Cenozoic stratigraphy of the southern Salar de Antofalla region, northwestern Argentina

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ABSTRACT

In the region of the southern Salar de Antofalla (Catamarca Province, northwestern Argentina), Late Eocene to Pliocene/(?)Pleistocene successions are exposed with thicknesses of up to 1,600 m. They consist of fluvial, lacustrine and eolian sediments with intercalations of pyroclastic rocks and lava flows. The sedimentary deposits represent 'alluvial fan-playa-complexes' accumulated under a semi-arid to arid climate. From the Late Eocene to the Early Miocene, the sedimentation took place in broken-foreland basins, while from the Early Miocene to the Late Pliocene/(?)Early Pleistocene, the sediments mainly accumulated within compressional retroarc basins in which volcanoes partly formed additional basin boundaries. Seven stratigraphic units can be differentiated on the basis of different lithofacies, angular unconformities and different regional distributions: the Late Eocene to Early Miocene Quiñoas Formation, which can be subdivided into the Campo Negro Member, the Cadillo Member and the Aguada Member, the Early/(?)Middle Miocene Potrero Grande Formation, the Late Miocene Antofalla Formation, which can be subdivided into the Cajeros Member and Bordo Blanco Member, the Late Miocene Salina beds, the Late Miocene Pozuelos Formation (Orilla Member), the (?)Late Miocene/Early Pliocene Sijes Formation (Uncal Grande Member) and the Late Pliocene/(?)Early Pleistocene Singuel Formation (Agua Escondida Member). While the Quiñoas Formation, the Potrero Grande Formation, the Antofalla Formation and the Salina beds have been newly introduced, the strata which represent the other formations can be assigned to the existing stratigraphic division of the southern Puna. Owing to the fact that these strata had no lateral connection to the strata of their type localities, which crop out near the Salar Pastos Grandes, they were defined as lateral members.

Keywords: Tertiary, Alluvial fan-playa-complexes, Salar de Antofalla, Southern Puna, Northwestern Argentina.

RESUMEN

Estratigrafía del Cenozoico en la región sur del Salar de Antofalla, noroeste de Argentina. En la parte sur del Salar de Antofalla (Provincia de Catamarca; noroeste de Argentina) afloran sedimentitas continentales de edad eocena tardío a plio-pleistocena con espesores de hasta 1.600 m. Están compuestas por materiales aluviales, lacustres, eólicos e intercalaciones de lavas y rocas piroclásticas. Las sedimentitas continentales representan complejos de abanicos aluviales y depósitos de playa acumulados bajo condiciones climáticas áridas y semiáridas. Desde el Eoceno Tardío al Mioceno Temprano la sedimentación se desarrolló en cuencas de antepaís desmembradas, mientras que a partir del Mioceno Temprano al Plioceno Tardío-Pleistoceno temprano(?) la sedimentación se desarrolló, en su mayoría, dentro de cuencas de retroarco compresionales. Volcanes formaron límites locales de estas cuencas. Sobre la base de diferencias de litofacies y discordancias angulares se distinguieron siete unidades estratigráficas: Formación Quiñoas del Eoceno Tardío a Mioceno Temprano, la cual a su vez, puede ser subdividida en los miembros Campo Negro, Miembro Cadillo y Aguada; la Formación Potrero Grande del Mioceno Temprano/Medio; Formación Antofalla la cual puede ser subdividida en los miembros Cajeros y Bordo Blanco; las capas Salina del Mioceno Tardío; Formación Pozuelos del Mioceno Tardío (Miembro Orilla); Formación Sijes del Mioceno/Plioceno Temprano (Miembro Uncal Grande) y Formación Singuel del Plioceno/Pleistoceno temprano (Miembro Agua Escondida). Las formaciones Quiñoas, Potrero Grande y Antofalla y las capas Salina constituyen unidades nuevas, en tanto que las otras formaciones son conocidas en la división estratigráfica de la Puna meridional. Los estratos que no tienen conexión lateral con aquellos de sus localidades tipos, y que afloran cerca del Salar Pastos Grandes, se definieron como miembros laterales.

Palabras claves: Terciario, Complejos de abanicos aluviales y depósitos de playa-lake, Salar de Antofalla, Puna austral, Noroeste de Argentina.

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INTRODUCTION

One of the most striking features of the South American Central Andes is the Altiplano/Puna plateau, which has an average elevation of about 4 km and stretches in a north-south direction over an area about 2,000 km long and 300 km wide (*e.g.* Isacks, 1988; Allmendinger *et al.*, 1997; Fig. 1). In its southernmost part, the southern Puna, several non-marine, closed basins with saline pans (salars) in their centers (*e.g.*, the basin of the Salar de Arizaro, the Salar de Hombre Muerto, the Salar de Antofalla and the Salar Pastos Grandes) were formed during the Cenozoic. The basins are limited by fault-bounded ranges and in some cases by Neogene volcanic edifices. Their evolution occurred against the background of an eastward-directed subduction of the Pacific Nazca plate beneath the South American plate, as well as contractional and strike-slip deformation, uplift and Miocene to Recent volcanism within the plateau (*e.g.*, Alonso *et al.*, 1984a; Allmendinger *et al.*, 1989; Coira *et al.*, 1993; Marrett *et al.*, 1994; Kraemer *et al.*, 1999; Voss, 2000). Within the basins, fluvial, lacustrine and eolian sedimentation took place predominately under semi-arid to arid climatic conditions (*e.g.* Donato, 1987; Alonso, 1992; Vandervoort, 1993; Voss 2000).

Uplifted, variably deformed Cenozoic sedimentary successions bounded by intrabasinal unconformities are exposed within or adjacent to modern depocenters. Available stratigraphic subdivision of these successions is based mainly on investigations carried out in the Salar Pastos Grandes basin (see for instance Turner, 1960; Alonso, 1992; Vandervoort, 1993; Fig. 1). In that region, the type localities for the most often cited Cenozoic formations of the southern Puna are located. The units include the Middle Eocene to (?)Oligocene Geste Formation, the Late Miocene Pozuelos Formation and the Late Miocene to Pliocene Sijes Formation of the Pastos Grandes Group (Turner, 1960) as well as the Pliocene Singuel Formation (Alonso and Gutiérrez, 1986). In the Salar de Antofalla region, sedimentary Cenozoic successions with thicknesses of up to 1,600 m are exposed (Kraemer *et al.*, 1999; Voss, 2000). In this paper, a description of these strata is presented and it is shown how they can be correlated with sedimentary successions from other parts of the southern Puna, especially with those of the Pastos Grandes area. The recording of several profiles at outcrops and radiometric Ar-Ar- and K-Ar-determinations form the basis for the results presented here.

GEOLOGICAL SETTING

The working area is the region around the southern part of the Salar de Antofalla between 67°40' and 68°15'W and 25°40'S and 26°20'S in the Argentine province of Catamarca (Fig. 1). The Salar de Antofalla forms the center of a NNW-SSE-striking basin, which is approximately 140 km long and 4 to 10 km wide. The surface of the Salar lies at an altitude of 3,340 m. It is surrounded by steep slopes with peaks of up to more than a thousand meters above the surface of the Salar. About 10 km west of the Salar de Antofalla, the Salina del Fraile lies in the center of another modern basin.

At the western and eastern boundary of the working area, north-south trending ranges with altitudes of more than 5,000 m (Sierra de la Quebrada Honda and Sierra de Calalaste) occur. Within the area there are many monogenetic and polygenetic volcanoes. The most striking one is the Late Miocene Antofalla stratovolcano with an altitude of 6,409 m. To the west lie the volcanoes of the Miocene to Recent Andean magmatic arc.

Pre-Cenozoic rocks are present at several places in the area under study. Metamorphic rocks are exposed in the Sierra del Campo Negro and south of the Vega Orohuasi (Segerstrom and Turner, 1972; Allmendinger *et al.*, 1982; Alonso *et al.*, 1984a; Palma, 1990; Mon and Hongn, 1991 and González, 1992; Fig. 1). They consist of magmatic gneiss as well as mica-schist, phyllite and quartzite and metabasite affected by greenschist-facies metamorphism. While Mon and Hongn assigned the gneisses to the Pre-Cambrian, Lucassen *et al.*

