up to a few decimetres thick beds and consist of small carbonate (calcite dominated) vertical to sub-vertical tubules up to 0.8 mm in diameter and a few centimetres long. Travertine layers record the development of marginal vegetation zones, which encroached on marginal lacustrine zones and record shallowing of the water column.

Massive to nodular grey sandy and marly intraclastic microbreccias, which display an upward increase in the fine matrix percentage also characterize this facies assemblage. Microbreccias are almost unconsolidated, forming centimetre- to decimetre-thick, gently lenticular layers with tens of metres of lateral extent. Silicified marl intraclasts make up most of the microbreccia framework together with volcanic pumicite and ash clasts. Gastropod bioclastic lenses and accumulations of fragmented travertine tubules are associated with this facies whereas root traces, mostly infilled by marly sediment, often occur. This facies records the action of tractive currents which eroded and reworked marginal lacustrine deposits which were later rooted by hygrophilous shoreline vegetation.

3.5. Inner-shallow lacustrine assemblage

This assemblage is only recorded in the middle part of the Cerro Mogote section (Fig. 3) where it consists of an up to 7 m thick succession of massive to poorly laminated, white to very pale brown marls (35–65% $CaCO_3$), diatomaceous marls (5–35% $CaCO_3$) and diatomite beds (lesser 5% $CaCO_3$).

Tabular to gently lenticular (decametre to hectometre in scale), up to 0.5 m thick marl (*ma*) and diatomaceous marl (*dim*) beds are related to pure diatomite beds. They are whitish to yellowish, massive or thin laminated and often include thin, millimetre-thick lenses of pure diatomite. Diatomaceous marls often grade upwards into whiter, purer, thicker diatomite beds. Fragmented diatom frustules, charophytes, disarticulated ostracode valves and gastropod remains as well as minor quartz, feldspar and volcanic vitric shards are frequent components.

Pure diatomites (*di*) are white, soft and very porous although some of them are silicified and include decimetre- to metre-sized chert nodules. They form lenticular and decimetre-thick tabular beds, which are at least hundreds of metres in lateral extent. Locally, diatomites display a lamination defined by siliceous-carbonate laminae couplets. These couplets consist of diatom laminae and carbonate intraclasts, micritized ostracodes and charophyte oogonia. Diatom frustules can be well preserved but they are often rather fragmented. These diatomitic facies were deposited under subaqueous persistent lacustrine conditions in transition zones between marginal to inner lake zones.

3.6. Sequential evolution

The Quillagua Formation sequence facies arrangement allows recognition of the evolution of the Late Miocene–Pliocene lacustrine system developed in the Longitudinal Valley region. Two low order expansive–retractive lacustrine alluvial sequences can be observed in the 55-m-thick Cerro Mogote succession providing a general insight to the overall evolution of the paleo-lake system. Low order sequences (curve `a', Fig. 3) resulted from the interaction between the lake zones and the Coastal Range alluvial and they split into minor, higher order transgressive–regressive sequences related to terminal fan delta progradations and retrogradations and/or lacustrine water level risings and falls (curve `b', Fig. 3).

The fluvial-deltaic to marginal lacustrine facies in the Quebrada Temblor section record an overall trend of lacustrine spreading and retreat (curve `a', Fig. 4) which includes higher order transgressive–regressive sequences (curve `b', Fig. 4) driven by processes similar to those observed in the Cerro Mogote. Deltaic and marginal lacustrine evolution gave rise to minor sequences which could have resulted either from lake level changes or from the autogenic evolution (i.e. progradation–retrogradation and lateral shifts) of the deltaic environments.

4. Diatom analysis

4.1. Material and methods

Samples from the Quebrada Temblor (*n*=21) and from the Cerro Mogote (*n*=22) sections were selected for diatom study in the diatomaceous earth (diatomites, marls and travertines). All the samples were treated with acetic acid and H_2O_2 and washed repeatedly in distilled water; 0.5 ml of treated subsample was strewn evenly onto cleaned 22×22 mm coverslips. Slides were mounted using Naphrax diatom mountant (r.i. = 1.74).

Diatom counts were made at ×1000 following random transects with a Nikon Optiphot II phase contrast microscope. At least 350 diatom valves were counted per sample. The counting categories considered during the analysis were selected in accordance with Schrader and Gersonde (1978). Raw counts were converted to percent abundances. Percent of broken vs. whole valves in a sample was also estimated. Even though fragmentation may be caused by grazing, low sedimentation rates, bioturbation, specific water depths and varying degrees of valve robustness (Beyens and Denys, 1982; Juggins, 1992; Flower, 1993), the index was used as a rough estimator of the transportation of the diatom assemblages.

Identification of diatom taxa was undertaken in accordance with general literature (Hustedt, 1930; Hustedt, 1930–1966; Patrick and Reimer, 1966–1975; Germain, 1981; Krammer and Lange-Bertalot, 1986–1991; Sims, 1996) and with available references on the study area or neighbouring geographical context (Hustedt, 1927; Frenguelli, 1929 ; Frenguelli, 1936; Servant-Vildary, 1978 ; Servant-Vildary, 1984; Servant-Vildary and Blanco, 1984; Servant-Vildary and Roux, 1990).

The Shannon diversity index (Magurran, 1988) for both sections was calculated as:

$$H' = -\sum_{i=1}^{n} p_i \ln p_i$$

where *pi* are the proportions of individuals of each species with respect to the total amount of individuals in a sample. This diversity index was used in our case as a tool to recognize the possible effects of taphonomical overprint on diversity and modifications of the diatom assemblages caused by clastic reworking.

Because diatom-based water chemistry calibration sets were not available for the study area, paleoecological interpretation was based on general literature on diatom ecology (Beaver, 1981; De Wolf, 1982; Denys, 1991; Krammer and Lange-Bertalot, 1986–1991; Van Dam et al., 1994), available autoecological information on South-American saline diatoms (Servant-Vildary, 1978 ; Servant-Vildary, 1984; Servant-Vildary and Blanco, 1984) and, in some cases, on autoecologies derived from several diatom based-water chemistry models of saline lakes for the neighbouring region (Servant-Vildary and Roux, 1990; Servant-Vildary, 1993) and overseas (Gasse et al., 1987; Gell and Gasse, 1990; Cumming and Smol, 1993; Fritz et al., 1993; Wilson et al., 1996). This approach was also adopted due to the limitations imposed on paleoecological transfer functions by non-analogue situations in pre-Quaternary sediments (Sachs et al., 1977).

4.2. Quebrada Temblor diatom zonation

A total of 142 taxa were identified in this section. Abundances of the most characteristic species are shown in Fig. 5. Diatom preservation was variable. Travertine facies showed a poor preservation with a high number of corroded valves. Shallow waters subjected to intermittent desiccation and high alkaline conditions might account for poor valve conservation in this case. Preservation can be considered moderate to high in diatomitic and tufitic terms. Samples QT-074 and QT-283 were almost barren and samples QT-086 and QT-270 contained only valve fragments. Therefore, these samples were removed from any further study.

Saline diatoms (oligosaline, mesosaline and eusaline groups) represent about 45% of the taxa found in Quebrada Temblor, while freshwater diatoms comprise about 30%. The remaining taxa consisted of diatoms with a broad range of salinity preferences or diatoms whose salt requirements are unknown from the literature. The classification of diatoms according to their habitat requirements shows the minor presence of euplanktonic diatoms and the dominance of periphytic and tychoplanktonic forms, suggesting shallow conditions throughout the section (Fig. 6A). According to the diatom and sedimentological features of the alluvial-lacustrine facies present in the Quebrada Temblor section, three diatom zones have been identified which enable us to define evolution stages in the lacustrine system:

