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Eocene to Pleistocene lithostratigraphy, chronostratigraphy and tectono-sedimentary evolution of the Calama Basin, northern Chile

Geoffrey May

Department of Geology & Petroleum Geology, King's College,
University of Aberdeen, Aberdeen AB24 3UE, U.K.
Present address: Marathon Oil Co. PO Box 3128,
Houston, Texas, 77253-3128 USA
geoff-may@hotmail.com

Adrian J. Hartley

Department of Geology & Petroleum Geology, King's College,
University of Aberdeen, Aberdeen AB24 3UE, U.K.
a.hartley@abdn.ac.uk

Guillermo Chong

Departamento de Ciencias Geológicas, Universidad Católica del Norte,
Avenida Angamos 0610, Casilla 1280, Antofagasta, Chile
gchong@ucn.cl

Fin Stuart

Isotope Geoscience Unit, Scottish Universities Environmental
Research and Reactor Centre, East Kilbride, G75 0QF, U.K.
F.Stuart@suerc.gla.ac.uk

Peter Turner

School of Earth Sciences, University of Birmingham,
Edgbaston, Birmingham, B15 2TT, U.K.
p.turner@bham.ac.uk

Stephanie J. Kape

School of Earth Sciences, University of Birmingham, Edgbaston,
Birmingham, B15 2TT, U.K.
Present address: CNR International,
St. Magnus House, Guild Street,
Aberdeen AB11 6NJ, U.K.
Stephanie.Kape@cnrinternational.com

ABSTRACT

New $^{40}Ar/^{39}Ar$ radiometric, sedimentological and structural data from post-Paleocene sedimentary strata in the Calama Basin, northern Chile suggest that the established lithostratigraphy of the basin-fill requires revision. A new lithostratigraphic scheme for the Eocene-Pleistocene stratigraphy of the Calama Basin is proposed here. The key features of this scheme are that the existing Calama Formation is retained although the age of the formation is redefined as (?Lower) Eocene to (?)Lower Miocene. The El Loa Formation is elevated to group status and redefined as Lower Miocene to Upper Pliocene in age. The El Loa Group includes four newly defined formations: the Jalquinche, Opache, Lasana and Chiquinaputo formations. The existing definition of the uppermost unit within the Calama Basin, the Upper Pliocene to Pleistocene Chiu-Chiu Formation, is retained. The tectono-sedimentary evolution of the Calama Basin-fill reveals three distinct unconformity-bounded phases of sedimentation: Eocene-Oligocene, early Miocene to late mid-Miocene and late Miocene to late Pliocene. Sedimentation commenced in the Eocene with deposition of alluvial braidplain deposits (Calama Formation). This style of sedimentation occurred across northern Chile throughout the Oligocene following the Incaic Orogeny. From 22 Ma to 10 Ma ephemeral fluvial sediments were developed along the Calama Basin flanks (Lasana Formation), playa sandflat and mudflat deposits (Jalquinche Formation) in the basin centre. Equivalently-aged sediments in both the Salar de Atacama and Pampa del Tamarugal basins also indicate deposition in endorheic basins. Late Miocene sedimentation occurred diachronously across the north Chilean forearc. The Pampa del Tamarugal and Calama Basin areas were linked around 6 Ma following tectonic activity. Regional palustrine carbonate sedimentation occurred in the Calama Basin centre (Opache Formation) with fluvial sedimentation along the eastern basin margin (Chiquinaputo Formation). The change in depositional style is attributed to increased rainfall in drainage basins. At about 3 Ma the Calama Basin was subject to gentle folding, followed by entrenchment of the Río Loa and Río San Salvador through Miocene to Pliocene strata to reach a new base-level caused by breaching of the Coastal Cordillera by the Río Loa to reach the Pacific. Localised diatomite and evaporite (anhydrite) deposition took place in depressions created by either folding of older strata or geomorphic features (Chiu-Chiu Formation). Up to 5 unconformities are present in the Calama Basin-fill and occur across either the whole of the basin or localised areas of the basin. They are not present in adjacent basins which suggests they were generated by movement on the Precordilleran/West Fissure Fault Systems. Facies analysis of the Eocene to Pleistocene succession suggests that sedimentation took place under an arid/semi-arid climate throughout this time period. Occasional fluctuations in climate suggesting increased runoff are indicated by the development of diatomites together with lacustrine and palustrine limestones. However, it is unlikely that the climate was never more humid than semi-arid. Similar facies developments in the Pampa del Tamarugal and Salar de Atacama basins during the Oligocene to Pleistocene suggest that climate changes affected the whole of the forearc and were not restricted to individual basins.

Key words: Northern Chile, Calama Basin, Stratigraphy, $^{40}Ar/^{39}Ar$ dating, Cenozoic.

RESUMEN

Litoestratigrafía, cronoestratigrafía durante el Eoceno al Pleistoceno y evolución tectono-sedimentaria de la Cuenca de Calama, norte de Chile. Los resultados obtenidos de estudios estructurales, sedimentológicos y dataciones radiométricas de las secuencias sedimentarias post Eoceno de la Cuenca de Calama, sugieren que la litoestratigrafía establecida para su relleno sedimentario, requiere una revisión. En este trabajo, se propone un nuevo esquema litoestratigráfico pos-Paleoceno para esta cuenca. Las características claves de este esquema son que la Formación Calama se mantiene aunque su edad es considerada como Eoceno Inferior (?) a Mioceno Inferior (?). La Formación El Loa es redefinida como Grupo y asignada al Mioceno Inferior-Plioceno Superior. Este Grupo incluiría la definición de quatro nuevas formaciones: Jalquinche, Opache, Lasana y Chiquinaputo. Finalmente, se mantiene la definición de la Formación Chiu-Chiu, la unidad más superior en la Cuenca de Calama, con su edad Plioceno a Pleistoceno. La evolución sedimentaria del relleno de la Cuenca de Calama muestra tres fases distintas de sedimentación limitadas discordantemente: Eoceno-Oligoceno, Mioceno Temprano a Mioceno Medio y Mioceno Tardío a Plioceno Tardío. La sedimentación se inició en el Eoceno Inferior con depósitos de llanuras aluviales (Formación Calama). Este estilo de sedimentación es reconocido en todo el norte de Chile durante el Oligoceno como consecuencia de la Orogénesis Incaica. Entre los 22 y 10 Ma sedimentos de corrientes fluviales efímeras fueron formados a lo largo de los flancos de la Cuenca de Calama (Formación Lasana); arenas y limos de playa sedimentaron en la parte central de la cuenca. Sedimentitas equivalentes, tanto en el Salar de Atacama como en la Pampa del Tamarugal, indican depositación en cuencas endorreicas. Sedimentación miocena tardía se produce diacrónicamente en el antearco del actual norte de Chile. La Pampa del Tamarugal y la Cuenca de Calama se conectaron alrededor de los 6 Ma debido a actividad tectónica. Sedimentación carbonatada palustre se deposita en la parte central de la Cuenca de Calama (Formación Apache) con sedimentación fluvial a lo largo de su margen oriental (Formación Chiquinaputo) cambio que se atribuye a una mayor precipitación en las cuencas de drenaje. Alrededor de los 3 Ma se produce un plegamiento suave en las secuencias sedimentarias, la que es seguida por el encajonamiento de los ríos Loa y Salvador cuando las secuencias Mioceno-Plioceno alcanzan un nuevo nivel de base debido a la apertura de la Cordillera de la Costa cuando el río Loa alcanza el Océano Pacífico. Por cambios geomorfológicos locales y/o plegamiento de las secuencias sedimentarias antiguas se depositan diatomitas y evaporitas (anhidritas) de la Formación Chiu-Chiu. En la Cuenca de Calama se reconocen hasta cinco disconformidades que ocurren tanto en forma generalizada como localizada. Estas disconformidades no están presentes en cuencas adyacentes lo que sugiere la posibilidad que se hayan generado por actividad de estructuras de los sistemas Precordillerano/Falla oeste. Los análisis de facies de la sucesión Eoceno-Pleistoceno sugieren que la sedimentación tuvo lugar en condiciones climáticas áridas a semiáridas durante este lapso. Fluctuaciones climáticas originales sugeridas por incremento en los flujos están indicadas por la depositación de diatomitas y carbonatos palustres. Sin embargo es poco probable que el clima haya sido más húmedo que semiárido. Desarrollo de facies simlares en el Salar de Atacama y la Pampa del Tamarugal durante el Oligoceno hasta el Plioceno sugieren que los cambios afectaron a la totalidad del Antearco y no se restringieron a cuencas individuales.

Palabras claves: Norte de Chile, Cuenca de Calama, Estratigrafía, Datación $^{40}Ar/^{39}Ar$, Cenozoic.

INTRODUCTION

The Calama Basin is situated at 2000 to 3500 m altitude between 22 and 23°S in northern Chile, where it forms one of a series of Tertiary forearc basins (Fig. 1). The basin is located largely within the Precordillera, occupying an important part of the forearc linking two of the major Tertiary depocentres of northern Chile: the Central Depression (Pampa del Tamarugal) and the Salar de Atacama (Fig. 1). An understanding of the lithostratigraphic development within the Calama Basin will facilitate correlation between the sedimentary successions in these adjacent basins and allow elucidation of the tectono-stratigraphic development of northern Chile in the late Paleogene to Neogene.

The basin is bounded by basement highs composed of ?Precambrian to Palaeogene volcanic, plutonic and sedimentary rocks to the north (Sierra de Moreno), south (Sierra de Limon Verde) and west (Cerros de Guacate). The north east basin margin is constrained by volcanic rocks that form part of the Miocene to Recent volcanic arc (Western Cordillera). To the southeast the basin-fill is overthrust by Late Cretaceous to Eocene sedimentary and volcanic rocks of the Purilactis Group and younger formations (Mpodozis *et al.* 1999). The basin contains up to 700 m of continental sedimentary strata that unconformably overlie Triassic to Eocene sedimentary, volcanic and plutonic rocks. The basin-fill can be traced westwards into the Central Depression across a topographic low within a basement ridge between the Sierra de Moreno and the Cerros de Guacate (Fig. 2).

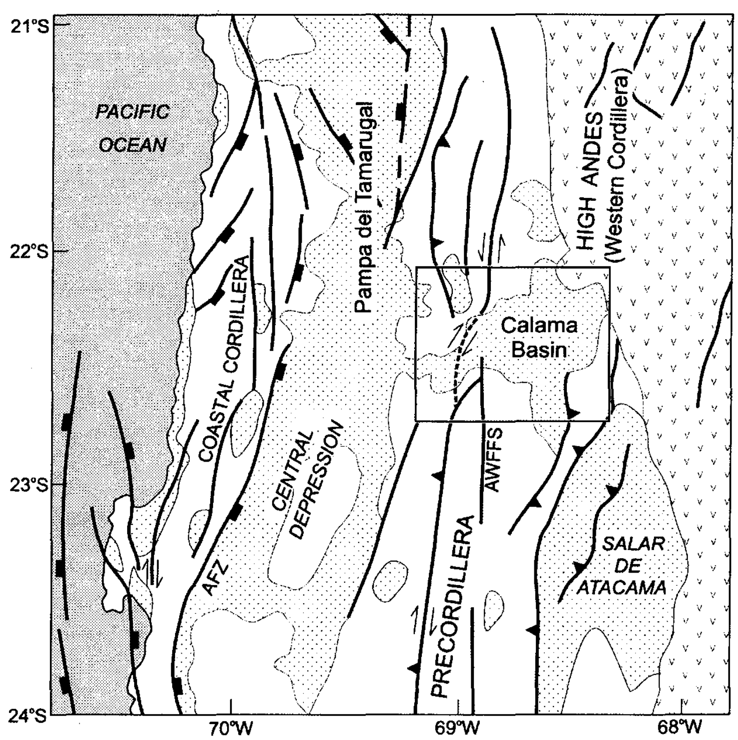


FIG. 1. General distribution of Tertiary (post-Eocene) sedimentary basins in the north Chilean forearc. Box outlines area of figure 2. **AFZ=** Atacama Fault Zone; **AWFFS=** Argomedo-West Fissure Fault System. Stipple pattern indicates late Eocene to Holocene basins; **v=** volcanic arc, unpatterned area is pre-Eocene basement.

