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Late Cenozoic geomorphologic signal of Andean forearc deformation and tilting associated with the uplift and climate changes of the Southern Atacama Desert (26°S–28°S)

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Abstract

We analyze remarkable examples of the large (~10,000 km^2) and local-scale (~100 km^2) landscape forms related to Late Cenozoic geomorphologic evolution of the Andean forearc region in the Southern Atacama Desert. We also consider the continental sedimentary deposits, so-called "Atacama Gravels", which are related to the degradation of the landscape during the Neogene. Our analysis integrates 1:50,000 field cartography, Landsat TM images observations, ~1:1000 sedimentary logging data, and 50 m horizontal resolution topographic data to reconstruct the Late Cenozoic geomorphologic evolution of this region and discuss the factors that control it, i.e., Miocene aridification of the climate and Neogene Central Andean uplift. We determine that the Precordillera was already formed in the Oligocene and most of the present-day altitude of the Precordillera was reached before that time. Afterward, five episodes of geomorphologic evolution can be differentiated: (1) the development of an Oligocene deep incised drainage system cutting the uplifted Precordillera (up to 2000 m of vertical incision) and connecting it to the Ocean; followed by (2) the infilling of deep incised valleys by up to 400 m of Atacama Gravels. This infill started in the Early Miocene with the development of fluvial deposition and finished in the Middle Miocene with playa and playa lake depositions. We propose that playa-related deposition occurs in an endorheic context related to tectonic activity of the Atacama Fault System and Coastal Cordillera uplift. However, the upward sedimentologic variation in the Atacama Gravels evidences a progressive aridification of the climate. Subsequently, we have identified the effects of the Middle–Upper Miocene slow tectonic deformation: the Neogene Andean uplift is accommodated by a tilting or flexuring of the inner-forearc (Central Depression and Precordillera) related to some hundreds of meters of uplift in the Precordillera. This tilting or flexuring results in (3) the Middle Miocene re-opening of the valley network to the Pacific Ocean. Upper Miocene aridification, from arid to hyperarid, induces alluvial fans backfilling in the Central Depression (4) resulting in up to 50 m of Atacama Gravel deposition.

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Finally, in response to an increase in the rate of tilting, a new phase of vertical incision (up to 800 m in the Precordillera) allows the development of the canyon that crosses the forearc (5).

Keywords: Neogene; Atacama Desert; Tectonics; Climate changes

1. Introduction

The Central Andes is located in a compressive tectonic regime of rapid convergence (65–85 mm/year) between the subducting oceanic Nazca and the continental South America plates (DeMets et al., 1994; Klotz et al., 2001). The Altiplano–Puna is the main geomorphologic unit of the Central Andes (Fig. 1). The origin of the Altiplano–Puna is attributed to crustal shortening and thickening, and magmatic accretion due to continuous subduction since the Jurassic (e.g. Coira et al., 1982; Jordan et al., 1983; Mpodozis and Ramos, 1989; Sempere et al., 1990; Kay et al., 1991; Kay and Abbruzzi, 1996; Baby et al., 1997; Kay et al., 1999), or ductile mass transfers within the lower crust (Gerbault et al., 2002; Husson and Sempere, 2003). The Altiplano–Puna forms a wide (up to ~400 km) and high (~4000 m average altitude) plateau whose present-day altitudes were reached essentially in the Oligocene–Neogene (e.g. Isacks, 1988; Sempere et al., 1990; Allmendinger et al., 1997; Lamb et al., 1997; Gregory-Wodzicki, 2000). Two main longitudinal segments can be differentiated: the Altiplano northern segment and the Puna southern segment (Fig. 1).

The large-scale topography of the forearc region is considered as a first-order expression of tectonic processes operating during the late Cenozoic (e.g. Isacks, 1988; Muñoz and Charrier, 1996; Lamb et al., 1997; García, 2002; Victor et al., 2004; Garcia and Hérail, 2005). Two different, but complementary, mechanisms have been invoked in order to explain how the forearc region accommodates the Altiplano uplift. The first mechanism considers an isostatically-induced monoclinal flexure-fold located above the tip of the asthenospheric wedge (Isacks, 1988). The monoclinal flexure-fold contributes, in great measure, to an altitude increment of the inner forearc (Central Depression, Precordillera and Western Cordillera; Fig. 1) of ~3500 m in the Western Cordillera. It also controls the development, between Arica and Iquique (18°S–21°S), of a gentle west-sloping surface: the Tarapacá Pediplain (Mortimer et al., 1974; Isacks, 1988; Lamb et al., 1997; García et al., 1999, 2002). The second mechanism considers the existence of a west-vergent and high-angle thrust system, accommodating the Altiplano uplift in the inner forearc region, at least between 18°S and 21°S (Muñoz and Charrier, 1996; Victor, 2000; García, 2002; Garcia and Hérail, 2005; Pinto et al., 2004) (Fig. 1).

In the forearc region of the Puna segment, little has been reported in the literature on the geomorphologic evolution and its relation with the Neogene Andean uplift. Flexuring or tilting have been suggested in the pioneering work on the Southern Atacama Desert (26–28°S) (Mortimer, 1973; Clark et al., 1967; Sillitoe et al., 1968). These authors indicate that both the Neogene sedimentary deposits (the Atacama Gravels; Mortimer, 1973), and the extensive west-inclined glacis surfaces recorded in the inner forearc region (the Atacama Pediplain; Mortimer, 1973), could result from the progressive tilting or flexuring of the Andean western slope. Recent studies show that Neogene tectonic activity affects the forearc region of southern Atacama Desert (Riquelme, 2003; Riquelme et al., 2003; Audin et al., 2003). In the inner forearc region, subtle folding and faulting affecting the landscape surface are compatible within an almost E–W compressive context. However, they do not explain accommodation of the Neogene Andean uplift in the forearc region (Audin et al., 2003).

In this paper we address the landscape evolution of the Southern Atacama Desert (Fig. 1). In this region the arid climate condition was established by the middle Miocene (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996, Nishiizumi et al., 2005) and the hyperarid climate by the late Pliocene (Hartley and Chong, 2002). These climatic conditions have permitted the excellent preservation and exposition of the landscape forms and related deposits. This makes the region an excellent place to investigate the Neogene Andean uplift by using the geomorphologic evolution during this span time. We analyze the geomorphologic evolution considering different landforms at different scales (from ~10,000 to ~100 km^2) and using different methods. Our analysis integrates field and Landsat TM image observations, and interpretation of topographic data obtained from 50 m horizontal resolution DEMs. We first reconstruct the morphology of the bedrock surface of the Neogene deposits using field cartography and gravimetric data obtained by Gabalda et al. (2005). From a 1:50,000 field cartography of the Neogene deposits and the acquisition of six ~1:1000 sedimentary logging, we determine the

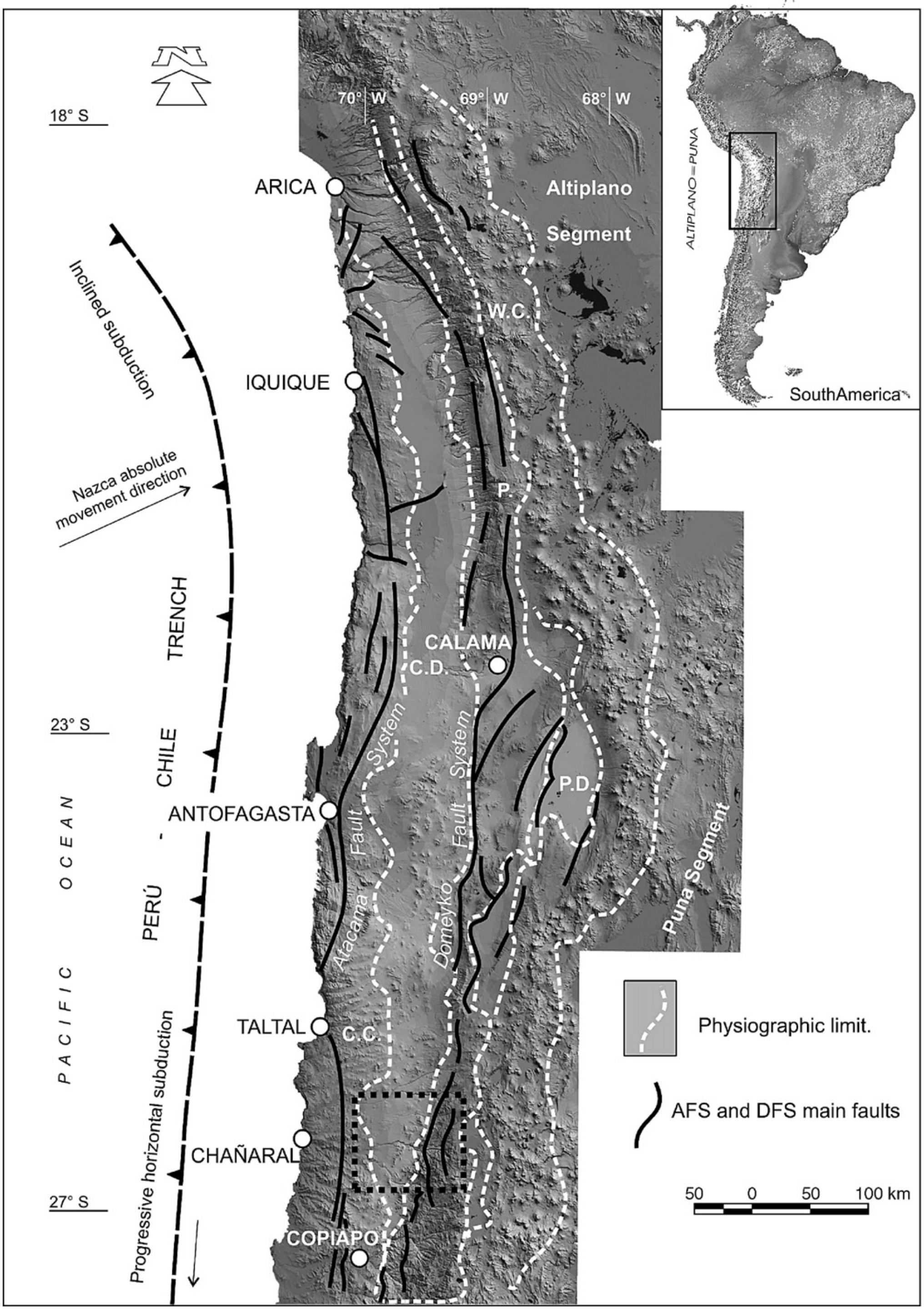

Fig. 1. The Altiplano–Puna plateau forearc region: geomorphologic and geodynamic framework of the Central Andes convergence system in northern Chile. Main physiographic units of the forearc region are depicted: CC, Coastal Cordillera, CD, Central Depression, P, Precordillera, DC, Domeyko Cordillera, PD, Preandean Depression and, WC, the present-day Volcanic Arc and Western Cordillera the present-day Volcanic Arc, and WC, Western Cordillera. Black lines represent the structures of the main fault systems of the forearc region: the Atacama Fault System (AFS) in the Coastal Cordillera and the Domeyko Fault System (DFS) in the Precordillera. In the Precordillera, between 18°S and 21°S, these black lines represent a west-vergent thrust system, accommodating the Altiplano uplift during the Neogene (see the text for references). Black circles indicate the main localities referred in the text. The box shows the study area (Southern Atacama Desert) and the location of Figs. 2 and 3.

large-scale distribution of the sedimentary environment recorded by the Atacama Gravels. We also propose a sedimentary evolution for Atacama Gravel deposition which is related to the evolution of the paleomorphology in which they are deposited. We explore the large-scale landscape characteristics inherited from the pre-Neogene tectonic configuration of the inner-forearc region.

Finally, we discuss the significance of the Neogene landscape surfaces and deposits, at the scale of the forearc region, in documenting the variations of incision and uplift controlling landscape evolution. We provide detail on landforms previously described and we add new geomorphological field observations, presenting remarkable examples of landforms and related deposits from which Neogene geomorphic and neotectonic processes can be deduced. The erosional and depositional landforms are analyzed, discussed and reinterpreted in terms of tectonic activity of the inner forearc. In our discussion we include the possible influence of relative base level change and Neogene climate change on the Southern Atacama Desert geomorphologic evolution.

