Morphostratigraphic evolution of the northwestern margin of the Salar de Atacama basin (23° S-68° W)

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ABSTRACT

The 2,500 km² Salar de Atacama forms the center of a large Cenozoic depositional basin in the Andes of northern Chile. The stratigraphy and geomorphology of the western uplifted margin of this basin correlates well with the stages of the piedmont evolution resulting from the main Andean uplift. These uplifting/erosional processes produced the accumulation of sediments which infill the basin. Major NNE oriented morphostructural features largely controlled the distribution of the sedimentary units in this part of the basin. The sediments include red sandstones, siltstones, conglomerates and evaporites. Evaporites were mainly deposited to the center of the basin, whereas the piedmont deposits accumulated closer to the basin margin. The basin was originated during the Oligocene and deposition is still active. A pediment-type planation which produced a gravel veneer matches well with the Atacama pediplain. It is suggested that the Oligo-Miocene morphostratigraphic evolution of the Salar de Atacama basin, which is correlated with the Andean piedmont, is closely related to the rates of convergence and geodynamic effects on the southeastern Pacific region.

Key words: Morphostratigraphic evolution, Cenozoic, Andean piedmont, Pediment, K-Ar dating, Salar de Atacama, northern Chile.

RESUMEN

Evolución morfoestratigráfica del margen occidental de la cuenca del Salar de Atacama. El Salar de Atacama, de 2.500 km², constituye el centro de una cuenca deposicional cenozoica en los Andes del norte de Chile. La estratigrafía y geomorfología del margen occidental solevantado de esta cuenca, muestra una buena correlación en las diversas etapas de evolución del piedemonte formado como consecuencia del alzamiento de los Andes. La erosión de los terrenos alzados produjo la acumulación de los sedimentos que rellenan la cuenca del salar, cuya distribución en el borde occidental está controlada por rasgos morfoestructurales mayores de orientación NNE. Los sedimentos incluyen arenas y limos rojos bien consolidados, así como gravas y evaporitas. Estas últimas fueron depositadas principalmente hacia el centro de la cuenca, mientras que los depósitos de piedemonte se acumularon hacia el margen occidental. La cuenca se originó durante el Oligoceno y los procesos de acumulación aún son activos. Un allanamiento del relieve por procesos de pedimentación que produjeron una cubierta de gravas, coincide bien con el pediplano de Atacama. Se sugiere que la evolución morfológica oligo-miocena de la cuenca del Salar de Atacama que se correlaciona con el piedemonte andino, se vincula con la velocidad de convergencia de placas y efectos geodinámicos en la región del Pacífico suroriental.

Palabras claves: Evolución morfoestratigráfica, Cenozoico, Piedemonte andino, Pedimento, Dataciones K-Ar, Salar de Atacama, norte de Chile.

Revista Geológica de Chile, Vol. 21, No. 1, p. 91-103, 8 Figs., 2 tables, July 1994.

INTRODUCTION

Most Cenozoic sediments in northern Chile are the erosional products of the Andean uplift and include ignimbrite deposits. The main Andean physiographic elements include the Coastal Cordillera, a central depression, the Cordillera de Domeyko and the Andean Cordillera (Fig.1). Generally, Cenozoic sediments have been trapped in the central depression between the Coastal Cordillera to the west and the Cordillera de Domeyko to the east.

The evolution of the central depression was discussed by Naranjo and Paskoff (1985) who proposed that sedimentation there started in Oligocene time, as a consequence of the uplift of the adjacent ranges. The continental sediments are apparently nonfossiliferous but numerous K-Ar dates on interbedded pyroclastic flow deposits have provided chronostratigraphic information (Lahsen, 1982; Naranjo and Paskoff, 1985). Between the Cordillera de Domeyko and the Andean Cordillera there are some closed basins where debris flows and evaporites have been deposited. At the western margin of the most complex of these endorheic basins, the Salar de Atacama basin (Fig.1), a sedimentary series reveals the main features of the erosion and accumulation processes. A 40 km northwest-southeast field transect across this margin is analysed (Fig. 2), from the Altos de Purilactis Range to the east across the Llano de la Paciencia, the Cordillera de la Sal down to the village of San Pedro de Atacama. An ignimbritic plateau borders the basin to the east, extending from the present surface of the salar at 2,500 to 4,000 m a.s.l, obliterating any sedimentary succession.