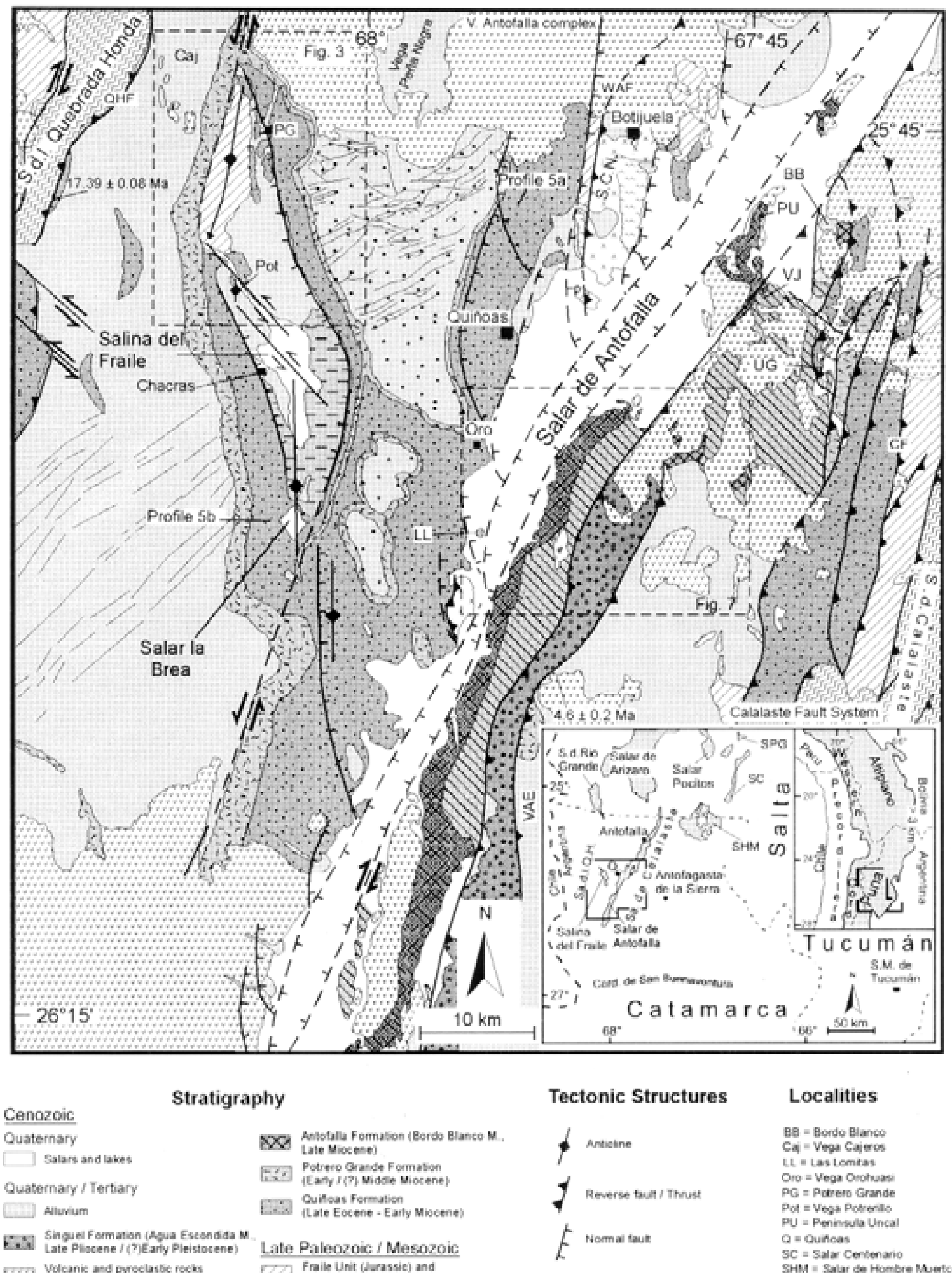


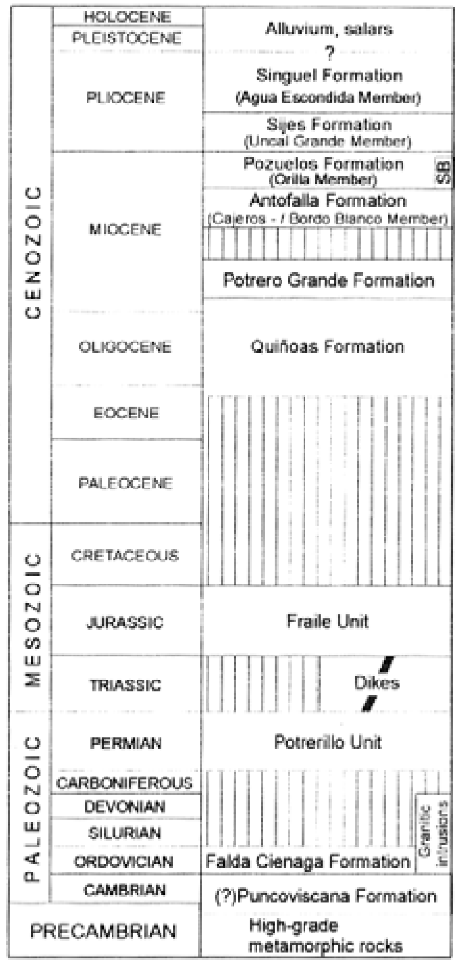
FIG. 1. Geological map of the region surrounding the southern Salar de Antofalla and location of the area studied. Included on the map are the locations and ages of some of the samples, on which radiometric age determinations were carried out.

(1996) put them on a par with high-grade metamorphic rocks in northern Chile and north western Argentina, whose Sm/Nd-ages point to a peak metamorphism of a protolith, possibly of Precambrian age, around 500 Ma. The mica-shists, phyllites and quartzites are metasediments which grade laterally into anchimetamorphic sedimentary rocks that can be lithologically correlated with the metasedimentary and anchimetasedimentary rocks of the Late Proterozoic/Cambrian Puncoviscana Formation (Turner and Méndez, 1979; Kraemer *et al.*, 1999). In the Sierra de Calalaste and the Sierra de la Quebrada Honda Ordovician low-grade metamorphic rocks in greenschist-facies are exposed (Aceñolaza *et al.*, 1975, 1976; Coira and Pezutti, 1976; Allmendinger *et al.*, 1982; Alonso *et al.*, 1984a; Palma *et al.*, 1990; González, 1992 and Zimmermann *et al.*, 1996). The Ordovician of the Sierra de Calalaste is made up of metasediments (Falda Ciénaga Formation, after Aceñolaza *et al.*, 1975, 1976), metavolcanic and metamorphic basic intrusive rocks. From the Sierra de la quebrada Honda Ordovician metabasites, layers of chert with manganese-nodules and turbiditic sand- and mudstones are described.

The Precambrian/Cambrian rocks as well as the Ordovician rocks exposed in the Sierra de la quebrada Honda are intruded by Early Paleozoic granites (Coira and Pezutti, 1976). Radiometric age determinations yielded an age of 417±8 Ma (Voss *et al.*, 1996) for a granite from the Sierra del Campo Negro and an age of 389±9 Ma (Kraemer *et al.*, 1999) for another one, which is exposed south of the Vega Orohuasi (Fig. 1).

Permian clastic and evaporitic sediments as well as pyroclastic rocks (Potrerillo Unit, Voss *et al.*, 1996; Kraemer *et al.*, 1999) crop out in the northern part of the Salina del Fraile basin, in the Sierra del Campo Negro and at the western margin of the Sierra de Calalaste (Figs. 1, 2 and 3). The Potrerillo Unit is exposed with a thickness of up to several hundred meters. A few layers of tuff are intercalated within the successions. From these, ages of 277±6 and 256±5 Ma (Voss *et al.*, 1996) as well as 268±6 Ma (Kraemer *et al.*, 1999) were obtained.

In the northern part of the Salina del Fraile basin, folded strata of the Potrerillo Unit are cut by Triassic dikes, which are east-west striking, several meters wide and up to a few hundred meters long. One of these yielded an age of 212±15 Ma (Voss *et al.*, 1996; Figs. 2 and 3).



SB: Salina beds

FIG. 2. Stratigraphy of the Salar de Antofalla region.

In the same area the Jurassic Fraile Unit (Voss *et al.*, 1996; Kraemer *et al.*, 1999; Voss, 2000) follows on top of the Potrerillo Unit (Figs. 2 and 3). The Fraile Unit is more than 200 m thick and consists of sandstones (partly with oscillatory ripples), marls, beds of coquina and oolithic limestone, tuffites and intercalations of volcanic rocks (some as pillow lava). Ages of 194±6 Ma (Voss *et al.*, 1996) and 198±5 Ma (Kraemer *et al.*, 1999) were obtained from the volcanic rocks.

In almost the whole area under study, Cenozoic terrigeneous clastic and evaporitic continental sediments, in which lava flows and pyroclastic rocks are intercalated, are present and form successions with thicknesses of up to 1,600 m (Fig. 1).

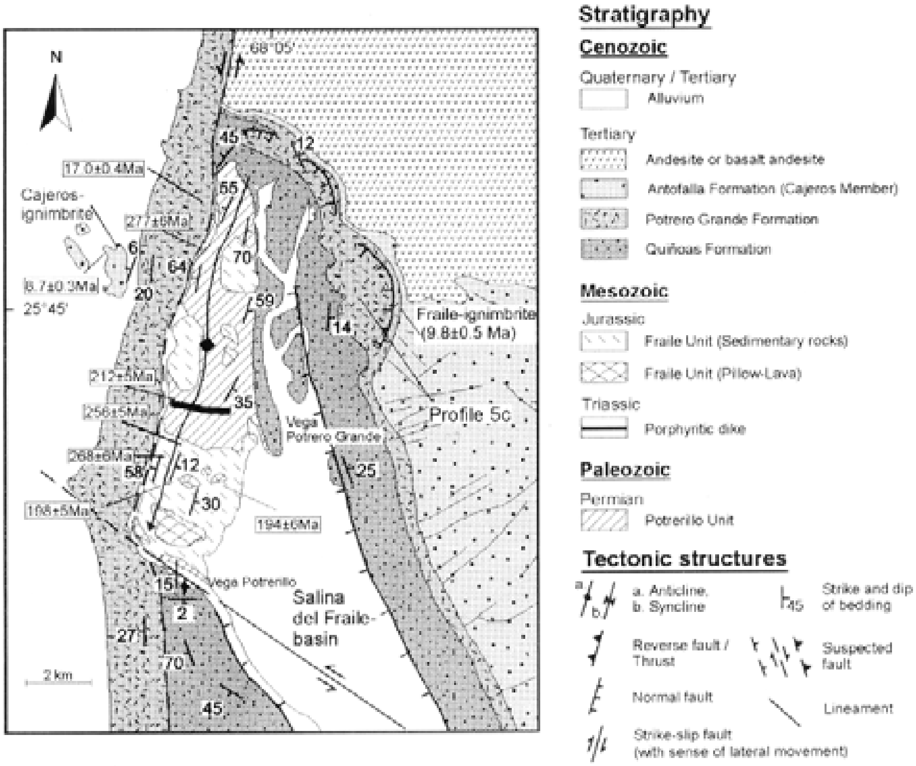


FIG. 3. Geological map of the northern Salina del Fraile basin and its surrounding area. The Permian Potrerillo Unit, the Jurassic Fraile Unit and Triassic dikes are exposed in the core of an anticline. Also shown are the Cenozoic Quiñoas Formation, Potrero Grande Formation, the Cajeros Member of the Antofalla Formation and lava flows. The location of radiometric age determinations with the corresponding dates and the location of the stratigraphic profile 4c complete the map. Location of the map: see figure 1.

The Cenozoic deformation of the area studied took place in several intervals of tectonic movements, which resulted in NNE-SSW-striking thrusts, reverse faults and folds. NW-SE, NE-SE- and NNW-SSE-striking strike-slip faults and NNW-SSE-striking normal faults were also active during that time, but of minor importance. As a consequence of the tectonic activity, Cenozoic basin-fills were deformed and uplifted.

A Miocene to Recent volcanism led to the formation of the mono- and polygenetic volcanoes in the area studied (Coira and Pezzutti, 1976; Kraemer, 1999; Kraemer *et al.*, 1999). Their lava flows and pyroclastic deposits contributed to the filling of the contemporary basins. Owing to changes in the volume and composition of the volcanic products and to different structural features, the volcanic evolution of the area under study during that time-span can be subdivided into two periods (Kraemer *et al.*, 1999). During the Early Miocene to Late Miocene an extensive volcanism led to the formation of several stratovolcanoes (*e.g.*, the Volcán Antofalla complex, see Fig. 1), which are made up mainly by silicic andesites, dacites and subordinate rhyolites. In addition to that, low-volume ignimbrites and pyroclastic fall deposits occurred during this period. Since the Late Miocene the volcanic activity has been decreasing. Monogenetic centers composed of basaltic andesites and, to a smaller extent, of basalts, andesites and dacites, as well as widespread ignimbrite sheets were the characteristic features of this period. Besides that, intermediate lava and low-volume ignimbrites point to a continuous activity of the stratovolcanoes during this time.

During the Late Eocene to Early Miocene, sediments accumulated in two broken-foreland basins within the area studied, the Cajeros basin west of the recent Salar de Antofalla and the Juncalito basin east of it (Voss, 2000). The basins were situated east of the Incaic mountain chain, the remnants of which form the Chilean Precordillera today (Fig. 1). Main sediment sources were the NNE-SSW-striking Antofalla High (Voss, 2000), which was located in the area, occupied today by the southern Salar de Antofalla and its western margin, and the precursor of the Sierra de Calalaste, the NNE-SSW-striking Pre-Calalaste High. Both highs were uplifted by west-verging reverse faults at their western boundaries (West Antofalla Fault, Calalaste Fault; Fig. 1).

With the formation of the Miocene to Recent magmatic arc in the region of the Western Cordillera in the Early Miocene (*e.g.*, Coira *et al.*, 1993), the basins became compressional retroarc basins. While the sedimentation in the Juncalito basin continued until the Late Pliocene/(?) Early Pleistocene, it ended in the Cajeros basin in the Late Miocene. The precursor of the Sierra de la Quebrada Honda, the Pre-Sierra de la Quebrada Honda, which was uplifted at its eastern boundary by an east-verging reverse fault (Quebrada Honda Fault; Fig. 1) as well as volcanoes within the area studied, formed additional sediment sources and basin boundaries during this period of basin evolution.