2. Pre-Neogene geologic and tectonic setting

In the forearc region of northern Chile, between the Arica and Copiapo (18°S–27°30′S), five N–S-oriented longitudinal physiographic units can be differentiated. From west to east these units are: the Coastal Cordillera, the Central Depression, the Precordillera, the Preandean Depression and the Western Cordillera (Fig. 1). These physiographic units contain the Mesozoic–Cenozoic geological record of an eastward-migrating magmatic arc (e.g. Mpodozis and Ramos, 1989; Scheuber and Reutter, 1992). In the Puna segment (20–28°S), the

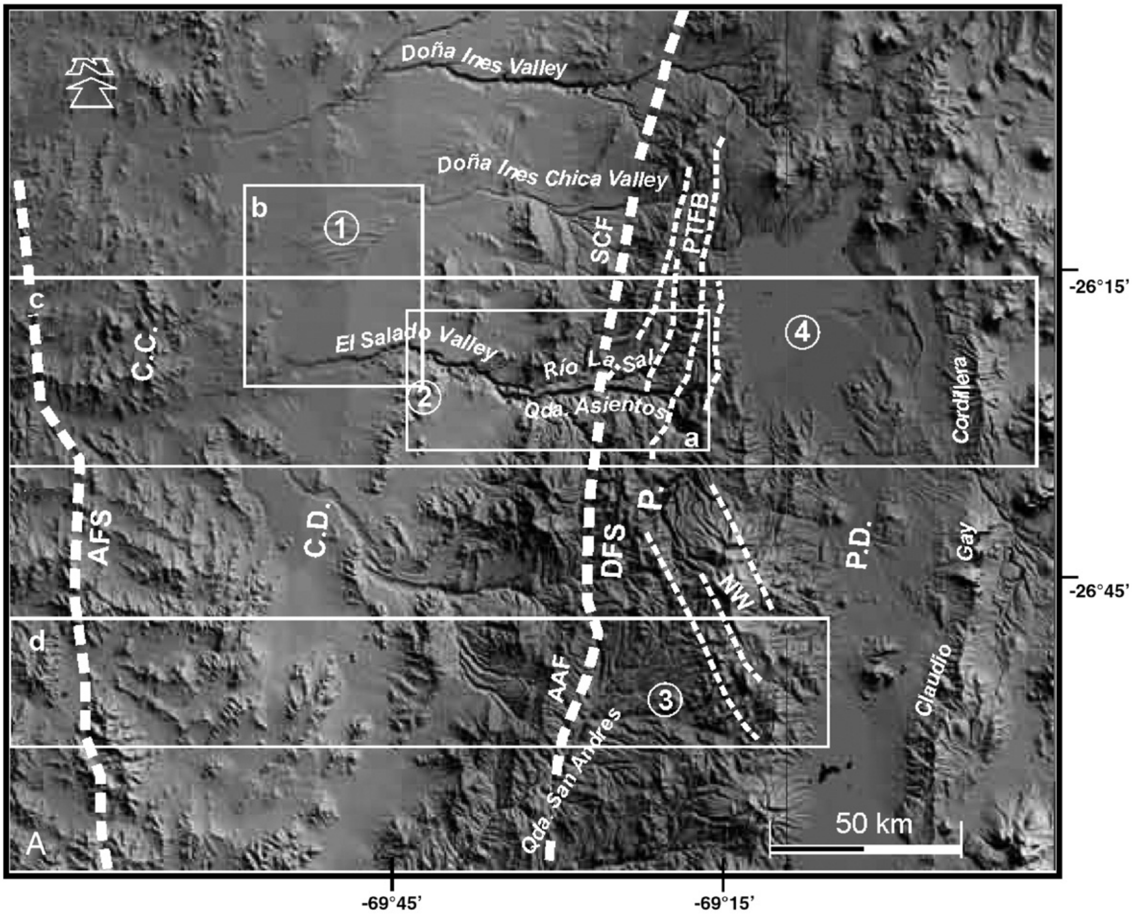

Fig. 2. Shaded relief map of the study area based on SRTM 90m DEM including the main physiographic and structural features as referred in this paper. AFS: Atacama Fault System, DFS: Domeyko Fault System (including its main structural systems: SCF, Sierra Castillo Fault; AAF, Agua Amarga Fault; PTFB, Potrerillos thrust and fold belt; NW, northwest-oriented sinistral faults), C.C.: Coastal Cordillera, C.D.: Central Depression, P: Precordillera, P.D.: Preandean Depression. (a, b) Location of Figs. 4 and 7, respectively. (c, d) Location of profiles c and d, respectively, in Fig. 8. 1: Cerro Torrent, 2: Sierra Caballo Muerto, 3: San Andres watershed basin, 4: Pedernales Salar.

migration of the magmatic arc is accompanied by the development of two north–south-trending intra-arc fault systems: the Atacama Fault System (AFS) in the Coastal Cordillera (e.g. Scheuber and Andriessen, 1990; Scheuber and Reutter, 1992; Grocott et al., 1994; Dallmeyer et al., 1996), and the Domeyko Fault System (DFS) in the Precordillera (e.g. Maksaev, 1990; Tomlinson et al., 1993; Mpodozis et al., 1993; Reutter et al., 1996; Maksaev and Zentilli, 1999; Riquelme, 2003) (Fig. 1).

The major structural system exposed in the study region corresponds to the DFS, which includes two main faults: the subvertical Sierra Castillo Fault (SCF) to the north, and the east-vergent Agua Amarga Fault (AAF) to the south (Cornejo et al., 1993; Cornejo and Mpodozis, 1996; Tomlinson et al., 1999) (Fig. 2). The DFS separates two areas with contrasting Mesozoic histories indicating activity since the Jurassic (Cornejo et al., 1993, Cornejo and Mpodozis, 1996; Tomlinson et al., 1999). The last major deformational event accommodated by the DFS corresponds to the Eocene–Early Oligocene "incaic" tectonic phase, and is responsible for most of the important structures in the region (Cornejo and Mpodozis, 1996; Tomlinson et al., 1999; Randall et al., 2001). At this time, in the north of the study area, transpressive sinistral deformation along the SCF occurred in association with the development of the east-vergent Potrerillos fold and thrust belt (Fig. 2). In the central parts, NW-sinistral faults related to and located east of the AAF were generated (Tomlinson et al., 1993, 1994; Mpodozis et al., 1994; Randall et al., 2001). The Early–Midde Miocene volcanism developed between the Precordillera and the Western Cordillera, and is represented by identifiable stratovolcanoes forming the highest summits of the mountain (>6000 m).

Different episodes of Late Cenozoic landscape evolution of the southern Atacama Desert have been described, based on the recognition of remnant levels of erosion surfaces at different altitudes (Clark et al., 1967; Sillitoe et al., 1968; Mortimer, 1973; Paskoff and Naranjo, 1979; Naranjo and Paskoff, 1980). The "Summit Surface" (Sillitoe et al., 1968), also called the "Cumbre Surface" (Mortimer, 1973), is the highest surface recognized in the area. It corresponds to the oldest stage of landscape evolution. A Paleogene age was attributed to the Cumbre Surface considering that it underlies up to 1000 thick series of Lower Eocene rhyolitic lavas (Mortimer, 1973). The "Intermediate Surface" (Sillitoe et al., 1968) or "Sierra Checo del Cobre Surface" (Mortimer, 1973) corresponds to the end of a predominantly erosional episode (perhaps Eocene in age) that developed after the deposition of the volcanic flows that covered the Paleogene landscape. This episode was identified in most of the Coastal Cordillera and Precordillera between 26°S and 28°S. The Neogene evolution of the region is responsible for most of the present-day topography. This evolution is described herein.

3. Geomorphologic context

The Coastal Cordillera is about 60 km wide, with a mean altitude of ~1500 m and maximum altitudes up to 2000 m (Fig. 2). The limit between the Coastal

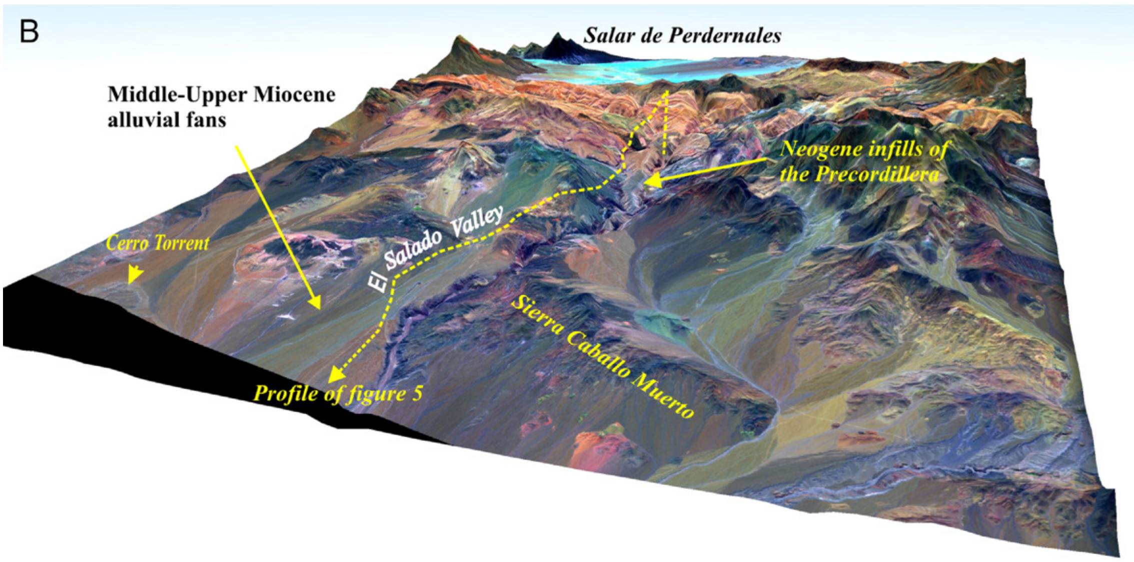

Fig. 3. Northeast view of a block diagram resulting from the superposition of Landsat TM 7,4,1 image and a digital elevation model. Image shows the Central Depression and the Precordillera of the El Salado valley.

Cordillera and the Central Depression is transitional. East of the studied area, the endorheic Preandean Depression develops to an altitude of 3500–3700 m and is mostly occupied by the Pedernales and Maricunga salars. The eastern limit of the Preandean Depression corresponds to the Claudio Gay Cordillera; this N–S-trending mountain range with a mean altitude of 4200 m forms the western border of the Puna.

The Central Depression in the studied region is a smooth and flat surface with altitudes varying between 1100 m in the west and 1500 m in the east. The surface is interrupted by numerous isolated hills and ranges (e.g. Cerro Torrent; Figs. 2 and 3). Most of these ranges are located in the eastern side of the Central Depression (e.g. Sierra Caballo Muerto; Figs. 2 and 3) representing transitional limits with the Precordillera. Maximum altitudes of the Precordillera vary between 3800 and 5000 m. Several approximately east–west-oriented river systems develop from the Precordillera–Preandean Depression border to the east (e.g. Doña Ines and El Salado canyons; Figs. 2 and 3). The Neogene Atacama Gravel infills are widely distributed throughout the Central Depression. In the Precordillera, these deposits can be recognized inside the present-day watershed basin, around the main rivers. We particularly concentrate on the El Salado drainage system (Fig. 3), which is composed of an E–W-oriented canyon–the El Salado canyon–that crosses the Central Depression and divides into two E–W parallel canyons at the Precordillera: the Quebrada Asientos to the south and the Rio de la Sal to the north.

4. The Neogene geomorphological and sedimentological evolution of the El Salado area

4.1. Paleomorphology of the Atacama Gravel Bedrock

The base of the Atacama Gravel deposits in the Precordillera is extensively and continuously exposed along the El Salado drainage system. It is possible to reconstruct precisely the paleo-topography of the bedrock surface underlying the Atacama Gravels,