This paper provides a review of the stratigraphy in

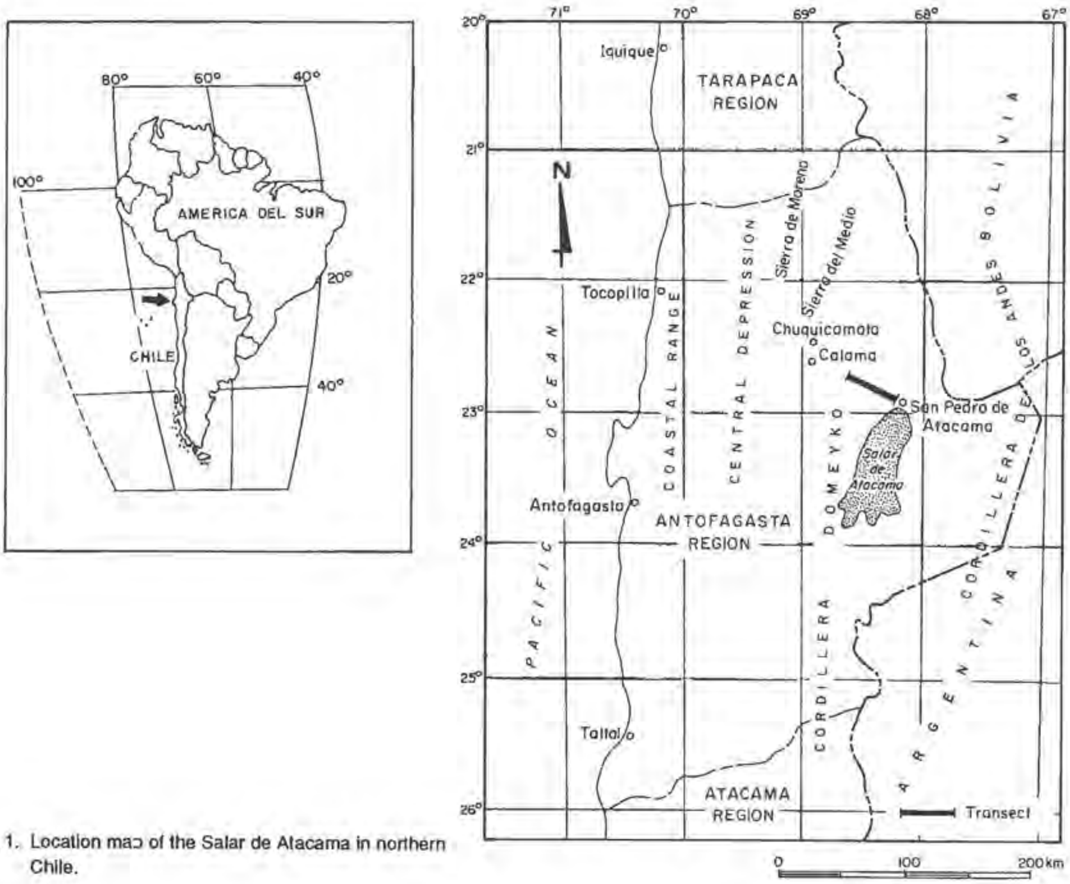


FIG. 1. Location map of the Salar de Atacama in northern Chile.

the area and discusses the relation of sedimentation to the stages of morphologic evolution of the sedimentary cover of the western marginal range of the basin (Cordillera de Domeyko). New K-Ar dates also provide a time framework for landform chronology. Local stratigraphic nomenclature defined by Brüggen (1934), Dingman (1963, 1965), Moraga *et al.* (1974) and Marinovic and Lahsen (1984) has been preserved. Modifications to the stratigraphic framework defined by Flint (1985, 1987) and Hooper and Flint (1987) as the Llano de la Paciencia Group, and of the morphologic framework given by Abele (1988), are suggested in the light of new data. Macellari *et al.* (1991) have pointed out that the sediments of the Paciencia Group were accumulated at the toe of a thrust front which produced the uplift of their source and a shortening of 4.2 km. More recently, Flint *et al.* (1993) interpreted the evolution of the Salar de Atacama from a non-arc-related rift, through back-arc and inter-arc stages, to a Neogene fore-arc basin, since Permian times.

MAJOR MORPHOSTRUCTURAL FEATURES

The northern extension of the Cordillera de Domeyko is locally termed Altos de Purilactis in the study area and is oriented NNE (Fig. 2). Its western slope is gently inclined towards the Loa River basin (Marinovic and Lahsen, 1984). Morphological elements extending parallel to the Purilactis Range (3,500-4,000 m) form the Salar de Atacama basin. The westernmost part of this basin is the plain called Llano de la Paciencia (2,500 m), interrupted to the east by the Cordillera de la Sal (3,000 m). The present Salar de Atacama (2,300 m) forms the central part of the basin. Farther east, the western slope of the Altiplano dips westwards from approximately 4,000 m to the border of the salt crust forming the salar.

STRATIGRAPHY

The arid conditions prevailing in the area have created a unique morphology, where the stratigraphical relationships of the sedimentary units are well exposed. This corresponds to one of the best areas to identify morpho-sedimentary events that occurred in connection with the main Andean uplift.

The succession exposed along the western margin of the Salar de Atacama basin (Fig. 2) consists essentially of sandstones, siltstones, evaporites and debris-flow deposits, with some tuffaceous intercalations. Radiometric dates on these tuffs indicate Oligocene to Pliocene ages. The stratigraphy of this area has been described by several authors. Brüggen (1934, 1942) defined the main units as San Pedro and Tambores formations and assigned these continental clastics to the Eocene. More recently, Flint (1985, 1987) proposed an extension of the Tertiary stratigraphy based on field observations in the San Bartolo area, with newly delineated lithostratigraphic units grouped in the Llano de la Paciencia Group. In this paper, observations through a northwest-southeast transect, normal to the main structural trend, give a revised and extended stratigraphic framework (Table 1) which includes the inferred morphogenetic events.

TABLE 1. STRATIGRAPHY ALONG THE NORTHWEST-SOUTHEAST TRANSECT, WESTERN MARGIN OF THE SALAR DE ATACAMA BASIN.

	Ma	Altos de Purilactis	Cordillera de La Sal
Quaternary		Llano de La Paciencia Gravels	
Pliocene-Quaternary	2		Vilama Formation
Upper Miocene-Pliocene		Ignimbrites	
	10		
		Hollingworth Gravels (pedimentation)	
		Tambores Formation (main Andean uplift)	
Lower Miocene			
	25		
Oligocene			(parallel unconformity) San Pedro Formation
Cretaceous		Purilactis Formation	