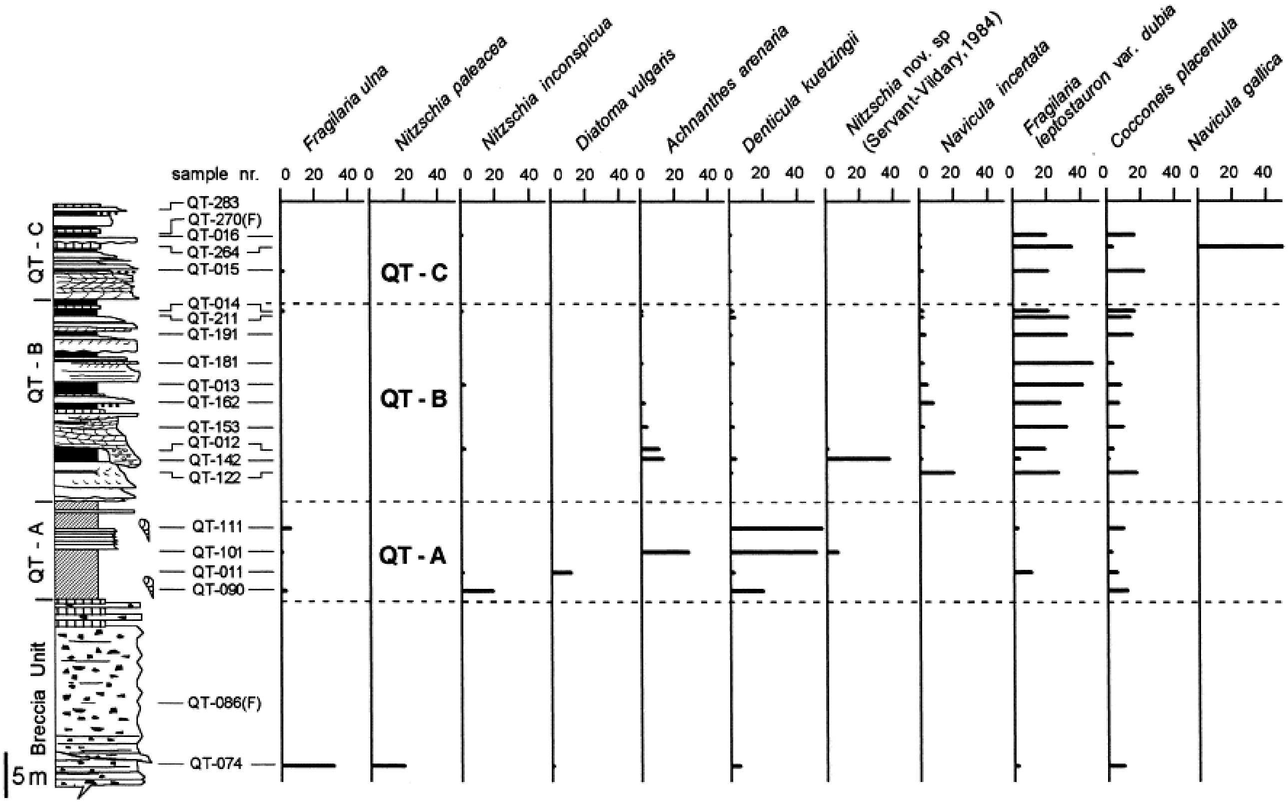

Fig. 5. Diatom percentage diagram showing most abundant species in the Quebrada Temblor section; *(F)* indicates levels containing only valve fragments. See legend for the lithostratigraphic log in Fig. 3.

4.2.1. Diatom zone QT-A

This zone includes the samples QT-090, QT-011, QT-101 and QT-111 and it is characterized by the highest percentages of oligosaline and mesosaline diatoms in the whole section (Fig. 6B) and very low planktonic : periphytic ratio values (Fig. 6A) suggesting the presence of a very shallow mesosaline waterbody during this stage. High percentage values of periphytic diatoms, mainly epiphytes, indicate permanent palustrine conditions with abundance of macrophytes. The most relevant species include saline forms such as *Fragilaria pulchella* (Ralfs) Lange-Bertalot, *Achnanthes atacamae* Hustedt, *Achnanthes arenaria* Amossé, *Cocconeis placentula* Ehrenberg, *Nitzschia inconspicua* Grunow, *Nitzschia valdecostata* Lange-Bertalot and Simonsen or *Denticula kuetzingii* Grunow and freshwater forms such as *Diatoma vulgaris* Bory or *Fragilaria leptostauron* var. *dubia* (Grunow) Hustedt.

Although high abundances of periphytic diatoms suggest the dominance of low energy conditions due to the dominant contribution of epiphytes to this group, level QT-011, mainly characterized by a peak in the tychoplanktonic and oligotrophic *Diatoma vulgaris*, attests to the development of more open waters and a relative lacustrine level deepening. *Diatoma vulgaris* is also a rheophilic species (Patrick and Reimer, 1966–1975; Denys, 1991) and might record major punctuated river runoff fed by the axial fluvial system. The freshwater character of this taxon, as well as that of the accompanying *Fragilaria leptostauron* var. *dubia*, contrasts with the high abundances reached during this stage by the saline diatoms. The co-occurrence of freshwater and saline species in this sample suggests short-term fluctuations in salinity and/or spatial juxtaposition of habitats (Gasse et al., 1987; Barker et al., 1990). Prevailing mesosaline conditions during this stage might be interrupted by intermittent inflows of freshwater that would bring allochthonous diatoms to a saline waterbody or alternatively lead to lake stratification with the development of a more or less persistent freshwater plume which could support an autochthonous planktonic diatom flora. Percentage values of fragmented freshwater diatoms with respect to complete freshwater valves during this diatom zone

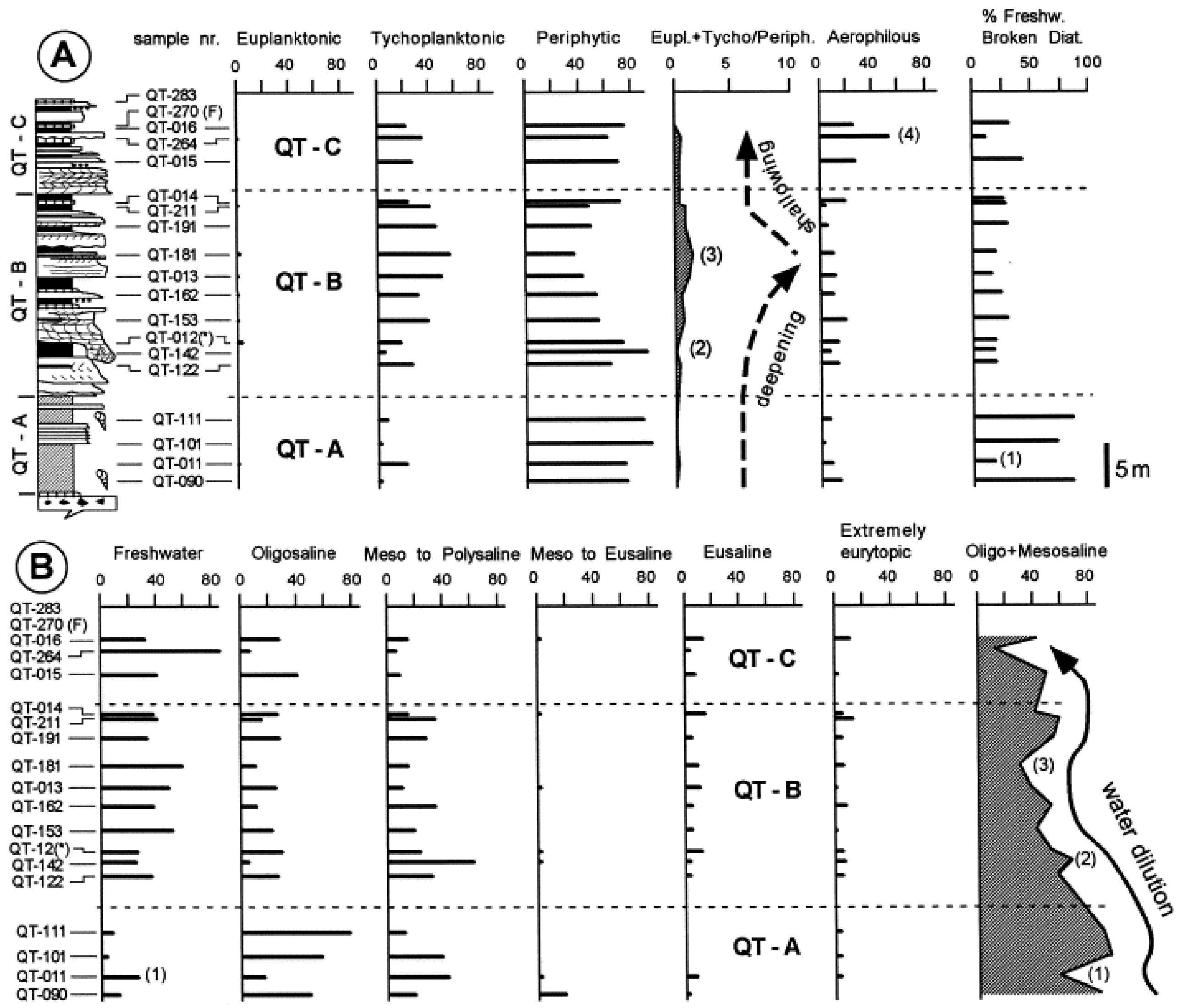

Fig. 6. Diatom stratigraphy in the Quebrada Temblor section. Vertical distribution of diatoms grouped according to (A) life forms and (B) salinity classes. Percentages of freshwater broken valves are also indicated in (A). *(1)* = saline stratification episode; *(2)* = saline episode, mesosaline, maximum lowstand in stage *QT-B*; *(3)* = freshwater episode, maximum highstand in stage *QT-B*; *(4)* = significant desiccation event; *QT-012(*)* = significant hydrothermal influence. See explanation in text.

(Fig. 6A) show maximum fragmentation conditions related to the more saline episodes (levels QT-090, QT-101 and QT-111) indicating that probably most of the freshwater diatoms are allochthonous. The minimum fragmentation value recorded during the pulse of freshwater infilling (sample QT-011) might indicate the development in a shallow waterbody of a persistent freshwater plume where an autochthonous freshwater and tychoplanktonic flora could develop. This would be consistent with a more saline related bottom waterbody inhabited by periphytic saline diatoms.