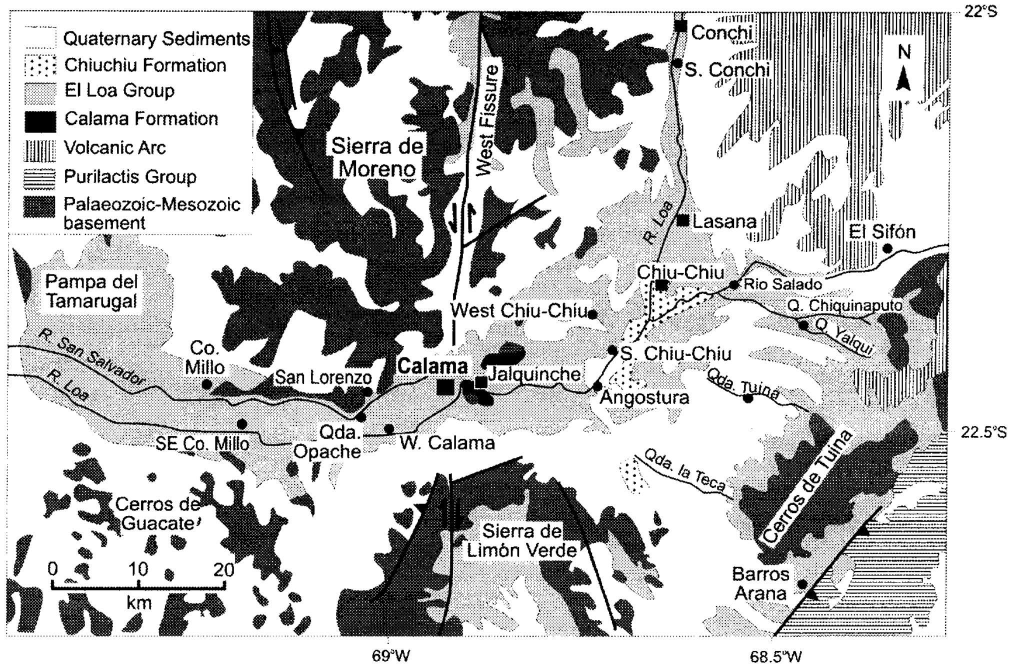


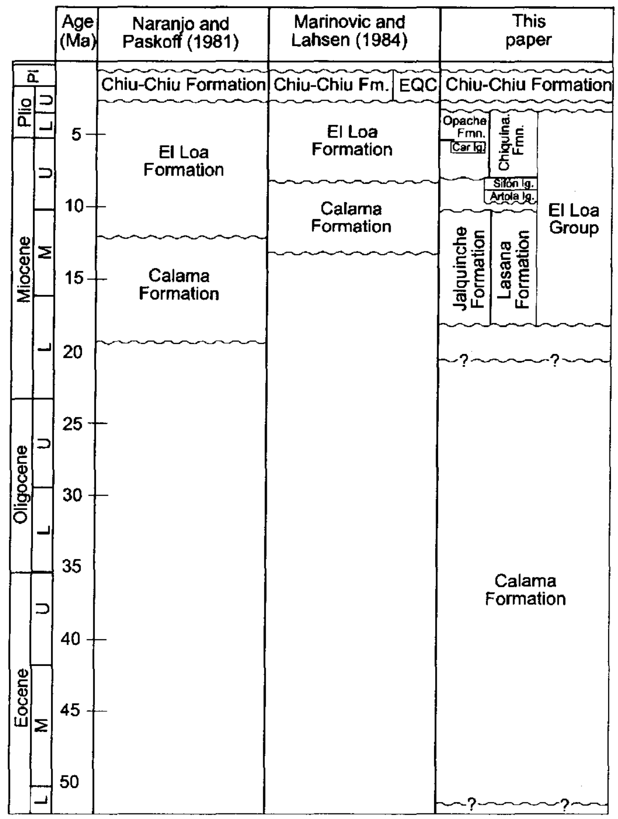
FIG. 2. General geological map of the Calama Basin (modified after Marinovic and Lahsen, 1984), showing the location of the studied sections.

PREVIOUS WORK

Previous work on the sedimentology, lithostratigraphy and chronostratigraphy of the post-Eocene succession in the Calama Basin has been undertaken by Wetzel (1927); Biese (1950); Brüggen (1950); Hofstetter *et al.* (1957); Münchmeyer and Urqueta (1974); Baker (1977); Mortimer *et al.* (1978); Naranjo and Paskoff (1981); Marinovic and Lahsen (1984), de Silva (1989); Salinas *et al.* (1991); May (1997); May *et al.* (1997, 1999); Hartley and May (1998) and Blanco *et al.* (2003). The established stratigraphy of the post-Eocene succession within the Calama Basin (Table 1) is based largely on the work of Naranjo and Paskoff (1981), and Marinovic and Lahsen (1984). A review of the stratigraphic nomenclature for the post-Eocene succession of the Calama Basin was given by Marinovic and Lahsen (1984).

Marinovic and Lahsen (1984) following Naranjo and Paskoff (1981) divided the Calama basin-fill into 3 unconformity-bounded units: the Mid to Upper Miocene Calama Formation, the Upper Miocene to Lower Pliocene El Loa Formation and the Upper Pliocene to Pleistocene Chiu-Chiu Formation (Table 1). In addition, they also recognised an informal stratigraphic unit referred to as 'Estratos Quebrada Chiquinaputo' of Upper Pliocene to Pleistocene age, that was considered to be a lateral equivalent of the Chiu-Chiu Formation. New $^{40}Ar/^{39}Ar$ radiometric, sedimentological and structural data from the Calama Basin (May, 1997; May *et al.*, 1999), indicate that the existing post-Eocene stratigraphy requires redefinition. Specifically, the El Loa Formation, as currently defined, includes a number of lithologically distinct sediments of differing age which form extensive, mappable units and should therefore be considered as individual formations. Also, the age of the Calama Formation is redefined. The redefinition of the post-Eocene succession

TABLE 1. COMPARISON OF THE LITHOGRAPHY AND CHRONOSTRATIGRAPHY OF THE OLIGOCENE TO PLEISTOCENE SUCCESSION WITHIN THE CALAMA BASIN.



Opache Formation-Opache Formation; Chiquina Foramtion; Chiquinaputa Foramtion; Ig= Ignimbrite; EQC= Estratos Quebrada Chiquinaputo; Car= Carcote.

within the Calama Basin is based on the North American Commission on Stratigraphic Nomenclature (1983). The revised lithostratigraphy when combined with the new radiometric data allow erection of a high resolution chronostratigraphic framework from which an analysis of the tectono-sedimentary evolution for the Calama basin-fill is undertaken. In addition a discussion of the relationship between the tectono-sedimentary evolution of the Calama Basin and adjacent, equivalent-aged basins (the Pampa del Tamarugal and Salar de Atacama basins) is presented.

METHODOLOGY

Sedimentological data have been acquired through sedimentary logging at scales of 1:10, 1:25 and 1:50, of 47 sections exposed along the length of the Río Loa and Río San Salvador gorges and tributaries (data are presented in May, 1997). A stratigraphic synthesis of a 100 km west to east traverse following exposed strata is presented (Fig. 3). These data are supplemented by limited borehole

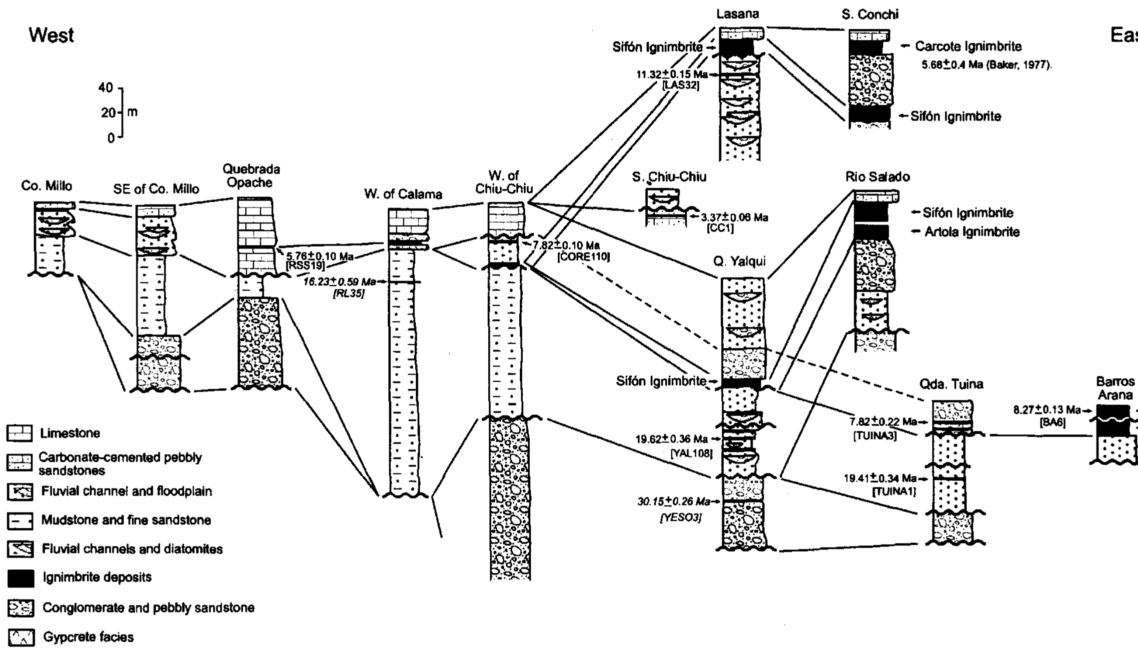


FIG. 3. West to east stratigraphy of the Calama Basin. See figure 2 for the location of sections studied. Correlations are based on the dated volcanic ashes an lithological similarities. Sample numbers for the volcanic ashes and ignimbrites are given in brackets and correspond to those presented in table 2. Age ashes.

information available in the Calama region (a continuous core was used to generate the west of Chiu-Chiu section). The sedimentary succession has been described and interpreted in detail by May (1997) who recognised a number of facies associations. Facies association development in the upper part of the basin-fill (Late Miocene to Pleistocene) has been summarised previously by May *et al.* (1999). Here the authors document the lithological characteristics of individual units and give a brief environmental interpretation.