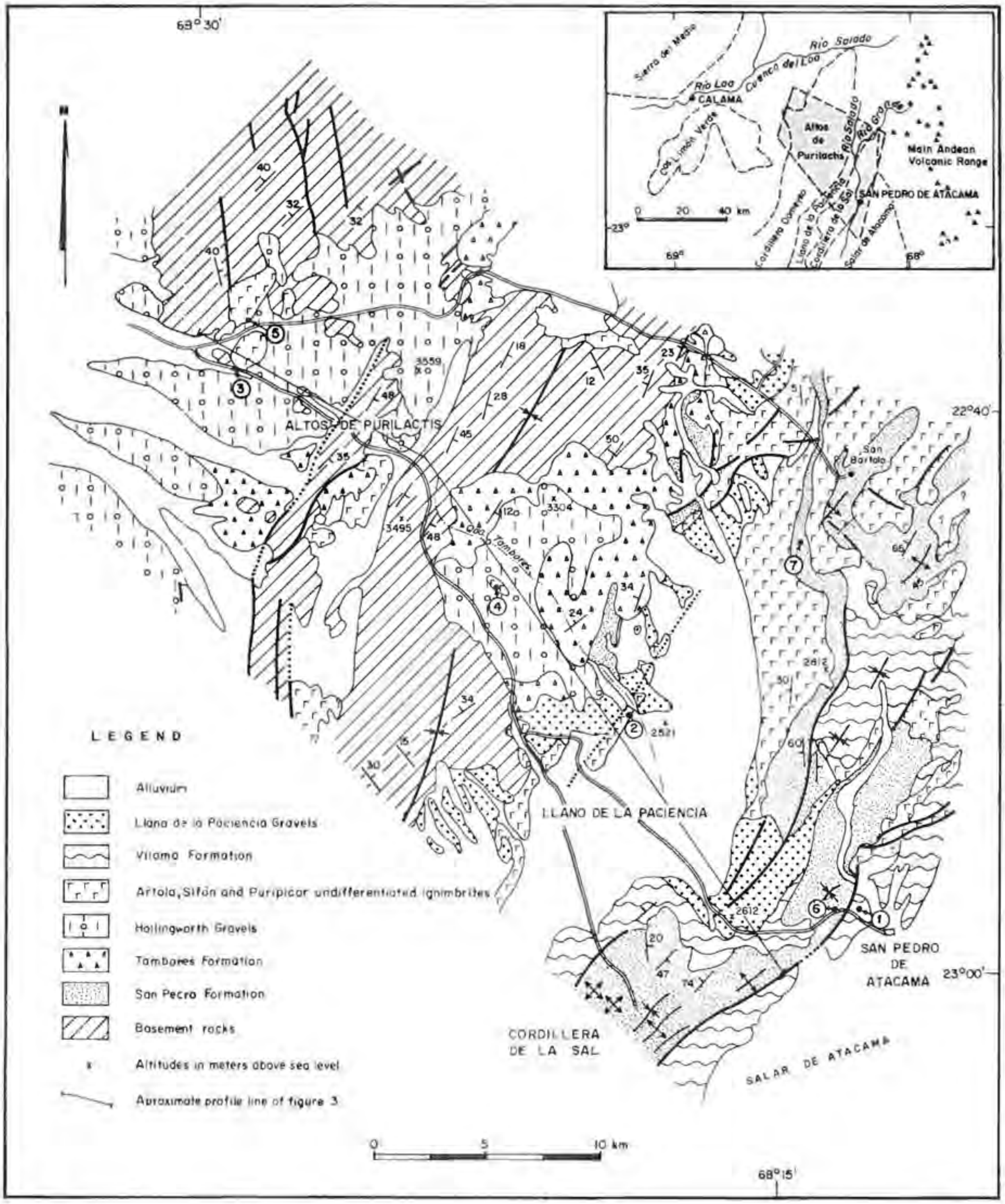


FIG. 2. Geological map of the northwestern margin of the Salar de Atacama basin (modified from Marinovic and Lahsen 1984). Circled numbers refer to K-Ar dates in table 2 (see p. 99).

SAN PEDRO FORMATION

The San Pedro Formation (Brüggen, 1934, 1942) is formed of continental siltstones, sandstones, conglomerates and evaporites, with scarce tuffaceous intercalations. To the north of the Atacama basin, this unit overlies unconformably Cretaceous volcanic and sedimentary rocks of the Lomas Negras Formation (Marinovic and Lahsen, 1984) and in the western margin of the basin (Quebrada Tambores) it is overlain, with parallel unconformity, by continental conglomerates of the Tambores Formation (Figs. 3, 4). The thickness of the unit is variable. Dingman (1963) measured 2,100 m of fine-to coarse-grained red sandstones and siltstones, containing intercalations of thick beds of salt, minor conglomerate intercalations and rare cemented tuffaceous beds, in the northern part of the Cordillera de la Sal. Siltstones predominate in the lower part of this unit in the San Bartolo area (Fig. 2), where Ramírez (1979) reported a thickness of 1,000 m. These red sediments are well stratified, in beds of 0.2-1.4 m thick and cut by abundant gypsum veins. Detailed descriptions of the San Pedro Formation lithologies are given in Marinovic and Lahsen (1984).

The parallel unconformity, exposed at Quebrada Tambores between the red sediments of the San Pedro and the overlying gravels of the Tambores Formation (Fig. 4) conspicuously indicates a depositional regime change at the western proximal facies of the basin.

The San Pedro Formation was deformed into large scale folds about NNE axis (Fig. 5) during the early-middle Miocene (Hooper and Flint, 1987). A series of salt domes and doubly plunging synclines and anticlines are present in the northern Cordillera de la Sal (Dingman, 1962). This deformation is likely related to a major basement fault dipping steeply to the west under the Cordillera de Domeyko (Forsythe, 1988; written communication).

Tuff intercalations have yielded K-Ar ages of 28±6 Ma and 24.9±1 Ma at Río Salado and Cordillera de la Sal, respectively (Table 2) (Travisany, 1978; Marinovic and Lahsen, 1984). Thus, the San Pedro Formation was deposited during the Oligocene. Furthermore, Wilkes and Görler (1988) found lacustrine fossils (charophytes, gastropodes and ostracodes) around Río Grande and San Bartolo, which suggested an oligohaline and mixohaline environment and indicated distinctive freshwater influx at the northern margin of the basin.

Paleocurrent directions indicate that fine clastic debris was shed southeastward from the Cretaceous Purilactis Formation (Flint, 1985; Wilkes and Görler, 1988) at Altos de Purilactis, into the early Atacama basin.

TAMBORES FORMATION

The Tambores Formation is a succession of almost unconsolidated gravels and sands distributed along the Quebrada Tambores on the western margin of the Salar de Atacama basin, which were also derived from the western flank and northern part of the Altos de Purilactis. The source of these sediments was the unconformably underlying Purilactis Formation of Late Cretaceous age. Downstream, to the east of Quebrada Tambores, this succession is also unconformably underlain by the San Pedro Formation (Fig. 4). In both flanks of Altos de Purilactis, Tambores Formation gravels are partly eroded and are unconformably overlain by the Hollingworth Gravels (Fig. 6) (see p. 80). The Tambores Formation is dominated by crudely stratified matrix supported gravels (and boulders), containing intercalations of sandy beds, up to 20 cm thick, partially cemented by calcite. Gravel beds are 0.1-2 m thick being pale gray-brownish to pale reddish-brown in colour. The clasts are angular, 1-15 cm in diameter and correspond to andesites, sandstones, and granitoid gravels derived from the Purilactis Formation.