In the region east of the Salar de Antofalla, the basin of the Salina del Fraile was formed in the Late Miocene. This basin is interpreted as a strike-slip basin (McClay and Dooley, 1995; Voss, 2000). The basin of the Salar de Antofalla is interpreted as a (?)Late Pliocene/Early Pleistocene to Recent polyhistory basin, which has evolved from a half ramp basin and a strike-slip basin (Voss, 2000).

PREVIOUS STUDIES

The first descriptions of Cenozoic strata in the region of the Salar de Antofalla came from Turner (1969 and 1970). Turner divided an up to 4,500-m-thick succession into three parts. A lower part of dark-violet to red-brown conglomerates and sandstones, a more fine-grained middle part, which is made up of red and gray conglomerates and sandstones as well as beds of halite near the top and an upper part, which consists of gray, green and light-brown interbedded sand- and mudstone beds with borates and intercalations of volcanic rocks. Turner called the lower two parts 'Estratos Calchaqueños', the upper part 'Estratos Araucanenses' and assigned both units to the Pliocene. In 1976 Coira and Pezutti described a Cenozoic succession exposed in the Sierra de la Quebrada Honda. There a lower unit of dark-violet and dark-brown conglomerates, sandstones and mudstones is capped by an upper unit of grayish and brown volcaniclastic-rich conglomerates and sandstones. The authors correlated these strata with the Geste and Pozuelos Formation of the Pastos Grandes Group (Turner, 1960) or the 'Estratos Calchaqueños' and assigned them to the Miocene. In the middle of the 80's and the beginning of the 90's, some papers concerning the stratigraphy of the Miocene to Pliocene evaporitic strata which are exposed at the eastern margin of the Salar de Antofalla were published (Alonso *et al.*, 1984b; Alonso, 1991; Alonso *et al.*, 1991). Palma and Irigoyen (1987) reported tertiary continental deposits exposed west of the Sierra del Campo Negro and assigned them to the Pastos Grandes Group. In the same publication, the authors mentioned an exposure of fanglomerates east of Botijuela for which they also assigned a Cenozoic age.

Bassi (1992) reported a several hundred-meter-thick succession of conglomerates with minor sandstone from a valley east of the Cerro Antofalla, which is located due north of the area studied. These deposits were assigned a Cenozoic age. Singer *et al.* (1994) reported an age of 26.3 ± 1.6 Ma from a tuff intercalated within Cenozoic red beds. Kraemer *et al.* (1999) published the first detailed and precise work about the stratigraphic, tectonic and paleogeographic evolution of the region of the Salar de Antofalla during Cenozoic times.

CENOZOIC STRATIGRAPHY

In the Salar de Antofalla region the Cenozoic successions consist of Late Eocene to Recent terrigeneous clastic and evaporitic continental sediments, in which lava flows and pyroclastic rocks are intercalated. Apart from a few exceptions, no fossils were found in the sedimentary record. The sediments are interpreted as products of fluvial, lacustrine and eolian processes (Voss, 2000). They were formed within 'alluvial fan-playa-complexes' (Eugster and Hardie, 1975; Hanford, 1982) predominately under a semi-arid to arid climate. The maximum composite thickness for the exposed Cenozoic sedimentary formations is approximately 3,000 m.

Seven stratigraphic units can be differentiated on the basis of different lithofacies, angular unconformities and different regional distributions: **a-** the Late Eocene to Early Miocene Quiñoas Formation, which can be subdivided into the Campo Negro Member, the Cadillo Member and the Aguada Member; **b-** the Early/(?)Middle Miocene Potrero Grande Formation; **c-** the Late Miocene Antofalla Formation, which can be subdivided into the Cajeros Member and Bordo Blanco Member; **d-** the Late Miocene Salina beds; **e-** the Late Miocene Pozuelos Formation (Orilla Member); **f;** the (?)Late Miocene/Early Pliocene Sijes Formation (Uncal Grande Member) and **g-** the Late Pliocene/(?)Early Pleistocene Singuel Formation (Agua Escondida Member).

The stratigraphic subdivision of the Cenozoic successions presented in this paper mainly differs in three points from that one published by Kraemer *et al.* (1999; Fig. 4):

- The Late Eocene to Early Miocene strata in the area of the southern Salar de Antofalla are combined into a single unit, the Quiñoas Formation, whereas Kraemer *et al.* (1999) subdivided them into two units, referring to the Late Eocene to Late Oligocene strata as Quiñoas Formation and to the Late Oligocene to Early Miocene strata as Chacras Formation.
- Kraemer *et al.* (1999) combined the Middle Miocene to Pliocene deposits into a single unit, the Juncalito Formation. Within this paper these deposits are subdivided on the basis of different lithologies, angular unconformities and differences in the regional distribution into three different units: the Antofalla Formation, the Pozuelos Formation and the Sijes Formation.
- In contrast to Kraemer *et al.* (1999), who introduced local formation names for the Late Miocene to Pliocene/(?) Pleistocene strata (Fig. 4), the attempt was made in this paper to assign the strata in the region of the Salar de Antofalla as far as possible to the already existing stratigraphic division of the southern Puna. Hence Late Miocene to Pliocene/(?)Pleistocene stratigraphic units in the region of the Salar de Antofalla were correlated lithologically and chronologically with the formations from the area of the Salar Pastos Grandes (Pozuelos, Sijes and Singuel Formation). Because sedimentation in the southern Puna took place at least from the Miocene in separated, intramountainous basins (Alonso *et al.*, 1991; Jordan and Alonso, 1987; Salfity *et al.*, 1984; Vandervoort *et al.*, 1995), the strata in the region of the Salar de Antofalla had no lateral connection to the strata that crop out near the Salar Pastos Grandes. For this reason, the stratigraphic units in the region of the Salar de Antofalla were defined as their lateral members. This procedure is in agreement with the recommendations of the 'International Subcommission on Stratigraphic Classification of IUGS International Commission on Stratigraphy' (Salvador, 1994).

QUIÑOAS FORMATION (LATE EOCENE TO EARLY MIOCENE)

The Late Eocene to Early Miocene Quiñoas Formation (Kraemer *et al.*, 1999; Voss, 2000) is mainly made up of red, brown and gray conglomerates, sandstones and mudstones as well as white evaporites (Fig. 5, a and b). Claystones, marls and thin tuff layers are occasionally intercalated. In the area studied, strata of the Quiñoas Formation are exposed west as well as east of the Salar de Antofalla and show a thickness of up to ~1,500 m. The Quiñoas Formation constitutes the base of the Tertiary record and rests upon Ordovician, Permian and Jurassic rocks in angular unconformity. It is overlain by the Early/(?)Middle Miocene Potrero Grande Formation in angular unconformity. Besides that angular unconformity the low content of pyro-

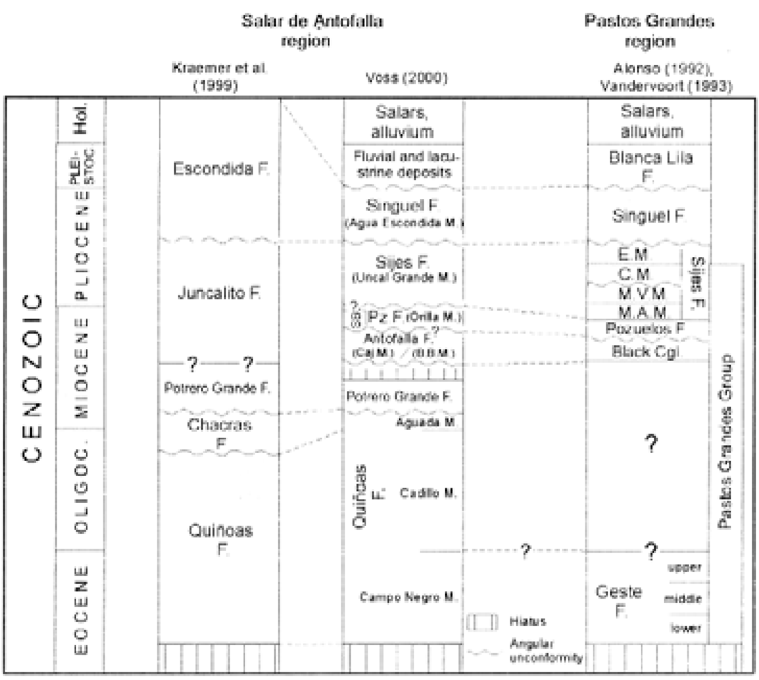


FIG. 4. Correlation between the Cenozoic sedimentary successions from the region of the southern Salar de Antofalla and the surrounding area of the Salar Pastos Grandes. **B.B.M.=** Bordo Blanco Member; **Caj.M.=** Cajeros Member, **C.M.=** Conglomerate Member, **E.M.**= Esperanza Member, **M.A.M.**= Monte Amarillo Member; **M.V.M.**= Monte Verde Member, **Pz.F.**= Pozuelos Formation; **SB=** Salina beds.

clastic material of the Quiñoas Formation serves as a criterion to distinguish it from the Potrero Grande Formation. This difference is also reflected by the different colors of both formations.

A complete -approximately 1,500 m thick succession of the Quiñoas Formation is exposed west of the Sierra del Campo Negro (25°46'S-67°52'W, Figs. 1 and 5, a). There, the Quiñoas Formation can be subdivided into three members by means of different lithologies and a local intraformational angular unconformity.

- The **Campo Negro Member** in the lower part of the succession is ~370 m thick and characterized by conglomerates and sandstones. It is made up of clast-supported conglomerates, pebbly sandstones, sandstones and subordinate mudstones, claystones and layers of marl. Some mud- and sandstone beds contain intrasedimentary-grown nodules of gypsum, which are a few millimeters in diameter. Bedding ranges from thinly-laminated to very thickly-bedded. The sediments exhibit sheet-like geometries as well as channel-fill facies. Most conglomerates are massive, poorly to moderately sorted and have clast-sizes of up to 20 cm. Imbrication of clasts was observed. Also moderately sorted conglomerates with cross-bedded gravel occur. These form sets of some dm-thickness. The sandstones are horizontally-bedded, asymmetric ripple cross-laminated, planar cross-bedded with up to 0.5-m-thick sets or massive. In some clay- and mudstone layers 'teepee structures' were found.

An up to 32 m thick section of poorly sorted conglomerates constitutes the base of this member. Their clasts are sub-angular to sub-rounded and show sizes of up to 20 cm. The conglomerate contains clasts of quartz arenites from the Potrerillo Unit as well as sandstone, foliated quartzite, schists, gneisses, granitoids and quartz from the local basement.

The top of the Campo Negro Member is formed by a 3 m thick section of calcite-cemented clast-supported conglomerates and sandstones. In the sandstone beds rooted zones were found. This section can be interpreted as paleosol ('calcrete').

The sediments of the Campo Negro Member were deposited in an alluvial fan, alluvial sand flat and playa mud flat environment.