4.2.2. Diatom zone QT-B

This zone includes the samples QT-122, QT-142, QT-012, QT-153, QT-162, QT-013, QT-181, QT-191, QT-211 and QT-014. Maximum values for the planktonic : periphytic ratio and the increase in freshwater forms characterize this zone. The increase in the planktonic : periphytic ratio (Fig. 6A) is mainly due to the contribution of *Fragilaria* facultative planktonic diatoms, indicators of shallow but open waters (Fan Hui et al., 1996). A deepening and dilution of the lacustrine waters might occur during this episode as indicated by the freshwater *Fragilaria* *leptostauron* var. *dubia*. Although the diatom data point to a general decrease in the salinity, the coeval abundance of oligosaline and meso- to polysaline forms suggests that low oligosaline and not freshwaters were present (Fig. 6B). Saline conditions are especially important for level QT-142 where meso to polysaline diatoms reach a maximum for the whole section mainly due to *Nitzschia* nov. sp. (Servant-Vildary, 1984; Servant-Vildary and Roux, 1990) whose salinity requirements are known from the nearby Bolivian saline lakes. This species develops in waters with high calcium and magnesium contents (Servant-Vildary and Roux, 1990). Although its abundances are rather low (ca. 5% of the total diatom assemblage), this sample also includes species such as *Anomoeoneis sphaerophora* (Ehrenberg) Pfitzer which are typical of sodium-carbonate waters with pH higher than 9 (Gasse et al., 1987; Servant-Vildary and Blanco, 1984), *Cymbella pusilla* Grunow which may dominate the communities in $CaSO_4$ environments (Gasse et al., 1987) or the alkalibiontic *Surirella sella* Frenguelli with preference for shallow Na_2SO_4 lakes (Servant-Vildary and Blanco, 1984). At the top of this zone, a return to more paludine conditions is recorded by the diminution of the planktonic : periphytic ratio mainly due to the increase in *Cocconeis placentula* and the expansion of aerophilic forms (mainly *Achnanthes lanceolata* (Brébisson) Grunow).

This shallow lacustrine stage indicates an enhancement of the freshwater influxes to the basin. In spite of this, the *Fragilaria*-dominated biofacies, as well as the low abundances of euplanktonic diatoms, point to the predominance of shallow lacustrine conditions just a few metres in depth.

Low fragmentation conditions recorded for the freshwater component and the periphytic character of the saline forms (Fig. 6) indicate that most of the diatoms are probably of autochthonous origin. Besides this, the maximum equitable partition between two contrasting ecological components whose salinity spectra do not overlap, the freshwater and meso to polysaline diatoms, is found during this stage. All the data support the idea of strong mixture conditions of the diatom assemblages. This could account for more abundant freshwater influxes during the episode. Level QT-142 would represent the minimum water level for this lacustrine sequence with the dominance of saline diatoms whereas QT-181 sample would record the maximum highstand, representing a pulse of an almost freshwater condition. In between the two contrasting situations recorded by samples QT-142 and QT-181, the presence of a stratified waterbody cannot be ruled out. Moreover, a peak in *Achnanthes thermalis* (Rabenhorst) Schönfeldt recorded in sample QT-012 (Fig. 6) also indicates the influence of water discharges from a nearby hot spring (Hustedt, 1927; Patrick and Reimer, 1966–1975).

4.2.3. Diatom zone QT-C

This zone includes the samples QT-015, QT-264, QT-016, QT-270 and QT-283. Characteristic species are the saline diatoms *Cocconeis placentula*, *Brachysira aponina* Kützing, *Nitzschia amphibia* Grunow or *Denticula valida* (Pedicino) Grunow and especially the freshwater forms *Fragilaria leptostauron* var. *dubia*, *Achnanthes lanceolata* or *Navicula gallica* (W. Smith) Lagerstedt. The epiphytic *Cocconeis placentula* attain maximum representation during this phase suggesting the development of denser aquatic vegetation. Aerophilous diatoms also acquire their maximum relative abundances and, therefore, major episodic desiccation events associated with shoreline environments can be deduced for this stage. These are especially significant for sample QT-264 where the aerophilous *Navicula gallica* comprises 50% of the total diatom assemblage. Predominance of freshwater and aerophilic taxa in this level might indicate an enhanced infiltration capacity of the shoreline floor and direct influence of freshwater discharges. Both situations would explain the strong freshwater conditions associated with the shallow marginal-littoral areas of the lacustrine system.

Scarcity of valves (level QT-283) or high amounts of fragmented diatoms in some samples (level QT-270) confirm the existence of shallow high energy conditions associated with intermittent desiccation events characteristic of a very marginal lacustrine situation.

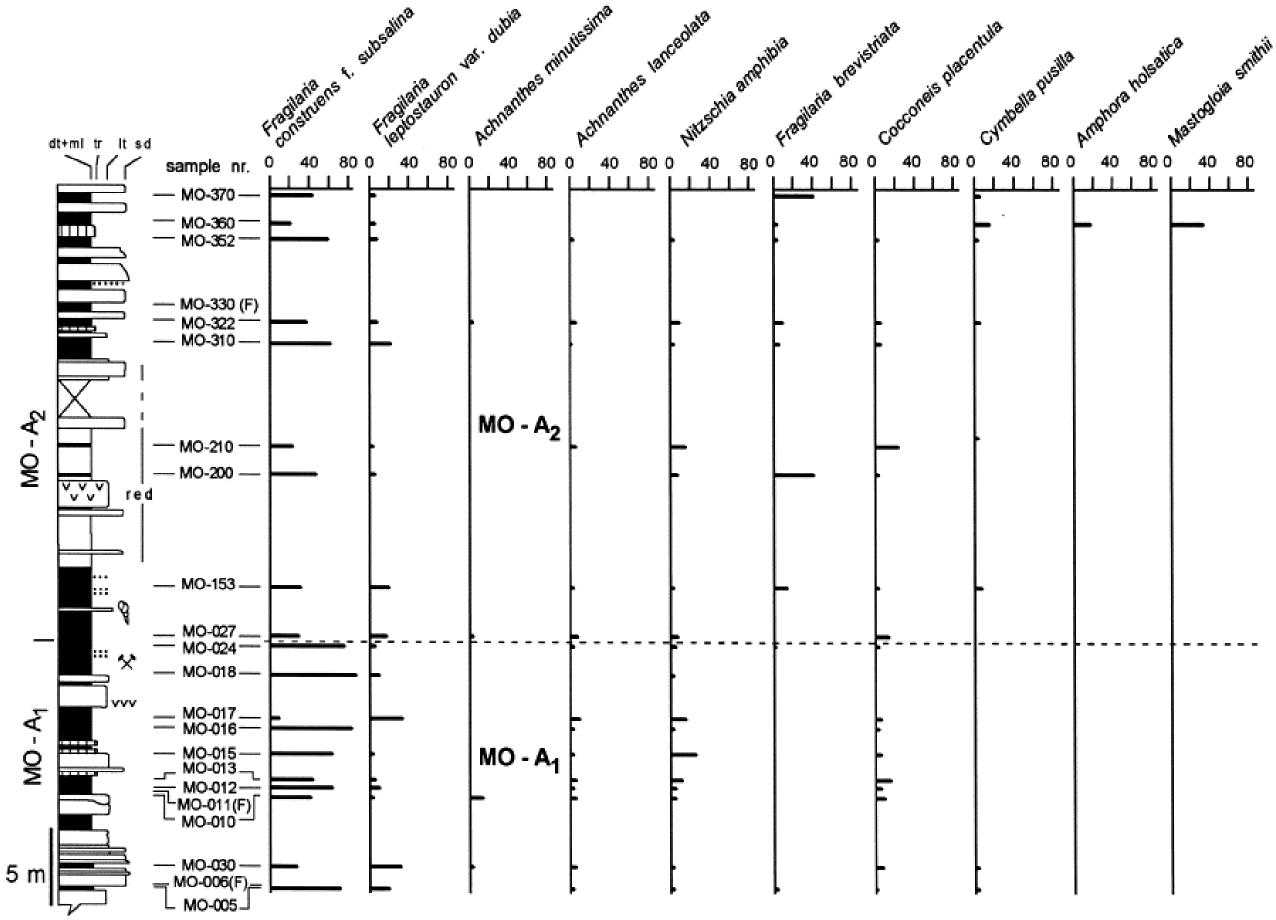

Fig. 7. Diatom percentage diagram showing most abundant species in the Cerro Mogote section. One diatom zone (MO-A) for the whole section subdivided in two subzones (*MO-A*$_1$ and *MO-A*$_2$) has been considered. See legend for the lithostratigraphic log in Fig. 3.

4.3. Reworked facies in the Lower Breccia unit

This unit includes samples QT-074 and QT-086 at the bottom of the section, and comprises two levels with a high content of fragmented diatoms (Fig. 4). The scarcity of intact specimens in sample QT-086 did not allow diatom counting. The most characteristic species of the low diversified diatom assemblage of level QT-074 were *Fragilaria ulna* (Nitzsch) Lange-Bertalot (30%) and *Nitzschia paleacea* Grunow (18%). These two species have broad habitat preferences, both occurring as planktonic or benthic (Gasse, 1986). The association of the freshwater *Fragilaria ulna* and *Nitzschia paleacea* which tolerates great variations in oxygen and medium to high electrolyte contents (Krammer and Lange-Bertalot, 1986–1991) might suggest running water conditions associated with this sample. Not only the facies of this unit but also the observed taphonomical conditions indicate a clear allochthonous origin for the diatom assemblage. The percentage abundance of broken diatoms acquired a maximum for the whole section during this stage (Fig. 4) and most of the dominant *Fragilaria ulna* specimens also showed teratological morphologies that may be related to high metal concentrations (McFarland et al., 1997). The erosion of pre-existing lacustrine deposits from the eastern basin zones could account for the origin of the reworked diatoms in this unit.