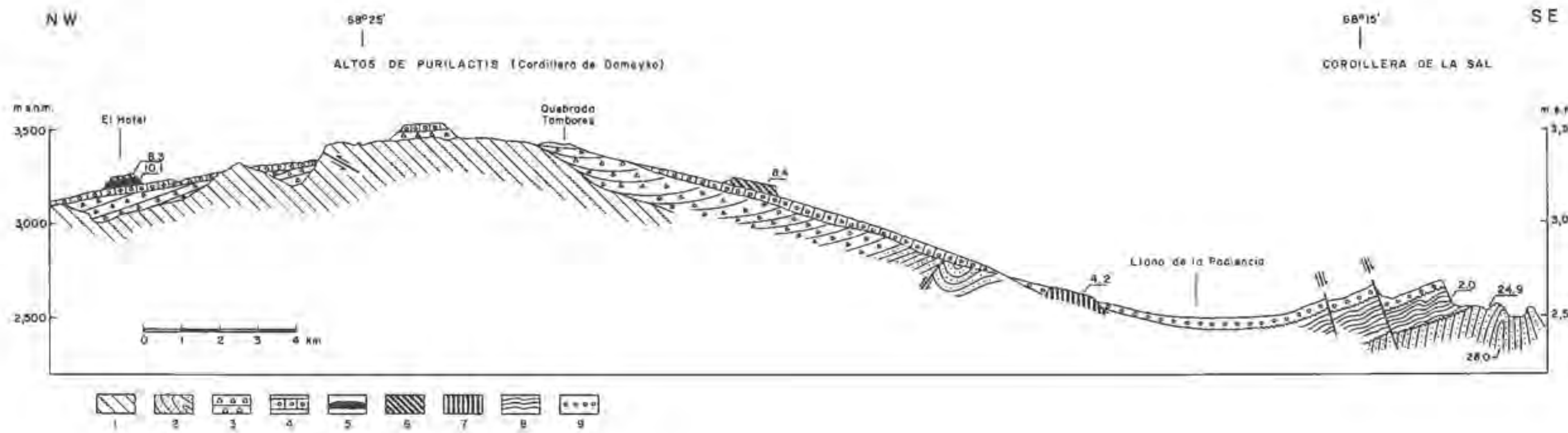
The sedimentary structures of these deposits indicate that most of them were deposited as matrix supported debris-flows. Cross-bedding in sands and imbrication of rare clast-supported gravels indicate a transport direction from the Altos de Purilactis in the west (Marinovic and Lahsen, 1984; Flint, 1985).

The Tambores Formation is overlain by 8.3-10 Ma ignimbrites constraining its upper-age limit to the Miocene (Table 2). Since the gravels of the Tambores Formation overlie the fine grained sediments of the San Pedro Formation it is suggested that there is no interfingering between these two successions along the studied profile area, as inferred by Dingman (1963, 1967) and Marinovic and Lahsen (1984).

HOLLINGWORTH GRAVELS*

These are alluvial gravels, up to 2 m thick, that cover unconformably the Tambores Formation, on both the eastern and western flanks of Altos de

* This new name is proposed here to honour Professor S.E. Hollingworth who worked with a group of graduate students from the University College, London, in the Atacama Desert during the 60's. According to his will, his ashes were spread in this area.



1- Purilactis Formation
2- San Pedro Formation
3- Tambores Formation
4- Hollingworth gravels
5- Artola ignimbrite
6- Silón ignimbrite
7- Puripicar ignimbrite
8- Vilama Formation
9- Llano de la Paciencia gravels. Age data (Ma) as in table 2.

FIG. 3. Sketch profile between El Hotel and Cordillera de la Sal, northwestern margin of the Salar de Atacama basin (22°50'S).

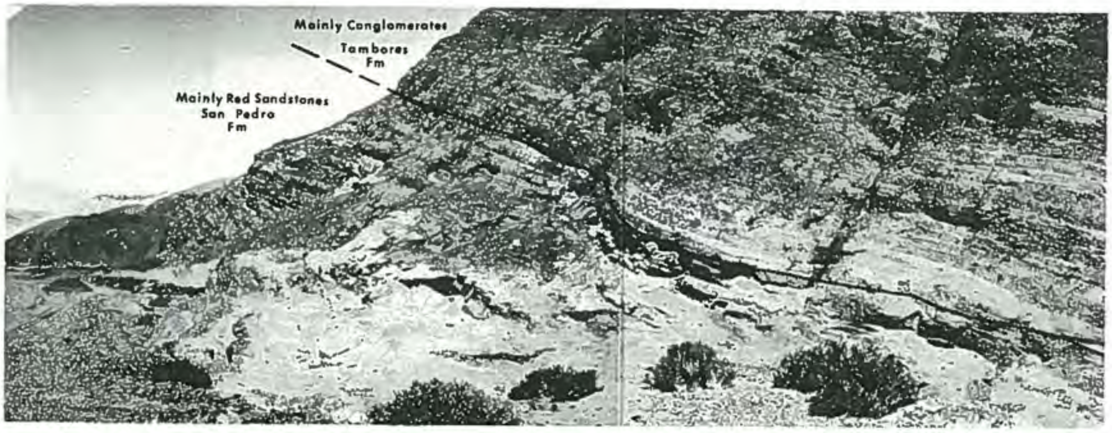


FIG. 4. Conformable transition from the red siltstones and sandstones of the San Pedro Formation to coarser debris-flow deposits of the Tambores Formation at Quebrada Tambores. Looking to the south. Bushes are about 0.5 m tall.