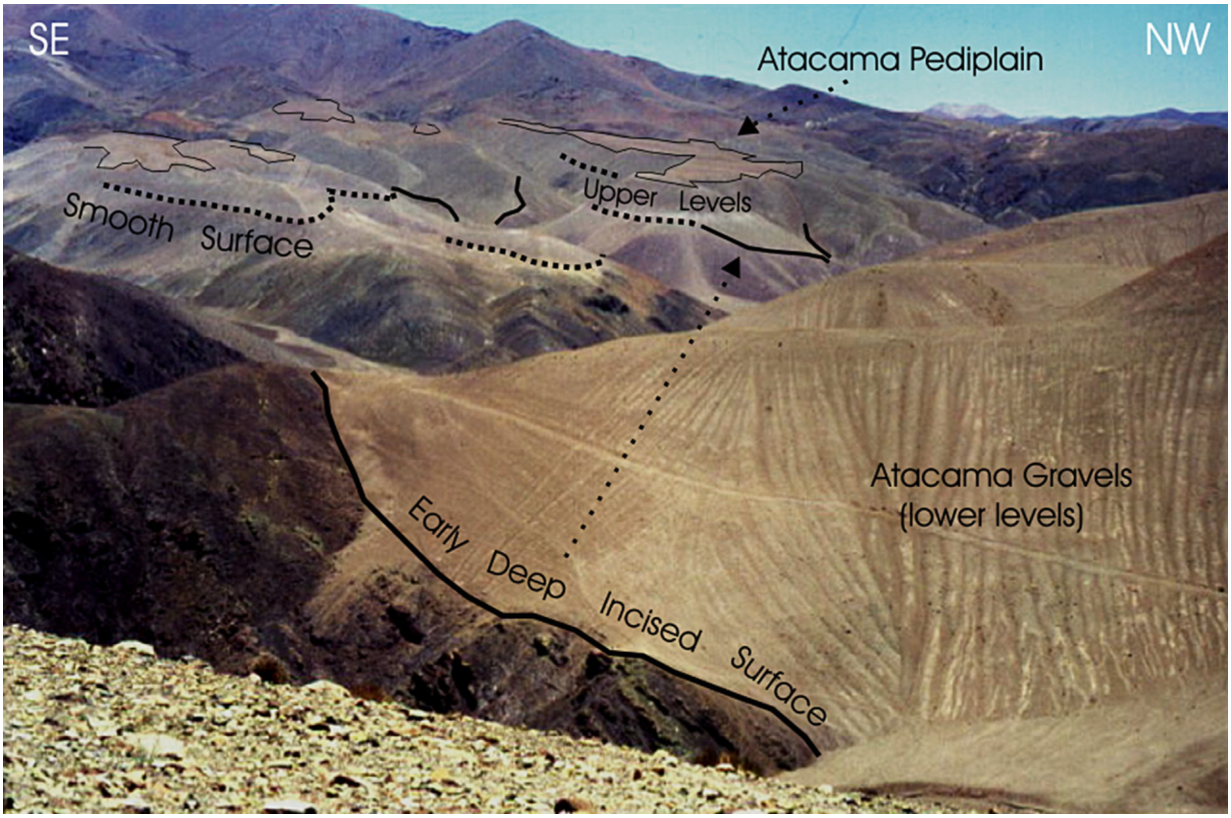

Plate I. SW view of the Quebrada Asientos tributary canyon (in the Precordillera), taken close to the intersection of the Sierra Castillo Fault with the El Salado drainage system. The picture shows the early incised surface, near the bottom of the canyon, filled by fluvial and proximal alluvial Neogene deposits (lower levels of the Atacama Gravel). Upper parts of the canyon flanks expose alluvial fans and pediment related deposits (upper levels of the Atacama Gravel), overlain the smooth surface of the Atacama Gravel Bedrock.

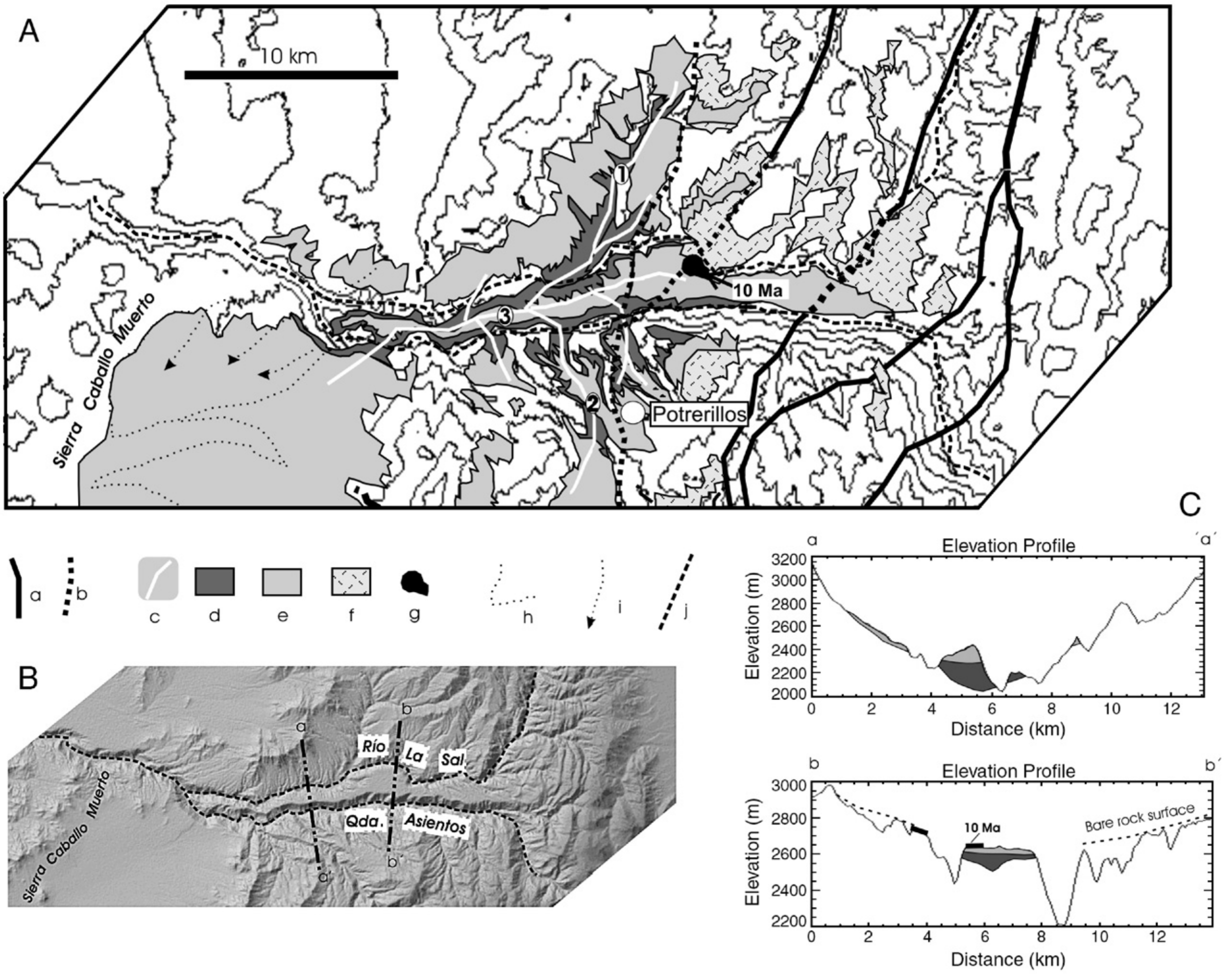

Fig. 4. (A) Neogene large-scale landscape forms and related deposits superimposed on a topographic map of the Precordillera of the El Salado valley. (a) Main faults of the DFS cutting the pre-Neogene substratum and (b) non-outcropping faults underlying Neogene deposits. (c) Paleovalleys formed during the early deep incision. Neogene deposits (Atacama Gravel): (d) Lower–Middle Miocene fluvial and proximal alluvial deposits; (e) Middle–Upper Miocene alluvial and pediment related deposits. (f) Middle Miocene pediment surfaces. (g) The 10 My San Andres Ignimbrite. (h) Limits of the Middle–Upper Miocene alluvial fans and (i) its paleo-flow directions. (j) Main tributaries of the El Salado canyon. (B) Shaded relief map of the considered region indicating the two main tributaries of the El Salado canyon, the Río La Sal and the Quebrada Asientos, and the location of the profiles aa′ and bb′ of (C). Legend of (C) as in (A).

hereafter referred to as the “Atacama Gravel Bedrock”. Two different late Cenozoic landscape evolution events can be differentiated from this reconstruction.

4.1.1. The Early incised surface

The first event in the landscape evolution is identifiable mainly west of the Sierra Castillo fault (SCF) near the bottom of the present-day canyons of the El Salado drainage system (Plate I, Fig. 4A). It is shown by deep paleovalleys excavated in the pre-Neogene substratum which form a particularly deeply incised paleo-drainage system. Here, two long (more than 10 km) N–S-oriented paleovalleys, running parallel to the SCF on the west side of this fault, can be recognized (1 and 2 in Fig. 4A). They correspond to tributaries of a main E–W-oriented paleovalley that developed between the two present-day canyons of the El Salado drainage system (3 in Fig. 4A). The main paleovalley did not flow directly into the Central Depression like the present-day El Salado canyon, but toward the SW between the eastern slope of the Sierra Caballo Muerto and the western slope of the Precordillera.

4.1.2. The smooth surface

The second event is evidenced both east and west of the SCF, in the upper part of the present-day canyons' interfluve (Plate I, Fig. 4C). There, the contact between the Atacama Gravels and the pre-Neogene substratum defines a smooth surface.

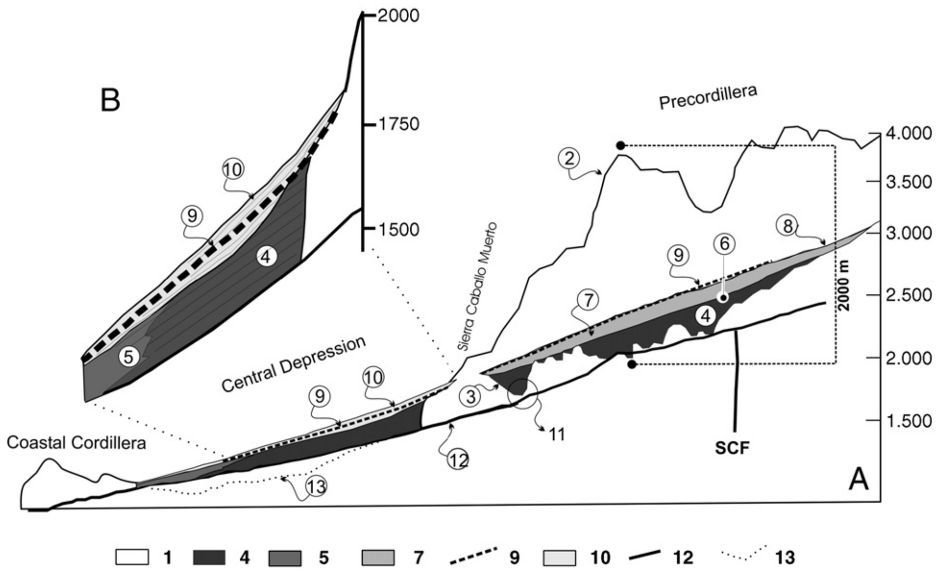

Fig. 5. (A) E–W longitudinal profile of the Neogene deposits and landscape surfaces along El Salado valley. Location of the profile is shown in Fig. 3B. (1) Pre-Neogene substratum. (2) Maximal E–W peak altitudes. (3) Early incised surface (Atacama Gravel Bedrock). (4) Early–Middle Miocene fluvial and proximal alluvial deposits. (5) Early–Middle Miocene playa related deposits. (6) ca. 15 Ma tuff level (Cornejo et al., 1993). (7) Middle Miocene distal alluvial and pediment related deposits. (8) Atacama Pediplain surface. (9) ca. 10 Ma San Andres Ignimbrite (Sillitoe et al., 1968; Cornejo et al., 1993; this work). (10) Middle–Upper Miocene alluvial fan deposits. (11) Cross-section of the main paleovalley of the early drainage system in the Precordillera (3 in Fig. 4). (12) Present-day El Salado canyon thalweg profile (Qda. Asientos in the Precordillera). (13) Atacama Gravel Bedrock in the Central Depression inferred from the gravity data in Gabalda et al. (2005). SCF: Sierra Castillo Fault. (B) Schematic geologic section of the Neogene deposits and surfaces showing the contact with the substratum of the Sierra Caballo Muerto, in the eastern side of the Central Depression.

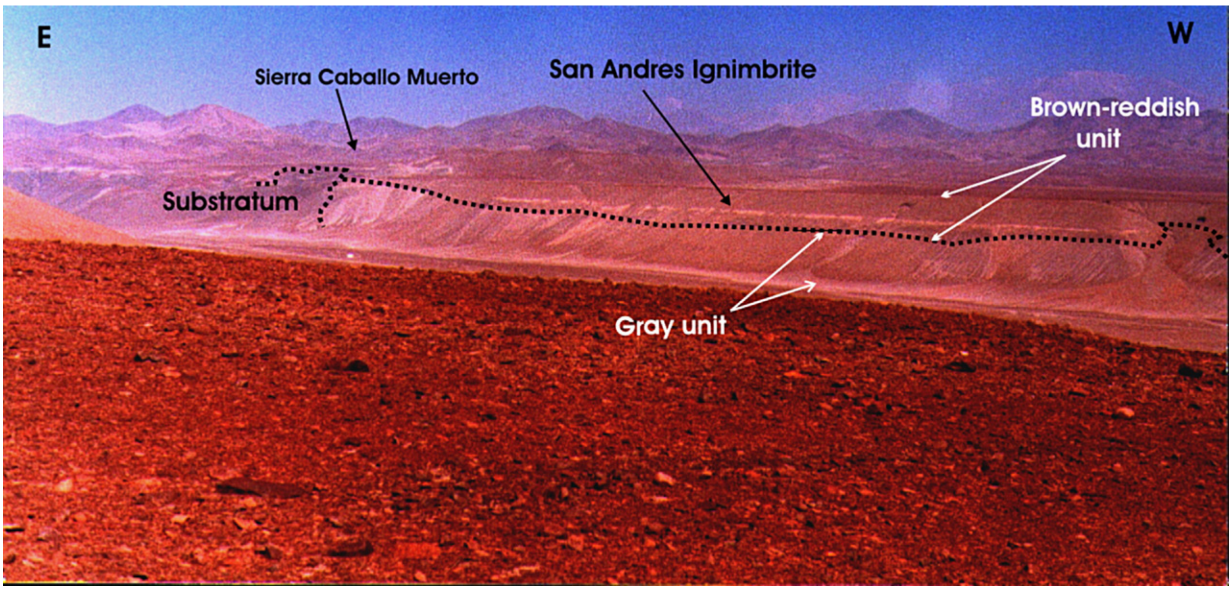

Plate II. SE view of the El Salado canyon showing the two units that can be differentiated in the Atacama Gravels in the Central Depression: the Early–Middle Miocene fluvial and alluvial sequence (gray unit) unconformably overlain by the Middle–Upper Miocene alluvial to playa sequence (brown-reddish unit). The gray unit is vertically accreted to the substratum in the Sierra Caballo Muerto, whereas the brown-reddish unit onlaps this range. The San Andres Ignimbrite separates the two Atacama Gravel sequences close to the Sierra Caballo Muerto and becomes progressively intercalated in the brown-reddish unit to the west.