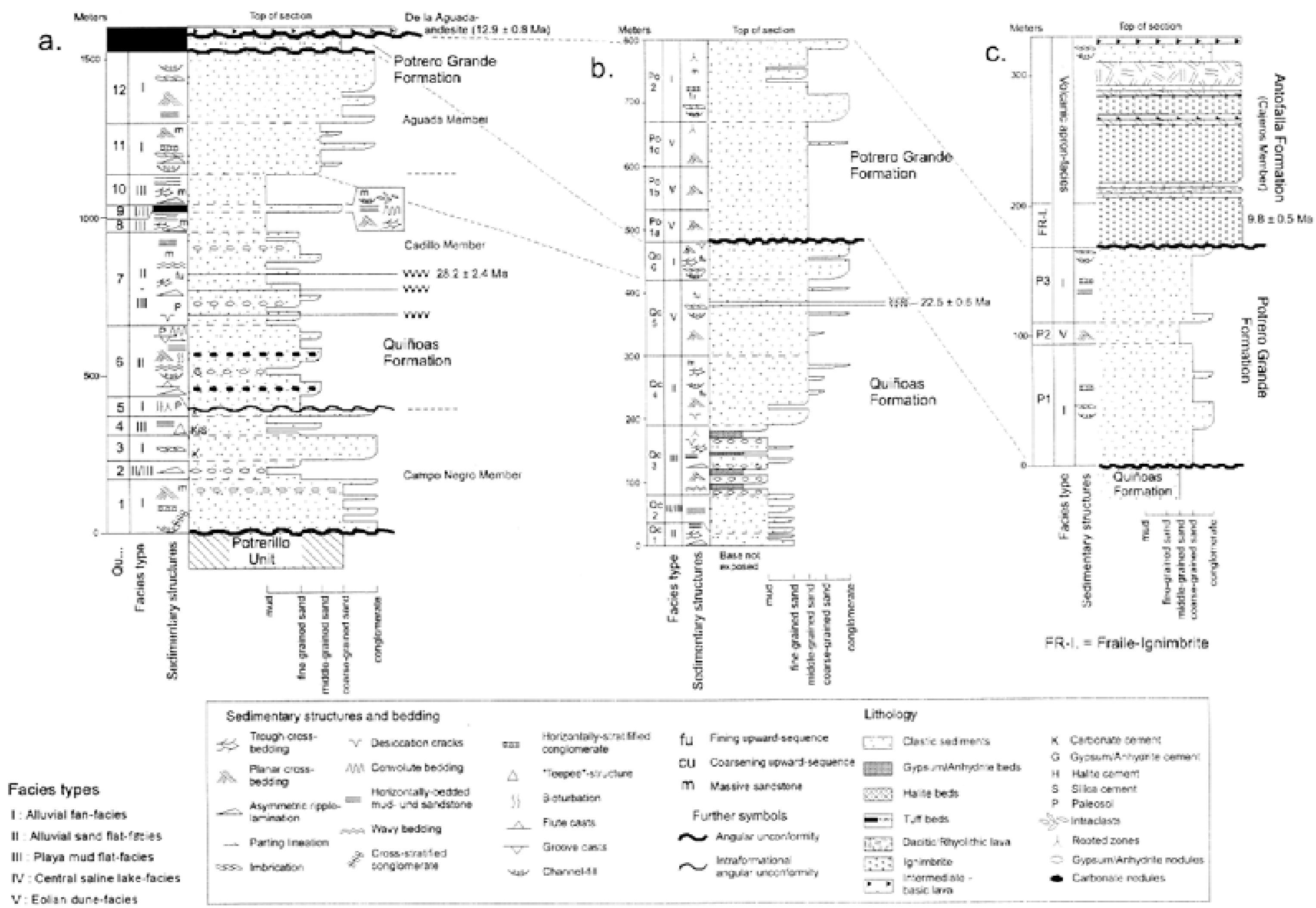
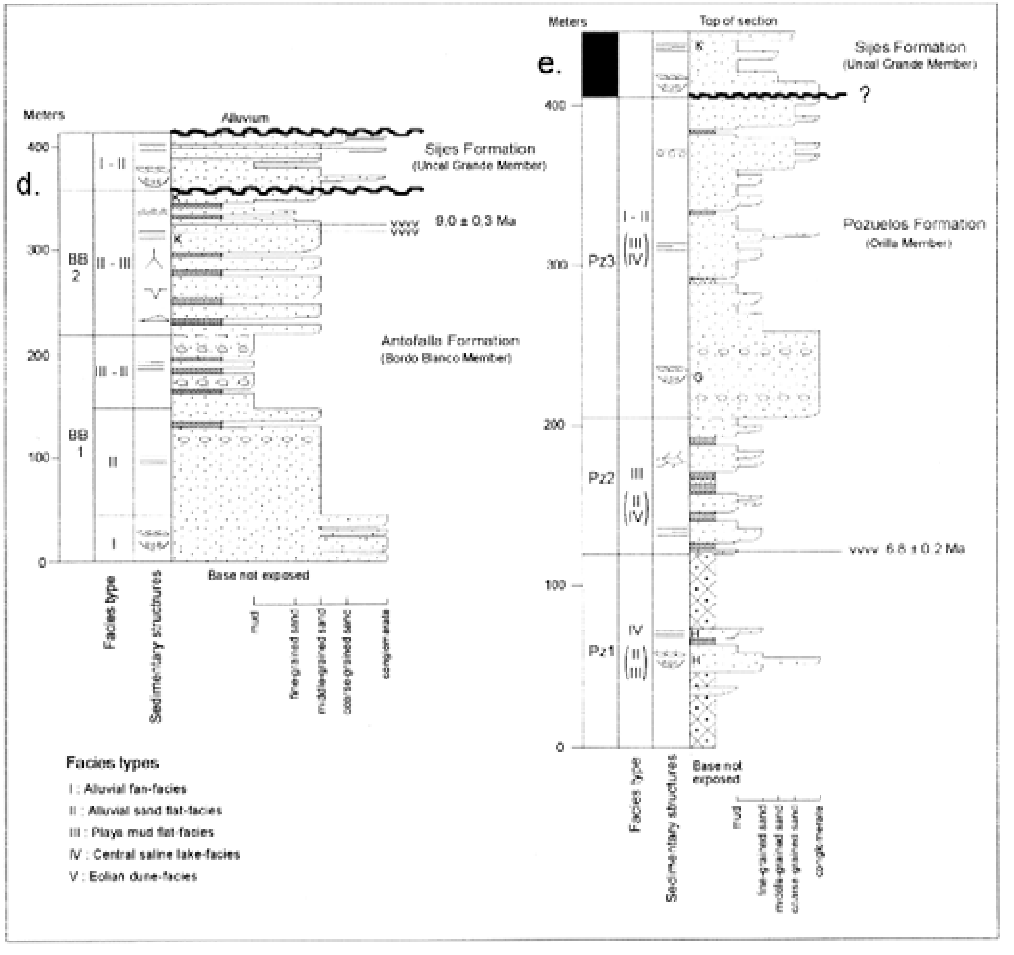


FIG. 5. Lithologic profiles of Cenozoic stratigraphic formations in the Salar de Antofalla region. Also shown are sedimentary structures, facies types and radiometric dates. The locations of these profiles are shown in figure 1, 3 and 7.

(Fig. 5 continued, see legend on the previous page)



• The **Cadillo Member** in the middle part of the succession has a thickness of ~740 m. It overlies the Campo Negro Member with an intraformational angular unconformity, which can be put down to tectonic movements of the Antofalla High. The Cadillo Member shows a fining upward-trend and is mainly made up of thinly- to thickly-bedded sandstones, mudstones and claystones. Intercalated within its upper part is a 20 m thick interval of poorly to moderately sorted, clast-supported pebble conglomerates and sandstones. Some of the clay, mud- and fine-grained sandstone beds contain gypsum as cement or in the form of intrasedimentary-grown nodules, with sizes between 0.2 and 1.5 cm. Three 10 to 15 cm thick, white layers of tuff are intercalated in the Cadillo Member. The uppermost of these yielded an age of 28.2 ± 2.4 Ma (Fig. 5, a and Table 1).

Sediment bodies with sheet-like geometries predominate within this member. Channels up to a few decimeters deep and up to several meters wide are only occasionally intercalated. The sandstones are horizontally-bedded, trough and planar cross-bedded with sets of up to 50 cm thick, ripple cross-laminated, climbing ripple cross-laminated, or massive. Parting lineation, flute casts, groove casts and convolute bedding can be observed in sandstone beds. Centimeter-deep and decimeter-wide channels filled by coarse-grained sand are intercalated within some finer grained sandstone beds. Subordinately calcrete horizons occur in the form of gray carbonate nodules with sizes of up to several cm, which are arranged in horizontal layers. Fining upward-sequences with thicknesses between 1 and 30 cm made up of sand, silt and clay are also found

TABLE 1. ANALYTICAL DATA FOR K-Ar AND Ar-Ar AGES OF VOLCANIC AND INTRUSIVE ROCKS FROM THE SALAR DE ANTOFALLA REGION.

No	Sample No.	Rock	Method (mineral)	K (%)	^{40}K (ppm)	$^{40*}Ar/Ar_{tot}$	$^{40*}Ar$ (ppm)	$^{40*}Ar/^{40}K$	No. of analysis	Isochron (MSDW)	$^{40}Ar/^{36}Ar_{initial}$	Age (Ma ± 2σ)	Latitude Longitude
1	KSF 036	Tuff	K-Ar	3.535	4.217	0.344	0.008581	0.001991				34.0±0.9	25°46'689'S
			(Biotite)	3.534		0.338	0.008212						68°03'341'W
2	An 052	Tuff	Ar-Ar						7	35	289±7	28.2±2.4	25°46'359'S
			(Biotite)										67°53'666'W
3	An 054	Tuff	K-Ar	0.413	0.492	0.105	0.000764	0.001528				26.1±1.3	26°09'756'S
			(Amphibole)	0.412		0.155	0.00074						68°02'996'W
4	SAF 095/64	Tuff clast	K-Ar	0.718	0.852	0.295	0.000937	0.001127				19.3±0.9	25°50'449'S
			(Plagioclase[1])	0.711		0.249	0.000985						67°40'167'W
5	SAF 095/19	Tuff	K-Ar	3.086	3.67	0.237	0.003987	0.00111				19.0±0.6	26°05'046'S
			(Glass[1])	3.067		0.249	0.004164						67°54'929'W
6	KSF 008	Pumice	K-Ar	6.244	7.548	0.193	0.007497	0.000992				17.0±0.4	25°40'185'S
			(Biotite)	6.41		0.211	0.007484						68°05'530'W
7	An 051	Andesite	Ar-Ar						10	2.9	297±1	12.9±0.8	25°45'889'S
			(Plagioclase)										67°53'938'W
8	An 176	Tuff	K-Ar	7.62	9.048	0.19	0.004783	0.000525				9.0±0.3	25°55'757 S
			(Biotite)	7.549		0.246	0.004719						67°47'277'W
9	KSF 014	Ignimbrite	K-Ar	4.845	5.816	0.35	0.002991	0.000508				8.7±0.3	25°44'969'S
			(Glass[1])	4.905		0.333	0.002915						68°07'139'W
10	SAF 166	Ignimbrite	K-Ar	6.453	7.801	0.167	0.003841	0.000491				8.4±0.3	25°49'408'S
			(Biotite)	6.625		0.195	0.003827						68°12'868'W
11	SAF 137	Tuff	Ar-Ar									8.1±0.3	25°51'711'S
			(Biotite)										68°02'273'W
12	SAF 088	Tuff	K-Ar	7.489	9.064	0.433	0.003558					6.8±0.2	26°00'961'S
			(Biotite)	7.706		0.454	0.003575						67°55'149'W
13	SAF 095/80	Basalt	K-Ar	1.916	2.286	0.98	0.000728	0.000323				5.6±0.3	25°57'S
		Andesite	(Whole rock[1])	1.916		0.93	0.000825						67°53'W
14	An 070	Ignimbrite	Ar-Ar						10	0.7	295.6±0.3	3.61±0.01	26°13'603'S
			(Feldspar)										67°59'983'W
15	SAF 272	Tuff	Ar-Ar									0.44±0.03	25°47'770'S
			(Biotite)										67°42'548'W

[1] Treated with diluted HF and HNO_3.