4.4. Cerro Mogote zonation

A total of 112 taxa were identified in this section. The percentage abundance diagram of the most characteristic species is shown in Fig. 7. Three samples (MO-006, MO-011 and MO-330) showed only valve fragments and were, therefore, rejected

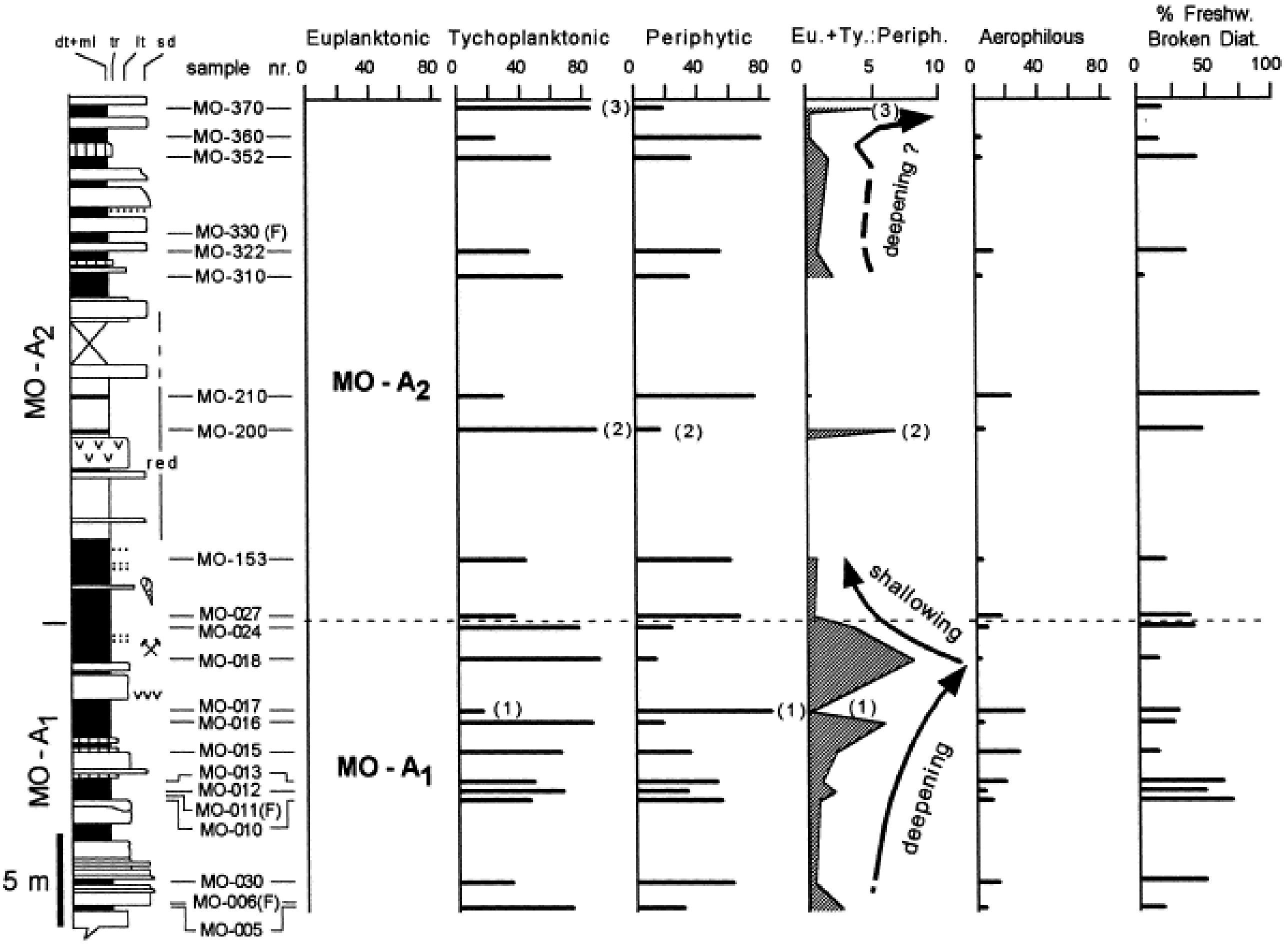

Fig. 8. Vertical distribution of diatoms grouped according to life forms in the Cerro Mogote section. Percentages of total broken and freshwater broken diatoms are also indicated. *(1)* = fall water level episode; *(2)* and *(3)* = rise water level episodes. See explanation in text.

from further quantitative study. However, the diatom preservation found was good for almost the entire section. In general terms, lower diatom diversity than in the Quebrada Temblor was found. The almost complete absence of euplanktonic diatoms, high levels of facultative planktonic taxa and low values of the planktonic : periphytic ratio along the studied section (Fig. 8), imply the development of shallow water conditions with the establishment of extensive areas of open waters. This makes a clear distinction between Cerro Mogote and Quebrada Temblor, where inshore palustrine conditions with dense aquatic vegetation and direct river runoff prevailed. According to diatom data, inner shallow lacustrine facies seem to be preferentially developed along the Cerro Mogote section.

Saline diatoms comprise about 46% of the taxa encountered and freshwater forms about 20%. Although similar values are found in the Quebrada Temblor section, the quantitative contribution of each saline group is very different in the Cerro Mogote section (Fig. 9). Saline diatoms comprise more than 70% of the total diatom assemblage in more than half of the samples. Nevertheless, oligosaline water conditions can be reconstructed for the whole section with some moderate shifts in salinity mainly marked by the contributions of freshwater and meso to polysaline diatoms.

The general high abundances of *Fragilaria construens* f. *subsalina* (Hustedt) Hustedt imply apparently minor differences in the diatom assemblages along the Cerro Mogote section when compared to those in the Quebrada Temblor section. For this reason, only one diatom zone (MO-A), subdivided into two subzones (MO-A_1 and MO-A_2), was distinguished.

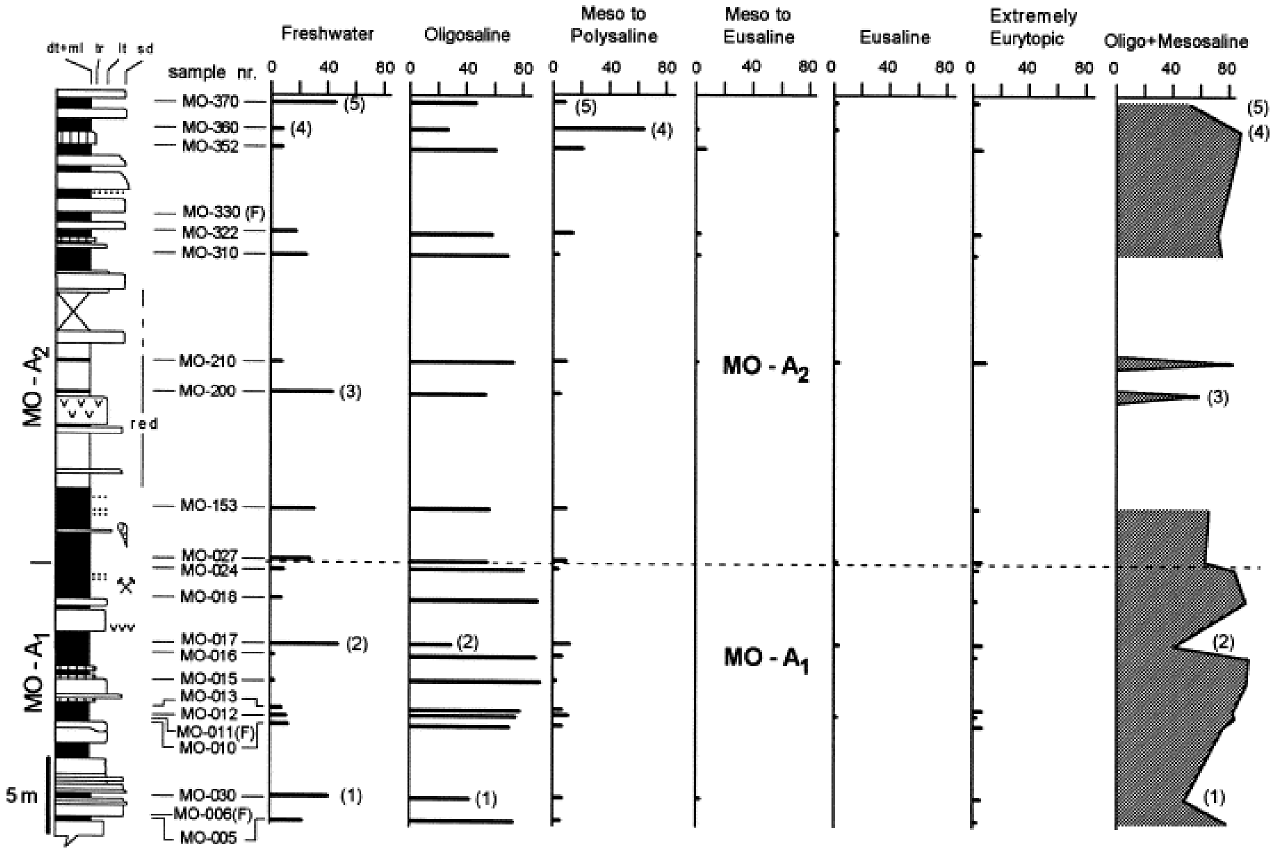

Fig. 9. Vertical distribution of diatom salinity classes in Cerro Mogote. Unclear sequential trends are recognized in this section. *(1), (2), (3)* and *(5)* = water dilution episodes; *(6)* = evaporative salt concentration episode. See explanation in text.