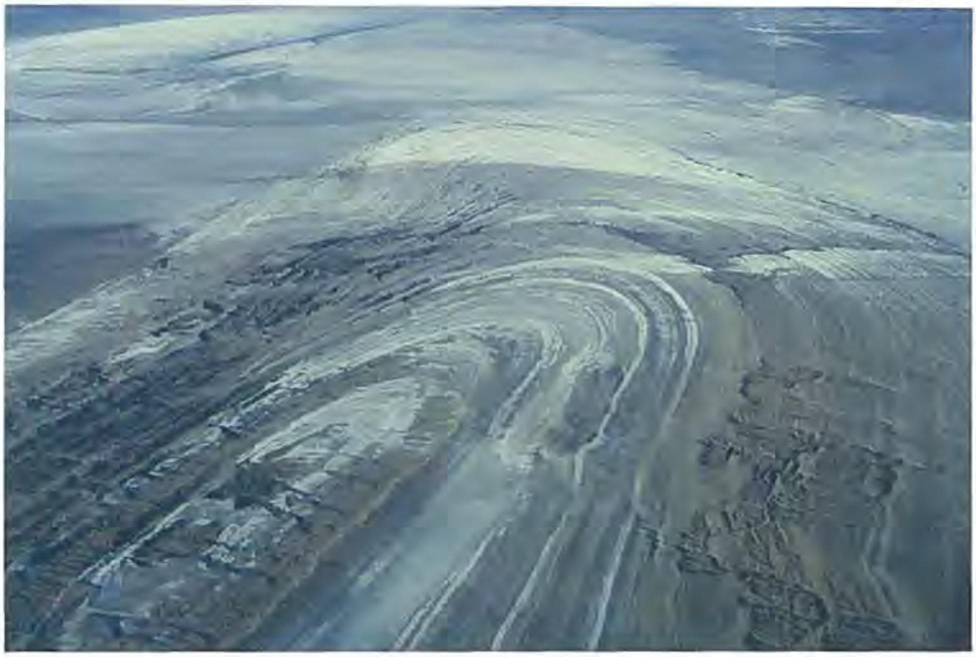


FIG. 5. Aerial view of large-scale (5-10 km wide) anticlinal pericline in the San Pedro Formation at the southern end of Cordillera de la Sal.

Purilactis. They are coarser than the Tambores gravels, with subrounded clasts up to 10-20 cm in diameter, within a subordinate grey-sandy matrix. Grading was not observed, and stratification is absent. These deposits form conspicuous veneers (rock-floor) on the Tambores gravels (Figs. 6, 7).

They are interpreted as deposits resulting from an interval of pedimentation which was probably due to an attenuation or cessation of the continuous tectonic uplift, in addition to favourable arid climate conditions. During that interval, a pediment-type surface developed on the Tambores and Purilactis formations; the surface is capped by two ignimbrite flows, with ages of 10 and 8.3 Ma (Table 2, see p. 99).

FIG. 6. In the background, light colour debris-flow deposits of the Tambores Formation capped by darker thin deposits of the Hollingworth gravels in the western flank of Altos de Purilactis. To the left, ignimbrite sheets at El Hotel locality cover both units.

FIG. 8. Unconformity between the Oligocene San Pedro Formation and the Pliocene Vilama Formation besides the road to San Pedro de Atacama.

FIG. 7. Thin deposits of Hollingworth gravels (<50 cm thick) conformably sealed by the Sifón ignimbrite and unconformably overlying barely-stratified and westward dipping gravels of the Tambores Formation; eastern flank of Altos de Purilactis.

VILAMA FORMATION

The Cordillera de la Sal, in the northwestern part of the Salar de Atacama basin, is partially covered by the 60 m thick Vilama Formation (Moraga *et al.*, 1974). This unit overlies unconformably the San Pedro Formation (Figs. 3, 8).

Pale reddish-brown silts and fine to coarse-grained sands (calcite and halite cemented) are the dominant and characteristic components of the Vilama Formation. The succession is well laminated with layers commonly less than 2 cm thick. Intercalations of stromatolitic limestones and white diatomites are subordinate, as well as minor ash beds less than 1 m thick. Biotites in these ash beds have yielded a K-Ar age of 2.0±0.9 Ma (Table 2). The Vilama Formation contains lacustrine and piedmont deposits. In some places, coarse debris deposits record small rivers flowing into the basin.

Local overturned folds of 50 cm wavelength disturb these strata with axes trending northeast, parallel to the San Pedro Formation folds (Marinovic and Lahsen, 1984). Normal faults with a similar strike produce displacements of up to 25 m in the Vilama Formation, as well as in the overlying deposits (Llano de la Paciencia gravels).

LLANO DE LA PACIENCIA GRAVELS

This unit consists primarily of coarse gravels with polymictic clasts up to 15 cm in diameter with a grey-sandy matrix, and thick planar cross-bedding. These deposits constitute coalescent alluvial fans draining southwestward and forming a wide, open, funnel-like basin towards the Llano de la Paciencia depression. The fans are inferred of Quaternary age, and spread out from the gorges on the eastern flank of the Altos de Purilactis and the western flank of the Cordillera de la Sal. Reverse faults (Forsythe, 1988: written communication) and continued erosion have disrupted these deposits along the core of this cordillera.

K-AR GEOCHRONOLOGY

Some radiometric dates have been previously reported (Table 2) from sites within the study area. Unfortunately, it was not possible to find the exact location of four samples dated by Dingman (1965), in the immediate area of the transect.

K-Ar ages displayed in table 2 are consistent with the stratigraphy and relative chronology observed for the units. Five new K-Ar ages (this paper) combined with previously published dates provide an absolute chronology for the events that occurred during the evolution of the basin. They also constitute a basis for the stratigraphic correlations.

TABLE 2. K-AF ANALYTICAL DATA FROM DATED SAMPLES OF THE NORTHWESTERN MARGIN OF SALAR DE ATACAMA BASIN.