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In the Central Depression the Atacama Gravel Bedrock is only visible on the flanks of El Salado canyon in the western slope of Sierra Caballo Muerto (Fig. 5, Plate II). As in the Precordillera, two events of landscape evolution can be identified: near the bottom of El Salado canyon it is a deeply incised surface, and it changes upwards to a west-inclined smooth surface.

In the Precordillera, we can reconstruct a longitudinal profile of the Atacama Gravel Bedrock surface exposed along the northern flank of the Quebrada Asientos (Figs. 4B and 5A). The longitudinal profile shows the irregularity of the Atacama Gravel Bedrock surface that corresponds to a cross-section through several minor paleovalleys formed during the early incision. These minor paleovalleys flowed to intersect, only a few hundred meters farther north of Quebrada Asientos, the main E–W-oriented paleovalley (3 in Fig. 4A). East of Sierra Caballo Muerto, the profile crosses the main paleovalley (3 in Fig. 4A, 11 in Fig. 5A). Fig. 5A also integrates the results of a precise gravity survey recently carried out to determine the paleo-topography of the Atacama Gravel bedrock and to quantify the thickness of Atacama Gravel deposits in the Central Depression (Gabalda et al., 2005). Two-dimensional gravity data modelling along a 30 km E–W-oriented profile, located 4 km north of El Salado canyon, indicates that the Atacama Gravel Bedrock is an irregular surface. The maximum gravel infill might locally reach 200 to 400 m (Gabalda et al., 2005; Fig. 5A). The E–W slope of the deeply incised drainage system, estimated by considering the slope of the main paleovalley in the Precordillera and the maximum thickness proposed for the gravel infill in the Central Depression (400 m thick), is slightly greater (up to 0.3° greater) than the regional slope of the present-day El Salado canyon.

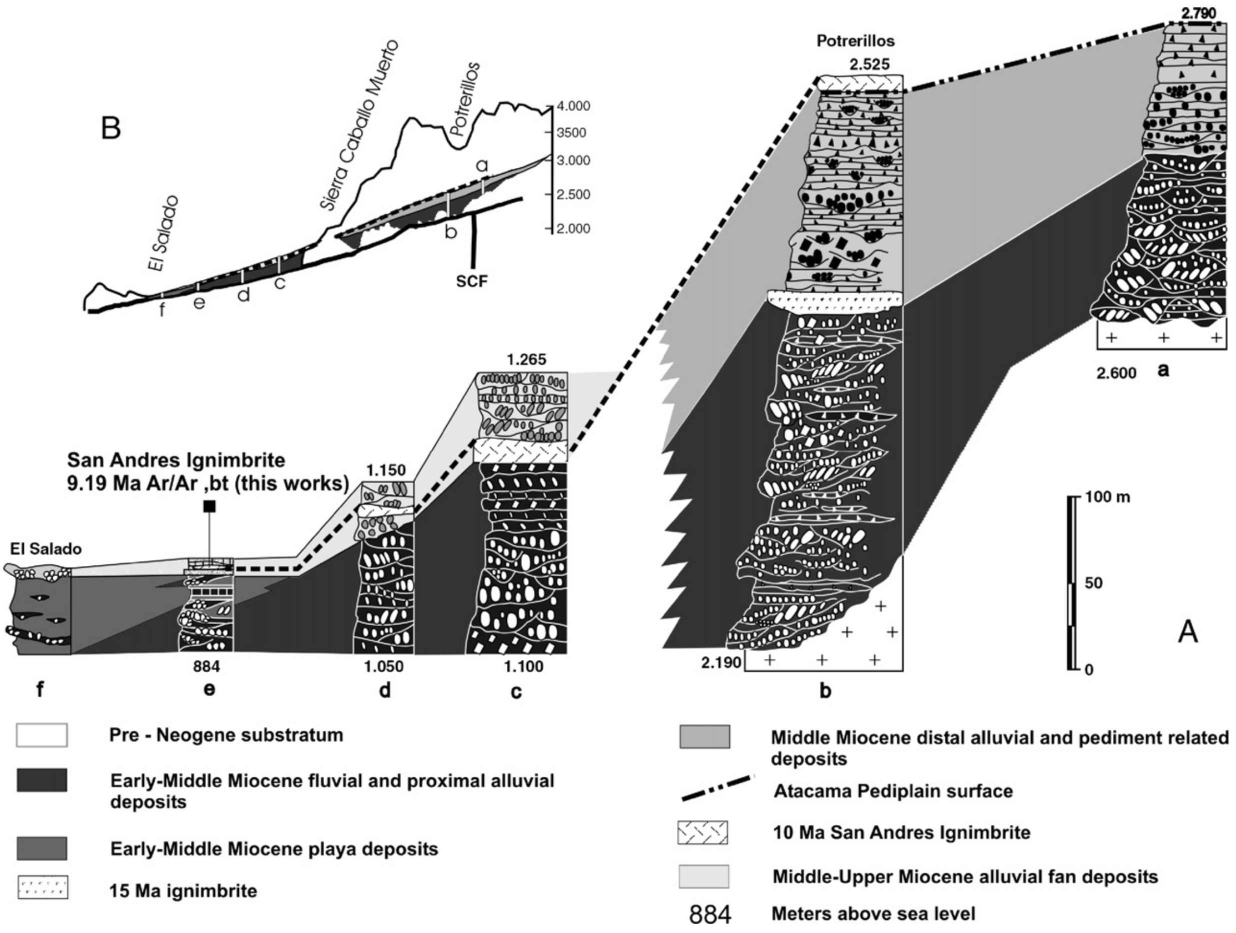

Fig. 6. (A) Stratigraphic logs of the Neogene deposits, showing the position of the tuff levels intercalated in these deposits, along the El Salado valley flanks: (a, b) stratigraphic logs in the Precordillera, (c, d, e, f) stratigraphic logs in the Central Depression. See text for further details. (B) E–W longitudinal profile of the Neogene deposits and landscape surfaces along El Salado valley showing the location of the logs (a), (b), (c), (d), (e), (f) in (A).

The irregularity of the Atacama Gravel Bedrock observed in the Central Depression and Precordillera has also been reported along El Salado canyon in the Coastal Cordillera (Riquelme et al., 2003): before the Atacama Gravel deposition, rivers connected to the ocean were actively eroding this part of the forearc.

The organization of the early deeply incised drainage system differs to the present-day El Salado drainage system. The main paleo-tributary valleys (1 and 2 in Fig. 4A) followed the western side of the SCF, whereas, the two present-day main canyons cross the SCF upstream toward the eastern boundary of the Precordillera. In the eastern side of Sierra Caballo Muerto, the main paleovalley followed a SW direction (3 in Fig. 4A). In contrast, the present-day El Salado canyon flows directly to the Central Depression following an E–W trend. The distribution of the early deeply incised drainage system is spatially associated with the main contractional structures of the pre-Neogene substratum, which is not the case for the present-day drainage systems.

4.2. Large-scale sedimentology of the Atacama Gravels

Mapping of sedimentary facies combined with sedimentary logging (Figs. 4A, 6, and 7)) reveal, among other features, that tuff levels intercalated in the gravels allow to constraint the age of the deposits. The San Andres Ignimbrite has a particular importance for the correlation of the deposits exposed in the Precordillera and Central Depression (Clark et al., 1967; Mortimer, 1973). This sanidine-rich ignimbrite is a conspicuous pink tuff level widely distributed in the Southern Atacama Desert (e.g. Cornejo et al., 1993). K–Ar ages of approximately 10 Ma (Clark et al., 1967; Sillitoe et al., 1968; Mortimer, 1973; Cornejo et al., 1993) have been obtained in this tuff level in the El Salado and San Andres valleys.

4.2.1. Precordillera

Atacama Gravels correspond here to a normal graded series in which the upward sedimentologic changes are in close correspondence with the changes in the paleotopography: the transition between deeply incised paleovalleys to smoother paleo-surfaces corresponds to a progressive change from fluvial to alluvial fan deposits. Maximum gravel thicknesses, up to 400 m thick, are reached along the deeper incised paleovalleys; the deposits become progressively thinner where they onlap the pre-Neogene substratum toward the outer parts of these paleovalleys (Figs. 4C and 5A, Plate I).

Fluvial facies can be recognized on the western part of the Precordillera restricted to the basal levels of the Atacama Gravels that infill the deeply incised paleovalleys (Figs. 4 and 6A(a, b)). These facies are mainly composed of single storey, concave-up, erosive-based channel-fill conglomerates that are 1 to 5 m thick. Lateral extensions enlarge upward: close to the base of the Atacama Gravels, the channels are between 10 and 30 m wide, whereas 200 m upward from the base they reach up to 100 m wide. The channel-fills comprise massive, imbricated, moderately to well-sorted, well-rounded and clast-supported conglomerates which rapidly fine upwards. Close to the base of the Atacama Gravels, the channel-fills reach up to 5 m thick and comprise cobble and boulder grade clasts (long axes up to 50 cm) within a poorly sorted coarse sand matrix, which fine upward to cobble conglomerates (long axes up to 20 cm). Large boulders up to 1 m in diameter are common at the contact with the substratum and probably reflect lag deposits. From 100 to 200 m upwards from the base, the grain size of these channel-fills ranges from mainly cobble conglomerates (long axes up to 20 cm) fining upwards in the top few decimeters to pebble and granule conglomerates or pebble sandstones. Up to 3 m thick massive or horizontally bedded and imbricated conglomerates are found in some places either erosively overlying or grading upwards from the channel-fills. These layers are mainly composed of pebble to cobble grade conglomerates (long axes up to 20 cm), however, upwards in the Atacama Gravels, horizontally bedded pebbly sandstones are more common. Planar- and trough-cross-stratified conglomerates and pebbly sandstones, which form sets up to 0.5 m high, can be occasionally recognized horizontally or vertically limiting the massive and laminated conglomerates layers.