4.4.1. Diatom subzone MO-A$_1$

This subzone includes samples MO-005, MO-006, MO-030, MO-010, MO-011, MO-012, MO-013, MO-015, MO-016, MO-017, MO-018 and MO-024. *Fragilaria construens* f. *subsalina* was the dominant taxa in this subzone. *Fragilaria leptostauron* var. *dubia*, *Nitzschia amphibia* and *Cocconeis placentula* were the main accompanying species. Moderate to high values of the planktonic : periphytic ratio suggest the existence of extensive open waters in a shallow environment mainly occupied by facultative planktonic diatoms. Upwards increase in oligosaline diatoms (Fig. 9) indicates a salinization trend which is parallel to the development of open waters as shown by the general increase in the planktonic : periphytic ratio (Fig. 8). Sample MO-017 records an event of freshwater influence, mainly due to the contribution of *Fragilaria leptostauron* var. *dubia*. This event is also accompanied by an increase in the aerophilic components (e.g. *Navicula seminulum* Grunow or *Nitzschia amphibia*) which testify to desiccation. Similar periods of desiccation could favour the development in some cases of poor preservation such as those registered in sampled levels MO-006 and MO-011 which contained only valve fragments.

Inner shallow lacustrine environments with extensive areas of open water deduced from some facies in the Cerro Mogote section explain the development of facultative planktonic taxa with an oligosaline character due to the minor influence of freshwater inputs in these positions. During this stage, drops in water level with a parallel increase in aerophilic forms and freshwater discharges might be explained by the activity of the alluvial fan systems which were probably the primary controllers of freshwater input in this part of the basin.

4.4.2. Diatom subzone MO-A$_2$

This subzone includes samples MO-027, MO-153, MO-200, MO-210, MO-310, MO-322, MO-330, MO-352, MO-360 and MO-370. The diatom record of this subzone documents a general drop in the water level and freshening of the typical oligosaline waters in comparison to the previous subzone (Fig. 8 ; Fig. 9). The change to more paludine conditions shows, however, two brief events of water deepening characterized by two peaks of *Fragilaria brevistriata* Grunow (samples MO-200 and MO-370). Both peaks represent the uniquely large occurrence of this species in both the Cerro Mogote and Quebrada Temblor sections. This species can exist in both tychoplanktonic and periphytic habitats. Moreover, not only the extent of open waters but changes in nutrient content and the lacustrine spatial mixing regime can affect its abundance in the sediments (Gasse et al., 1997). High percentage values for this species in Cerro Mogote are not followed by a parallel increase in periphytic taxa (e.g. *Cocconeis* spp., *Navicula* spp., *Nitzchia* spp.) nor seem to affect a sharp reduction in facultative planktonic diatoms (mainly constituted by *Fragilaria construens* f. *subsalina*) and for this reason peaks of *Fragilaria brevistriata* are interpreted, in our case, as indicators of freshwater inputs associated with true highstands in water level.

This subzone also records an event of high oligosaline to mesosaline waters (level MO-360) mainly recognized from the occurrence of the meso to polysaline *Mastogloia smithii* Thwaites, *Amphora holsatica* Hustedt and *Cymbella pusilla*. Both *Mastogloia smithii* and *Cymbella pusilla* are indicators of $CaSO_4$ rich waters (Gasse et al., 1987). High values of the meso to polysaline diatoms (which can reach 60% of the total diatom assemblage) indicate a probable evaporative salt concentration event maybe associated with the isolation of a small waterbody.

4.5. Diatom diversity and transport

Diatom diversity records maximum values for the Quebrada Temblor section while reduced diversity is recorded in Cerro Mogote due to the overwhelming abundance of *Fragilaria construens* f. *subsalina* (Fig. 3 ; Fig. 4). As the interpretation of the diversity indices in terms of biological community structure alone is not justified for the fossil record due to taphonomical processes (Beerbower and Jordan, 1969), the possible effects of diversity biasing by transported diatoms were examined.

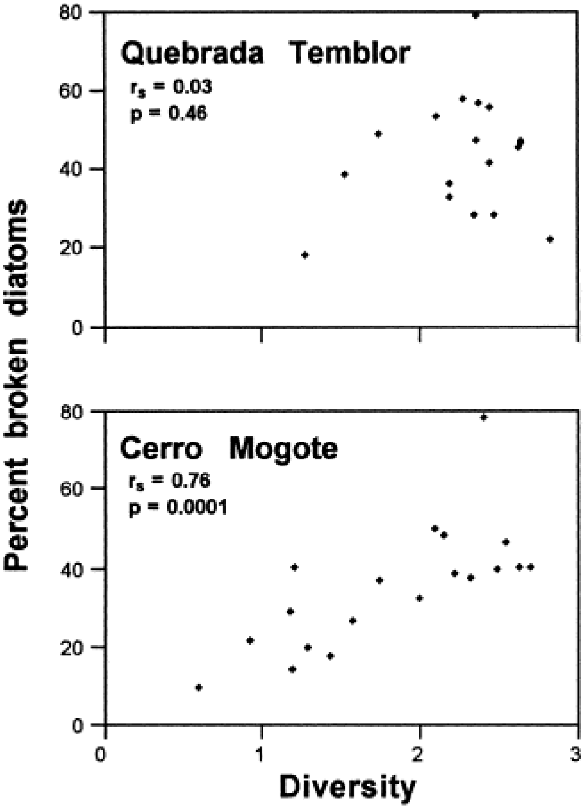

Fig. 10. Relationship between diatom diversity and percent of total broken diatoms. r_s is the Spearman rank correlation coefficient. Note the high correlation for the Cerro Mogote section in contrast with the Quebrada Temblor section, suggesting the strong influence of clastic reworking on final composition of the diatom assemblages in Cerro Mogote.

Diatom diversity shows a high correlation with the percent of total fragmented valves in Cerro Mogote (Spearman correlation r_s=0.76, one tailed p=0.0001, Fig. 10) indicating that most of the diversity in this inner lacustrine facies is apparently due to diatoms of allochthonous precedence. However, both variables are not significantly correlated in Quebrada Temblor (r_s=0.03 one tailed p=0.46, Fig. 10), suggesting that other factors have to be considered. Shifts in sedimentary environments are more obvious for Quebrada Temblor where three contrasting diatom zones have been defined. Long-term environmental changes in this section might be the leading cause for its diatom diversity. This is not the case of Cerro Mogote, where a more homogeneous dominant inner lacustrine facies persists throughout the whole