Sample No. Correl.	Sample No. Field	Location Lat. S	Location Long. W	Rock type	Analized material	%K tot.	Vol. ^{40}Ar rad. (nl/g)	%^{40}Ar Atm	Age(*) and error ± 2σ (Ma)	Reference	Stratigraphic unit
1	NP-90	22°53.9'	68°12.9'	Ash tuff	Biotite	6.082	0.477	96.1	2.0±0.9	This paper	Vilama Formation
2	NP-76	22°48.9'	68°18.5'	Ignimbrite	Biotite	6.957	1.150	90.0	4.2±0.8	This paper	Puripicar Ignimbrite
3	NP-69A	22°40.8'	68°18.5'	Ignimbrite	Biotite	6.762	2.189	62.0	8.3±0.4	This paper	Silón Ignimbrite
4	NP-91	22°47.0'	68°20.5'	Ignimbrite	Biotite	6.039	1.974	61.0	8.4±0.4	This paper	Silón Ignimbrite
5	NP-69E	22°40.0'	68°28.0'	Ignimbrite	Biotite	7.371	2.915	80.7	10.1±0.9	This paper	Artola Ignimbrite
6	MC-777	22°54.2'	68°13.3'	Ash tuff	Biotite				24.9±1.0	Marinovic and Lahsen, 1984	San Pedro Formation
7	SB-T	22°47.7'	68°13.0'	Ash tuff	Biotite				28.0±6.0	Travisany, 1978	San Pedro Formation

* Constants used: $\lambda_\epsilon = 0.581 \times 10^{-10} yr^{-1}$; $\lambda_\beta = 4.96 \times 10^{-10} yr^{-1}$; $^{40}K/K = 0.01167$

LANDFORM CHRONOLOGY AND STRATIGRAPHIC CORRELATIONS

The Andean uplift, which gave rise to the present mountain range, is the consequence of tectonism probably initiated during early Oligocene times (Naranjo and Paskoff, 1985). This uplift also conditioned the formation of continental sedimentary basins where Oligocene-Miocene sequences such as the San Pedro and Tambores Formations were deposited. These basins were oriented aproximately NNE and received the sediments eroded from orogenic highlands.

Remarkable similarities with the San Pedro Formation, are found in the sandy-conglomerate and evaporitic lithofacies associations of the Sichal Formation, distributed between the Cordillera de Domeyko or Sierra de Moreno and the upper Loa river, about 150 km to the north of the Atacama basin (Maksaev, 1978); an age of 34.1±1 Ma was reported for an ignimbrite intercalated in the lower-middle part of the Sichal Formation. Lithologic features indicate that the lower part of the Sichal and the San Pedro formations were deposited in an environment which is similar to that of the present salars.

An arid climate, with high evaporation rate, explain the abundance of evaporites (salt and gypsum) interbedded with fine to medium-grained red sediments in the Cordillera de la Sal and in the mouth of the Quebrada Tambores. Some volcanic activity also occurred at the end of the deposition of these sediments in the San Pedro and San Bartolo area (Fig. 2), represented by thin beds of volcanic ash.

The uplift of the Altos de Purilactis block triggered a period of erosion which was strongly active and debris-flow accumulations were spread towards both sides of the Altos de Purilactis block. Probably due to the instability of the basin, the relief of this block was gradually increased, and only coarser debris (gravels) was deposited in the Tambores Formation.

A similar situation could be interpreted for the uppermost gravels of the Sichal Formation in the western flank of the Sierra de Moreno (Skarmeta and Marinovic, 1981). In both areas such deposits clearly represent piedmont gravels as those that are widely distributed in the Atacama Desert, better known as the Atacama Gravels to the south (Mortimer, 1973; Naranjo and Paskoff, 1980), Calama Formation in the Calama area (Naranjo and Paskoff, 1981; Marinovic and Lahsen, 1984) and Altos de Pica Formation in northern Chile (Galli and Dingman, 1962; Naranjo and Paskoff, 1985), or Oligocene to Miocene in age. The accumulation of these gravels probably ceased after the climatic desiccation during the middle Miocene along the Atacama Desert (Alpers and Brimhall, 1988).

After this episode, a tectonic quiescence stage apparently began probably associated with climatic conditions propitious for sheet flood generation, which might have been responsible for the areal planation phenomena of pediment type, producing the highland retreat. This pedimentation process left the thin, but conspicuous deposits defined here, as the Hollingworth Gravels, which unconformably cover the Tambores Formation.

Highly explosive volcanism became more active to the east and some ignimbrites were spread into the basin, passing over the Altos de Purilactis, and sealing the contemporaneous pedimentation surfaces. These pyroclastic flows are the Artola (10.1±0.9 Ma) and Sifón (8.3 Ma) ignimbrites (Ramírez, 1979). The middle Miocene pedimentation-type surfaces are of remarkable wide distribution and are synchronous along the Atacama desert. They have been recognized between 18°S and about 28°S (Naranjo and Paskoff, 1985). In most places the surface is sealed by lavas and ignimbrites of about 9-10 Ma (Mortimer, 1973; Naranjo and Paskoff, 1980).

Strong subsequent incision affected the area, resulting in gorges that cut the former formations as deeply as the folded Cretaceous Purilactics Formation. The erosional detritus was spread on to the Llano de la Paciencia basin. Ignimbritic volcanism occurred in this part of the Andes at 4.2 Ma and the Puripicar ignimbrite (Guest, 1969) filled some gorges and covered parts of the area. The thicker outcrops are close to the basins, while the ignimbrite thins towards the highlands.

A new quiescence stage was reached and the lowest topographic areas were covered by shallow lakes where some alluvial and chemical deposits (fresh water limestones) formed the Vilama Formation. A thin ash layer dated at 2 Ma denotes some coeval explosive volcanism, probably derived from the east. Younger fine grained sediments corresponding to this formation could be correlated with other localized lake deposits of Plio-Pleistocene age (Chiuchiu Formation) on a paleo-karst surface developed on the calcareous El Loa Formation (Naranjo and Paskoff, 1981).

Deformation affecting the Vilama Formation, the Puripicar ignimbrite and, consequently, the San Pedro Formation, is displayed at the mouth of Quebrada Tambores (Dingman, 1962), changing the base level of the basins (Llano de la Paciencia and Salar de Atacama). Erosion began subsequently to supply coarse materials to these basins originating the sands and gravels grouped here as Llano de la Paciencia Gravels, which are currently filling the basins, as debris-flow alluvial sediments derived from the uplifted terrains.

DISCUSSION

The stratigraphic and morphologic evolution of the sedimentary cover at the western margin of the Salar de Atacama basin as presented here, appears to be more complex than that described by Flint (1985, 1987). In fact, one of the main controversies that have led to confusion arises because The San Pedro and The Tambores Formations have been considered as a single chronostratigraphic unit (the Paciencia Group), without any significant age-break between them (Flint *et al.*, 1993). These authors described the Group as a 2 km thick succession of continental sedimentary rocks, whose minimum age would be restricted by a lava that 'unconformably overlies the Paciencia Group', dated in 17±2 Ma (Ramírez, 1979). However the date was obtained in the Jorquencal-Machuca Volcanic Group, which unconformably overlies the San Pedro Formation (Ramírez, 1979), but not the Tambores Formation, the conglomerate succession that crops out to the southwest of The San Bartolo area.