The numbers in the first column refer to figure 6, except No. 2, found in figure 5. $^{40*}Ar$ refers to radiogenic ^{40}Ar. The laser $^{40}Ar/^{39}Ar$ age determinations were performed by the GEOMAR Forschungszentrum in Kiel, Germany, by P. van den Bogard. Samples were irradiated in the reactor at the GKSS Research Center (Geesthacht, Germany), using Taylor Creek rhyolite sanidine (TCR 85G003) as the flux monitor (27.92 Ma). All K/Ar age determinations were done by GEOCHRON Laboratories, Krueger Enterprises Inc. in Cambridge, Massachusetts (USA). The analyses were taken in the size fraction –80/+200 mesh (177 to 74 microns). The potassium concentrations were measured on a Beckman DU flame spectrophotometer, while the argon isotopic compositions were analysed in a AEI MS10 mass spectrometer operated in a static mode.

in this member. In addition to that, sand and mud form layers with lenticular-bedding.

Desiccation cracks were observed in clay- and mudstones beds. Intraclasts of clay and mudstone were found in conglomerates as well as in coarse-grained sandstone.

The Cadillo Member reflects the transition from an alluvial sand flat-facies to a playa mud flat-facies. The intercalation of conglomerates and sandstones in its upper part is interpreted as distal alluvial fan-facies.

- The **Aguada Member** forms the upper part of the Quiñoas Formation in this succession. It is around 400 m thick and consists mainly of conglomerate. Sandstone beds occur subordinately. The conglomerates and sandstones of the Aguada Member appear without transition above the mudstone beds at the top of the Cadillo Member and form a coarsening upward-sequence. Bedding within this member ranges from thinly to very thickly bedded. The sediments were deposited as beds with sheet-like geometries as well as within few dm-deep and several meter wide channels. The conglomerates occur as poorly to moderately sorted, clast-supported, massive conglomerates as well as matrix-supported conglomerates. Their clasts are sub-angular with sizes of up to 30 cm. Imbrication of clasts was observed. The sandstones are massive, planar cross-bedded with sets up to 40 cm thick, asymmetric ripple cross-laminated or horizontally-bedded.

The Aguada Member can be interpreted as alluvial fan-facies.

In another exposure of the Quiñoas Formation at the Salar la Brea (25°58'S-68°03'W, Figs. 1 and 5, b), a more than hundred meter thick section was found, in which gypsum occurs in the form of nodules with sizes of up to 30 cm within clastic strata and as massive layers. The latter ones are between a few and 100 cm thick and are interbedded with layers of mudstone. For this section a playa mud flat-deposition is assumed.

In the same profile, an approximately 110 m thick section of medium- to thickly-bedded sandstone with sets of planar cross-bedding was observed. Single sets are between 0.5 and 3 m thick. These sandstones are interpreted as deposits of eolian dunes. Intercalated within them are two 1 to 2 cm thick, white layers of tuff. The older one has an age of 22.5±0.6 Ma (Kraemer *et al.*, 1999).

Kraemer *et al.* (1999) subdivided the Quiñoas Formation into Member I and II. Apart from the uppermost part of the Cadillo Member, the strata which are described as Campo Negro Member and Cadillo Member correspond to Member I. The uppermost part of the Cadillo Member corresponds to Member II. The strata which are described as Aguada Member here, Kraemer *et al.* (1999) placed into their Chacras Formation (see below). The following observations were the decisive factors that the strata described as Aguada Member are assigned to the Quiñoas Formation in this paper. Even though in many profiles of the Quiñoas Formation, conglomeratic successions constitute the upper part, in none of these profiles was angular unconformity between these successions and the strata beneath them observed. In addition to that, there are no lithological differences between the conglomerates and sandstones from the Aguada Member and conglomerates and sandstones from the strata of the Cadillo Member below.

Age and correlation: radiometric age determinations from tuff intercalations within the Quiñoas Formation yielded ages of 37.6±0.3, 28.9±0.8, 24.2±0.9 and 22.5±0.6 Ma (Kraemer *et al.*, 1999), 26.3±1.6 Ma (Singer *et al.*, 1994) as well as 34.0±0.9, 28.2±2.4 and 26.1±1.3 Ma (Voss, 2000; Fig. 6 and Table 1). The age of 37.6±0.3 Ma shows, that the accumulation of the Quiñoas Formation must have started prior to 37.3 Ma. An age of 19.3±0.9 Ma from the Potrero Grande Formation reveals that the deposition of the Quiñoas Formation could have lasted at maximum until 18.4 Ma. Therefore the Quiñoas Formation has a Late Eocene to Early Miocene age.

Dated sedimentary successions, whose ages fall into this timespan, were described from two other regions of the southern Puna.

In the region of the Salar de Pastos Grandes the Geste Formation (Turner, 1960) forms the base of the Cenozoic succession. On the basis of its fossil content it was assigned to the Middle/Late Eocene (Pascual, 1983; Alonso 1992). Due to its Eocene age the Geste Formation can chronologically be correlated at least with the lower strata -possibly the Campo Negro Member- of the Quiñoas Formation (Fig. 4). A stratigraphic assignment of the Late Eocene to Early Miocene strata of the Salar de Antofalla region to the Geste Formation is rejected, because the Geste Formation in the region of the

Salar de Pastos Grandes is interpreted as deposits of stable, exhorreic rivers, which flowed through a hot, subtropical and wooded region (Alonso, 1992), whereas the Quiñoas Formation was deposited in nearly vegetation-free 'alluvial fan-playa-complexes' under semi-arid to arid climatic conditions.

In the surrounding area of the Salar de Pocitos (Fig. 1) a 3,000 m thick succession of red siltstone is exposed, from which an age of 23.8±0.4 Ma (Vandervoort, 1993) was obtained. The base of these strata is not exposed. These strata can be correlated lithologically and chronologically with the Cadillo Member of the Quiñoas Formation.

Kraemer *et al.* (1999) described a 350 m thick section with fluvial conglomerates and pebbly sandstones in the lower part and eolian dune sandstones in the upper part from a valley west of Chacras (Fig. 1). These authors reported that this section is bounded by two angular unconformities. The one at its base separates it from strata of the Quiñoas Formation below, whereas the one at its top forms the boundary to the Potrero Grande Formation above. Kraemer *et al.* (1999) called these strata Chacras Formation and placed them on the basis of an age determination of 22.5 ± 0.6 Ma into the Late Oligocene to Early Miocene (Fig. 4).

This description conflicts in some ways with observations made by the author of this paper 10 km further to the south at the Salar la Brea. Though conglomerates crop out there, which can be correlated laterally with the conglomerates of the lower part of the section at Chacras, no angular unconformity was observed between these conglomerates and the sandstone beds of the Quiñoas Formation below (see Fig. 5, b). Therefore, and for the reasons given above, the conglomerates were assigned as Aguada Member to the Quiñoas Formation.

The conglomerates which form the lower part of the Chacras Formation of Kraemer *et al.* (1999) must be younger than reported by these authors, because the 22.5±0.6 Ma old tuff is not from the profile at Chacras, but from the profile at the Salar la Brea and was obtained from strata which are the lateral continuation of strata, which were assigned to the Quiñoas Formation by Kraemer *et al.* (1999). The conglomerates can therefore be assigned to the Early Miocene.

The dune sandstones in the upper part of the succession referred to by Kraemer *et al.* (1999) as Chacras Formation can be laterally correlated with dune sandstones from the Potrero Grande Formation, which crop out at the Salar la Brea at the same stratigraphic level (Fig. 5, b, see below). There, the dune sandstones rest in angular unconformity upon the Quiñoas Formation. High contents of volcanic grains in the compositions of these dune sandstones are another reason for an assignment to the Potrero Grande Formation.

As at Chacras, at the Salar la Brea the upper dune sandstones were overlain by conglomerates, though there was no angular unconformity observed between either of them.

POTRERO GRANDE FORMATION (EARLY/(?)MIDDLE MIOCENE)

The Early/(?)Middle Miocene Potrero Grande Formation (Kraemer *et al.*, 1999; Voss, 2000) consists predominately of gray, white, green, brown and black conglomerates and sandstones and pyroclastic deposits in the form of tuff, layers of pumice and tuffite (Fig. 5, b and c). In the area studied the Potrero Grande Formation is exposed west as well as east of the Salar de Antofalla (Fig. 1). West of the Salar de Antofalla, its thickness varies between several hundred meters west of the Salina del Fraile and a few decameters at the western border of the Salar de Antofalla. East of the Salar de Antofalla the Potrero Grande Formation crops out north- to southeast of the Salar Uncal Grande, where it is exposed with a thickness of ~150 m, and at the eastern border of the Salar de Antofalla, north of the Vega Agua Escondida.

The strata of the Potrero Grande Formation rest upon the Quiñoas Formation in angular unconformity. It is overlain with angular unconformity by the Cajeros Member of the Late Miocene Antofalla Formation north of the Salina del Fraile and by the 'De la Aguada-andesite' (informal unit; 12.9±0.8 Ma, Table 1) west of the Sierra del Campo Negro.

In a profile east of the Vega Potrero Grande (25°45'S-68°03'W, Figs. 3 and 5, c), the Potrero Grande Formation lies with angular unconformity over the Quiñoas Formation and shows a thickness of approximately 180 m. This succession of the Potrero Grande Formation can be subdivided into three units:

- The lower unit (P1) is 95 m thick and consists of gray tuffaceous sandstone, pebbly sandstone and conglomerates. Bedding ranges from thinly- to thickly-bedded. The sediments were deposited as beds with sheet-like geometries and within 10 to 30-cm-deep and several meter wide channels. Sandstone beds are massive. Some of them contain clasts of feldspar with sizes of up to 1 cm. Intercalated within the sandstones are clast- and matrix-supported conglomerates. The clast-supported ones are poorly to moderately sorted and contain sub-angular clasts with sizes of up to 2 cm. Imbrication of clasts was found. Clasts in matrix-supported conglomerates reach sizes of up to 10 cm.

- The middle unit (P2) is built up by a 25 m thick succession of white to gray tuffaceous sandstone, tuffite, tuff and layers of pumice. The tuffites are planar cross-bedded with sets of up to 0.5 m thick.
- The upper unit (P3) consists of a 58 m thick succession of brown and black conglomerates and pebbly coarse-grained sandstone. Bedding ranges from thinly- to thickly-bedded. The sediments were deposited as beds with sheet-like geometries as well as within channels. The channels are several dm deep and up to a few decameters wide, and contain fining upward-sequences of conglomerates. The clasts of these conglomerates are sub-angular to sub-rounded and have sizes of up to 20 cm. Imbrication was found. The pebbly sandstones contain clasts of feldspar with sizes of up to 0.5 cm and occasionally intraclasts of mudstone and sub-angular tuff clasts with sizes of up to 1 cm.

The sedimentary deposits of this profile are interpreted as alluvial fan-facies.