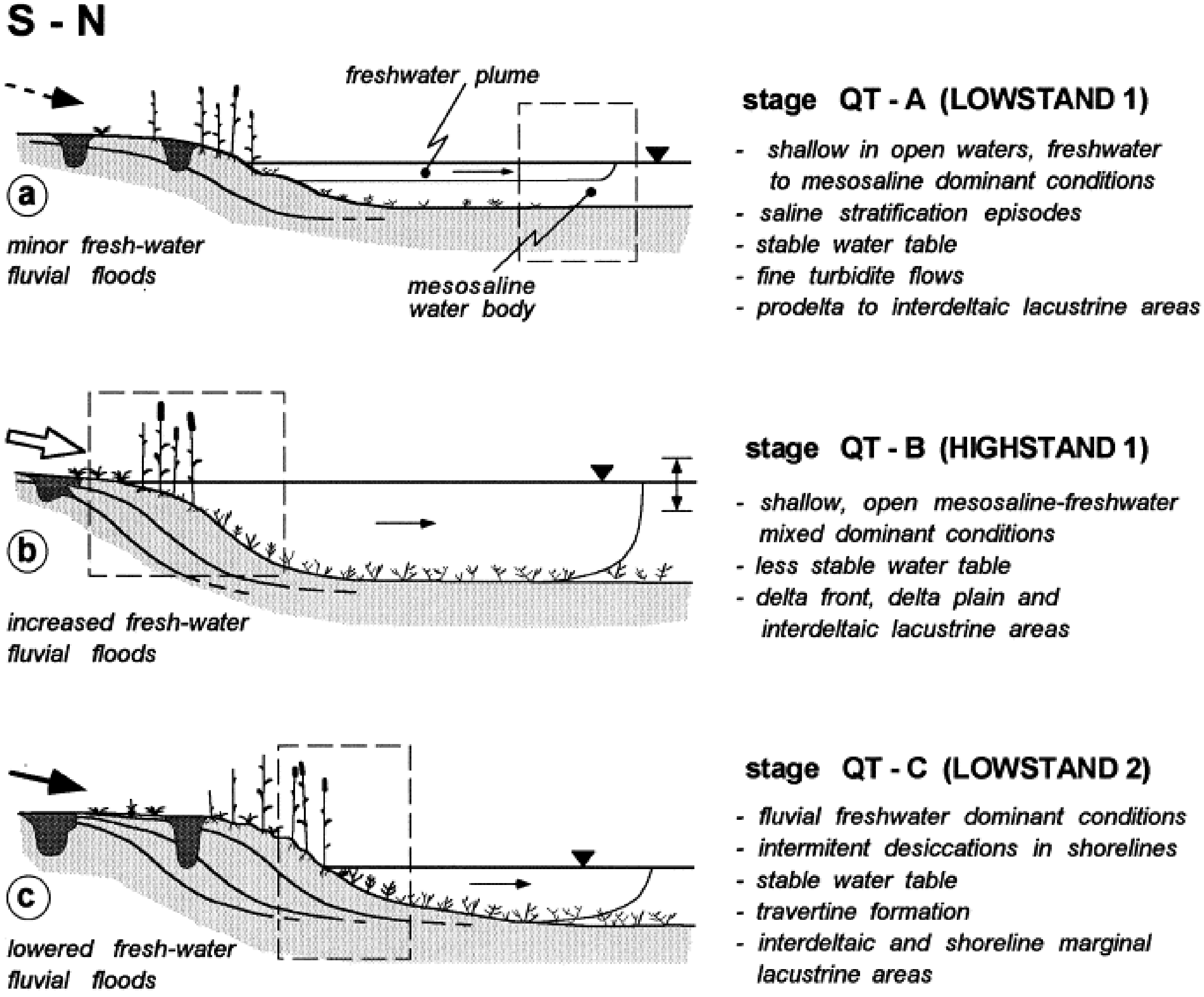

Fig. 11. Sedimentary model (not to scale) for diatom zones in the Quebrada Temblor section. Dashed rectangle indicates the location of the subenvironments where diatom assemblages developed. See explanation in text.

section. This probably links diversity to inputs of diatoms from allochthonous precedence by the episodic currents generated at the alluvial fan zones and which affected the marginal and the inner, lacustrine areas.

4.6. Diatom-based lake system evolution

Changes in the diatom record allow a tentative reconstruction of the paleohydrological evolution of the Quillagua Llamara Basin during the sedimentation of the Quillagua Formation. (Fig. 11Fig. 12). This interpretation is, however, complicated by the fact that diatom assemblages of a sampled level are usually composed of a mixture of diatoms depicting different environmental conditions. This is a common feature in the lacustrine systems of arid or semiarid zones and may reflect both the spatial juxtaposition of coeval habitats or short-term fluctuations in the paleosystems which means one sample represents different stages of lacustrine evolution (Gasse et al., 1987). The Quebrada Temblor section displays an upward trend in salinity reduction (Fig. 6B) which shows a parallelism with the increase in freshwater fluvial influence as deduced by the stratigraphic succession (curve `a', Fig. 4). Maximum salinity conditions in unit QT-A gave this lacustrine marginal zone a mesosaline character interrupted by episodic freshwater inputs which, when at a minimum degree of persistence, probably gave rise to water stratification situations (Fig. 11a, level QT-011). The dilution pattern exhibited along diatom zone QT-B (Fig. 11b) is reflected in a change from mesosaline to oligo

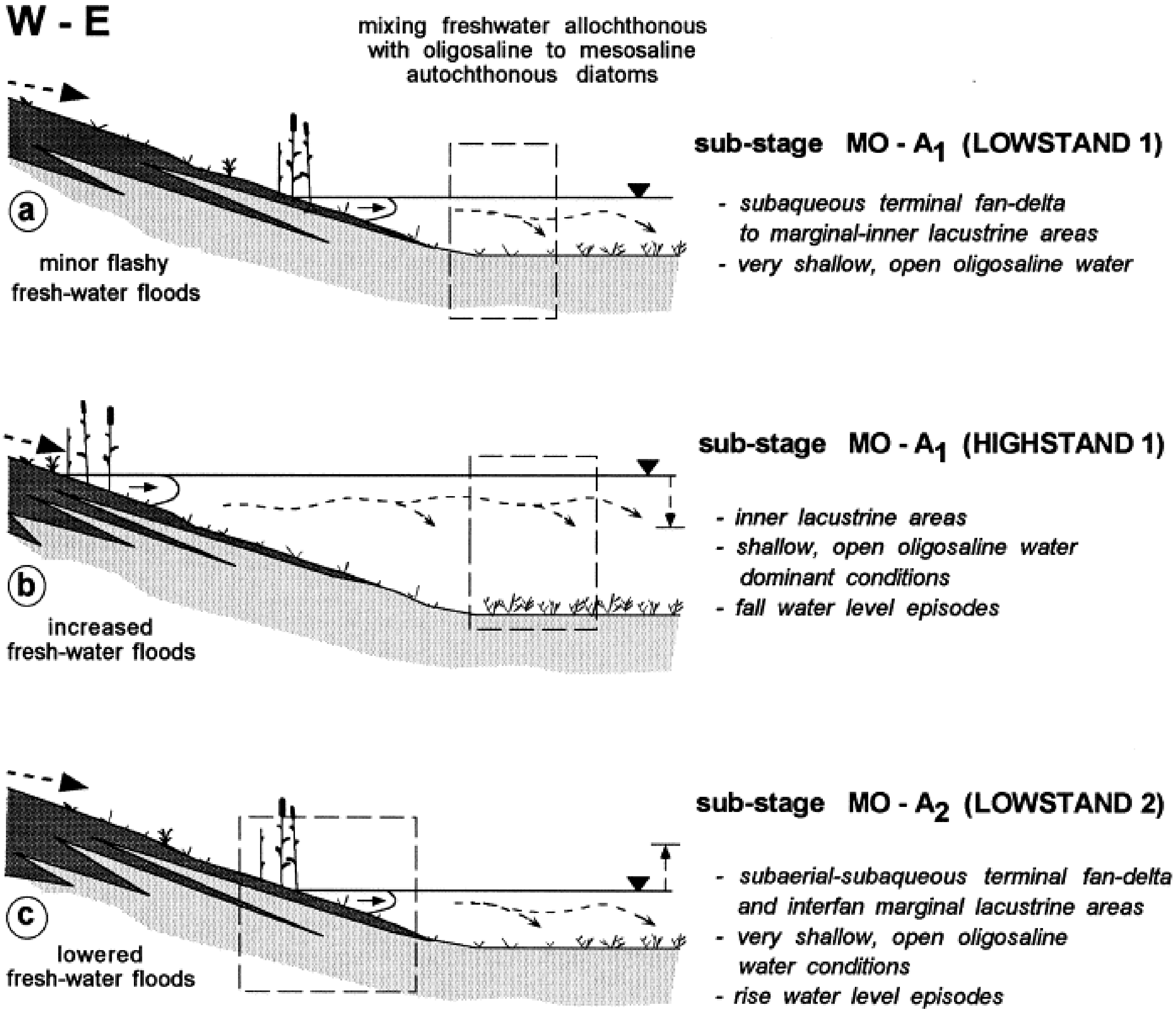

Fig. 12. Sedimentary model (not to scale) for diatom zones in the Cerro Mogote section. Dashed rectangle indicates the location of the subenvironments where diatom assemblages developed. See explanation in text.

saline waters (Fig. 6B). Substantial shifts in freshwater volume of fluvial floods led however to extreme events of saline lacustrine dominance (QT-142) and of an almost freshwater fluvial dominance (QT-181). In between these two contrasting situations, standard circumstances in zone QT-B would reveal a dominant oligosaline situation and probably stratification events as suggested by the mixture of freshwater and saline forms of predominantly autochthonous character. During the sedimentation of diatom zone QT-C (Fig. 11c), an oligosaline (QT-015 and QT-016) to freshwater (QT-264) waterbody occupied the site, where both travertine facies and abundance of aerophilous diatoms indicate a shoreline subjected to intermittent desiccation events. Low water levels and freshwater influence are therefore compatible with a freshwater delta-marsh controlled by the direct influence of fluvial surface drainage.

4.6.2. Cerro Mogote (Fig. 12)

The lack of an euplanktonic diatom record in this section indicates that shallow water conditions were also typical for Cerro Mogote. Very high abundances of tychoplanktonic diatoms during MO-A_1 subzone imply, however, that deeper water conditions and more extensive open waters were recorded when compared to Quebrada Temblor (Fig. 12a, b). Both lithofacies and changes in the planktonic : periphytic ratio in subzone MO-A_2also reflect marginal conditions for this site (Fig. 12c). Cerro Mogote also documents sharp bathymetric changes in its history (Fig. 3 ; Fig. 8). An almost continuous upward deepening trend inside substage MO-A_1 is followed by a relative shallowing trend which included the distal alluvial red beds in subzone MO-A_2. A new deepening trend may possibly be identified at the top of this stage (MO-370). These general trends are interrupted by lowering and rising pulses (levels MO-017 in MO-A_1 and MO-200 in MO-A_2).