The spatial and temporal development of sediment deposition within the basin has been constrained by laser fusion $^{40}Ar/^{39}Ar$ dating of biotites from interbedded volcanic rocks. The location and stratigraphic position of samples subject to $^{40}Ar/^{39}Ar$ dating are shown in figure 3. Previously dated ignimbrites (Baker, 1977; Baker and Francis, 1978; Marinovic and Lahsen, 1984; De Silva, 1989) were only sampled where comparison with previous K/Ar dates was required (*e.g.*, the Sifón and Carcote ignimbrites, BA6 and LAS28 respectively; Fig. 3, Table 2). Ashes were considered to be pristine if they did not overlie an erosion surface, draped palaeotopography, had sheet-like bed geometries and contained no clasts (apart from pumice) in the matrix. Where possible, samples were collected when all these criteria could be met. Exceptions were made for two reworked ashes from stratigraphically important locations (RL35 from the section west of Calama and YESO3 from the Quebrada Yalqui section; Fig. 3, Table 2), where dating would, at least, provide a maximum age for each of these horizons.

Dates were obtained from five or more splits of a small number of grains from each sample to assess potential problems of xenocrystic contamination. Biotites were separated by flotation in water and heavy liquids, then hand picked under a binocular microscope. Optical examination revealed minimal alteration which was confirmed by the high K content (7-9% K_2O). Samples were irradiated along with splits of Taylor Creek Canyon sanidine monitor (17.92 Ma) at 1 MW for 50 h in the TRIGA research reactor at Oregon State University. Samples were analysed in static mode on a MAP 215 mass spectrometer with Nier-type source (Burgess *et al.*, 1992). A detailed description of experimental procedures is given in May (1997). Uncertainties for the ages (Table 2) are quoted at the 2σ level and included the estimated error in J. Eleven samples produced reliable age determinations (Table 2), five of which were previously reported in May *et al.* (1999). Radiometric ages have been applied to the stratigraphy using the geologic time scale of Harland *et al.* (1990).

FORMAL LITHOSTRATIGRAPHY

The formal lithostratigraphy of the Calama Basin is summarised in table 1. The distribution of lithostratigraphic units is shown in figure 4 and a chronostratigraphic correlation in figure 5. The stratigraphic and chronostratigraphic framework has been established largely by radiometric dating of interbedded volcanic ashes and ignimbrites. Three of the ignimbrites present within the post-Eocene stratigraphy of the Calama Basin: the Sifón, Artola and Carcote ignimbrites comprise members of the San Bartolo Group as defined by de Silva (1989), following the earlier work of Hollingworth and Rutland (1968), Ramírez (1979), Ramírez and Gardeweg (1982) and Marinovic and Lahsen (1984). The remainder of the dated volcanic ashes within the Calama Basin have not been assigned formal lithostratigraphic status, but those younger than 11 Ma are considered to be laterally equivalent (more distal) to the ignimbrites of the San Bartolo Group.

In the revised stratigraphic scheme proposed here, the Calama and Chiu-Chiu Formations are retained, although the age of the Calama Formation is reconsidered. The El Loa Formation is elevated to group status. It comprises four newly defined formations: the Jalquinche, Lasana, Chiquinaputo and Opache formations. Details of the each of the proposed stratigraphic units are given below.

CALAMA FORMATION

Name: the name was originally introduced by Naranjo and Paskoff (1981).

Type sections and thickness. The type-section, originally described by Naranjo and Paskoff (1981),

TABLE 2. THE WEIGHTED MEAN AGE, APPROXIMATE LOCATION (SEE FIG. 2 FOR LOCATIONS) AND PRECISE LATITUDE, LONGITUDE AND STRATIGRAPHIC HEIGHT OF EACH CONCORDANT $^{40}Ar/^{39}Ar$ ANALYSIS.

Sample	Location	Latitude and Longitude	Stratigraphic height	Age (Ma)
CC1	South of Chiuchiu	22.38°S/68.66°W	7.5m below top of fold axis	3.37±0.06
RSS19	West of Qda. Opache	22.48°S/69.08°W	21m above unconformity	5.76±0.10
TUINA3	Qda. Tuina	22.48°S/68.45°W	20m below top of section	7.82±0.22
CORE110	Core SE4, West of Chiuchiu	22.36°S/68.71°W	28m below top of core	7.82±0.10
BA6	Barros Arana	22.68°S/68.47°W	Sifon ignimbrite	8.27±0.13
LAS32	Lasana	22.30°S/68.64°W	17m below Sifon Ign	11.32±0.15
RL35*	West of Calama	22.52°S/69.02°W	38m from top of section	16.23±0.59
TUINA1	Qda. Tuina	22.48°S/68.45°W	35m below upper conglomerate	19.41±0.34
YAL108	Qda. Yalqui	22.40°S/68.39°W	34m above lower conglomerate	19.62±0.36
YESO3*	Qda. Yalqui	22.40°S/68.38°W	20 m below unconformity	30.15±0.26

*Reworked ashes (see May, 1997 for discussion).

is located at Cerro Calama, 3 km east of Calama. Up to 120 m of conglomerates and sandstones are exposed here and unconformably overlain by the El Loa Group. The exposed thickness of the Calama Formation does not exceed 120 m, but unpublished borehole data suggest that a maximum thickness of 400 m underlies the region east of Calama.

Lithology: the Calama Formation is composed of conglomerates, pebbly sandstones and sandstones with a sheet-like geometry. Cobble grade conglomerates are typically 0.2-0.6 m thick, clast-supported and have a coarse sand matrix. Beds are generally massive but may display normal grading and imbrication. Pebbly sandstone or pebble and granule grade conglomerates with a poorly sorted coarse sand matrix are thicker (0.1-2 m), more laterally continuous and volumetrically more significant than the cobble conglomerates. Beds may be massive, imbricated, horizontally or low-angle cross-stratified with alternating coarse and fine layers 2-15 cm thick. Occasional sandstone beds 5 to 50 cm thick are laterally continuous for up to 100 m. The basal surfaces of the sheet sandstones and conglomerates are planar non-erosive to very gently erosive. Sandstone lenses 1 to 15 cm thick and up to 5 m wide are occasionally interspersed with the sheet sandstones. Sandstones are poor to moderately sorted, coarse grained, locally granular to pebbly with occasional mudstone intraclasts. A typical section is shown in figure 6.

The sheet-like conglomerates, pebbly sandstones and sandstones of the Calama Formation are interpreted to represent deposition on the coalesced aprons of alluvial fans (bajada) fringing the front of the mountain ranges that surrounded the Calama Basin (May 1997). The basin was internally-drained during this time period.

Boundaries and distribution: the Calama Formation is the lowermost unit within the Calama Basin. It can be traced throughout the basin cropping out along the Río Loa and Río San Salvador gorges west of Calama, the Cerros Calama, Loma Negra and Milagro to the north-east of Calama, and in Quebradas Tuina and Yalqui to the east (Fig. 2). The base of the formation is unconformable upon various pre-Oligocene (primarily Triassic to Cretaceous) basement. It is overlain disconformably or unconformably by the Lasana Formation (El Loa Group) in the east of the basin and the Jalquinche Formation (El Loa Group) in the west and central part of the basin.

Age: the Calama Formation has previously been assigned a Lower to Middle Miocene age (Naranjo and Paskoff, 1981) or a Middle to Upper Miocene age (Marinovic and Lahsen, 1984). The age of the formation is re-defined as (?)Lower Eocene to (?)Lower Miocene. The age of the base of the formation has recently been defined by the work of Blanco *et al.* (2003). These authors dated a number of interbedded volcanics and clasts of volcanic strata from the lower part of the Calama Formation and suggested that sedimentation commenced in the lower to middle Eocene between 52 and 47 Ma.

The upper age of the Calama Formation is not

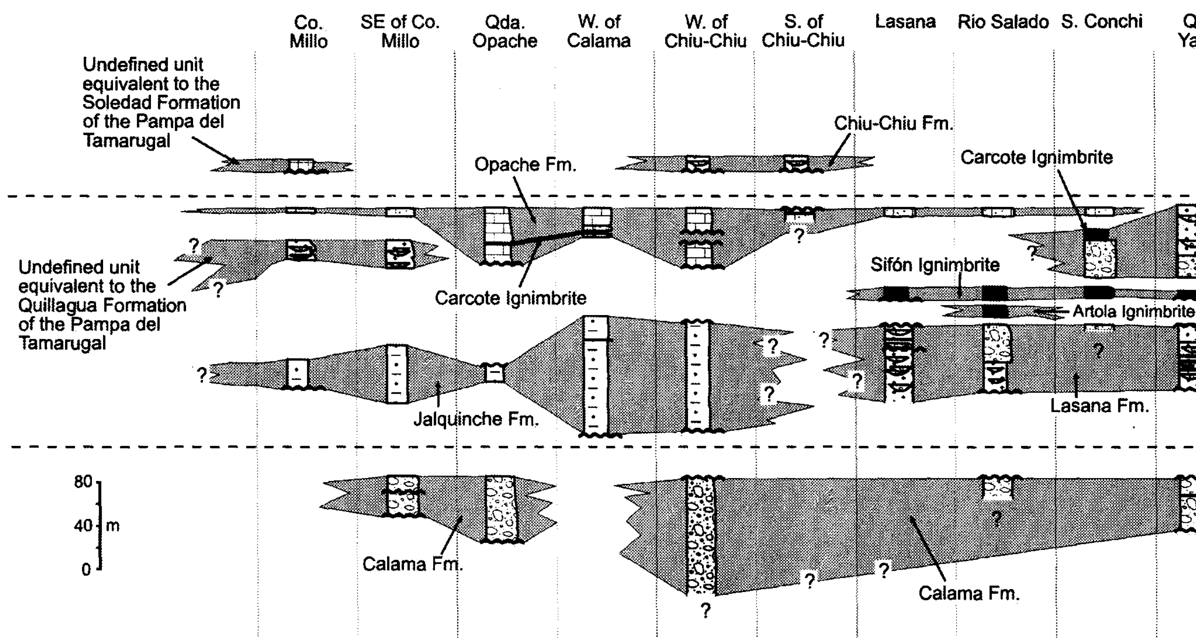


FIG. 4. Proposed lithostratigraphy for the Calama Basin. Lithologies and thicknesses correspond to those shown in figure 3. Six formations are recognised within the Formation comprises the basal unit of the basin-fill. It is overlain by the El Loa Group, which consists of the Jalquinche, Opache, Lasana, and Chiquinaputo comprise the Chiu-Chiu Formation. See text for discussion.