Above the fluvial depositional series, alluvial fan deposits are widely distributed along the main tributary valleys of the El Salado canyon, and can be recognized upstream until 10 km east of the Potrerillos mining district (Figs. 4 and 6A(a, b)). The alluvial depositional facies comprises coarse- and fine-grained facies that form 100- to 150-m-wide sheet-like to lensoid shaped beds. Coarse-grained beds are composed of subrounded to rounded pebble and cobble conglomerates. They are typically 0.5 to 1 m thick, although their thickness can reach 2 m. They are mainly clast-supported and contain up to cobble grade clasts (15 cm in diameter) within a coarse sand matrix. Beds are generally massive, moderately to poorly-sorted, but locally display normal or inverse grading and clast imbrication. Basal surfaces of the beds are planar non-erosive to gently erosive. Fine-grained beds, typically 0.5 to 2 m thick, are much less common. They correspond to pebbly sandstones or granule to pebble grade conglomerates within a coarse

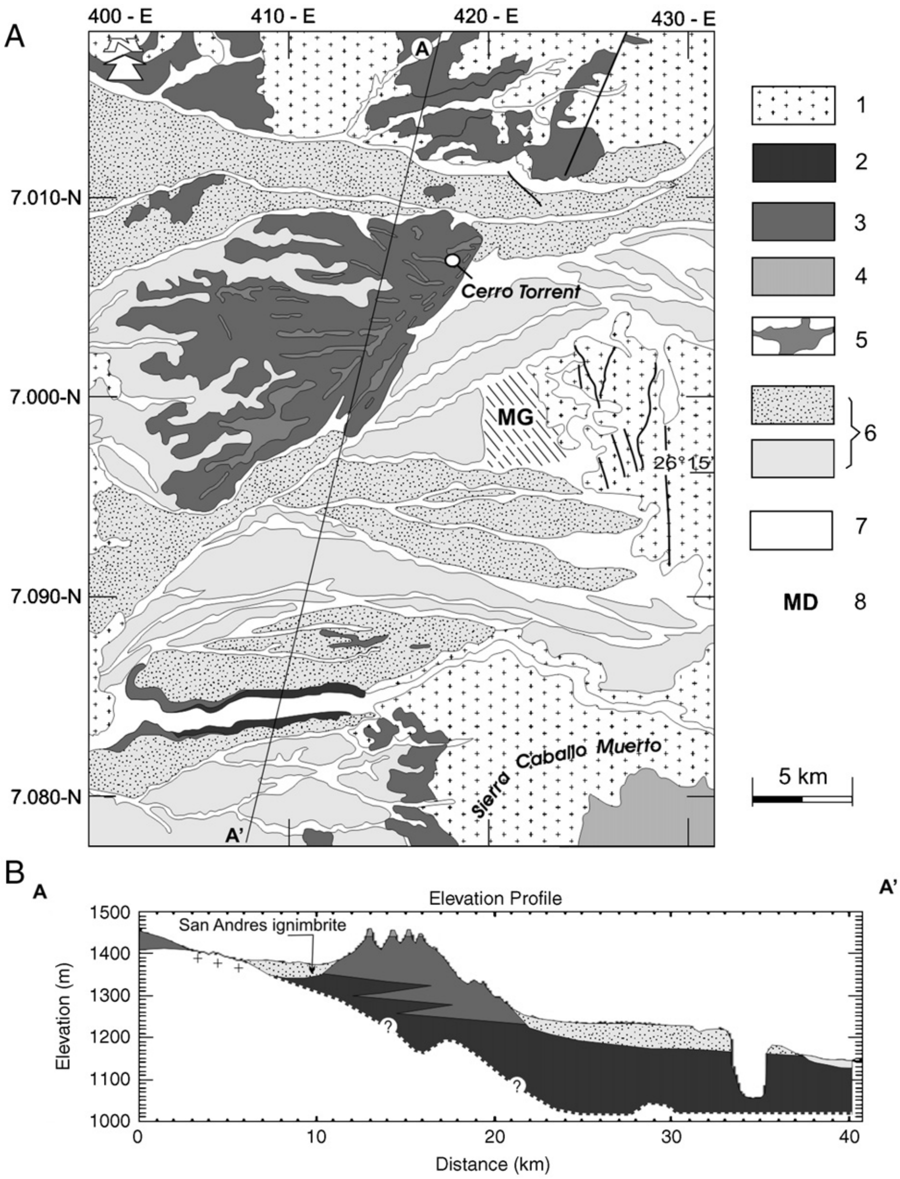

Fig. 7. (A) Geological map of the Central Depression between the Doña Ines Chica valley and the El Salado valley. The map shows the distribution of the Neogene depositional and geomorphologic surface and the main localities cited in the text. (1) Pre-Neogene substratum. Atacama Gravels: (2) Early–Middle Miocene fluvial and proximal alluvial deposits; (3) Early–Middle Miocene playa related deposits; and (4) Middle Miocene distal alluvial and pediment related deposits. (5) Up to 1 m thick layer of rounded boulders overlain the Cerro Torrent. (6) Middle–Upper Miocene alluvial fan deposits. (7) Modern debris flow and present-day valleys. (8) Mining Dump. (B) Interpretative geological section of the Central Depression oriented as indicated in (A).

sand matrix. These beds are generally flat or slightly-obliquely stratified with alternating coarse (granule or pebble grade conglomerate) and fine (pebbly sandstone) 10- to 30-cm-thick layers.

The basal Atacama Gravel levels preserved in the bottom of the paleovalleys mainly contain fining upward, erosive-based, channel-infills comprising well-rounded and imbricated conglomerates. These features can be interpreted as the product of deposition from bedload transport in fluvial channels during a waning flood stage (May et al., 1999). The presence of cross-stratified conglomerates and pebbly sandstones can be related to deposition from bedload transport in barforms under variable fluid flow and sediment

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discharge conditions. The massive and horizontally stratified, imbricated conglomerate levels probably reflect the sporadic deposition of less confined distal debris flows. Such depositional features are characteristic in gravel-dominated fluvial systems (Vincent, 2001; Wysocka and Swierczewska, 2003). In contrast, the upward widening of the channel-infills suggests the progressive development of less confined flows. The absence of channelisation in the upper Atacama Gravel levels, the alternation of fine- and coarse-grained beds with non-erosive to gently erosive basal surfaces, suggests deposition from unconfined to semi-confined debris flow or sheet-floods in mid- to distal alluvial fan positions (Ballance, 1983).

4.2.2. Central Depression

The Atacama Gravels cover most of the Central Depression between the El Salado and Doña Ines Chica valleys (Fig. 7). Two depositional units can be distinguished cropping out along El Salado Canyon flanks: (1) a lower gray colored unit unconformably overlain by (2) an upper brown-reddish colored unit (Plate II). A third unit crops out in the Cerro Torrent (Fig. 7), an isolated NE–SW-elongated, 15-km-long and 10-km-wide plateau, located between the El Salado and Doña Inés Chica valleys. Cerro Torrent deposits represent topographically the highest Neogene depositional units in the Central Depression. However, field observations in the Doña Ines Chica valley show that they are unconformably overlain by alluvial fan deposits corresponding to the upper brown-reddish unit (Fig. 7). In fact, the Cerro Torrent deposits are stratigraphically over the lower gray units; and they were eroded in the El Salado valley area before the deposition of the upper brown-reddish unit (Fig. 7B).

4.2.2.1. Alluvial fan and playa deposits

4.2.2.1.1. The lower gray depositional unit. The lower gray units can be recognized in the El Salado canyon flanks throughout the Central Depression. It is a partially sulphate-cemented sedimentary series vertically accreted to the deeply incised paleo-surface of the Atacama Gravel bedrock (Plate II). In the eastern part of the Central Depression, it corresponds to granule to pebble grade conglomerates, locally including boulders up to 50 cm in diameter, interbedded with sheet-flood sandstones and pebble sandstones (Fig. 6A(c, d)). Conglomerates are imbricated, poorly to moderately sorted, subrounded to rounded. They form erosive-based, open-lensoid shaped beds, up to 2 m thick, and between 10 and 30 m wide. Sheet-flood coarse-grained sandstones and pebble sandstones comprise up to 1 m thick, planar non-erosive to gently erosive beds that continue laterally for several tens of meters. Parallel- and cross-stratification are occasionally visible in these layers. Granule to pebble breccia-dominated beds are rarely interbedded in the unit close to the Sierra Caballo Muerto (Fig. 6A(c)). These beds form erosive-based sheet-like shaped beds that reach up to 1 m thick and extend for several tens of meters. They are poorly to moderately sorted, clast- to matrix-supported within a coarse sand matrix.

The grain size of the lower gray unit decreases from the east to the west: fine- and coarse-grained sandstone beds are progressively more frequent and claystone and siltstones beds appear (Fig. 6A(e)). Close to El Salado town, the unit is a horizontally and laterally continuous (>100 m wide), planar-based stratified unit that reaches up to 50 m thick (Fig. 6A(f)). Mainly siltstones, claystones and abundant evaporite levels are interbedded with fine- to coarse-grained sandstones. Siltstones and claystones have a powdery nature and form massive, occasionally planar laminated, beds that range between 0.5 and 2 m thick. Sandstones comprise planar, non-erosive to gently erosive-based beds that range from 0.25 to 1 m thick. They are generally well sorted, commonly planar laminated or normally graded, however, trough-cross-stratification can be recognized rarely. White cohesive evaporite levels, up to 1 m thick, are frequent. These levels have a planar basal and top surface and are devoid of clastic material. They are generally structureless but locally expose paleo-desiccation cracks. Other sedimentary facies that have been recognized in the unit, close to the El Salado town, correspond to thin (5 to 10 cm thick) calcareous, algal mats and ostracod-bearing lime beds (Riquelme et al., 2003; Vernon et al., 2005). The lower gray units can be followed downstream along the El Salado valley to the Atacama Fault System (Riquelme et al., 2003).

4.2.2.1.2. Cerro Torrent deposits. The Cerro Torrent exposes a horizontally planar-based stratified unit, up to 100 m thick, that is composed of fine-grained and poorly consolidated deposits. Outcrops comprise mainly siltstones, claystones and minor sulphate evaporite levels interbedded with granule to pebble grade conglomerates. Deposits are highly cemented by sulphate which is mainly recognizable in coarser beds. Beds of siltstone and claystone have a powdery nature and are gray to white colored, 0.5 to 2 m thick, planar based and laterally continuous. They resemble massive units, but sulphate cements may be obscuring most of primary sedimentary structures. White sulphate evaporite levels, up to 2 m thick, locally expose paleo-desiccation cracks. Granule to pebble channel-fills conglomerates up to 2 m thick can be traced by up to

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tens of meters across an individual exposure. They are imbricated erosive-based and multi-storey. Up to 50-cm-thick sandstones and granular to pebble sandstones are occasionally interbedded in the channel-fill conglomerates. These beds are planar non-erosive to gently erosive. Sandstones are massive, planar stratified or trough-cross-stratified. The Cerro Torrent deposits are generally overlain by an up to 1 m thick layer of rounded boulders (up to 1 m in diameter).

4.2.2.1.3. Interpretation. The sedimentary facies and the regional basinal (the Central Depression) setting for the lower gray unit and the Cerro Torrent deposits provide information on their depositional environment. The facies associations of the lower gray unit close to Sierra Caballo Muerto suggest deposition from poorly confined debris flow and sheet-floods which are common in mid-alluvial fan positions (e.g. Ballance, 1983; Blair and MacPherson, 1994). The lower gray unit granulometry decreases westward indicating that alluvial fans become more distal. The facies association present close to El Salado town can be attributed to a low-energy depositional environment, such as terminal fringes of alluvial fan systems or playas. The common occur rence of sulphate evaporite levels indicates the presence of ephemeral saline playas and playa lake environments.

Facies association exposed in Cerro Torrent can be attributed to deposition in terminal fringes of the alluvial fans, playas or ephemeral playa lakes. However, Cerro Torrent deposits also comprise channel-fill conglomerates and sandstone levels that can be related to ephemeral to semi-perennial channel systems crossing the Central Depression. Fine-grained deposits interbedded with abundant sulphate evaporite levels similar to those of the Cerro Torrent are also widely distributed in the Central Depression (Fig. 7A). North of the Doña Inés Chica valley, these deposits form thin patches, up to 20 m thick, deposited directly on the pre-Neogene substratum. In the El Salado canyon area, fine-grained deposits interbedded with abundant sulphate evaporite levels can be recognized as thin patches, up to 10 m thick, cropping out in the western slope of the Sierra Caballo Muerto. The extensive distribution of these deposits indicates that playa and playa lake depositional environments developed in a large basin that extended at least from 26°S to 26°30′S.

4.2.2.2. Backfilling alluvial fans deposits: the upper brown-reddish unit. The upper brown-reddish unit is a conspicuous series that unconformably overlies the lower gray and Cerro Torrent units (Plate II, Fig. 7B). As seen on satellite images, this brown-reddish series presents the morphology of a giant E–W-oriented alluvial fan complex running parallel to the El Salado canyon (Fig. 7A). The vertical cross-section of this series along the canyon flanks exposes a wedge shape geometry that thins westward. To the east, the upper brown-reddish deposits onlap at a low angle the Mesozoic–Early Tertiary substratum of Sierra Caballo Muerto (Figs. 5 and 6, Plate II).

Close to the Sierra Caballo Muerto the upper brown-reddish unit reaches 50 m thick (Fig. 6A(c, d)). It is composed of interbedded finer and coarser beds which have a sheet-like to thin lensoid cross-section shape. Fine beds are more voluminous than coarse beds; they have a greater thickness (0.3 to 1.5 m) and lateral continuity (up to 10 m). They contain pebble sandstones to granule grade conglomerates with a matrix of poorly sorted coarse sand. Beds are massive or horizontally stratified with alternating 5 to 10 cm thick coarse and fine layers. Coarser beds include up to 1 m thick, non-erosive to gently erosive-based pebble and cobble grade conglomerates. They are clast-supported and contain up to cobble grade material within a coarse sand matrix. Beds are massive or display normal grading and clast imbrication.

The upper brown-reddish unit is represented close to El Salado town by a large channel-fill that unconformably overlies the lower gray unit (Fig. 6A(f), Plate III). Channel-fills show a gentle, 100-m-wide and up to 10-m-thick, concave-upward geometry. The base of the channel-fills comprises three fining upward cycles, up to 2 m thick, of pebble to cobble grade conglomerates. Upwards the grain size of the channel-fill quickly decreases and comprise concave-shaped sandstone and siltstone beds that progressively become more horizontal towards the top. The thickness of each bed reaches up to 1 m along the channel axis, decreasing towards the mar gins. The upper brown-reddish unit results from the prog ressive infill of a large valley eroded in the lower gray unit. It begins with the episodic deposition of bed load transported conglomerates, and quickly passes upward to distal alluvial sandstones and siltstones deposits.