Lithological reconstruction of inner lacustrine facies stability for Cerro Mogote (curve `a', Fig. 3) shows a close relation with shifts in lake depth deduced by the planktonic : periphytic ratio (Fig. 8). This would mean, in contrast with Quebrada Temblor, that lacustrine stability conditions in Cerro Mogote must be closely related with true major changes in the water content of the whole basin.

Changes in salinity are of a lower order of magnitude in Cerro Mogote than in Quebrada Temblor due to the inner position of Cerro Mogote which makes it less sensitive to freshwater inputs. No clear salinity trends are recognized, but some punctuated dilution episodes took place (MO-030, MO-017, MO-200, MO-370). An oligosaline waterbody occupied the site for most of the Quillagua system evolution and the more episodic and weaker character of freshwater influxes was not favourable for the development of permanent freshwater plumes. Shallower conditions in MO-A_2 might explain marginal exposure of the site (red bed stretch) and thus a maintenance by freshwater discharges from alluvial fans which have a direct effect on the increase of diatom diversity by inputs of allochthonous diatoms. Episodic high salinity conditions recorded in upper MO-A_2(MO-360) could be related to very poorly water fed shallow marginal zones.

5. Major changes in base lake level

Reconstruction of the expansive–retractive cycles based on lithofacies analysis and of changes in bathymetry deduced from the grouping of diatoms according to their life-form spectra allows the major changes in the lacustrine system which occupied the Quillagua–Llamara Basin during the Late Miocene–Pliocene to be established (Fig. 13). Comparison of the changes experienced by each of the analyzed sections will trace the evolution of the basin as a whole. Taking this into account, any variability in the Cerro Mogote section would be more representative of the whole basin than of Quebrada Temblor, which is more frequently subjected to local processes.

Highstand stages in both sections can be characterized by the double condition of (1) high relative contributions of inner lacustrine facies relative to marginal lacustrine and alluvial facies and (2) high relative values for the diatom planktonic : periphytic ratio (Fig. 13). The specific values of both parameters which discriminate low from highstands must be different in both sections due to marked differences in detritic influx and topography. Highstand conditions for Cerro Mogote have thus been defined for values of the planktonic : periphytic ratio higher than 2 and an accumulative thickness of lacustrine facies reaching 50% of the total thickness for that specific stretch. On the contrary, values for Quebrada Temblor were established at 1 and 35%, respectively.

Lowstand ascending conditions are recorded from the base of Cerro Mogote to level MO-013 (lowstand 1, Fig. 13). Between levels MO-015 and MO-024 sedimentation occurred during a highstand situation which had a summit in level MO-018 where the ascending–transgressive trend (transgression 1) transformed in a descending–regressive trend (regression 1). The stretch formed between levels MO-027 and MO-360 sedimented during lowstand conditions (lowstand 2) and is characterized in its intermediate part by the disappearance during several significant periods of the water lens in the area (alluvial red-bed sedimentation) (Fig. 13). A return to a rising and transgressive trend begins again in level MO-310 where stable lacustrine conditions were re-established. The lake level remained stable between levels MO-310 and MO-360. This situation lasted until level MO-370 when a rapid increase in the lacustrine conditions gave rise to a probable new highstand situation (highstand 2). The lack of a

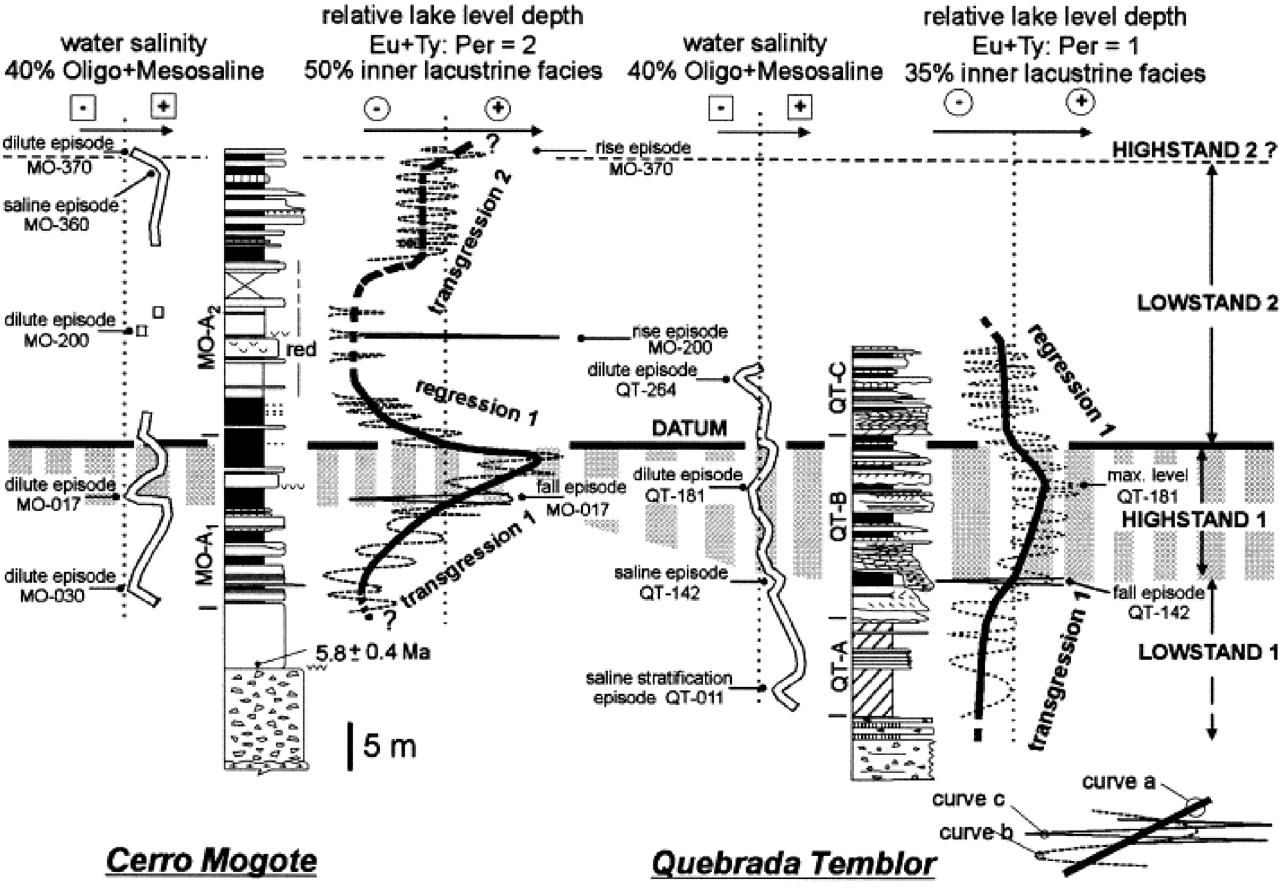

Fig. 13. Lake level oscillation hierarchy and water salinity trends deduced for the Cerro Mogote and Quebrada Temblor sections. Remarkable lowering and rising level episodes and also main diluted and saline episodes are highlighted. Curve `a' shows lower order low frequency variability (4th order) based on both the ratio of marginal-inner lacustrine facies and the (Euplanktonic + Tychoplanktonic):Peripytic diatom ratio. Note that relative highstands in the Cerro Mogote section are defined on base of (1) occurrences of inner lacustrine facies higher than 50% of the total thickness and (2) an Eu + Ty : Per ratio higher than 2. Highstands in the Quebrada Temblor section are defined by values greater than 35% for inner lacustrine facies occurrence and 1 for the diatom ratio. Curve `b' shows 5th order high-frequency variability, which is mainly interpreted from lithofacies analysis. Curve `c' shows higher frequency variability (6th order or higher) which is deduced from the Eu + Ty : Per diatom ratio. Water salinity curve (on the left side of the logs) was made up using oligosaline plus mesosaline diatom percentages; vertical line indicates a value of 40%, which has been assumed as being a significant salinity boundary. Highstand 1 position in both sections is emphasized with vertical gray bars.

diatom record during sedimentation of the red beds in lowstand 2 and the definition of highstand 2 by a unique sample make the definition of real bathymetric trends for the upper part of Cerro Mogote uncertain.

The transgressive and regressive trends defined above were interrupted by rise and drop pulses, respectively. Highstand 1 showed a sharp water drop during sedimentation of level MO-017. Lowstand 2 records a strong positive pulse during level MO-200 and probably MO-370.

Quebrada Temblor shows a similar evolution in water lake level but the record displays less pronounced trends when compared to Cerro Mogote (curves `a', Fig. 13). The lower part of the section was sedimented during lowstand and rising transgressive conditions, from the base of the section to level QT-142 (lowstand 1 and transgression 1). Between levels QT-012 and QT-211, sedimentation occurred during a relative highstand (highstand 1) acquiring maximum depth conditions around level QT-181. A regressive phase followed this level (regression 1) and a new relative lowstand (lowstand 2) is identified from level QT-014 to the top of the section. This lowstand records periods of minimum depth conditions occurring during intermittent subaerial sedimentation.

As in Cerro Mogote, the dominant trends were interrupted by small lowering and rising pulses. The most significant occurred during sedimentation of level QT-142 where a drop in the lake level, accompanied by a salinization event, probably due to stronger evaporation conditions, interrupted the transgressive trend. This pulse, as with those in Cerro Mogote, must be related to high or intermediate order bathymetric variations as will be discussed later.