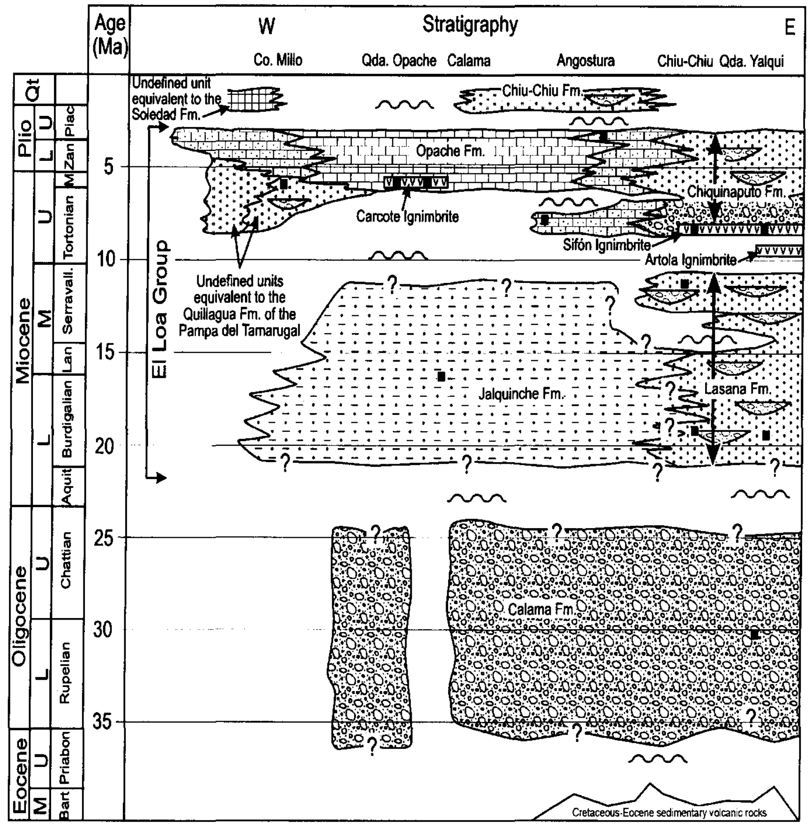


FIG. 5. Chronostratigraphic correlation of the Oligocene to Recent succession within the Calama Basin from Co. Millo in the west to Quebrada Yalqui in the east. The spatial and temporal development of angular unconformities are shown. Formation names correspond to proposed redefinition of the Calama Basin stratigraphy (see text). The dated ashes described in the text are indicated by the ▪ symbol. Bart-Bartonian; Priabon-Priabonian; Aquit-Aquitanian; Lan-Langhian; Serravall-Serravallian; M -Messinian; Zan-Zanclian; Piac-Piacenzian. Cretaceous-Eocene sedimentary volcanic rocks-Cretaceous to Eocene sedimentary and volcanic strata.

well defined. The 30.15±0.26 Ma 'YESO3' reworked volcanic ash (Table 2) located 20 m below the unconformity with the overlying Lasana Formation in Quebrada Yalqui (Fig. 3), indicates that deposition continued until at least the 'middle' Oligocene. The 19.62±0.36 Ma (YAL108) and 19.41±0.34 Ma (TUINA1) volcanic ashes (Table 2) within overlying El Loa Group deposits in Quebradas Yalqui and Tuina (Fig. 3) indicate that deposition must have ceased by the latest Oligocene or earliest Miocene along the eastern basin margin. Elsewhere in the basin, the upper age of the formation is less precisely constrained. The oldest age obtained from volcanic ashes above the Calama Formation is Mid-Miocene in the central and western parts of the basin (Fig. 3).

EL LOA GROUP

Name: the name was originally introduced as the El Loa Formation by Fuenzalida (in Hofstetter *et al.*, 1957, see also Biese, 1950). The term 'El Loa (Formation)' has become synonymous for the Miocene deposits of the upper course of the Río Loa. In its current usage, it comprises a number of depositional units which can be shown to be spatially and temporally discrete formations. For this reason, the name 'El Loa' is retained and the formation is raised to group status.

Type area and thickness: the El Loa Group is exposed over large areas of the Calama Basin (Fig. 2) and is defined on the constituent units of its

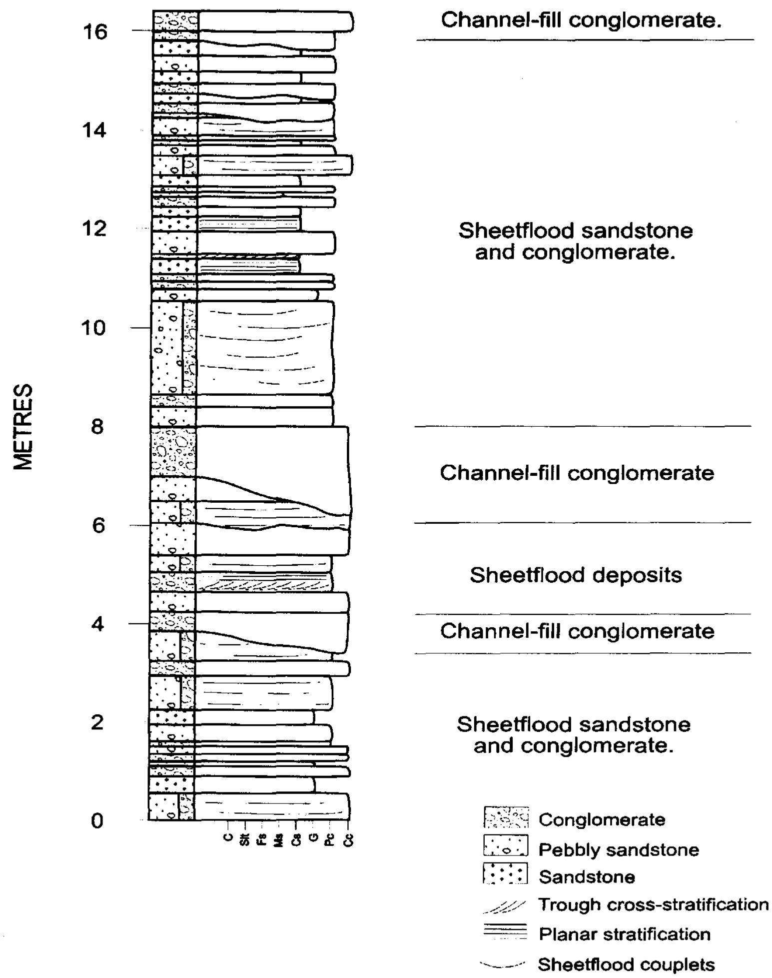


FIG. 6. Sedimentary log through the Calama Formation exposed at the north side of Quebrada Opache at 22º46'/69º02.

formations (see below). The group is at least 230 m thick as indicated from CODELCO borehole data near Calama (Fig. 3), although the thickness distribution of the group varies considerably, decreasing to 70 m on the western flank of the basin at Cerro. Millo (Fig. 3).

Lithology: the El Loa Group is informally divided into lower and upper parts separated by an angular unconformity (Figs. 4 and 5). The lower part of the group along the eastern basin margin is characterised by sandstones, mudstones and conglomerates of the Lasana Formation. In the central part of the basin evaporitic mudstones and sheet sandstones of the Jalquinche Formation characterise the lower part of the group. This unit is overlain by carbonate-cemented sandstones and conglomerates, peloidal and oolitic wackstones, packstones, grainstones and biomicritic limestones of the Opache Formation. The upper part of the group along the eastern basin margin is characterised by conglomerates, channel-fill sandstones and sheet sandstones of the Chiquinaputo Formation (Fig. 4).

Boundaries and distribution: the El Loa Group is exposed over large areas of the Calama Basin (Fig. 2), with good vertical successions visible in the canyon walls of the Río Loa and the Río San Salvador (summarised in Fig. 3). The contact between the base of the group and the underlying Calama Formation is exposed in the following areas: 4 km to the east of Cerro Millo, in Quebrada Opache, at Angostura and in Quebrada Yalqui. East of Calama the contact is an angular unconformity. West of Calama the contact is abrupt with mudstones and sandstones of the Jalquinche Formation sharply overlying the Calama Formation. An angular unconformity separates the top of the group from diatomites and pebbly sandstones of the Chiu-Chiu Formation and is exposed at Angostura and 7 km SSE of Chiu-Chiu. Elsewhere, the top of the group forms the present day surface or is overlain by Quaternary gravels.

Age: the El Loa Group is defined as Lower Miocene to Upper Pliocene in age. The age is based upon radiometric dates determined from volcanic ashes interbedded within the constituent formations of the group, discussed in detail below.

Subdivision: the El Loa Group includes the newly defined Jalquinche, Lasana, Chiquinaputo and Opache Formations (Figs. 4 and 5, Table 1).

JALQUINCHE FORMATION

Name: named after the village of Jalquinche located 5 km east of Calama.

Type area and thickness: a 30 m thick section is exposed near the village of Jalquinche (22°27'S 68°53'W), and is taken as the type-locality. Borehole data indicate a maximum thickness of 200 m for the formation in this region.

Lithology: the Jalquinche Formation comprises interbedded red, fine grained sheet sandstones and mudstones with evaporites (Fig. 7) and is often poorly exposed. Sheet sandstones are trough cross-stratified or planar-stratified, mudstones are massive or poorly planar stratified. Beds often form 10 to 50 cm thick fining-upwards sequences of sandstone to mudstone, often with a claystone cap. Gypsum crystals are developed in both mudstones and sandstones. Occasional sandstone channel-fill deposits up to 1 m thick and 40 m wide are present forming <20 m thick coarsening-upwards cycles (Fig. 7). The predominantly sheet-like, fine grained, evaporite-bearing sediments of the Jalquinche Formation are thought to represent deposition in playa sandflat and mudflat environments, traversed by occasional ephemeral fluvial channels in an internally drained basin (May 1997).

Along the northern central basin margin (San Lorenzo area, Fig. 2) a locally developed, pebble and cobble grade pebbly sandstone and clast-supported conglomerate displaying imbrication, planar and low angle cross-stratification is present. These deposits are interbedded with poor to moderately sorted, coarse grained pebbly sandstones with a sheet-like geometry that display planar and trough cross-stratification. The pebbly sandstones and conglomerates represent deposition on an alluvial braidplain that fringed the northern edge of the Calama Basin and which passed basinwards into the finer grained facies described above (May, 1997).

Boundaries and distribution: the Jalquinche Formation extends from 7 km south of Chiu-Chiu across the basin centre to Cerro Millo at the western basin margin (Figs. 4 and 5). It unconformably overlies the Calama Formation and is unconformably overlain locally, by the Opache Formation. East of Angostura the formation is inferred to interfinger laterally with the coarser deposits of the Lasana Formation (see below), but this contact is not exposed.

Age: the age of the base of the Jalquinche Formation is only constrained by a reworked volcanic ash located 38 m below the top of the formation in the Calama area. The ash (RL35, Table 2) yielded a lower Middle Miocene age of 16.23±0.59 Ma. A Lower Miocene age is assumed as 180 m of strata occur beneath the ash, as such, the formation age is considered to extend below the 16.3 Ma Lower-Middle Miocene boundary. The age of the top of the formation is constrained by a 7.82±0.10 Ma volcanic ash (CORE110, Table 2) from the overlying Chiquinaputo Formation, located 22 m above the angular unconformity with the Jalquinche Formation (Fig. 3). The time gap between cessation of Jalquinche Formation deposition and commencement of Chiquinaputo Formation deposition is not constrained. The top of the Jalquinche Formation is tentatively considered to be of uppermost Middle Miocene to lowermost Upper Miocene age.