In the northwestern part of the Salina del Fraile, the Potrero Grande Formation is built up by a several hundred-meter-thick succession of clast-supported conglomerates overlying the Jurassic Fraile Unit and the Quiñoas Formation in angular unconformity. The conglomerates are rich in clasts of volcanic rocks. Their clasts show sizes of up to 70 cm. Imbrication was found. The conglomerates represent alluvial fan-facies. Intercalated within the conglomerates is a 50 m thick interval of white to gray layers of tuff, tuffite and pumice. From one layer of pumice, an age of 17.0 ± 0.4 Ma (Table 1) was obtained.

In another profile, which is located west of the Salar la Brea (25°57'S-68°07'W, Figs. 1 and 5, b), the Potrero Grande Formation is made up of a 210-m-thick section of white, green, and black eolian dune-sandstones in the lower part (Po1) and a 110-m-thick section of red and brown conglomerates, sandstones and mudstones in the upper part (Po2). The upper section represents a deposition under alluvial fan-, alluvial sand flat- and playa mud flat-conditions.

Age and correlation: ages of 18.5 ± 0.5, 18.0 ± 0.6, 17.39 ± 0.08 and 17,1 ± 0,3 Ma (Kraemer *et al.*, 1999) as well as 19.3 ± 0.9, 19.0 ± 0.6 and 17.0 ± 0.4 Ma (Voss, 2000) were obtained from the Potrero Grande Formation (Fig. 6 and Table 1). For the age of 22.5±0.6 Ma from the underlying Quiñoas Formation the maximum possible age for the base of the Potrero Grande Formation is 23.1 Ma. It can be assumed that, because the Potrero Grande Formation is overlain in angular unconformity by the 'De la Aguada-andesite' (informal unit), which has an age of 12.9 ± 0.8 Ma, its accumulation must have finished prior to 12.1 Ma. Owing to the fact, that all the ages from the Potrero Grande Formation fall into the period between 20.2 and 16.6 Ma, the Potrero Grande Formation can be assigned an Early Miocene age. It can not, however, be excluded that its accumulation lasted until the Middle Miocene.

From other parts of the southern Puna, no sedimentary successions have been described, where accumulation falls into the period of time, embraced by the ages from the Potrero Grande Formation (19.3±0.9-17.0±0.4 Ma). Therefore, Allmendinger *et al.* (1997) assumed a hiatus for the southern Puna during the Earliest Miocene up to approximately 15 Ma. The Early/(?)Middle Miocene strata of the Potrero Grande Formation show that this assumption is not valid at least for the Salar de Antofalla region.

ANTOFALLA FORMATION (LATE MIOCENE)

Late Miocene fluvial and lacustrine deposits as well as intercalated lava flows and pyroclastic rocks, constitute the Antofalla Formation (Voss, 2000; Fig. 5, c and d). The Antofalla Formation was deposited during a period of intensive volcanism within the Salar de Antofalla region. During that time the stratovolcanoes of the Volcán Antofalla complex and the Cerro Beltán stratovolcanic center, which lies directly north-east to the working area, were active (Kraemer *et al.*, 1999). This activity led - especially at the margins of the stratovolcanoes- to numerous intercalations of lava flows and pyroclastic flows within the fluvial or lacustrine deposits of the Antofalla Formation. Another effect of that volcanism is a high content of volcanic and pyroclastic clasts in the deposits of the Antofalla Formation.

Since the strata of the Antofalla Formation west and east of the Salar de Antofalla show different lithofacies, this formation is subdivided into the Cajeros Member, which crops out west of the Salar de Antofalla, and the Bordo Blanco Member, which is exposed east of the Salar (Figs. 1, 3 and 7).

CAJEROS MEMBER

The Cajeros Member is up to 160 m thick and made up of a white, light-red, brown and black volcanic-sedimentary succession ('Subunit 1') which grades laterally into a brown and black conglomeratic succession (Subunit 2'). The 'Subunit 1' consists of ignimbrites, rhyolithes/dacites and andesites, in which volcaniclast-rich sandstones and conglomerates are intercalated (Fig. 5, c). The base of 'Subunit 1' is formed by a 33 m thick ignimbrite ('Fraile-ignimbrite', informal unit, 9.8±0.5 Ma, age from Kraemer *et al.*, 1999). The conglomerates are clast- or matrix-supported. The clast-supported conglomerates are poorly to moderately sorted and up to several meters thick. Their clasts are sub-angular to sub-rounded and have sizes of up to 10 cm. Matrix-supported conglomerates are 10 to 100 cm thick and build up 'coarse-tail coarsening upward'-sequences. Their clasts show sizes of up to 2 cm. The regional distribution of 'Subunit 1' is confined to the surrounding area of the northern Salina del Fraile. In a profile east of the Vega Potrero Grande it shows a thickness of 156 m (25°45'S, 68°03'W, Figs. 3 and 5c). Towards the south, the 'Subunit 1' pinches out on a distance of 10 km, grading laterally into the conglomerates of 'Subunit 2'. This subunit is up to several tens of meters thick and is exposed east of the Sierra de la Quebrada Honda, between the Salina del Fraile and the Salar de Antofalla and at Las Lomitas (Fig. 1).

The Cajeros Member overlies the Potrero Grande Formation with angular unconformity. Locally - as for instance at Las Lomitas or at the northern margin of the Salina del Fraile basin -it rests upon the Quiñoas Formation in angular unconformity. While the 'Subunit 1' is concordant overlain by Pliocene lava, the conglomerates of 'Subunit 2' form the top of the sedimentary succession exposed between the Salina del Fraile and the Salar de Antofalla.

The strata of the Cajeros Member were assigned to the Potrero Grande Formation by Kraemer *et al.* (1999). The angular unconformity and a hiatus between both units (see below) do not support this assignment.

BORDO BLANCO MEMBER

The Bordo Blanco Member consists of fluvial and lacustrine deposits which include red, brown and black sandstones and conglomerates, red mudstones, tuffites and white layers of gypsum/anhydrite as well as pyroclastic rocks (ignimbrites and tuff layers; Fig. 5, d). The occurrence of the Bordo Blanco Member is restricted to the region east of the Salar de Antofalla. There it crops out at Bordo Blanco, west of the volcano El Diablo and south of the Vega Juncalito (Figs. 1 and 7). The base of the Bordo Blanco Member is not exposed. It is covered by Quaternary gravel or the saline deposits of the Salar de Antofalla. South of the Vega Juncalito, the Bordo Blanco Member is overlain by Pliocene/Quaternary lava, sediments of the Sijes Formation and unconsolidated Quaternary gravel in angular unconformity. From the exposed parts of the Bordo Blanco Member, a minimum thickness of ~360 m can be concluded.

In a profile located south of the Vega Juncalito (25°56'S-67°48'W, Figs. 5, d and 7), the exposed section of the Bordo Blanco Member can be subdivided into two units.

- The lower unit (BB1) is made up of redbeds, which are more than 220 m thick. These show a fining upward-trend with conglomerates at the base, sandstones in the middle and mudstones in the upper part. Gypsum occurs in the form of mm-sized nodules within sandstone or mudstone beds or as mm-thick laminae. Bedding is thickly- laminated to thickly-bedded. The deposits mainly form sediment bodies with sheet-like geometries. Channels with depths of up to 70 cm appear only near the base of this unit. The conglomerates are clast-supported, poorly to moderately sorted and made up of sub-angular to sub-rounded gravel with a maximum size of 40 cm. Resedimented sandstones from the Quiñoas Formation contribute to their clast composition. The sandstone and mudstone beds above the conglomerates are horizontally-bedded. Partly, they contain great amounts of tuff clasts. This unit is interpreted as transition from an alluvial fan- to an alluvial sand flat- and playa mud flat-facies.
- The upper unit (BB2) is built up by a ~140 m thick

succession of black and gray sandstone, red mudstone, white tuff and tuffite as well as gypsum and anhydrite. The thickly-laminated to thickly-bedded layers of this unit form sediment bodies with sheet-like geometries. The sandstones are horizontally-bedded or sometimes ripple cross-laminated. Some sandstones contain rooted zones. Horizontally-stratified laminae of mudstone are interbedded with mm-thick layers of gypsum and fine-grained sandstones. The mudstones are wavy-bedded in very few cases. Occasionally 1 to 2 mm thick curled clay flakes, which are arranged in layers, appear within some sandstone beds. Layers of gypsum/anhydrite with thicknesses of up to more than 1 m are present in this unit. In the upper part of this unit, white layers of tuff with thicknesses of several dm are intercalated. One of these yielded an age of 9.0±0.3 Ma (Voss, 2000; Table 1).

The deposits of this unit point to sedimentation on an alluvial sand flat and a playa mud flat dominated environment.

The strata which are described in this paper as Bordo Blanco Member of the Antofalla Formation, correspond to the strata of the lower part of the Juncalito Formation from Kraemer *et al.* (1999).

Age and correlation: ages of 11.2±0.3 and 9.8±0.5 Ma (Kraemer *et al.*, 1999) as well as 9.0±0.3 and 8.7±0.3 Ma (Voss, 2000) were obtained from the Antofalla Formation (Fig. 6 and Table 1). The base of the Antofalla Formation is diachronous: west of the Salar de Antofalla, the 9.8±0.5 Ma old 'Fraile-ignimbrite' points to a maximum possible age of 10.3 Ma for the base of the Cajeros Member. East of the Salar de Antofalla, an age of 11.2±0.3 Ma was obtained from pyroclastic rocks of the Bordo Blanco Member, hence its base must be older than 10.9 Ma.

The difference of 1.8 Ma between the age of the base of the Cajeros Member and the maximum possible age of the Potrero Grande Formation of 12.1 Ma, points to a hiatus between the Antofalla Formation and Potrero Grande Formation, at least for the region west of the Salar de Antofalla. The age of 17.0±0.4 Ma from the Potrero Grande Formation shows that this hiatus might have lasted up to 6.5 Ma.