In addition to the above mentioned formations, the Atacama basin-fill sequence includes other sedimentary units which involve a wider and younger age-range, and represent varied stages in the morphologic evolution of this margin. Contraction processes which took place during the early-middle Miocene (Flint *et al.*, 1993), possibly associated with local subsidence of the basin, are indicated by lithologic and structural breaks among the units.

The parallel-unconformable transition from the fine-grained sediments of the San Pedro Formation to the coarse clastics of the Tambores Formation evidences a clear change in the sedimentation style, as a result of an increasing rate of relief generation or uplifting. The gravels of the Tambores Formation were probably the product of radical changes in the tectonic processes occurring by that time. Thus, the debris-flow deposit record corresponds to an outstanding stage of the Andean uplift, which occurred between 25 and 10 Ma in the area. In addition, climatic conditions less arid than at present probably occurred during the early-middle Miocene along the Atacama Desert (Alpers and Brimhall, 1988), which contributed to generation of debris-flows.

Although Flint (1985) did not distinguish the Vilama Formation as a separate unit in the Paciencia Group, Hooper and Flint (1987), after Moraga *et al.* (1974), recognized it as a Pleistocene poorly-consolidated alluvial deposit or as a 'braided fluvial and lacustrine sequence' deposited during the Pleistocene, due to climatic cyclicity induced by glaciation (Flint *et al.*, 1993). As shown besides the road to San Pedro de Atacama (Fig. 8), the Vilama Formation is considerably younger than the important deformation that affected the San Pedro unit. Because of its lithology, structure and stratigraphic position, the Vilama Formation conspicuously represents a different and younger stage in the basin evolution.

It is noted here that the sediment accumulation and morphogenic evolution of the Salar de Atacama basin were linked to the past changes in the plate-tectonic setting along the western South American margin (Cross and Pilger, 1982; Pilger, 1981, 1983, 1984). These changes have been recorded as variations in the sedimentary regime among the described units. In fact, the transition from the San Pedro to the Tambores Formation indicates an uplift that might be induced by a rapid rotation of the oceanic plate from an oblique southeast subduction to a more orthogonal direction to the South American margin at *ca.* 26 Ma (Cande and Leslie, 1986). Due to the rapid (*ca.* 120 km/Ma) relative normal convergence, through a low-angle subduction zone, an efficient transmission of compressional stress was induced (Cross and Pilger, 1982). Thus, this compressional phase caused deformation and high rate of relief formation, which are recorded as the folding of the San Pedro sediments and the intense and widespread debris-flow deposition (Tambores Formation) originated from the denudation of the uplifted areas.

At *ca.* 10 Ma, the relative convergence rate between the Nazca and South American plates was dramatically reduced to 93 km/Ma (Cande and Leslie, 1986). Interestingly, in contrast, uplift might have stopped and subsequently, mountain masses (*e.g.* Altos de Purilactis) were partially consumed by pediment-type denudation (Hollingworth Gravels). Additional evidence for non-compressional deformation in about middle-late Miocene has been given by Hervé (1987) and Naranjo (1987). These authors concluded that final high angle normal movements along the 1,000 km long Atacama fault zone, in the Coastal Range of northern Chile, occurred at approximately 10 Ma B.P.

CONCLUSIONS

Regarding its location, the Salar de Atacama basin has been geographically classified as a fore-arc basin (Jordan and Alonso, 1987). The main stages of the Oligo-Miocene geomorphic and sedimentary history of the western part of the Salar de Atacama basin agree well with those of the Andean piedmont evolution in the Atacama Desert (Naranjo and Paskoff, 1980, 1985), which include:

- Basin formation and their consequent infilling (*e.g.* San Pedro Formation sediments).
- Relief formation, which triggered erosion and intense debris-flow emplacement as a piedmont constituent (Tambores Formation).
- Pediment-type denudation (Atacama pediplain) locally represented by veener deposits of the Hollingworth Gravels. The pediplain surface is sealed by ignimbrites of about 10 Ma.

The 'Atacama pediplain' surface is regarded for the first time as the counterpart of the Andean uplift, and hence formed under a non-compressional process. Therefore, it is suggested that at 10 Ma there was either a quiescent tectonic stage or extensional deformation, at least along the western flank of the north Chilean Andes.

Locally, the northwestern margin of the Salar de Atacama is still active and deformation affecting the youngermost Quaternary units, is also taking place at present.

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REFERENCES

Abele, G. 1988. Geomorphological west-east section through the north Chilean Andes near Antofagasta: *In* Lecture Notes in Earth Sciences (Bahlburg, H.; Breitkreuz,C.; Giese, P.; editors). *The Southern Central Andes. Springer Verlag,* Vol. 17, p. 153-168.

Alpers, C.N.; Brimhall, G.H. 1988. Middle Miocene climatic change in the Atacama Desert, northern Chile: Evidence from supergene mineralization at La Escondida. *Geological Society of America, Bulletin*, Vol. 100, p. 1640-1556.

Brüggen, J. 1934. Las formaciones de sal y petróleo en la Puna de Atacama. *Boletín de Minas y Petróleo,* Vol. 4, No. 32, p. 5. Santiago.

Brüggen, J. 1942. Geología de la Puna de San Pedro de Atacama y sus formaciones de areniscas y arcillas rojas. *In Congreso Panamericano de Ingeniería de Minas y Geología, No. 1, Anales,* Vol. 2, p. 345.

Cande, S.C.; Leslie, R.B. 1986. Late Cenozoic tectonics of the southern Chile trench. *Journal of Geophysical Research,* Vol. 91, No. B1, p. 471-496.

Cross, T.A.; Pilger, R.H. 1982. Controls of subduction geometry, location of magmatic arcs, and back-arc regions. *Geological Society of America, Bulletin*, Vol. 93, p. 545-562.

Dingman, R.J. 1962. Tertiary salt domes near San Pedro de Atacama, Chile. *U.S. Geological Survey Professional Paper,* No. 450-D, p. D92-D94.