The stratigraphic position of the 10 Ma San Andres Ignimbrite with respect to the upper brown-reddish unit is key to understanding the landscape evolution associated with the deposition of these units. The tuff layer is exposed continuously along most of the El Salado Canyon flanks in the Central Depression (Plate II). Immediately west of Sierra Caballo Muerto, it separates the upper brown-reddish unit from the lower gray unit (Figs. 5B and 6A(c)), whereas westward it becomes interbedded within the upper brown-reddish (Plate II, Figs. 5B and 6A(d, e)). The tuff layer can be commonly recognized in the western part of the Central Depression where a 9.19±0.61 Ma biotite Ar–Ar age

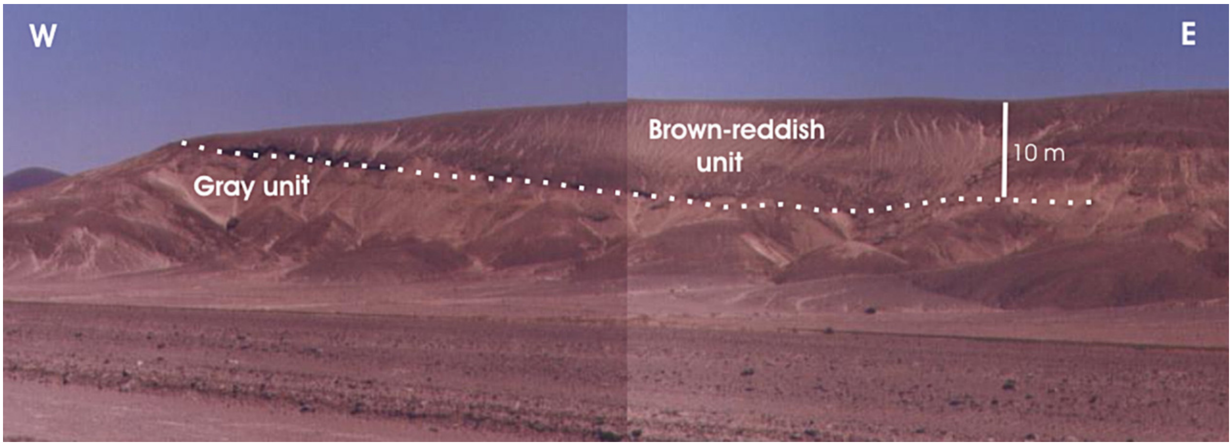

Plate III. The Atacama Gravel close to El Salado town. The lower gray unit is composed of siltstones, claystones and abundant evaporite levels, interbedded with fine- to coarse-grained sandstones. The upper brown-reddish unit unconformably overlies the lower gray unit and is represented by a large channel-fill exposing a gentle, 100 m wide and up to 10 m thick, concave-upward geometry.

has been obtained during this work (Fig. 6A(e)). Therefore, the contact between the lower gray and the upper brown-reddish unit is diachronous. The upper brown-reddish alluvial fan deposition began in the western side of the Central Depression prior to ~10 Ma, whereas, to the east, it onlapped the basement of the western side of Sierra Caballo Muerto only after ~10 Ma. The beginning of alluvial deposition is progressively younger to the east, indicating an episode of eastward alluvial fan backfilling of the Central Depression. This episode corresponds to the sedimentary aggradation of a previously eroded landscape surface and an upward 'distalization' of sedimentation in the western side of Central Depression, as shown by the large channel-fill deposits near El Salado town. The alluvial fan backfilling episode developed until the initiation of the present-day incision in the El Salado valley.

The episode of fan backfilling observed in the upper brown-reddish units can be applied generally to the entire Central Depression of the region. Giant E–W-elongated alluvial fans formed by debris coming from the Precordillera, similar to that represented by the upper brown-reddish unit, cover more than 70% of the Central Depression. In the Doña Ines Chica valley, one of these alluvial fans unconformably overlies the Cerro Torrent deposits (Fig. 7). The 10 Ma San Andres Ignimbrite is intercalated in this alluvial fan indicating a deposition age similar to that of the upper brown-reddish unit.

4.3. The Atacama Pediplain

4.3.1. Precordillera

In the Precordillera along the El Salado valley, the Atacama Pediplain is preserved as a high terrace along the canyons flanks (Fig. 4, Plates I and IV). This pediplain corresponds mostly to the surface of the upper alluvial deposits of the Atacama Gravels, but in many places, it can extend into the canyon flanks as a planar bare rock surface. These planar surfaces continue as rectilinear to concave hillslopes (Plates I and IV). Such surfaces developed at the foot of rectilinear to concave hillslopes are indicative of pediment-related backscarp retreat in arid regions (Cooke et al., 1993). Thus, pedimentation processes govern the geomorphologic evolution of the El Salado valley at the end of the alluvial sedimentation.

In the western part of the Precordillera, the morphology of the alluvial fans can be clearly identified both in the field and on Landsat images (Fig. 4A). One of these alluvial fans is exposed at the eastern side of the Sierra Caballo Muerto, and is NE–SW-elongated, parallel to the strike of this range. The ca. 10 Ma San Andres Ignimbrite is intercalated towards the top of the deposits that make up this alluvial fan. The tuff can also be observed into the 2-m-deep gullies that are incised on the alluvial fan surface. To the east, 7 km north of the Potrerillos mining district, the San Andres Ignimbrite seals a pediment surface, the bare rock surface and its downslope prolongation on the alluvial deposits, now perched above the El Salado canyon (Fig. 4A, Plate IV). These observations indicate that the San Andres Ignimbrite dates the end of the pedimentation processes and alluvial fan deposition that form the Atacama Pediplain in the Precordillera. This assertion has recently been corroborated by exposure age of cobbles collected on alluvial fan surfaces that compose the Atacama Pediplain near El Salvador: based on combined measurements of cosmogenic ^{10}Be, ^{26}Al, and ^{21}Ne concentrations, Nishiizumi et al. (2005) propose an age of

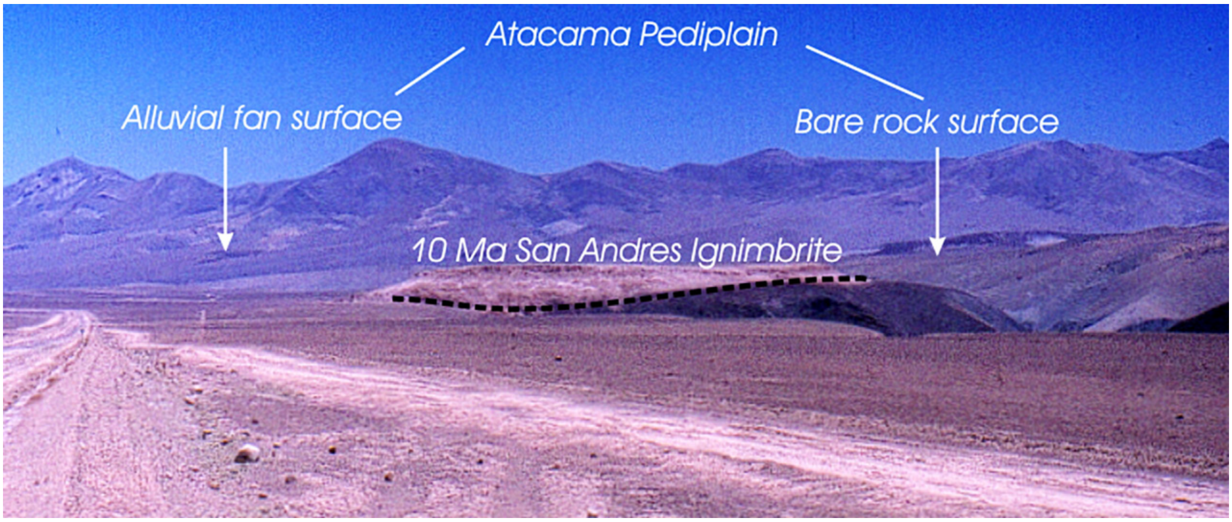

Plate IV. The Atacama Pediplain close to Potrerillos (Precordillera of the El Salado canyon). The pediplain corresponds to the surface of the upper alluvial deposits of the Atacama Gravels and can extend into the canyon flanks as a planar bare rock surface. The San Andres Ignimbrite seals the bare rock surface and the alluvial fan surface.

9 Ma. Thus, the Atacama Pediplain in the Precordillera of the El Salado valley can be interpreted as remnants of an Upper Miocene fossil pediplain surface.

4.3.2. Central Depression

The Central Depression is mainly covered by several E–W-elongated (30 km long vs. 10 km wide) alluvial fans (Fig. 7A). The surface of these coalescing alluvial fans defines a smooth undulating surface, usually termed the Atacama Pediplain (Sillitoe et al., 1968; Mortimer, 1973; Naranjo and Paskoff, 1980). The alluvial fan surfaces are, in the eastern side of the Central Depression, regularly dissected by narrow, steep (up to 5 m of vertical incision) and very linear E–W-oriented rivers (Fig. 7A). Darkly varnished pebbles and cobbles (up to 30 cm in diameter) and desert pavements cover most of the alluvial fan surface indicating it remained unchanged for long periods of time. More recent (fresh surfaces without desert varnish) alluvial fans only occupy a small surface of the Central Depression surface. They indicate, however, that alluvial fan deposition is still active.

In the Central Depression, the Atacama Pediplain represents the surface of "active" alluvial fans, whereas, in the Precordillera it represents a pediplain surface, i.e., a surface formed by the coalescense of pediment surfaces (e.g. Cooke et al., 1993). The deposition of alluvial fans in the Central Depression began prior to ~10 Ma (age of the San Andres Ignimbrite) and is still active; whereas, alluvial fan deposition related to pedimentation processes came to an end in the Precordillera at approximately the same time as the emplacement of the San Andres Ignimbrite. The Atacama Pediplain is, thus, a younger surface in the Central Depression.

4.4. The DFS controls on the large-scale present-day geomorphology

Averaged N–S topographic profiles along east–west 20-km-wide swaths in the northern and southern part of the study area demonstrate a correlation between the DFS and the main topographic features appearing at this scale (Figs. 2 and 8).

The northern profile (Fig. 8A), at the latitude of El Salado Canyon, shows a marked change in the slope at the western edge of the Preandean Depression. This change coincides with the easternmost structures reported for the Potrerillos fault-and-thrust belt (PTFB, Fig. 2). From there towards the western side of the Central Depression, the average altitude progressively decreases ca. 2600 m in 70 km (2.1°E to W dipping slope). East of the PFTB, the average altitude is constant (~3500 m). The PFTB is clearly marked in the topography of the Precordillera controlling the maximum altitudes reached by the rocks of the pre-Neogene substratum (Figs. 2 and 8A). Maximum altitudes recorded east of the PFTB correspond only to Early to Middle Miocene volcanoes (Figs. 2 and 8A). The degree of incision, defined as the difference between the maximum and minimum altitude on a N–S line of the swath, progressively decreases

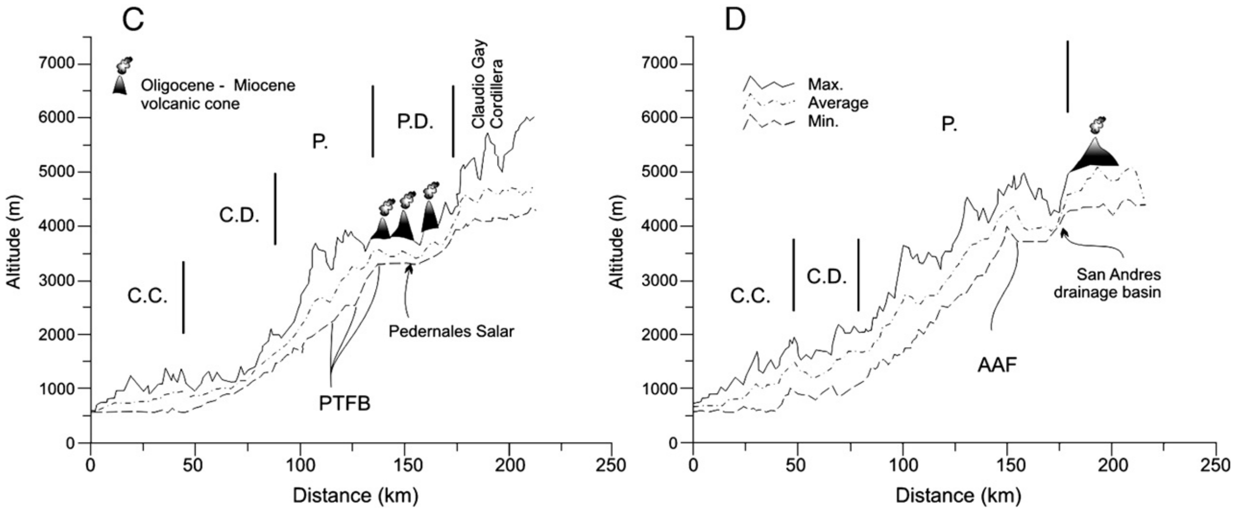

Fig. 8. N–S averaged, maximum and minimum altitudes taken along 20-km-wide E–W-oriented swath for C, a northern, and D, a southern profile. Abbreviation of the main physiographic units as in Fig. 1. The main faults of the DFS are indicated: PTFB, Potrerillos thrust and fold belt; AAF, Agua Amarga Fault. East of Precordillera the highest altitudes are reached only by Early–Middle volcanic cones. Location of the profiles is indicated in Fig. 2.

toward the west from up to 2000 m in the Precordillera to 100 m in the Central Depression. A second major topographic change is located east of the study area. It corresponds to a step of ca. 1000 m in the Cordillera Claudio Gay (Figs. 2 and 8A). There, Neogene faulted and folded syntectonic sediments are exposed, indicating that this area represents a locus of Miocene tectonic deformation (Mpodozis and Clavero, 2002).