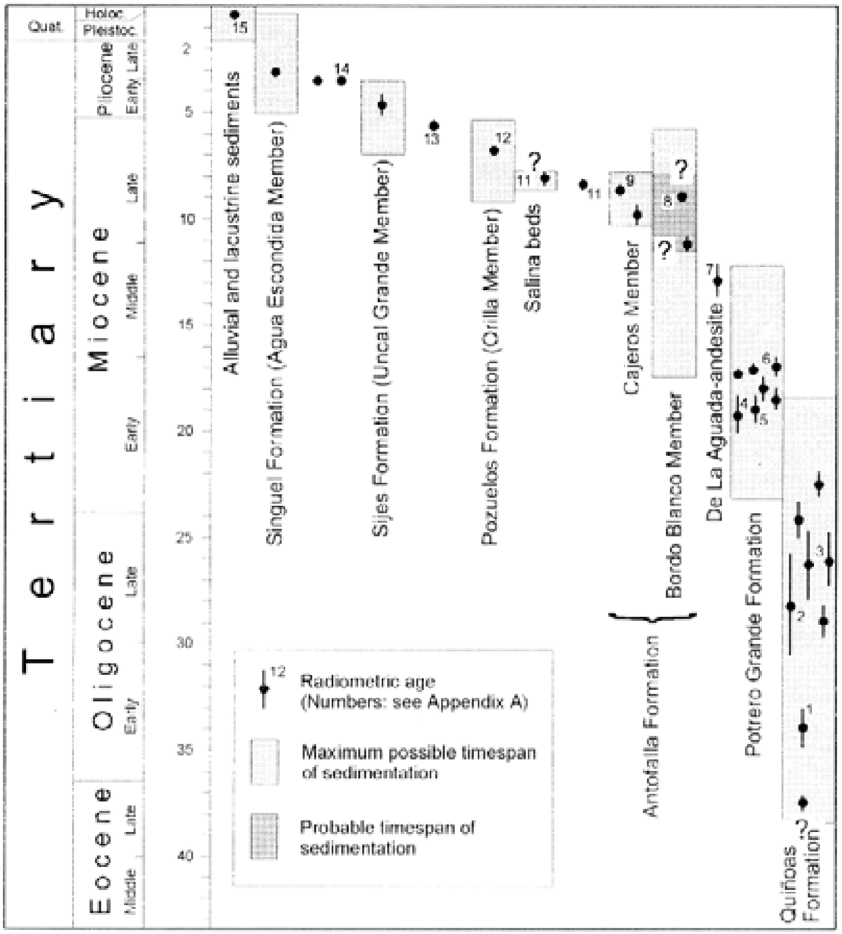
West as well as east of the Salar de Antofalla, the deposition of the Antofalla Formation must have finished during the Late Miocene. In the case of the Cajeros Member this can be inferred from the age of the Salina del Fraile basin. Because the margins of this basin cut into the strata of the Cajeros Member, the Cajeros Member must have been deposited before the formation of the basin. An age of 8.1±0.3 Ma from strata deposited within the basin (see below), reveals that the basin was already formed by 7.8 Ma. Therefore, the accumulation of the Cajeros Member must have ended prior to 7.8 Ma. An age of 6.8 ± 0.2 Ma from the Pozuelos Formation, which follows stratigraphically above the Antofalla Formation, indicates that the sedimentation of the Bordo Blanco Member ended before 6.6 Ma. Hence the age determinations point to a Late Miocene age for the Antofalla Formation.

The Antofalla Formation can be correlated chronologically with the 'Black Conglomerate' (Vandervoort, 1993) from the Salar Pastos Grandes region. At Tolar Grande and Siete Curvas, strata are exposed from which radiometric ages were obtained (see Vandervoort, 1993), which fall into the timespan of the accumulation of the Antofalla Formation.

SALINA BEDS (LATE MIOCENE)

The Late Miocene Salina beds (Voss, 2000), which are up to 120 m thick, consist of interbedded red, black and white, fluvial and lacustrine conglomerates, sandstones, mudstones, tuffites and layers of gypsum and halite. Layers of tuff are intercalated in these successions. The Salina beds are restricted to the basin of the Salina del Fraile (Fig. 1), where they rest upon strata of the Quiñoas Formation in angular unconformity.

Age: a maximum age for the base of the Salina beds was obtained by taking the age of the formation of the Salina del Fraile basin. Two 8.7±0.3 and 8.4±0.3 Ma old ignimbrites, which crop out above the north-western flank of the basin or at the eastern side of the Sierra de la Quebrada Honda must have been deposited prior to the basin, because otherwise they would have flowed into the basin and remnants of them would be found within the basin today. Therefore the basin as well as the onset of the accumulation of the Salina beds must be younger than 8.7 Ma. A tuff intercalated into the Salina beds has an age of 8.1±0.3 Ma (Fig. 6 and Table 1). On the basis of these age determinations, the Salina beds were assigned to the Late Miocene.



Geological time table: see Palmer (1983)

FIG. 6. Distribution of radiometric data from Cenozoic stratigraphic units as well as volcanic rocks. The maximum possible age ranges for each stratigraphic unit from the surrounding area of the Salar de Antofalla are also shown. Geological time table (Palmer, 1983).

POZUELOS FORMATION (ORILLA MEMBER-LATE MIOCENE)

In the region of the Salar de Antofalla, Late Miocene successions are exposed which consist of red, brown, black and white layers of sandstone, conglomerate, evaporite in the form of anhydrite, gypsum and halite as well as tuff. These successions can be correlated lithologically and chronologically with the Pozuelos Formation (Turner, 1960) from the area of the Salar Pastos Grandes and are called Orilla Member of the Pozuelos Formation (Voss, 2000). The Orilla Member is exposed at the eastern border of the Salar de Antofalla (Figs. 1 and 7). West of the Salar there are no corresponding strata. The base of the Orilla Member is covered by the young saline deposits of the Salar de Antofalla, which explains why the nature of its contact with the Antofalla Formation is not exposed. The Orilla Member is overlain by the (?)Late Miocene/Early Pliocene Uncal Grande Member of the Sijes Formation (see below) in angular unconformity. Locally, Pliocene lava and ignimbrites rest in angular unconformity upon the Orilla Member. From the exposed section of the Orilla Member a minimum thickness of 400 m for this unit has been proved.

North of the Vega Agua Escondida (26°01'S-67°55'W, Figs. 5, e and 7) the Orilla Member can be subdivided into three units:

- The lower unit (Pz 1) is ~120 m thick and consists

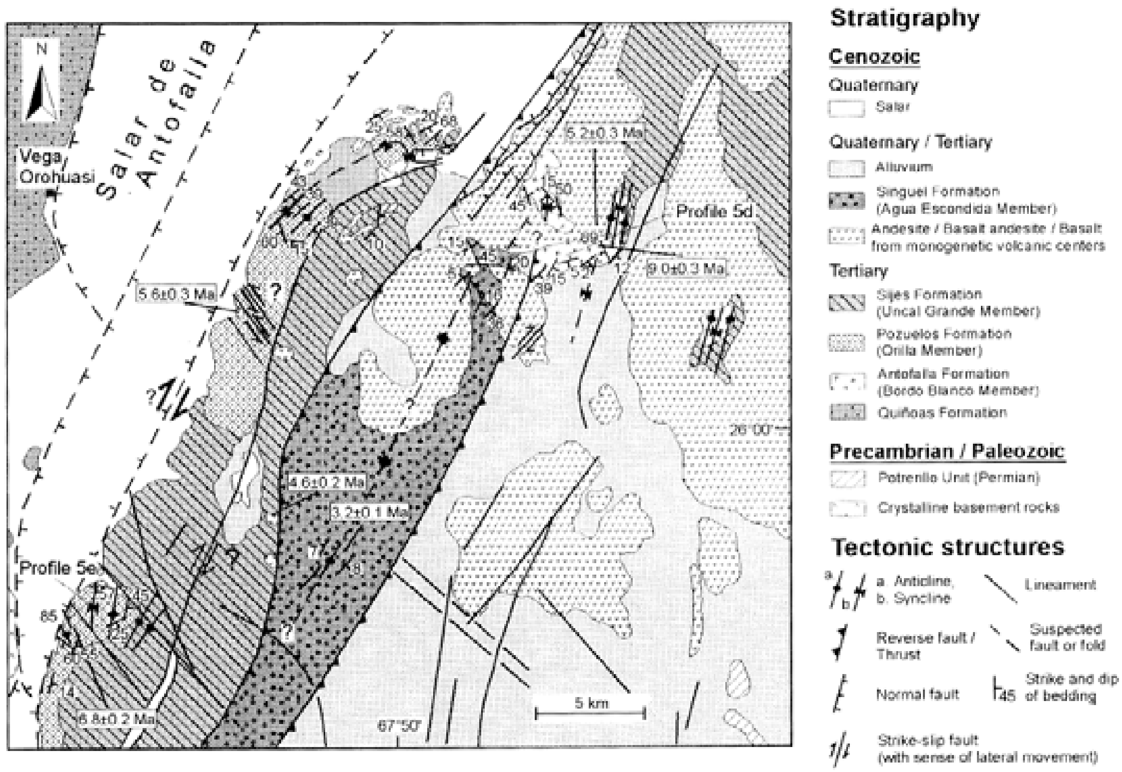


FIG. 7. Geological map of a part of the eastern border of the Salar de Antofalla. The Antofalla Formation (Bordo Blanco Member), the Pozuelos Formation (Orilla Member), the Sijes Formation (Uncal Grande Member), the Singuel Formation (Agua Escondida Member) and lava from mongenetic centers are exposed. Also shown are locations of samples, on which radiometric age determinations were performed, including the corresponding dates and the sites of profiles 5d and 5e. Location of the map: see figure 1.

mainly of halite. Interbedded are brown mudstones, brown, black and green sandstones, conglomerates and layers of gypsum. Bedding ranges from thickly-laminated to very thickly-bedded. The deposits form mainly sediment bodies with sheet-like geometries. In rare cases, channels with a depth of up to 15 cm occur. The sand- and mudstones are horizontally-bedded. Gypsum occurs as mm thick layers or in the form of nodules with sizes of a few mm. Clast-supported conglomerates form up to a few dm-thick beds. Their clasts reach maximum sizes of 15 cm. Imbrication of clasts was found.

The halite beds are interpreted as a central saline playa lake-facies, whereas the clastic sediments were deposited on a playa mud flat and an alluvial sand flat, respectively.

- The middle unit (Pz2) is ~80 m thick. It consists of interbedded layers of gypsum/anhydrite and black, brown, white and green sandstones or brown mudstones. Locally, halite and tuff layers are intercalated within the successions. The deposits of this unit form sediment bodies with sheet-like geometries. The sandstones are horizontally- or trough cross-bedded. Partly, sandstone and mudstone beds form couplets with 1 to 2 m thick layers of gypsum/anhydrite, in which 'chicken wire'-fabrics were often found. In these couplets, beds of halite with thicknesses of up to 30 cm are intercalated occasionally. An approximately 25 cm thick intercalation of tuff yielded an age of 6.8±0.2 Ma (Figs. 6, 7 and Table 1). The mudstones and layers of gypsum/anhydrite are interpreted as sediments of a playa mud flat, whereas the sandstones point to a deposition on an alluvial sand flat and the halite to the existence of a central saline playa lake.
- The upper unit (Pz3) shows a thickness of ~200

m and consists of medium- to thickly-bedded red sandstones, mudstones and conglomerates. Occasionally interbedded are layers of gypsum and halite. In addition to that, gypsum appears as nodules with sizes of 0.5 to 3 cm within mudstone beds. The sediments were deposited as beds with sheet-like geometries and within channels, which are up to one meter deep and several meters wide. The sandstones and mudstones are horizontally-bedded or massive. Poorly to moderately sorted, clast-supported conglomerates are intercalated within them. The clasts of the conglomerates are sub-angular to sub-rounded and have sizes of up to one meter. Imbrication of clasts was found.

The upper unit consists predominately of deposits, which point to an alluvial sand flat-facies. Intercalated are sediments of a playa mud flat-facies, a central saline playa lake-facies and an alluvial fan-facies.

The strata, which are described as Orilla Member here, Kraemer *et al.* (1999) assigned to the upper part of their Juncalito Formation (Fig. 4).

Age: the age of 9.0±0.3 Ma from the Antofalla Formation gives a maximum age of 9.3 Ma for the base of the Orilla Member of the Pozuelos Formation. Because the Orilla Member is overlain by a 5.6 ± 0.3 Ma old lava (Voss, 2000) in angular unconformity, it must be older than 5.3 Ma. From the Orilla Member itself, an age of 6.8 ± 0.2 Ma was obtained (Figs. 6 and 7). The strata of the Orilla Member are therefore assigned to the Late Miocene.