6. Discussion and concluding remarks

The Quillagua–Llamara Basin has experienced several endorrheic perennial lacustrine episodes since Late Miocene times (Sáez et al., 1999). The most perennial of these lacustrine episodes took place from the latest Miocene (5.8±0.4 Ma) to Early Pliocene in northern sectors of the basin when the latter was fed from the south by a major fluvial system. Tectonic activity in the Calama Basin, which acted as the main catchment area for this system, and in the linking threshold zone located between Calama and Quillagua–Llamara basins, controlled water discharge into the Quillagua–Llamara Basin. However, the wide extent of the lacustrine system meant it was also fed by more local, ephemeral alluvial fan floods. The alluvial fan systems contributed very different volumes of water depending on the extent of their drainage area in the Precordillera and the Coastal Range. All these factors meant that the paleohydrological evolution of the basin was not only strongly influenced by potential variations in the regional climatic system but also by variations in hydrological parameters, influenced by the evolution of local drainage.

The southern end of the lacustrine system (Quebrada Temblor area) received significant amounts of sandy to pebbly materials from the longitudinal fluvial system. This resulted in the development of fluvial-dominated lacustrine deltaic successions with a predominance of channelized facies and locally conforming some steeper bathymetric gradients as suggested by the deep channel entrenchment in the underlying lacustrine deposits and the occasional occurrence of euplanktonic diatoms (Fig. 6A). In contrast, granulometry, morphology and bathymetric gradient in the remaining basin margins (including Cerro Mogote area) were primarily conditioned by the different types of alluvial fan systems involved. Most of the margins of the lacustrine system were non-coincident and conformed by distal alluvial fan fringes which generated fine grained non-channelized deposits and resulted in very low marginal bathymetric gradients. Inner-open but shallow lacustrine deposits were only recorded in middle parts of the Cerro Mogote section and correspond to a number of depositional episodes in zones located at some distance from the southern fluvial influence.

The diatom records in both contrasting analyzed sections were useful for reconstructing local and general changes in the hydrological basin conditions. Aridity and internal drainage made the waterbody more saline than the waters which fed the basin. Dominant oligosaline conditions prevailed in the main waterbody during the studied period and are well recorded in the Cerro Mogote section. In the southern marginal sectors (near the Quebrada Temblor site) the freshwater inputs directly fed by the fluvial system resulted during some periods in the persistence of permanent freshwater plumes which probably gave rise to water stratification. Innermost lacustrine zones in the basin — represented by a certain amount of deposition in the Cerro Mogote section — received less freshwater feeding by alluvial fans. This fact resulted in more homogeneous, persistent oligosaline conditions during the studied interval. Periods of high oligosaline to mesosaline character and shallow water level have been reported both in the Quebrada Temblor section (stage QT-A and level QT-142) and the Cerro Mogote sections (lower parts of MO-A_1 diatom subzone and level MO-360). In the case of Quebrada Temblor, these periods might be explained by evaporative concentration processes associated with shallow environments as deduced from the planktonic : periphytic ratio. In the case of Cerro Mogote the higher oligosaline to mesosaline periods could have resulted from the lower freshwater inputs to the lacustrine system derived from alluvial fans with reduced drainage areas.

On the one hand the paleogeographic setting points to the fact that salinity was primarily related not to the lake level changes resulting from water volume changes but to local fluvial inputs in the Quebrada Temblor zone and to the more ephemeral, alluvial fan floods in the Cerro Mogote area. This meant that shallow conditions were not always directly coupled with water salinization events as might be supposed by salt concentration in a shrinking waterbody. This is evident in some Cerro Mogote episodes (MO-030, MO-017) and in all QT-C diatom zone (especially in QT-264), where shallowing of the lacustrine system is, in general, accompanied by situations of slight freshwater conditions. As suggested elsewhere (Bradbury, 1989), lowering of the lake water level (either by climatic or local hydrological factors) can place marginal sites under the influence of freshwater income which is shifted basinward. In our specific case, this meant terminal alluvial fan zones had a greater influence on formerly inner lacustrine areas. When this activity was significantly increased, freshwater influence was accompanied by a true deepening of the lake (levels MO-200 and MO-370).

On the other hand, highstands with no coeval freshwater conditions but associated with oligosaline situations in Cerro Mogote (upper part of diatom subzone MO-A_1, except MO-017) must be understood in the general depositional framework as being related to water inputs coming from the northward flowing fluvial system which raised the lake level in the whole lacustrine basin but did not result in significant widespread salinity changes.

Sequential analysis and paleoenvironmental interpretation of the sedimentary and diatom record distinguish up to four hierarchical orders of variability in the lake level of the Quillagua–Llamara Basin (4th order and higher; see review by Einsele et al., 1991). The mixing of diatoms of different ecological affinities (mainly as regards their salinity tolerances) in each of the sampled levels and the presence of some poorly developed fine laminated lacustrine facies, reflect the effects of the highest order (higher than 6th order) short-term intra- or inter-annual pulses experienced by the lacustrine system. Each sample represents the average signal imprinted in the sediments of diatom successions corresponding to several or, under some circumstances, just a single short-term hydrological cycle. Measurement of this very high frequency variability is difficult because of the interplay of several factors which hinder interpretation of the diatom record. Juxtaposition of ecologically incompatible diatom species might be explained not only by short-term temporal mixture but by the reworking of older sediments elsewhere in the catchment or by spatial coexistence due to stratification events (Barker et al., 1990). The latter could be the case for some levels in the lowermost part of the Quebrada Temblor section, interpreted as representing water stratification (level QT-011). Uncertainties derived from this make it impossible to draw a complete tentative curve for this very high frequency variability in Fig. 13.

Short-term variability contained in each of the samples might interfere with the interpretation of the longer-term trends. Shallow waterbodies of semi-arid or arid zones experience extremely large intra- and inter- annual variations (Gasse et al., 1997) whereas deeper waterbodies would probably buffer the range of this short-term variability. Perennial, shallow waterbodies were dominant along the studied interval in the Quillagua–Llamara Basin, and were not found to alternate with moderate to very deep waterbodies as could be deduced from the virtual absence of euplanktonic diatoms. The range of very short-term variability can thus be considered as more or less constant for the whole studied interval in both analyzed sections. This means the interpretation of variability at longer time intervals was not strongly biased by differences in the degree of short-term variations which might be the case when comparing shallow and deeper facies.

The higher order–high frequency variability (curves `c', Fig. 13) recorded in the studied sections corresponds to the punctuated interruptions of the minor order bathymetric sequential trends (curves `a' and `b', Fig. 13). This kind of variability (probably 6th order, 0.001–0.01 Ma) is more easily recognized when overall transgressive and regressive trends are interrupted by low and highstand pulses respectively. This is the case of negative pulses during the sedimentation of levels QT-142 and MO-017 corresponding to a transgressive assemblage or the interruption in Cerro Mogote of the lowstand 2 by at least one positive oscillation during the sedimentation of level MO-200. The significance of other similar pulses which are nested in the minor order trends is not clear due to their stratigraphic position at the base or the top of a section (levels MO-005 and MO-370). These do not discriminate if they represent a real short-term pulse or a change in direction of a minor order trend. The sampling strategy employed did not enable to recognize such cycles.

The deepening/shallowing facies arrangement of decimetre-thick sequences in both sections reveals a lower (5th order, 0.01–0.1 Ma) order of variability (curves b, Fig. 13). The use of diatoms to register changes occurring at this scale is also strongly conditioned by taphonomical circumstances. Whereas inner lacustrine facies displayed good preservation conditions, most of the travertine and marginal lacustrine detrital facies had poor diatom records or were even barren of diatoms. Data presented in this paper show, however, that some rather distinct lithofacies which are included in the same sequence trend, as are some marls or pure diatomites, do not show significant variations either in their percentage composition of saline diatoms or in their values of the planktonic : periphytic ratio. Travertine facies, however, do sometimes show more freshwater and aerophilic taxa than the remaining inner lacustrine facies which make up a sequence.

The combined use of lithofacies analysis and the diatom-based paleoenvironmental interpretation allowed us to trace the bathymetric variability which corresponded to the lower sequence order (4th order, 0.1–1 Ma) reported in the studied sections (curves a, Fig. 13). Relative highstands are defined for those section segments with high percentage contributions of inner lacustrine facies (higher than 30–50%) and high planktonic : periphytic ratio values. In contrast, relative lowstand stages show high percentages of marginal lacustrine carbonate (travertines) and detritic facies (mudstones, sandstones) which also show low planktonic : periphytic ratio values.

Based on these criteria, it is proposed that the basin underwent two well-defined low order highstand and two lowstand situations which entailed one regressive trend between two transgressive trends (Fig. 13). The second transgressive episode and the overlying highstand episode were, however, not recorded in the Quebrada Temblor section due to its shorter stratigraphic record. This minor 4th order variability is interpreted at a regional level as being related with the threshold response to the tectonic closure and opening of the neighbouring Calama Basin, to long-term climatic variability or, more probably, as the result of the interplay between both tectonic changes and climatic variability.

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