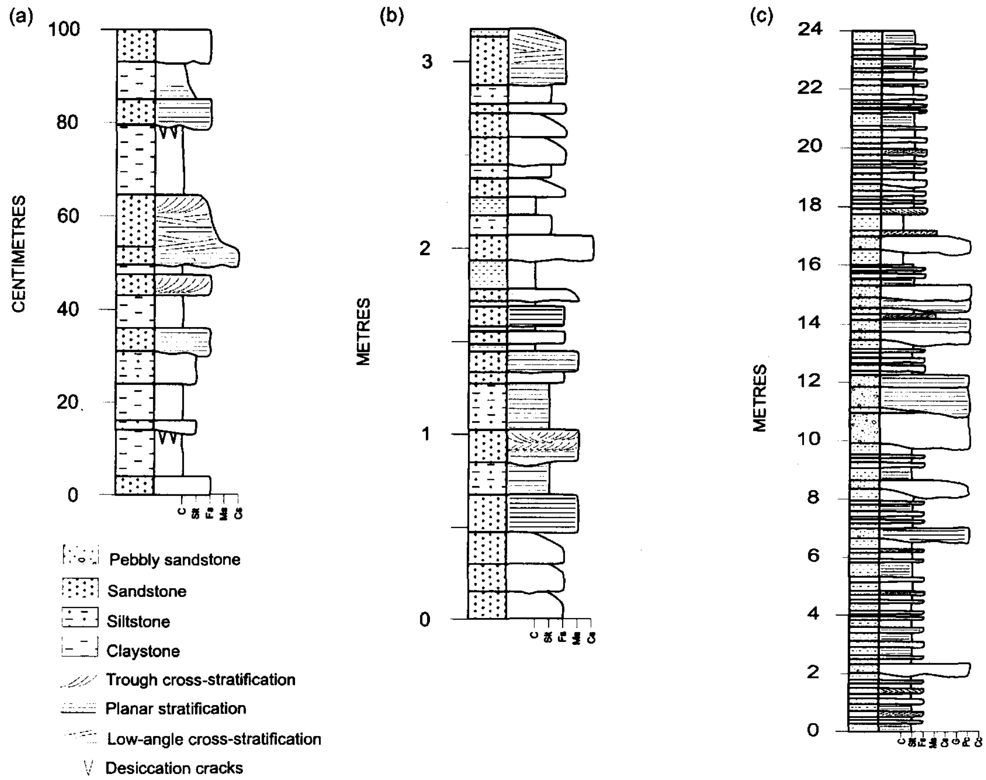


FIG. 7. Representative sedimentary logs through part of the Jalquinche Formation exposed in **(a)** the Río Loa valley 10 km east of of the Cerro Millo haigh (22º51'S/69º19'W; **(b)**- Río San Salvador valley at the Cerro Millo high (22º50'S)/69º24'W) and **(c)** the Río Loa gorge, 10 km wesdt of Calama (22º31'S/69º01'W).

LASANA FORMATION

Name: named after the village of Lasana, located 28 km northeast of Calama.

Type area and thickness: two type sections are recognised, the lower one exposed at the eastern end of Quebrada Yalqui (22°40'S/68°39'W) (Fig. 8a), and an upper one located in the Río Loa valley above the village of Lasana (22°26'S 68°63'W)(Fig. 8b). A full thickness of the formation is not revealed in a single exposed section, but totals approximately 150 m.

Lithology: the Lasana Formation largely comprises planar bedded and trough cross-bedded conglomerate channel-fill deposits, planar to trough cross-stratified coarse grained sheet sandstones and laterally continuous siltstone and claystone beds up to 120 cm thick. In addition, extremely poorly sorted matrix-supported pebbly sandstone beds, very well sorted, well rounded, trough cross-stratified, coarse grained sandstones and rare ash-fall and reworked ash deposits are present. Desiccation cracks may be present within the mudstones. Conglomerate channel-fills occur as either isolated 1 to 2 m thick bodies or as amalgamated multi-storey units up to 5 m thick and form the base of 10 to 15 m thick fining-upwards cycles.

The planar bedded and trough cross-bedded conglomerate channel-fill deposits represent deposition by strong, but intermittent flood events in ephemeral fluvial channels. The planar to trough cross-stratified coarse grained sheet sandstones represent unconfined overbank sheetflood events. Their coarse grained nature indicates deposition close to the main channel systems. In contrast, the siltstone and claystone beds are thought to represent

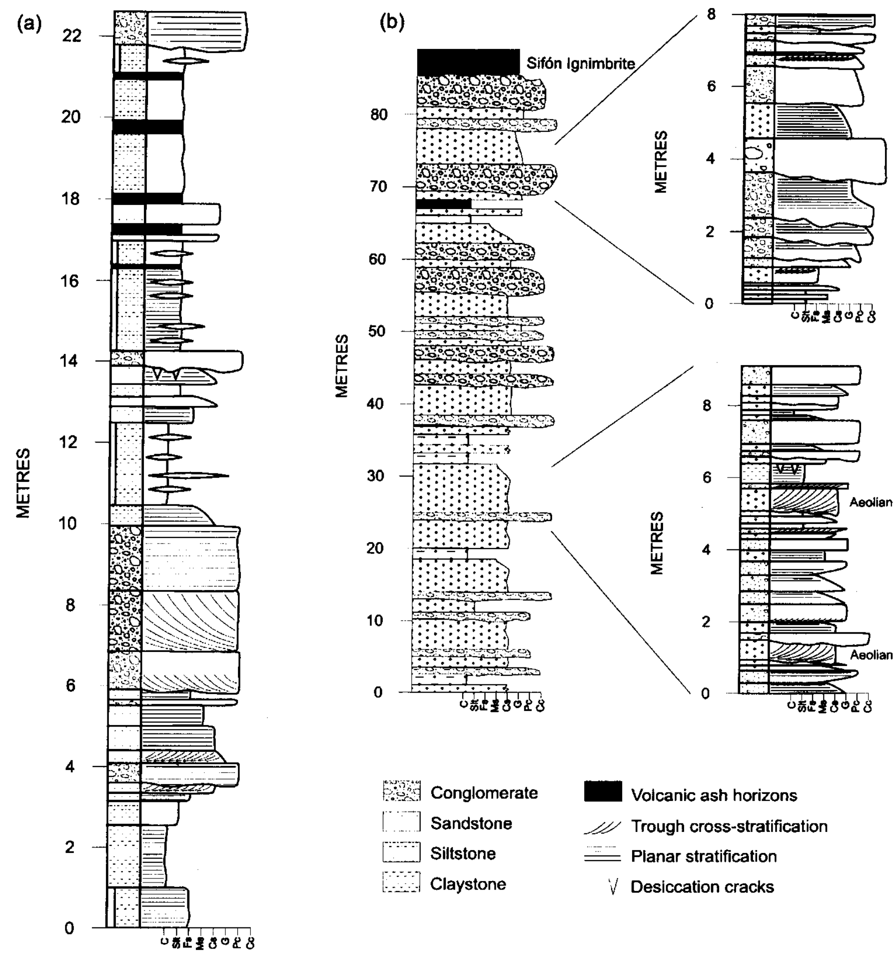


FIG. 8. Summary logs from the 2 type sections of the lasana Formation (a) the loweerr type sedction from the easstern end of quebarda Yalqui (22º40'S/68º63'), and (b) the upper type section exposed in the Río Loa valley near lasana (22º26'S/68º63'W), including two detailed sedimentary logs taken from 30 m and 70 m up the section. Note that the Sifón Ignimbrite caps the top section.

the more distal deposits of unconfined flood events. The very well sorted, well rounded, trough cross-stratified, coarse grained sandstones represent aeolian dunes formed by wind reworking of ephemeral fluvial deposits. The extremely poorly sorted matrix-supported pebbly sandstone beds are debris flow deposits.

Boundaries and distribution: the Lasana Formation incorporates the interbedded conglomerate channel-fill, sheet sandstone and mudstone deposits located along the eastern margin of the Calama Basin below the Artola and Sifón ignimbrites (Figs. 4 and 5). The formation has an unconformable contact with the underlying Calama Formation and a generally conformable contact with the Sifón Ignimbrite. The lateral boundary, to the west, with the time equivalent Jalquinche Formation is not exposed.

Age: the age of the Lasana Formation is middle Lower Miocene to lowermost Upper Miocene (Tortonian). The top of the formation is constrained by the age of the conformably overlying Artola

Ignimbrite dated by de Silva (1989) as 9.53±0.36, Ma or where this is absent, the 8.27±0.13 Ma Sifón Ignimbrite. A volcanic ash 17 m from the top of the formation at Lasana yielded an age of 11.32±0.15 Ma (LAS32, Table 2), indicating that deposition continued beyond the latest part of the Middle Miocene. The age of the base of the formation is more poorly constrained. A volcanic ash horizon 34 m above the base of the formation in Quebrada Yalqui (YAL108, Table 2) was dated at 19.62±0.36 Ma indicating at least a Lower Miocene age.

OPACHE FORMATION

Name: named after Quebrada Opache located 10 km southwest of Calama. Previously these deposits have been termed the upper El Loa Formation (Naranjo and Paskoff, 1981; Marinovic and Lahsen, 1984; May *et al.*, 1999), but as they form a distinct, mappable unit they are designated as a separate formation.

Type area and thickness: the type section is exposed in Quebrada Opache (22°48'S 69°08'W), 10 km southwest of Calama, where it is 66 m thick forming the thickest development of the formation in the basin (Fig. 9).

Lithology: the Opache Formation comprises a number of different lithologies (described and interpreted in detail by May *et al.*, 1999). Along the basin flanks, particularly in the west, the formation is represented by extensively carbonate-cemented conglomerates and sandstones. In these basin margin deposits, highly indurated carbonate cements obscure most primary sedimentary structures such that bed boundaries are difficult to identify. Conglomerates, pebbly sandstones and sandstones are clast-supported to carbonate matrix/cement-supported and composed of rounded to sub-angular clasts. Where visible, beds are up to 0.5 m thick and basal surfaces are planar and often erosive. Bed geometries appear to be laterally continuous. Parallel and cross-stratification is occasionally visible. The carbonate-cemented basin margin deposits represent extensive calcrete development, marginal to a carbonate-dominated lacustrine environment.

Basinwards, the carbonate-cemented conglomerates and sandstones pass laterally into peloidal and intraclastic wackstones, packstones and grainstones, grading to marls. Beds are 5 to 90 cm thick and composed of alternations of massive, well cemented limestone and friable marls. Both contain rare, non-carbonate, extraformational detritus. Patches of brecciated rock occur randomly throughout beds and fenestral cavities aligned sub-parallel to bedding are common. A pseudo-microkarst is sometimes present. The carbonates are usually beige to grey in colour but are locally reddened with white mottled spots up to 1 mm in diameter. An extensive peloidal and oolitic texture is only apparent in thin section. The majority of samples are packstones or grainstones. Other grains include rare gastropod and ostracod remains concentrated in discrete layers up to several centimetres thick. Tubular voids up to 5 mm in diameter and 10 cm long oriented parallel and oblique to bedding are present in some beds. These deposits represent marginal lacustrine carbonates subject to extensive calcretisation.

In the basin centre, grey coloured biomicritic limestones up to 1.5 m thick occur as structureless marls, wackstones and packstones. Bed boundaries are undulatory but laterally continuous. Upper bounding surfaces are often indistinct due to reddening and brecciation associated with horizontal and vertical cracks, and pseudo-microkarst cavities. Unbroken and uncompacted gastropod and ostracod bioclasts are abundant throughout this facies with charophyte gyrogonites present in some layers. Rare fine sand and silt-sized terrigenous grains dispersed randomly throughout the matrix comprise 1 to 2% of the rock. Cylindrical, lined burrows 1 to 3 mm diameter and up to 5 cm long are concentrated in discrete beds. These limestones are considered to have been deposited in shallow, low energy ephemeral lakes.