The southern profile also shows that the DFS, in this case the Agua Amarga Fault (AAF), is a first order topographic feature (Figs. 2 and 8B). West of the AAF the average altitude defines a morphologic surface inclined to the west, with a 100-km-wide, west-dipping slope of ca. 1.9°, starting at 3100 m. To the east of AAF, an abrupt decrease in the average altitudes corresponds to an intermontane depression in the Precordillera: the San Andres watershed basin (Fig. 2). This depression is limited to the east by the NW–SE-trending faults related to the DFS (Fig. 2). Higher summits of the Precordillera–Preandean Depression correspond to Oligocene–Miocene volcanoes. This profile shows a high degree of incision everywhere (>1500 m in the Precordillera), consistent with the strong incision of the San Andres drainage system.

According to these observations, the DFS controls the main topographic features at the regional scale. The DFS-related structures determine the changes in the E–W average topography and controls the maximum altitudes reached by the pre-Neogene rocks in the Precordillera. On the other hand, the Neogene Atacama Gravel infill develops along the Precordillera, crossing the structures related to the DFS, and there is no evidence of major fault activity affecting the Neogene deposits. Consequently, the control of the DFS on the main topographic features is inherited from a pre-Neogene geomorphologic evolution of the region.

5. Late Cenozoic landscape evolution

The late Cenozoic landscape evolution of the El Salado region began with the development of a deeply incised drainage system that can be recognized from the Precordillera to the Coastal Cordillera underneath the Neogene Atacama Gravel infills. This indicates that the forearc was connected to the Pacific Ocean and that erosional hydrologic conditions controlled the landscape evolution at that time. Valleys formed during that period of incision were as deep as 2 km below the highest neighbouring summits (Fig. 5A), showing that the Precordillera existed at that time and that it reached a most of its present-day ~3500 m altitude. The last major tectonic event accommodated by the DFS occurred during the Eocene–Early Oligocene “incaic” tectonic phase (Tomlinson et al., 1993, 1994; Mpodozis et al., 1994; Randall et al., 2001). Fission track data, obtained between the El Salado and Antofagasta latitudes, indicates that the Precordillera was affected by a strong denudation following this tectonic phase (Maksaev and Zentilli, 1999; Nalpas et al., 2005). In the Preandean Depression (Pedernales Salar), an important pulse of synorogenic deposits can be related to the Eocene–Early Oligocene tectonic activity on the DFS (Mpodozis and

Clavero, 2002). This indicates that the eastern side of the Precordillera drained to the east at this time. The early deep-incised drainage systems developed on the western flank of the Precordillera and its organization is spatially associated with the main structures of the DFS (Fig. 4A). This suggests that the early deep incision developed during the Oligocene immediately after or simultaneously with the last significant tectonic activity accommodated by the DFS.

In the Precordillera, the Atacama Gravels progressively filled the deeply incised drainage systems, indicating changes in the geomorphologic conditions. The sedimentological features exposed in the basal levels of Atacama Gravel indicate that the infilling resulted from bedload transport in fluvial channels. A 15 Ma tuff level intercalated in the Atacama Gravels near Potrerillos (Cornejo et al., 1993; Fig. 6A(b)) shows that fluvial deposition began prior to 15 Ma. In the Carrizo valley, also in the Precordillera, 50 km north of the considered region, K–Ar ages of 18–17 Ma have been obtained in tuff levels intercalated at the base of the Atacama Gravels (Cornejo et al., 1993). From those ages, we propose an Early to Middle Miocene age for the fluvial basal deposits of the Atacama Gravels (Fig. 9A). After 15 Ma the infilling follows with the deposition of unconfined to semi-confined debris flow and sheet-floods. It indicates a change to a depositional context characterized by extended alluvial deposition rather than localized deposition from bedload transport in fluvial channels. The alluvial deposition represents the distal counterpart of valley-side retreat erosion, which is progressively more and more distal due to the continuous retreat of the valley flanks. Valley-side retreat erosion finishes with the formation of pediment surfaces (Fig. 9B, C). The end of the alluvial fan deposition and pedimentation in the Precordillera is constrained by the ~10 Ma San Andres Ignimbrite emplacements.

Progressive infilling of the Central Depression can be described considering both the lower gray unit of the Atacama Gravels exposed in the El Salado canyon flanks and the Cerro Torrent deposits (Fig. 9A). The lower gray unit is the oldest Neogene sedimentary unit outcropping in the Central Depression. It is a laterally

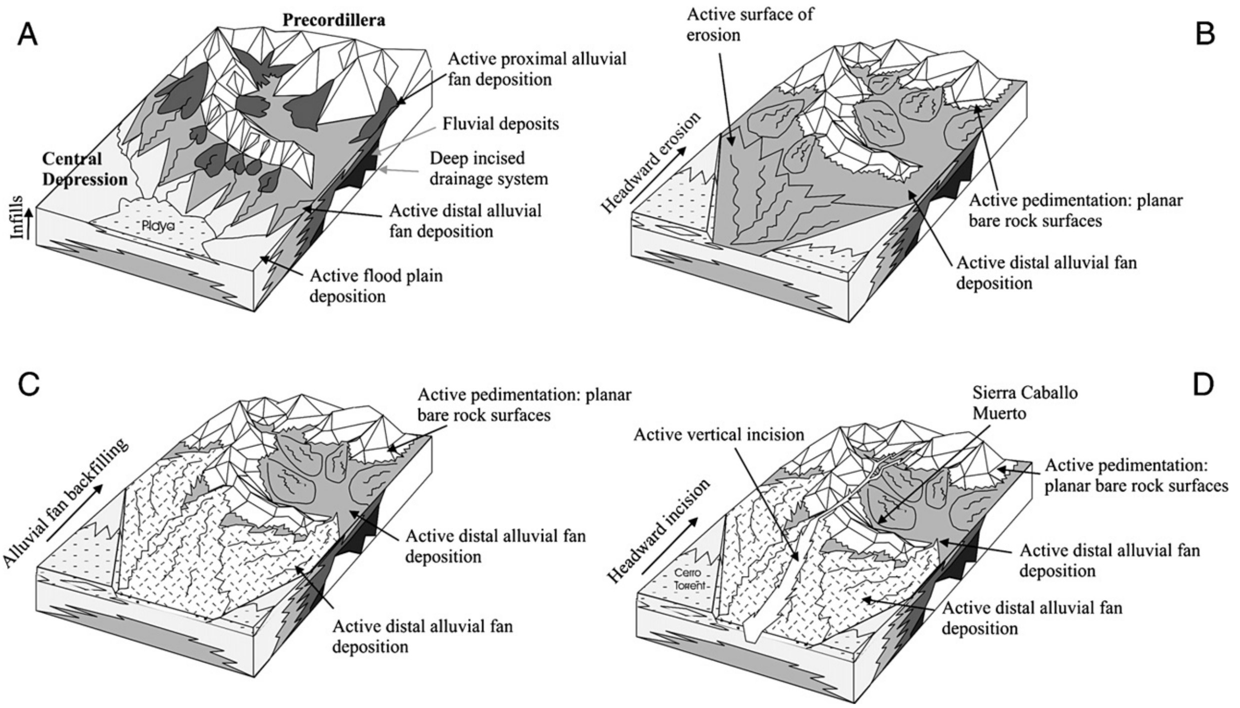

Fig. 9. Block diagrams that represent a NE-view (see Fig. 3) of the Central Depression and the Precordillera, for different stages of the Neogene landscape evolution of El Salado area. (A) Early–Middle Miocene infill of the Oligocene deep incised drainage systems: up to 400 m in the Precordillera and Central Depression. (B) Middle Miocene erosion in the Central Depression (up to 200 m), and valley-side retreat related to pediment development in the Precordillera. (C) Middle–Upper Miocene alluvial deposition in the Central Depression (up to 50 m), and valley-side retreat related to pedimentation processes in the Precordillera. (D) Upper Miocene vertical incision resulting from headward incision which progressively cut upstream the surface of the Central Depression and captured the Precordillera drainage systems. The present-day El Salado canyon reaches up to 100 m of vertical incision in the Central Depression and up to 800 m in the Precordillera.

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continuous record showing alluvial fan deposition in the eastern side of the Central Depression that becomes more distal westward to playa and playa lake deposition. Cerro Torrent deposits indicate that playa and playa lake deposition subsequently extended to reach the eastern side of the Central Depression. The infilling here reaches a thickness of 300 m considering the difference of altitude between the top of the Cerro Torrent deposits and the base of the Atacama Gravels in the El Salado canyon flanks. However, a maximum thickness of 600 m can be proposed if the difference of altitude between the top of the Cerro Torrent and the maximum thickness for the gravel infills reported from gravity data modelling is considered (Gabalda et al., 2005).

In contrast with what is seen in the Precordillera, an important episode of erosion affected the Central Depression (Fig. 9B). This episode resulted in the erosion of the upper parts of the Neogene deposits, and the formation of an unconformity separating the lower gray unit from the upper brown-reddish unit of the Atacama Gravels in the El Salado canyon flanks. The erosion is also shown by the unconformity affecting the Cerro Torrent deposits exposed in the Doña Ines Chica valley, where at least 200 m of Miocene sediment have been eroded. Following erosion, an episode of eastward alluvial fan backfilling affected the landscape surface of the Central Depression (Fig. 9C). This is evidenced by the upper brown-reddish unit and resulted in the formation of the large alluvial fans that cover the surface. Alluvial fan backfilling began before the deposition of the San Andres Ignimbrite and continued after the deposition of this tuff level.

Subsequently, geomorphologic conditions changed and induced the deep incision of the present-day El Salado canyon (Fig. 9D). An estimation of the age of incision can be made using the San Andres Ignimbrite. South of the El Salado area, in the San Andrés river valley (Fig. 2), this ignimbrite overlies a slightly dissected surface that affects the upper unit of Atacama Gravels (Mortimer, 1973; Riquelme, 2003). This indicates that vertical incision already affected the Precordillera region at ~10 Ma. In the Central Depression of El Salado area, incision started after this time because the surface of the alluvial fans dissected by the El Salado canyon is younger. The same observation is also valid for the Precordillera of the El Salado valley where the San Andres Ignimbrite seals the Atacama Pediplain before the onset of vertical incision. The San Andres valley is a tributary of the Copiapó valley, a drainage system that presently has a water discharge largely greater than the El Salado valley, and consequently a greater capacity for reaction to any change in the geomorphologic conditions. This perhaps accounts for why vertical incision started later in the El Salado than in the San Andres valley.

6. Discussion

A Late Paleogene(?) age has been proposed for the early deep incision discussed above (Mortimer, 1973). We further propose that this incision developed during the Oligocene. Afterwards, the Atacama Gravels (Sillitoe et al., 1968) infill the deeply-incised Oligocene landscape. To explain this deposition, two different processes have been invoked: (1) pedimentation process related to widespread valley-side retreat (Sillitoe et al., 1968; Mortimer, 1973); and (2) vertical aggradation (infill) of the drainage systems (Paskoff and Naranjo, 1979; Naranjo and Paskoff, 1980). As a consequence, two interpretations for the origin of the Atacama Pediplain have been suggested: the first regards the pediplain as the final result of widespread valley-side retreat; the second interpretation attributes pediment formation to erosion that cuts both the basement and the previously deposited Atacama Gravels.

Despite the interpretation considered for deposition of the Atacama Gravels, they are seen as a single episode of aggradation of the landscape. Our observations indicate that during the timespan of deposition, three episodes of landscape evolution can be differentiated: (1) Early–Middle Miocene infilling of the deeply incised drainage system (sediments of up to 500 m thickness) in the Precordillera and (up to 600 m thick) in the Central Depression; (2) Middle Miocene erosion of the infills in the Central Depression (up to 200 m deep); followed by (3) Middle–Upper Miocene alluvial deposition (up to 50 m thick). Finally, we show that the Atacama Pediplain corresponds to a perched and fossilized Upper Miocene pediplain surface in the Precordillera. In contrast, the Atacama Pediplain in the Central Depression corresponds to an alluvial fan surface mainly configured in the Upper Miocene, although it remains active.