Dingman, R.J. 1963. Cuadrángulo Tulor. *Instituto de Investigaciones Geológicas, Carta Geológica de Chile*, No. 11, 37 p.

Dingman, R.J. 1965. Pliocene age of the ash-flow deposits of the San Pedro area, Chile. *U.S. Geological Survey, Professional Paper,* No. 525C, p. C63-C67.

Dingman, R.J. 1967. Geology and groundwater resources of the northern part of the Salar de Atacama, Antofagasta Province, Chile, *U.S. Geological Survey, Bulletin*, No. 1219, 49 p.

Flint, S. 1985. Alluvial fan and playa sedimentation in an Andean arid closed basin: the Paciencia Group, Antofagasta, Province, Chile. *Geological Society of London, Journal,* Vol. 142, p. 533-546.

Flint, S. 1987. Diagenesis of Tertiary playa sandstones of Northern Chile; implications for Andean uplift and metallogeny. *Sedimentology*, Vol. 34, p. 11-29.

Flint, S.; Turner, P.; Jolley, E.J.; Hartley, A.J. 1993. Extensional tectonics in convergent margin basins: An example from the Salar de Atacama, Chilean Andes. *Geological Society of America, Bulletin*, Vol. 105, p. 603-617.

Galli, C.O.; Dingman, R.J. 1962. Cuadrángulos Alca, Pica, Matilla y Chacarilla. *Carta Geológica de Chile*, Vol. 3, No. 2, 3, 4 y 5, 125 p.

Guest, J.E. 1969. Upper Tertiary ignimbrites in the Andean cordillera of part of the Antofagasta Province, northern Chile. *Geological Society of America, Bulletin*, Vol. 80, p. 337-362.

Hervé, M. 1987. Movimiento normal de la falla Paposo, zona de Falla Atacama, en el Mioceno, Chile. *Revista Geológica de Chile,* No. 31, p. 31-36.

Hooper, B.; Flint, S. 1987. Miocene-Recent tectonic evolution of the San Bartolo area, northern Chile. *Zentralblatt für Geologie und Paläontologie*, Vol. 1, No. 7, 8, p. 967-

981.

Jordan, T.E.; Alonso, R.N. 1987. Cenozoic stratigraphy and basic tectonics of the Andes Mountains, 2°-28° South Latitude. *American Association of Petroleum Geologists, Bulletin*, Vol. 71, No. 1, p. 49-64.

Lahsen, A. 1982. Upper Cenozoic Volcanism and tectonism in the Andes of Northern Chile. *Earth-Science Reviews*, Vol. 18, p. 285-302.

Macellari, C.E.; Su, M.J.; Townsend, F. 1991. Structure and seismic stratigraphy of the Atacama basin, northern Chile. *In Congreso Geológico Chileno, No. 6, Actas*, Vol. 1, p. 133-137.

Maksaev, V. 1978. Cuadrángulo Chitigua y sector occidental del cuadrángulo Palpana. *Instituto de Investigaciones Geológicas, Carta Geológica de Chile*, No. 31, 55 p.

Marinovic, N.; Lahsen, A. 1984. Hoja Calama. *Servicio Nacional de Geología y Minería, Carta Geológica de Chile*, No. 58, 140 p.

Moraga, A.; Chong, G.; Fortt, M.A.; Henríquez, H. 1974. Estudio geológico del Salar de Atacama, provincia de Antofagasta. *Instituto de Investigaciones Geológicas, Boletín*, No. 29, 56 p.

Mortimer, C. 1973. The Cenozoic history of the Southern Atacama desert, Chile. *Journal of the Geological Society of London*, Vol. 129, p. 505-526.

Naranjo, J.A. 1987. Interpretación de la actividad cenozoica superior a lo largo de la zona de falla Atacama, Norte de Chile. *Revista Geológica de Chile*, No. 31, p. 43-55.

Naranjo, J.A.; Paskoff, R. 1980. Evolución geomorfológica del Desierto de Atacama entre los 26° y 33° latitud sur: revisión cronológica. *Revista Geológica de Chile*, No. 10, p. 85-89.

Naranjo, J.A.; Paskoff, R. 1981. Estratigrafía de los depósitos cenozoicos de la región de Chiuchiu-Calama. Desierto de Atacama. *Revista Geológica de Chile*, No. 13-14, p. 79-85.

Naranjo, J.A.; Paskoff, R. 1985. Evolución cenozoica del piedemonte andino en la Pampa del Tamarugal, norte de Chile (18-21°S). *In Congreso Geológico Chileno, No. 4, Actas*, Vol. 4, p. 5/149-5/165.

Pilger, R.H. 1981. Plate reconstructions, aseismic ridges, and low-angle subduction beneath the Andes. *Geological Society of America, Bulletin*, Vol. 92, p. 488-456.

Pilger, R.H. 1983. Kinematics of the South America subduction zone from global plate reconstructions. *In* Geodynamics of the eastern Pacific region, Caribbean and Scotia Arcs, Geodynamics Series, Vol. 9 (Cabre, R., S.J.; editor). *American Geodynemics, Geophysical Union*, p. 113-125. Washington.

Pilger, R.H. 1984. Cenozoic plate kinematics, subduction and magmatism: South American Andes. *Geological Society of London, Journal*, Vol. 141, p. 793-802.

Ramírez, C.F. 1979. Edades Potasio-Argón de rocas volcánicas cenozoicas en la zona San Pedro de Atacama-El Tatio, Región de Antofagasta. *In Congreso Geológico Chileno, No. 2, Actas*, Vol. 1, p. F37-F41.

Skarmeta, J.; Marinovic, N. 1981. Hoja Quillagua. *Instituto de Investigaciones Geológicas, Carta Geológica de Chile*, No. 51, 63 p.

Travisany, V. 1978. Mineralización cuprífera en areniscas de la Formación San Pedro en el distrito San Bartolo. Memoria de Título (Inédito), *Universidad de Chile, Departamento de Geología*, 70 p.

Wilkes, E.; Görler, K. 1988. Sedimentary and structural evolution of the Cordillera de la Sal, II Región, Chile. *In Congreso Geológico Chileno, No. 5, Actas*, Vol. 1, p. A173-A188.

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