Boundaries and distribution: the base of the Opache Formation is taken at the boundary with the underlying Jalquinche and Chiquinaputo formations, and the Sifón Ignimbrite (Figs. 4 and 5). The upper boundary is the present-day land surface, except for the area between Angostura and Chiu-Chiu, where the Chiu-Chiu Formation unconformably overlies the Opache Formation. The formation extends as far eastwards as Chiu-Chiu and as far northwards as Conchi (Figs. 2 and 4). To the west it pinches out in the Cerros de Guacate-Cerro Millo area.

Age: the age of the base of the Opache Formation is constrained by a 5.76±0.10 Ma volcanic ash (RSS 19, Table 2; May *et al.*, 1999) which occurs 25 m above the base of the formation, and the 7.82±0.10

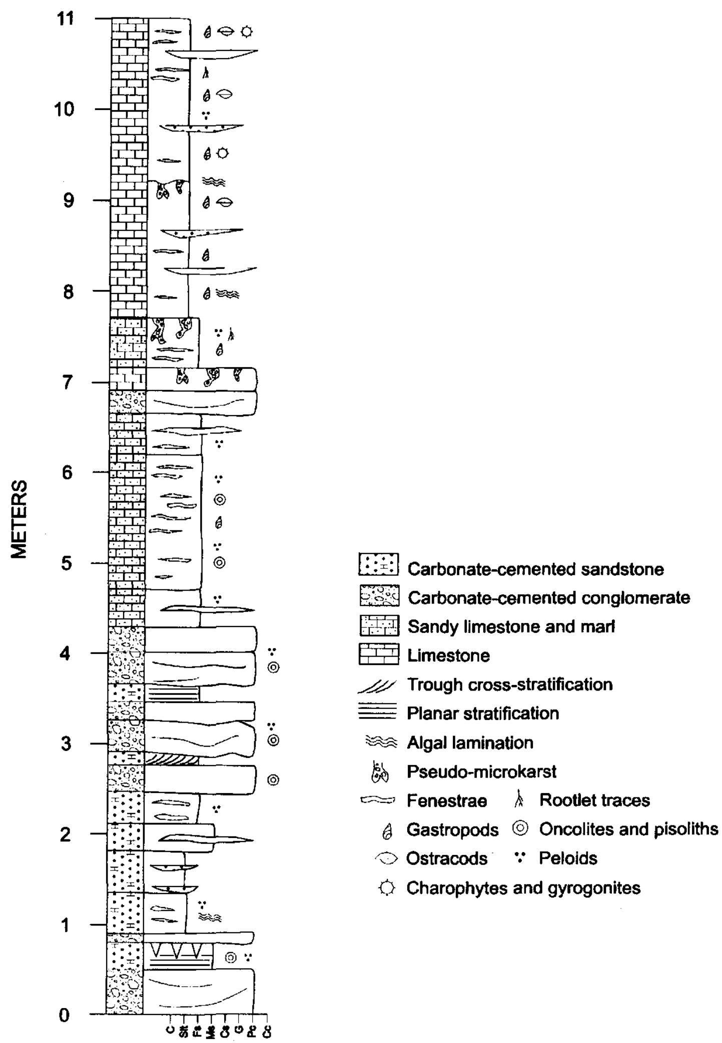


FIG. 9. Sedimentary log from the type section of the Opache Formation exposed to the west of Quebrada Opache (22º48'S/69º08'W).

Ma volcanic ash (CORE110A Table 2; May *et al.*, 1999) present 7 m from the top of the unconformably underlying Chiquinaputo Formation. The base of the formation is therefore Upper Miocene ranging from between 5.76 to 7.92 Ma. The age of the top of the formation is constrained by the 3.37±0.06 Ma volcanic ash (CC1, Table 2; May *et al.*, 1999) present 7.5 m beneath the unconformity separating the Opache Formation from the unconformably overlying Chiu-Chiu Formation, suggesting a lowermost Upper Pliocene aqe.

CHIQUINAPUTO FORMATION

Name: named after Quebrada Chiquinaputo, a westerly flowing, northern tributary to Quebrada Yalqui, located 20 km east of the village of Chiu-Chiu (Fig. 2).

Type area and thickness: the type section is taken at the confluence between Quebrada Chiquinaputo and Quebrada Yalqui (22°36'S/68°46'W) where the formation is 55 m thick (Fig. 10).

Lithology: the Chiquinaputo Formation comprises conglomerates, sandstones and mudstones. Conglomerates form 1 to 4 m thick channel-fill deposits commonly comprising clasts of the Sifón Ignimbrite up to 1 m in diameter. Stacking of 2 to 4 individual channels produces occasional multi-storey packages up to 10 m thick. Sandstones have a sheet-like geometry, are 10 to 110 cm thick and range from coarse to fine in grain size. They commonly display parallel or low angle planar cross-stratification and grade upwards into mudstone. Mudstones are planar-based, have a sheet-like geometry and are structureless or finely parallel laminated. They commonly contain desiccation cracks and moulds and nodules of displacive gypsum and/or halite crystals. Reworked volcanic ashes are occasionally present. Very well sorted, well rounded, trough cross-stratified, coarse grained grey sandstones occur as isolated bodies up to 15 m wide and 3 m thick within steep-sided erosional channel forms, and are aeolian in origin.

The channel-fill deposits of the Chiquinaputo Formation represent deposition by strong, but intermittent flood events in ephemeral fluvial channels. The sheet sandstones represent unconfined flood events, the fining upwards nature suggests an increasingly distal position relative to the main clastic sediment supply. The mudstones represent distal flood events deposited on an evaporitic playa mudflat.

Boundaries and distribution: the Chiquinaputo Formation is exposed along the eastern basin margin in Quebradas Yalqui, Chiquinaputo and their tributaries (Fig. 2). The base of the formation is taken at the contact with the Sifón Ignimbrite. The top of the formation is taken as the present day land surface. The lower, conglomerate-dominated part of the Chiquinaputo Formation is considered to be equivalent to the lower part of the Opache Formation (Fig. 4). The upper part of the formation interfingers laterally with, and is overlain by, the Opache Formation, but the boundary between the two is not widely observed in the basin.

Age: the base of the Chiquinaputo Formation is Upper Miocene (Tortonian), as it is taken at the contact with the 8.27±0.13 Ma Sifón Ignimbrite. The age of the top of the formation is difficult to constrain due to its likely diachronous nature. At Conchi where the top of the formation is taken at the 5.68±0.4 Ma (Baker, 1977) Carcote Ignimbrite, the Chiquinaputo Formation is overlain by 10 m of the Opache Formation. Further east in Quebradas Yalqui and Chiquinaputo where the upper part of the Chiquinaputo Formation coincides with the present day land surface, the formation is considered to be equivalent to the upper part of the Opache Formation suggesting an earliest Upper Pliocene age for the formation top.

Remarks: the Chiquinaputo Formation as defined here, is considered to be equivalent to the informal unit 'Estratos Quebrada Chiquinaputo' recognised by Marinovic and Lahsen (1984). These authors considered the 'Estratos Quebrada Chiquinaputo' to be laterally equivalent to the Chiu-Chiu Formation, suggesting an Upper Pliocene to Pleistocene age; however, based on regional mapping and radiometric dates the authors consider the Chiquinaputo Formation to be older (Upper Miocene to Lower Pliocene) than the Chiu-Chiu Formation and laterally equivalent to the Opache Formation.

CHIU-CHIU FORMATION

Name: originally named after the village of Chiu-Chiu by Naranjo and Paskoff (1981).

Type area and thickness: sections up to 50 m thick are present close to the village of Chiu-Chiu (Fig. 3) and constitute the type locality of the Chiu-Chiu Formation (Naranjo and Paskoff, 1981).

Lithology: the Chiu-Chiu Formation consists of interbedded conglomerate channel-fill deposits, sheet sandstones, diatomites, travertine and reworked volcanic ashes (Fig. 11). Channel-fill deposits are 0.4 to 1.5 m thick and no wider than 10 m. Rootlets and gastropods are present in many of the diatomite beds. The diatomite deposits of the Chiu-Chiu Formation record deposition in a low gradient, shallow, hydrologically-open, none-saline lake. The channel-fill deposits represent ephemeral fluvial activity during periods when the lakes had dried out. The sandstones represent unconfined sheet flood events that have may have been partially reworked by lacustrine processes and by vegetation.

Boundaries and distribution: within the central part of the Calama Basin the Chiu-Chiu Formation unconformably overlies folded strata of the Opache Formation (Figs. 4 and 5) (Naranjo and Paskoff, 1981; Marinovic and Lahsen, 1984). The formation represents the youngest unit within the central part of the Calama Basin; the top forms the present day land surface. Exposure is restricted to the area

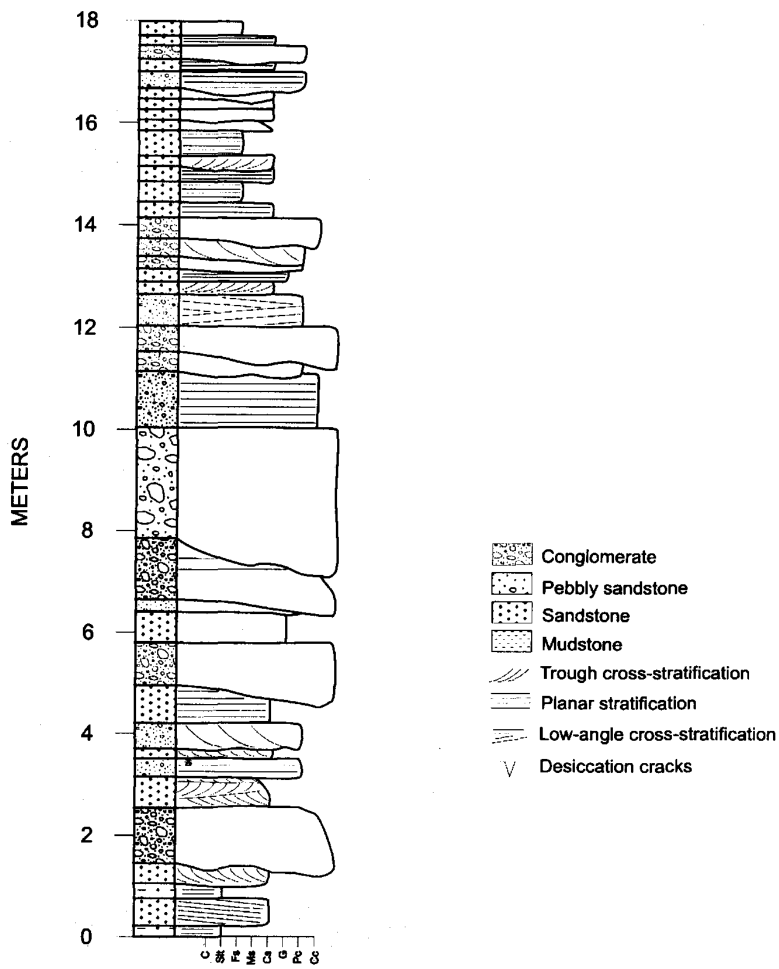


FIG. 10. Sedimentary log of the Chiquinaputo formation from the type section, taken from the western end of Quebrada Yalqui at 22º36'S/ 68º46'W close to the confluence with Quebrada Chiquinaputo.

around, and to the south of, the village of Chiu-Chiu (Fig. 2).