6.1. Tectonic and climatic controls on the geomorphological evolution of the studied area

6.1.1. Early–Middle Miocene infills

Changes in geomorphologic conditions must be invoked to explain the shift from deep incision in the Oligocene to infilling of the landscape in the Early–Middle Miocene. Three end-member factors could explain this change: (a) a base level rise, (b) climate aridification, (c) tectonic activity on the Atacama Fault System.

(a) A rise in the base level may result from global sea level rise or tectonic subsidence of the continent. However, global sea level changes were less than 250 m during the Neogene. Moreover, global eustatic curves (Hardenbol et al., 1997) indicate that the Early–Middle Miocene rather corresponds to a global fall of the sea level which should induce incision. On the other hand, Early–Middle Miocene corresponds to a period of Andean uplift (e.g. Allmendinger et al., 1997; Lamb et al., 1997; Gregory-Wodzicki, 2000) and no evidence of significant tectonic subsidence has been reported. Thus, the 500-m-thick Early–Middle Miocene infills cannot be related to tectonic subsidence inducing a rise of the base level.
(b) Aridification of the climate should diminish the capacity of drainage systems to evacuate sediment, and consequently favor valley infilling. In the Atacama Desert, arid climatic conditions established in the Middle Miocene (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996). Although this climatic change seems to have occurred slightly after the beginning of Atacama Gravel deposition, this phenomenon could have played an important role in the infilling of the landscape.
(c) Playa and playa lake deposits of the Central Depression can be followed to the west within the Coastal Cordillera to the Atacama Fault System (AFS), where their thickness reaches 300 m. This deposition has been explained by the activity of the AFS (Riquelme et al., 2003). The AFS accommodated the uplift of the western side of the Coastal Cordillera in the Neogene, and acted as a barrier for rivers coming from the west. Therefore, the infilling of the landscape east of the AFS is also partly controlled by the activity of this system of faults in the Early–Middle Miocene.

The control of the AFS on the Early–Middle Miocene sedimentation east of this system of faults has also been observed 200 km north of the study area, along the Paposo segment of the AFS. In this region, the uplift of the western side of the Coastal Cordillera accommodated by the AFS closed E–W-directed valleys resulting in Neogene playa-related deposition (Naranjo, 1987; Hervé, 1987). Clearly, Middle Miocene climate aridification favored deposition east of the AFS. However, basal levels of the Atacama Gravels in the Precordillera indicate hydrologic conditions of relatively abundant water discharge. In contrast, later alluvial fan deposition, valley-side retreat and formation of pediment surfaces indicate a relatively arid depositional context. Aridification also favors the extensive development of playa and playa lake deposition recorded in the upper parts of the infills in the Central Depression. Playa and playa lake sedimentological assemblages have also been reported north of the studied area, at the Antofagasta latitude (Fig. 1), and have been attributed to Neogene large-scale salars and evaporitic deposits (Chong et al., 1999). Then, the western Coastal Cordillera uplift being accommodated by the AFS is partly responsible for the landscape infilling to the east. However, this relatively modest uplift would not have generated an endorheic landscape to the east if the climatic conditions had not been so arid.

6.1.2. Middle Miocene erosion in the central depression

An unconformity separates the Upper Miocene alluvial fan deposits from the Early–Middle Miocene playa deposits. This unconformity is not present in the Precordillera, indicating that erosion only affected the Central Depression. To allow this erosion, the Central Depression must have been opened again to the ocean. An increase of the stream power resulting from a wetter climate cannot by itself explain the re-opening of the Central Depression to the ocean, because climatic conditions remained arid to hyperarid in the Atacama Desert from the Middle Miocene (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996; Hartley and Chong, 2002; Dunai et al., 2005, Nishiizumi et al., 2005). In fact, three possible scenarios can explain the end of the endorheic regime.

(1) Headward erosion in valleys flowing to the ocean in the western Coastal Cordillera could have captured the drainage systems of the Central Depression, permitting its erosion. Such headward erosion, however, should have occurred in all the valleys of that part of the Coastal Cordillera. West of the AFS, the Coastal Cordillera mainly corresponds to a landscape surface formed before the playa and playa lake deposition in the El Salado valley, and its relative uplift has been accommodated by tectonic activity on the AFS (Riquelme et al., 2003). Later incision of the landscape, resulting from headward erosion, is restricted to the westermost part of the drainage system, close to the coast. No evidence of headward erosion affecting the entire Coastal Cordillera is observed, nor can it be postulated in the drainage system elsewhere than the El Salado

Valley. The western part of the Coastal Cordillera represents a fossil landscape surface that did not adjust to the relative sea level changes. Thus, the re-opening of the Central Depression to the ocean cannot have resulted from headward erosion induced by relative changes of the ocean level. It is more likely related to factors controlling the landscape evolution within the Central Depression.

(2) The re-opening of the Central Depression could result from the end of the relative uplift of the western part of the Coastal Cordillera accommodated by the AFS. Sediment coming from the Precordillera would have infilled the Central Depression and the eastern part of the Coastal Cordillera of the El Salado valley, surpassing the AFS to the west and connecting the drainage system to the Pacific Ocean.

(3) A third scenario to explain re-opening to the ocean is an increase in slope because of tectonic activity. This increase induces a local rise in transport capacity of drainage system which, in turn, induces the erosion. The deposition of a rounded boulder layer at the top of Cerro Torrent deposits could be related to the onset of such increase in the transport capacity. We envisage an increase of the E–W slope as the most feasible scenario to explain this erosion.

6.1.3. Alluvial deposition in the Central Depression

The Middle–Upper Miocene landscape evolution of the Central Depression is characterized by alluvial fan deposition. The vertical cross-section of these deposits along the El Salado canyon flanks shows wedge shape geometry (Fig. 6A(c–f)). In addition, deposition corresponds to an event of eastward alluvial fan backfilling. Many factors influence the behaviour and final shape of alluvial fan deposition at the front of mountain ranges, like base level changes, climate, hydraulic conditions (water discharge or sediment yield), and tectonic movements (Miall, 1996; Blum and Törnqvist, 2000).

A rise of the Central Depression base level cannot explain by itself the onset of deposition. Such a rise could result from a relative ocean level elevation or from a relative uplift of the western part of the Coastal Cordillera accommodated by the AFS. In fact, ocean level elevation should have induced an important aggradation in the drainage systems of the Coastal Cordillera west of the AFS. In contrast, gravel deposits in the El Salado valley, west of the AFS, which can be correlated with the alluvial fan deposits of the Central Depression, are thinner than 10 m. These deposits indicate that the Central Depression was no longer endorheic. In fact, the decreasing thickness of gravel deposits toward the west shows that neither tectonic activity on the AFS nor sea level rise triggered this depositional event.

Changes in alluvial fan deposition also depend on changes in water discharges (Miall, 1996; Blum and Törnqvist, 2000), and the passage from arid to hyperarid conditions, as discussed before, may explain such deposition. The preservation of 9 Ma alluvial surfaces in the Precordillera (Nishiizumi et al., 2005) evidence long-term constantly low discharge conditions. Many works, including numerical and analogue approaches and field studies, consider the alluvial fan evolution under low discharge conditions (Paola et al., 1992, 1999; Bull, 1977; Harvey, 1989; Blum and Törnqvist, 2000; Milana and Tietze, 2002). They show that low discharge fans are characterized by important sediment accumulations near basin borders, while reworking processes along channels without important sediment input prevail at mid- and distal basin locations. In addition, models suggest that during low discharge periods deposition moves upstream in the form of alluvial fan backfilling (Milana and Tietze, 2002). In contrast, high discharge periods enhance proximal erosion and fast accumulation at mid- and distal basin positions (Milana and Tietze, 2002).

Therefore, we propose the alluvial fan deposition episode to be the consequence of an aridification, from arid to hyperarid climate, of that part of the forearc. As a matter of fact, it can result neither from the uplift of the western Coastal Cordillera, because sediments would have accumulated preferentially near the AFS, nor from important uplift rates of the Precordillera, as it would have resulted in the formation of steep alluvial fans exposing headward-eroding gullies and proximal depocenters (Burbank and Anderson, 2001; Viseras et al., 2003).

6.1.4. Vertical incision

The Middle–Upper Miocene alluvial fan deposition contrasts markedly with the Upper Miocene vertical incision shown in the present-day El Salado valley. Vertical incision reaches up to 800 m in the Precordillera, cutting through Early–Middle Miocene infills or even through the pre-Neogene substratum. It also affects the entire Central Depression, although incision is smaller there (>50 m). Simple depositional-erosional alluvial dynamics, for instance autocyclic entrenchment related to fan lobe shifting, cannot explain such vertical incision (e.g. Schumm et al., 1987), and additional external factors need to be invoked to explain it.

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Changes in the water discharge conditions or in the base level could be considered. Continental uplift with respect to sea level does not explain the amplitude of incision in the Precordillera, because this incision is observed in all the major valleys of the Southern Atacama Desert, even when they do not dissect the Central Depression to the west (see for instance the Doña Ines Chica Valley in Fig. 2). Only a relative increment of the slope of the Central Depression can explain that incision, because the Atacama Pediplain does not show any large fault that would have cut that part of the forearc following Atacama Gravel deposition.

An important episode of Central Andes uplift occurred during the Upper Miocene (e.g. Gregory-Wodzicki, 2000). In the Southern Atacama Desert, only minor Neogene fault activity has been observed. This tectonic activity can be seen as a forearc response to the Upper Miocene Andean uplift (Audin et al., 2003; Soto et al., 2005). However, vertical throws accommodated by these faults (always smaller than 30 m) cannot account for the huge vertical uplift. Another mechanism must have accommodated uplift of the Western Cordillera with respect to the Pacific Ocean. We propose that this was accommodated in the Southern Atacama Desert by a generalized west-tilting or flexuring of the inner forearc region (Central Depression and Precordillera). Tilting increased the regional slope which, in turn, induced the drainage system to restore a new equilibrium profile. Such a mechanism could explain the strong vertical incision shown by the present-day valley from the Central Depression to the east.

A tilting or flexuring of the Chilean forearc has been widely invoked to explain how the forearc region accommodated the Neogene Andean uplift and to explain the vertical incision initiating in the Upper Miocene in the Precordillera of northern Chile (Isacks, 1988; Lamb et al., 1997; García et al., 1999, 2002; Farías et al., 2005). At the Iquique latitude, a generalized 3° tilting of the entire forearc has been proposed by Lamb et al. (1997). Considering the Atacama Pediplain surface in the El Salado region (~26°30′ South Latitude) and the present-day slope of the Oligocene paleovalleys filled by the Atacama Gravels (1.3°) (Fig. 5A), a 3° tilting would imply pediment slopes and rivers flowing to the east before tilting. Therefore, although a tilting of the forearc can be proposed for the inner forearc, it remained smaller than 1.3° in this part of the Atacama Desert.

7. Conclusions

The Precordillera of the Southern Atacama Desert, before deposition of the Atacama Gravels, was deeply incised and already had a relief higher than 2000 m. A large part of the present-day ~3500 m Precordillera altitude can be related to the Eocene–Early Oligocene tectonic activity on the DFS. No major fault activity occurred in the DFS after that time; however, it still controlled the large-scale topography, showing that some characteristics of the present-day regional geomorphology are inherited from the Eocene–Early Oligocene tectonics. In the Oligocene the inner-forearc region (Precordillera and Central Depression) was connected to the Pacific Ocean by a deeply incised drainage system. This network became infilled in the Early–Middle Miocene. Sedimentological data indicate a progressive aridification of the climate during this period, at least in the lower part of the Andes (from Precordillera to the west), which could explain part of the infilling of the previous drainage network. The western Coastal Cordillera uplift accommodated by the AFS in the Neogene is partly responsible for the infilling of the landscape to the east, however this relatively modest uplift would not have generated an endorheic landscape to the east if the climatic conditions had not been so arid. Later landscape evolution was, in part, controlled by Andean uplift, which is accommodated by a flexuring or tilting of the inner forearc region that began in the Middle Miocene and induced the erosion of the Central Depression. Aridification, from an arid to hyperarid climate, and a relatively lower tilting rate were adjusted to in the Middle–Upper Miocene by alluvial fan backfilling in the Central Depression. An increment of the tilting rate in the Upper Miocene induced the vertical incision responsible for the present-day canyons that cross the inner-forearc region. To conclude, we propose that slow tectonic movements, such as a gentle forearc tilting accommodating the relative uplift the Precordillera constrained the morphologic evolution of the Southern Atacama Desert. This tilting cannot be detected by tectonic studies, although it accommodated several hundreds of meters of relative uplift.

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