SIJES FORMATION (UNCAL GRANDE MEMBER-(?)LATE MIOCENE/EARLY PLIOCENE)

In the region of the Salar de Antofalla, (?)Late Miocene/Early Pliocene successions are exposed which consist of conglomerates, pebbly sandstones, sandstones, mudstones, tuffites, marls, layers of gypsum, anhydrite and limestone as well as tuff horizons (Fig. 5, d). Near the southern end of the Salar de Antofalla, an ignimbrite is intercalated. The strata have light-red, light-green, brown, black and white colours. They can be correlated lithologically and chronologically with the Sijes Formation (Turner, 1960; Fig. 4) from the Salar Pastos Grandes basin. These strata are therefore called Uncal Grande Member of the Sijes Formation (Voss, 2000). The Uncal Grande Member is exposed at the eastern margin of the Salar de Antofalla (Figs. 1 and 7) and in the surrounding area of the Salar Uncal Grande with thicknesses of up to 100 m. West of the Salar de Antofalla, there are no corresponding strata. Adjacent to the eastern margin of the Salar de Antofalla, the Uncal Grande Member overlies the Orilla Member of the Pozuelos Formation in angular unconformity, while further east it rests in angular unconformity upon strata of the Quiñoas Formation and the Antofalla Formation. The Uncal Grande Member is overlain by Pliocene ignimbrites and Pliocene/Quaternary lava in angular unconformities.

The clastic sediments of the Uncal Grande Member were deposited as beds with sheet-like geometries as well as within channels, which are up to a few dm deep and several decameter wide. The conglomerates are poorly to moderately sorted and both clast- and matrix-supported. Some of the matrix-supported conglomerates consist almost exclusively of either sub-angular basalt- or basalt/andesite-clasts. The clasts of the clast-supported conglomerates are sub-angular to sub-rounded, have maximum sizes of 30 cm and are imbricated. Mudstones are intercalated in the form of cm- to dm-thick beds within the succession. Some sandstones and tuffites contain intraclasts of mudstone. Horizons of curled clay flakes were found in some sandstone beds. Limestones are repeatedly intercalated within the clastic sediments and occur as white and black, massive solid beds up to 1 m thick containing low amounts of sand grains, as fine-laminated, up to 6 cm thick layers and in the form of very soft highly calcareous mud ('Seekreide') The beds made up of highly calcareous mud contain ostracodes and plant impressions. Some sandstone beds contain horizons of cm sized nodules of carbonate. These beds are interpreted as paleosols ('calcrete'). Gypsum and anhydrite form gray layers with thicknesses of up to 50 cm. Tuff layers with thicknesses of a few cm are occasionally intercalated within the sediments. From one of these tuffs, an age of 4.6±0.5 Ma (Kraemer *et al.*, 1999) was obtained.

The deposits of the Uncal Grande Member are interpreted as alluvial fan-, alluvial sand flat- and playa mud flat-facies. For the carbonates an origin in local temporary lakes is assumed.

The strata which are described as Sijes Formation here, Kraemer *et al.* (1999) assigned to the uppermost part of their Juncalito Formation (Fig. 4).

Age: the age of 6.8±0.2 Ma from the Orilla Member of the Pozuelos Formation indicates that the base of the Uncal Grande Member must be younger than 7.0 Ma. Because the Uncal Grande Member is overlain in angular unconformity by two 3.61±00.1 Ma (Voss, 2000) and 3.605±0.005 Ma (Kraemer *et al.*, 1999) old ignimbrites, it has to be older than 3.6 Ma. From the Uncal Grande Member itself, an age of 4.6±0.5 Ma was obtained (Fig. 6). Therefore, the Uncal Grande Member can be assigned to the (?)Late Miocene/Early Pliocene.

SINGUEL FORMATION (AGUA ESCONDIDA MEMBER/LATE PLIOCENE/(?)EARLY PLEISTOCENE)

In the region of the Salar de Antofalla, Late Pliocene/(?)Early Pleistocene red, black, dark-gray, ochre and green successions made up of sandstones, conglomerates and gypsum as well as of tuffs are exposed, which can be correlated lithologically and chronologically with the Singuel Formation (Alonso and Gutiérrez, 1986) from the Salar Pastos Grandes basin. These successions are called Agua Escondida Member of the Singuel Formation (Voss, 2000; not to be confused with the Escondida Formation of Kraemer *et al.*, 1999). The Agua Escondida Member crops out at the eastern flank of the southern part of the Salar de Antofalla basin (Figs. 1 and 7). It is exposed with a thickness of up to 400 m. This value indicates a minimum thickness, because the base of the Agua Escondida Member is covered by recent deposits, while at its top it is bounded by thrusts or reverse faults. West of the Salar de Antofalla there is no equivalent of the Agua Escondida Member.

In a profile located north of the Vega Agua Escondida, the Agua Escondida Member is exposed as an ~ 400m thick succession, which consists almost exclusively of poorly sorted conglomerates (Fig. 1). Their clasts are sub-angular to sub-rounded and reach sizes of up to 80 cm. Imbrication of clasts was observed. On the basis of two intraformational unconformities and different clast compositions, three conglomeratic units can be differentiated:

- An ~150 m thick, dark-gray lower unit is made up of conglomerates, the clasts of which consist mainly of Ordovician metasediments. The base of this unit is covered by recent deposits.
- An ~80 m thick, ochre middle unit, which overlies the former one in angular unconformity. Its clast consists of granite (up to ~ 60%), gneiss, quartz, diabase, phyllite and metasediments.
- An ~170 m thick, green upper unit, which rest upon the former unit in angular unconformity and consists of conglomerates, the clasts of which are made up mainly of Ordovician metasediments and metavolcanics, as well as minor contributions of quartz and pyllite.

The conglomerates of this section are interpreted as proximal facies of an alluvial fan.

To the north, the conglomerates grade laterally into a succession made up of black and red conglomerates and sandstones, in which up to 3m-thick, white layers of tuff, pumice and tuffite are intercalated. One of these tuffs yielded an age of 3.2±0.1 Ma (Kraemer *et al.*, 1999; Fig. 6). A few kilometers farther to the north, layers of gypsum are interbedded with sandstone. These layers have thicknesses of up to 2 m. The sediments of this succession are interpreted as alluvial fan-, alluvial sand flat- and playa mud flat-facies.

The strata, which are described as Agua Escondida Member of the Singuel Formation in this paper, fall into the Escondida Formation of Kraemer *et al.* (1999; Fig. 4).

Age: the maximum possible age for the base of the Agua Escondida Member results from the age of 4.6±0.5 Ma from the Uncal Grande Member of the Sijes Formation and is 5.1 Ma. Accumulation and uplift of the Agua Escondida Member must have taken place before the formation of the alluvial fans at the margins of the recent Salar de Antofalla. The age of 0.44±0.03 Ma (Voss, 2000) obtained from one of these alluvial fans, reveals that the Agua Escondida Member must be older than 0.41 Ma. Because an age of 3.2±0.1 Ma was obtained from the Agua Escondida Member itself (Fig. 6), it is assigned to the Late Pliocene/(?)Early Pleistocene.

PLEISTOCENE LACUSTRINE AND FLUVIAL DEPOSITS

At the margin of the Salar la Brea and near the Vega Cajeros (Fig. 1), 1 to 5 m thick successions of fluvial and lacustrine sediments are exposed. These consist of interbedded layers of mud, highly calcareous mud ('Seekreide'), gypsum, calcareous and tuffaceous sandstone and tuffits. The highly calcareous mud beds in an outcrop near Lago Cajeros contain Pleistocene ostracodes, diatoms and charophyts. These fossils can be interpreted as an indicator for a lacustrine freshwater-facies (S.M. Bellas, oral communication, 1999).

The Pleistocene fluvial and lacustrine strata fall into the accumulation time of the Quaternary Blanca Lila Formation (Alonso and Menegatti, 1990; Alonso, 1992; Vandervoort, 1993) from the region of the Salar Pastos Grandes.

SUBRECENT TO RECENT SALARS, LAKES, ALLUVIAL FANS, DUNES, GEYSERS AND SINTERS

The recent Salar de Antofalla basin is interpreted as a (?) Late Pliocene/Early Pleistocene to Recent polyhistory basin, evolved from a half-ramp basin and a strike-slip basin (Voss, 2000). It is bounded at its western margin mainly by N-S to NNE-SSW striking normal faults and at its eastern margin by NNE-SSW-striking, west-verging reverse faults, NNE-SSW-striking normal faults and NNE-SSW-striking, divergent dextral strike-slip faults (Figs. 1 and 7). Apart from a free water surface of approximately 5 km^2 in its southernmost part, the center of the basin is occupied by a salt pan. Detritus is transported transversally into the basin, forming alluvial fans with sizes of up to 25 km^2 and small rims of talus at its western and eastern margins. A tuff intercalated into the deposits of one of these alluvial fans, has an age of 0.44 ± 0.03 Ma (Figs. 1, 6 and Table 1). Sediment sources are emerged Cenozoic and Permian successions, the metamorphic and plutonic rocks exposed at the western margin of the Salar de Antofalla, the rocks of the Sierra de Calalaste and the Neogene volcanic edifices found in the surrounding area of the Salar. Additionally to the alluvial fans and talus deposits, eolian dunes have formed at the margins of the basin. Recently formed sinter deposits can be found locally, for instance near Botijuela.

The center of the Salina del Fraile basin is occupied by a salt pan. Detritus is mainly transported longitudinally from the north, but alluvial fan and talus at its western and eastern margins also indicate a transverse sediment transport into the basin.

Beside the Salar de Antofalla and the Salina del Fraile, there are a few smaller salars in the area studied, as for instance the Salar Uncal Grande, in which sedimentation has recently taken place.

West of the Salina del Fraile, at the eastern front of the Sierra de la Quebrada Honda, a 'bajada' has been formed.

CONCLUSIONS

With the Late Eocene to Early Miocene Quiñoas Formation, the Early/(?)Middle Miocene Potrero Grande Formation and the Late Miocene Antofalla Formation, new formations have been introduced into the stratigraphy of the southern Puna. The strata described as Quiñoas Formation are the most complete known record of the Eocene to Early Miocene sedimentation history of the southern Puna and differ from the Eocene Geste Formation described by Alonso (1992) with regard to their lithofacies. Strata corresponding to the Potrero Grande Formation have not been described from other parts of the southern Puna until now and deposits, which may be correlated with the Antofalla Formation have not been given a stratigraphic name yet.

The Late Miocene to Pliocene/(?)Pleistocene strata exposed east of the Salar de Antofalla can be correlated chronologically and lithologically with the Pozuelos, Sijes and Singuel Formation from the Salar Pastos Grandes basin. Therefore, the formation names from the Pastos Grandes basin were taken for the respective strata from the Salar de Antofalla region. Owing to the fact that the successions exposed at the Salar Pastos Grandes and the Salar de Antofalla were deposited in separated closed basins, the strata from the Salar de Antofalla region were defined as lateral members and additionally given member names. Such a procedure is useful in a region like the southern Puna, where numerous separated closed basins exist, in which a comparable sedimentological evolution has taken place. In contrast to the approach by Kraemer *et al.* (1999), who introduced local formation names for the Late Miocene to Pliocene/(?)Pleistocene strata of the Salar de Antofalla region, this procedure will avoid the problem of every basin of the southern Puna having its own nomenclature, causing the stratigraphic division of that region to become more and more confusing. In addition to that, it offers the opportunity, that depending on the regional scale of investigations, *e.g.* local, regional or supra-regional, formation names or member names could be used.

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