Age: Salinas *et al.* (1991) suggested an Upper Pliocene to Pleistocene age (between 2.5 and 0.5 Ma) for the Chiu-Chiu Formation based on vertebrate remains. This age assignment is indirectly supported by the 3.37±0.06 Ma age (CC1, May *et al.*, 1999; Table 2) obtained from the volcanic ash that occurs within the Opache Formation 7.5 m below the unconformity with the Chiu-Chiu Formation.

TECTONO-SEDIMENTARY EVOLUTION OF THE CALAMA BASIN

The litho- and chronostratigraphic analysis of the Eocene to Pleistocene fill of the Calama Basin allows the recognition of three discrete unconformity-bounded sedimentary packages.

OLIGOCENE

Sedimentation in the Calama Basin commenced in the early Eocene (Blanco *et al.*, 2003) with deposition of the alluvial braidplain deposits of the Calama Formation unconformably over pre-Eocene basement. This style of sedimentation occurred throughout the basin for much of the Eocene and Oligocene (approximately 25 Ma) and may have extended into the earliest Miocene. Deposition took place under an arid to semi-arid climate in an endorheic basin. The coarse grained nature of these deposits suggests that relatively high relief surrounded the basin for much of the Eocene and Oligocene. Uplift and folding associated with the development of a basin-wide unconformity resulted in termination of Calama Formation deposition in the earliest Miocene.

EARLY TO MIDDLE MIOCENE

From approximately 22 Ma to 10 Ma sedimentation was continuous throughout both the central Calama Basin (Jalquinche Formation) and along the eastern basin margin (Lasana Formation). The ephemeral fluvial sediments of the Lasana Formation are considered to represent the proximal equivalent of the finer grained playa sandflat and mudflat deposits of the Jalquinche Formation. The generally fine grained nature of the Jalquinche Formation sediments, evidence for periodic sedimentation and the absence of any evidence for permanent, large-scale fluvial systems (such as stacked multi-storey, trough cross-stratified channel-fill deposits) suggests that the Calama Basin had an endorheic drainage system throughout this time period.

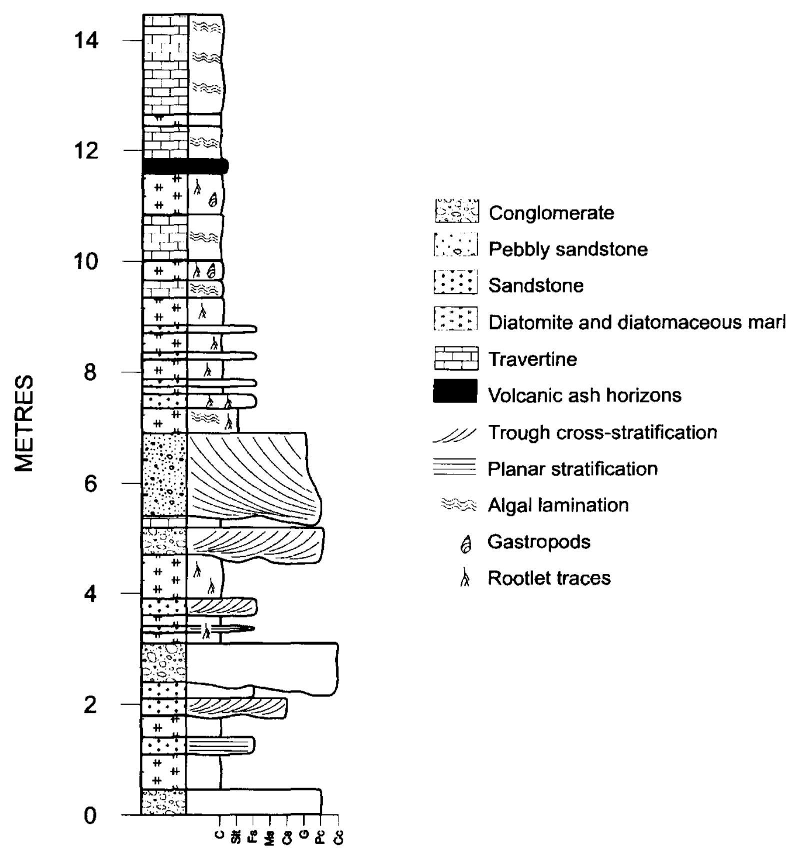


FIG. 11. Representative sedimentary log of part of the Chiu-Chiu Formation exposed in the region to the south of Chiu-Chiu (22º39'S/68º67'W).

LATE MIOCENE TO LATE PLIOCENE

From approximately 8 Ma braidplain sedimentation took place along the eastern basin margin (Chiquinaputo Formation; Fig. 5). No deposition is recorded between Calama and the western end of the basin represented by the Cerros de Guacate-Co. Millo basement high that comprises folded pre-Eocene strata (May 1997). West of the basement high sedimentation continued into the Pliocene. In contrast, in the centre of the Calama Basin sedimentation ceased and strata were locally folded prior to initiation of sedimentation around 6 Ma. Along the eastern basin margin, sedimentation was continuous into the Pliocene (Fig. 5). A late Miocene (between 7(?) and 6 Ma) phase of tectonic deformation was restricted to the central part of the Calama Basin.

Palustrine carbonate sedimentation prevailed across the central part of the Calama Basin between 6 and 3 Ma (Opache Formation) with alluvial braidplain and fluvial deposition along the flanks (Chiquinaputo Formation). After 3 Ma the basin-fill was subject to gentle folding followed by entrenchment as the Río Loa and Río San Salvador through Miocene and early Pliocene strata. A subsequent interval of diatomite deposition occurred in the central Calama Basin (Chiu-Chiu Formation) restricted to localised depressions (palaeo-topographic lows) generated by folding of older strata.

DISCUSSION

In order to assess the controls on sedimentation within the Oligocene to Pleistocene fill of the Calama Basin a comparison is made with other basin-fill succession of equivalent age in the Andean forearc. Comparative stratigraphic columns for the Pampa del Tamarugal, the Salar de Atacama and the Calama Basin are shown in figure. 12. Three time periods are discussed below.

EOCENE-OLIGOCENE

The revised age for the Calama Formation extends the age of the Calama Basin fill to Oligocene with recent work suggesting an early Eocene age (Blanco *et al.* 2003). This age is similar to other conglomerate-dominated successions such as the Sichal Formation of the Pampa del Tamarugal, (Skarmeta and Marinovic, 1981), the Loma Amarilla (Mpodozis *et al.* 1999) and Tambores (Dingman, 1963) Formations of the Salar de Atacama, Pampa Mulas Formation (Chong, 1973) and 'Piedemonte Andino' (Naranjo and Paskoff, 1985), suggesting that conglomerate deposition was largely synchronous across much of the forearc during Eocene and Oligocene times. In addition, within the Salar de Atacama deposition of the fine grained, evaporite-bearing San Pedro Formation (Brüggen, 1942) took place during this time period.

The Tambores, Calama and Sichal Formations are considered to record deposition in alluvial fan environments, whereas the San Pedro Formation records deposition in a distal fan/evaporitic playa setting (Flint, 1985; Naranjo *et al.*, 1994; Kape, 1996; May, 1997). As similar styles of proximal and distal alluvial fan sedimentation took place in different basins across northern Chile, it is likely that a semiarid/arid climate prevailed across the area during this time period. However, uncertainties associated with the age of these alluvial successions suggests that further work is needed before a clearer understanding of the lithostratigraphic and chronostratigraphic relationships between these successions can be established.

The unconformity developed between the Calama and Jalquinche/Lasana Formations in the late Oligocene to early Miocene does not appear to have a time equivalent in the Pampa del Tamarugal or Salar de Atacama basins (Fig. 12). Although it should be noted that in both these basins, the stratigraphic resolution may not be sufficient to determine whether an unconformity was developed during this time interval. The timing of the unconformity in the Calama Basin does coincide with the Pehueunche orogeny (Fig. 12; Hartley *et al.*, 2000), which has been recognised on the Puna (Jordan and Alonso, 1987). However as the unconformity appears to be restricted to the Calama Basin, then it may be related to Oligocene sinistral movement on the Precordilleran/West Fissure Fault Systems as documented by Tomlinson and Blanco (1997) in the west central part of the Calama Basin (Fig. 1).

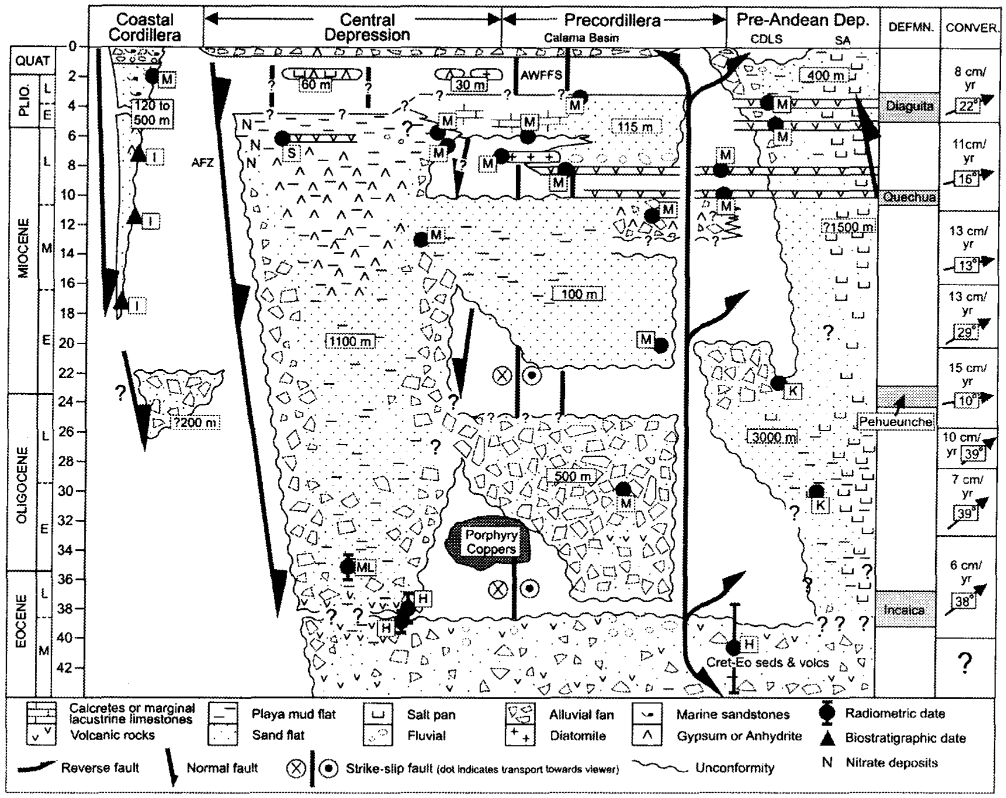


FIG. 12. Chronostratigraphic cross section for Andean forearc of northern Chile, 21º and 24ºS. Dates for the sections are indicated by the letters I-Ibaraki (1993), S-Sáez *et al.* (1999), H-Hammerschmidt *et al.* (1992), M-May (1997); ML-Marinovic and Lahsen (1984), K-Kape (1996); DEFMN. - main deformation phases recognized in Central Andes; CONVER. - rates and angles of relative plate convergence (from Somoza, 1998). Error bars are shown on radiometric dates where error is ± 0.5 m.y; CDLS-Cordillera de la Sal. SA-Salar de Atacama, AWFFS-Argomedo-West Fissure Fault System (modified from Hartley *et al.* (2000).

EARLY TO MID MIOCENE

Sedimentation during the early to mid-Miocene in the Calama basin was represented by a period of distal alluvial fan, sand-flat and playa sedimentation interspersed with ephemeral fluvial channel development. Similar environments are considered to have been developed in the Salar de Atacama (although sediments from this time period are only known from borehole data (Muñoz, *et al.*, 1997)) and the Pampa del Tamarugal (Fig. 12) at this time period. This observation is significant in that all three of these basins were endorheic in nature such that no paleo-Río Loa system was present during the early to late mid-Miocene.

The late mid-Miocene gap in sedimentation present in the Calama Basin and associated with gentle folding is not recorded in either the Salar de Atacama or the Pampa del Tamarugal. However it does coincide with the regional Quechuan deformation phase (Hartley *et al.*, 2000) that is considered to have affected the whole of the Central Andes (Megard, 1984; Jordan and Alonso, 1987). However the localised nature of the unconformity in the Calama Basin again suggests association with sinistral activity on the Precordilleran/West Fissure Fault Systems as noted by Tomlinson and Blanco (1997).

LATE MIOCENE TO LATE PLIOCENE

Late Miocene sedimentation occurred regionally, but diachronously, across the north Chilean Forearc. Sedimentation in isolated diatomaceous lakes began at 8 Ma in the Calama Basin. In the Pampa del Tamarugal alluvial and lacustrine sedimentation of the Quillagua Formation commenced around 7.3 Ma (Kiefer *et al.*, 1997) whilst Cabrera *et al.* (1995) and Sáez *et al.* (1999) favour initiation around 6.3 Ma. Although it is likely, that deposition of the Quillagua Formation was continuous from the underlying Sichal Formation. Similarly, lacustrine sedimentation in the Lauca Basin of northernmost Chile is believed to have begun at 6.5 Ma (Gaupp *et al.* 1999). In contrast, sedimentation along the northwestern margin of the Salar de Atacama Basin commenced unconformably over early Miocene sediments at about 10 Ma (Naranjo *et al.* 1994; Kape, 1996), although sedimentation had been virtually continuous in the main basin depocentre (Muñoz *et al.*, 1997).

The localised diachronous resumption of sedimentation across much of northern Chile in the late Miocene may be due to local differences in fault-controlled subsidence. This occurred in the central part of the Calama Basin where a phase of tectonic deformation can be defined between 7(?) and 6 Ma but not elsewhere. The areal restriction of this deformation phase again suggests that it was related to movement on the Precordilleran/West Fissure Fault Systems. Increased climatic humidity in the late Miocene is indicated by pedogenic/phreatic development within the alluvial braidplain sediments around the basin margins: gypcretes, which require <250 mm rainfall per annum to form (Watson, 1985), were developed in the mid Miocene whereas calcretes, whose present day distribution lies within zones where annual rainfall is 400-600 mm (Goudie, 1983), were formed in the late Miocene.

After 6 Ma sedimentation took place across the entire study area (Fig. 5). The areal expansion of sedimentation into the area between Calama and Co. Millo is related to movement on the West Fissure Fault System. This is indicated by changes in thickness of palustrine carbonates from borehole data: west of the fault they are 85 m thick but to the east, only 25 m are present, indicating downthrow to the west (May *et al.*, 1999). The localised deformation between 7 to 6 Ma therefore resulted in subsidence of the area between Calama and Co. Millo and linkage of the Calama and Pampa del Tamarugal basins as a single basin.

At the same time as the areal expansion of sedimentation took place at 6 Ma, a marked change from alluvial braidplain and open lacustrine deposition to fluvial and palustrine carbonate deposition occurred. A similar change in sedimentation from an open lacustrine environment to a saline lake has also been observed in equivalently-aged strata in the Quillagua Basin (Sáez *et al.,* 1999). The change in lacustrine sedimentation suggests a decrease in water supply to the Calama/Pampa del Tamarugal basins. However, a change from alluvial braidplain to more permanent fluvial sedimentation along the basin margins indicates increased pluvial activity in these areas. This change to fluvial sedimentation must be related to more permanent run-off relative to the underlying alluvial braidplain deposits. However, the decrease in apparent run-off in the centre of the basin could be related to a more efficient drainage network in the Pampa del Tamarugal than had been operative when the Calama and Tamarugal basins were separated. Sáez *et al.* (1999) also interpreted the synchronous change to ephemeral evaporitic sedimentation in the Quillagua Basin to changes in the regional drainage network induced by tectonic activity.

LATE PLIOCENE TO PRESENT DAY

Sedimentation in the Calama Basin ceased at 3 Ma and the Opache Formation was folded. Deformation is restricted to the Calama Basin and is not recorded in the Pampa del Tamarugal or Salar de Atacama Basins, again suggesting localised deformation likely related to movement on the Precordilleran/West Fissure Fault Systems. Following deformation, incision of the Río Loa and Río San Salvador took place prior to and synchronous with localised deposition of Late Pliocene to Pleistocene sediments. Sedimentation was restricted to small sedimentary basins created by tectonic or geomorphic features. For example, in the central Calama Basin folding produced a topographic barrier east of Angostura behind which the last phase of lacustrine development, the Chiu-Chiu Formation, was dammed. Similarly, minor evaporitic sediments accumulated in topographic lows in the eastern Pampa del Tamarugal (Soledad Formation) and within the Loa and San Salvador valleys.

The lack of widespread sedimentation in both the Calama Basin and Pampa del Tamarugal was caused by incision and by-passing of the Miocene to early Pliocene basins. Mortimer (1980) attributed the start of incision to be due to a change to the present day hyper-arid climate, although an alternative explanation related to a change in fluvial base-level can also be supported. It is possible that in the late Pliocene the Río Loa either: 1) broke through/overtopped the topographic barrier created by the Coastal Cordillera or 2) headcutting of coastal drainage systems inland resulted in breaching of the Coastal Cordillera watershed. Either mechanism whether acting independently or in combination would result in large-scale incision as the fluvial system responded to an approximate 1 km drop in base-level.

Between 4 and 3 Ma, it has been suggested that a switch to hyperaridity took place across the forearc region of northern Chile (Hartley and Chong, 2002; Hartley, 2003). This interpretation is based on the fact that across the forearc, upper Pliocene strata are overlain by up to 60 m of latest Pliocene to Pleistocene anhydrite, gypsum, and halite deposits (the Soledad Formation). These evaporites are restricted to localised basins and are thought to have formed by groundwater seepage (May *et al.* 1999). An extensive saline crust (0.5-5 m thick) composed of gypsum, anhydrite, and/or halite has developed over lower Pliocene and older strata and blankets hill slopes, summits, valley floors, and channel courses throughout northern Chile and southern Perú (Chong, 1988), attesting to the limited amount of post-late Pliocene runoff that has affected the Atacama Desert. Whilst it could be argued that incision of the Río Loa in response to base-level change could have resulted in abandonment of drainage systems in the Calama Basin, the fact that drainage abandonment occurs across the forearc region of northern Chile and southern Peru, suggests that there was a regional climate change. In the northernmost part of Chile and southern Perú, a series of deep valleys (*e.g.,* Quebradas Chaca, Tiliviche, Azapa, Camerones) were incised between the Western Cordillera and the Pacific coastline from 3 Ma to the present day (*e.g.,* Wörner *et al.,* 2000). The saline crust is well developed on the interfluves between the valleys and shows little or no evidence for active runoff (Mortimer, 1980). The valleys are considered to have been cut by runoff derived directly from the glaciated peaks of the Western Cordillera (Mortimer, 1980), incision was therefore generated by sources extraneous to the Atacama Desert and was not related to an increase in precipitation within the Atacama, which remained hyper-arid throughout this time period.

CONCLUSIONS

A lihostratigraphic analysis of the Calama Basin using detailed sedimentological and $^{40}Ar/^{39}Ar$ radiometric data has allowed redefinition of the Eocene to Pleistocene lithostratigraphy of the basin-fill. The existing Calama Formation is retained and redefined as (?)Lower Eocene to (?)Lower Miocene. The El Loa Formation is elevated to group status and assigned a Lower Miocene to Upper Pliocene age. The El Loa Group includes four newly defined formations: the Jalquinche, Opache, Lasana and Chiquinaputo formations. The existing definition of the Upper Pliocene to Pleistocene Chiu-Chiu Formation is retained.

A chronostratigraphic analysis of the tectono-sedimentary evolution of the Calama Basin reveals that basin development was more complex than previously thought. Three distinct periods of sedimentation separated by discrete deformation phases can be recognised together with a number of sedimentological changes. These periods include the Eocene-Oligocene, early Miocene to late mid-Miocene and late Miocene to late Pliocene. The following series of events can be recognised:

- Basin initiation commenced in the (?Lower) Eocene with deposition of up to 400 m of alluvial braidplain deposits throughout the basin. This style of sedimentation persisted throughout the Oligocene and occurred synchronously in a series of endorheic basins developed across much of northern Chile at the end of the Incaic Orogeny.

• From approximately 22 Ma to 10 Ma sedimentation was continuous throughout the Calama Basin with ephemeral fluvial sediments along the basin flanks (Lasana Formation) passing basinwards into finer grained playa sandflat and mudflat deposits (Jalquinche Formation) reflecting the continued endorheic nature of the basin. Similar environments were developed in the Salar de Atacama and the Pampa del Tamarugal at this time period indicating that all three basins were endorheic during this time period and that a paleo-Río Loa system was not present.

• Late Miocene sedimentation occurred regionally, but diachronously, across the north Chilean Forearc. From 8 to 6 Ma braidplain sedimentation sedimentation took place along the eastern margin (Chiquinaputo Formation). A Late Miocene (between 7(?) and 6 Ma) phase of tectonic deformation was restricted to the central part of the Calama Basin.

• The Pampa del Tamarugal and Calama Basin areas were linked around 6 Ma due to tectonic activity. Regional palustrine carbonate sedimentation took place in the Calama basin centre (Opache Formation) with fluvial sedimentation along the eastern basin margin (Chiquinaputo Formation). The change in depositional style is attributed to increased rainfall.

• At about 3 Ma the Calama basin-fill was subject to gentle folding, followed by entrenchment of the Río Loa and Río San Salvador through Miocene and Early Pliocene strata to reach a new base-level. The change in base-level is likely to have been caused by breaching of the Coastal Cordillera by the Río Loa to reach the Pacific. Localised diatomite and anhydrite deposition took place in depressions created either by folding of older strata or pre-existing geomorphic features (Chiu-Chiu Formation).

Up to 5 unconformities can be recognised in the Calama Basin. These unconformities occur across either the whole of the Calama Basin or localised areas of the basin, and are not recorded in adjacent basins. This suggests that throughout much of the sedimentation in the basin movement was taking place on the Precordilleran/West Fissure Fault Systems. This is supported by frequent changes in sediment thicknesses across fault zones that are considered to reflect different fault-controlled subsidence regimes (May, 1997).

Climatic changes have had important effects on the basin-fill development. This is illustrated by similar facies development in the adjacent but largely unconnected Pampa del Tamarugal and Salar de Atacama basins during much of the Oligocene and Miocene. Facies analysis of the Oligocene to Pleistocene succession suggests that sedimentation took place under an arid/semi-arid climate throughout this time period. Occasional fluctuations in climate suggesting increased runoff are indicated by the development of diatomites together with lacustrine and palustrine limestones. However, it is unlikely that the climate was never more humid than semiarid.

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