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A geomorphological approach to determining the Neogene to Recent tectonic deformation in the Coastal Cordillera of northern Chile (Atacama)

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Abstract

The large (≈ 10000 km^2) and local-scale (< 400 km^2) geomorphologic, geomorphometric and field evidence indicates that, from the mid-Miocene onwards, the Atacama Fault System (AFS) accommodated the relative uplift of the western side of the Chilean Coastal Cordillera of the Chañaral region (southern Atacama Desert). The mean regional altitude systematically decreases eastwards crossing the AFS, independent of the lithological characteristics of the substratum cut by this system of faults. Topographic analysis reveals a more incised landscape west of the AFS that, at the local scale, is reported by the distribution of the altitudes (hypsometric curves and integrals) of tributary basins and by the presence of terraces. In the Middle and Upper Miocene, a thick (>300 m) sedimentary succession was deposited east of the AFS. The succession fills previously deep paleovalleys. And it consists of gravel, so-called ‘‘Atacama Gravels’’, which passes laterally into fine-grained playa related deposits near the AFS. We interpret the deposition of this succession as a result of a blocking closure of the valley flowing from the Precordillera due to the activity on AFS. A pedimentation episode followed sediment deposition and is locally strongly re-incised by the main modern-day river valleys draining the Precordillera. Incision may result from either regional uplift of the forearc, and/or from more localized activity on the AFS. Furthermore, Recent (Quaternary?) tectonic activity on the AFS has been observed which is consistent with a localized relative uplift of the crustal block west of the AFS.

Keywords: Fluvial erosion; Neotectonics; Quantitative geomorphology; Andes; Chile

1. Introduction

The Andean forearc in the Atacama Desert (North of Chile) is divided into four main longitudinal morphological units, which are from west to east: The Coastal Cordillera, the Central Depression, the

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Precordillera, and the Western Andean Cordillera along which the present volcanic arc is developed (Fig. 1). The main tectonic feature of the Coastal Cordillera is the Atacama Fault System (AFS), a discontinuous and overlapping set of faults striking sub-parallel to the continental margin that can be followed for more than 1000 km from Iquique (20°30′ S) to La Serena (29°45′ S) (Fig. 1). Changes in orientation of this fault system allow the definition of three accurate segments (Naranjo, 1987; Thiele and Pincheira, 1987), that are, from south to north: the El Salado, the Paposo and the Salar del Carmen segments (Fig. 1).

The origin and evolution of the AFS during the Mesozoic is well established (Scheuber and Andriessen, 1990; Scheuber and Reutter, 1992; Scheuber et

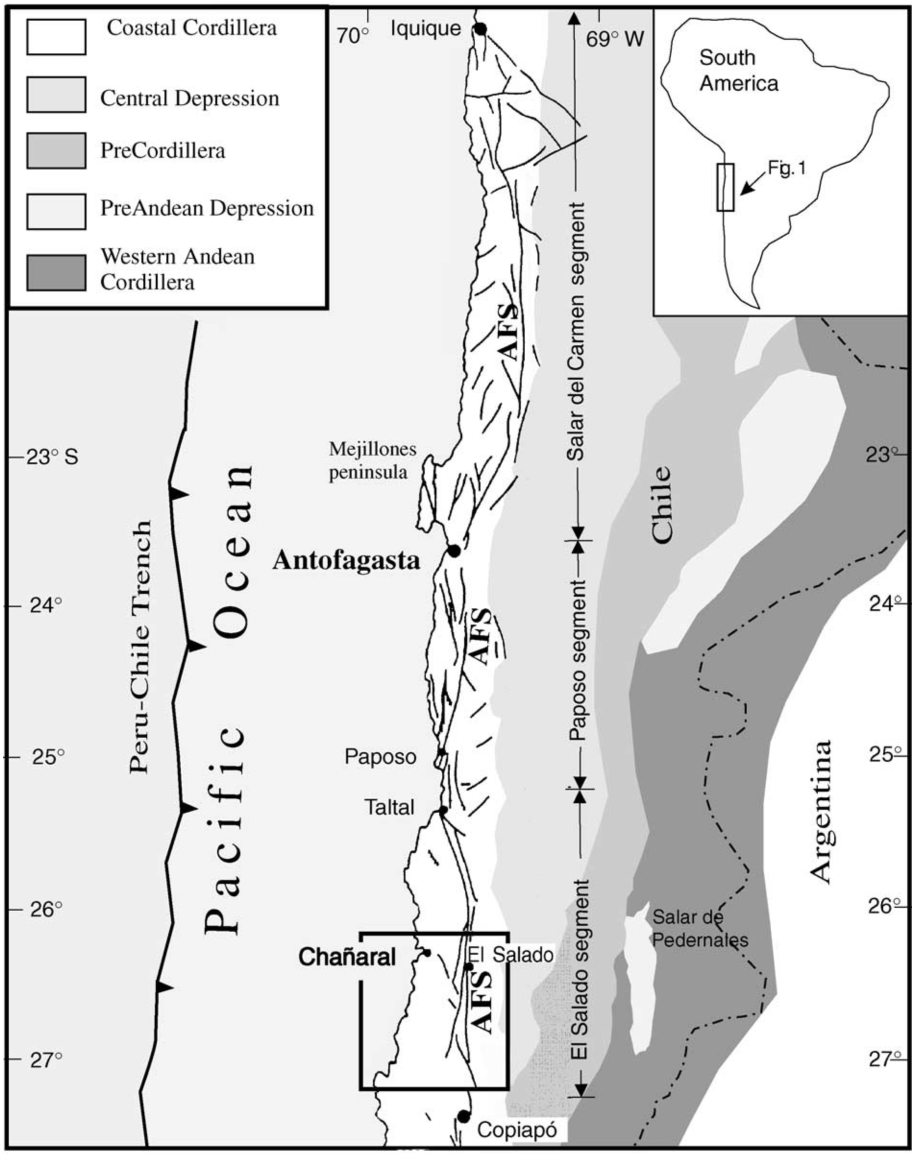


Fig. 1. Overview map of the Atacama Desert region showing the principal physiographic units of the forearc of northern Chile. The box shows the location of the study area. AFS: Atacama Fault System.

al., 1995; Brown et al., 1993; Grocott et al., 1994; Dallmeyer et al., 1996), but the nature of Cenozoic activity is still debated. North of Taltal, the Late Cenozoic activity has resulted in spectacular geomorphological features (Arabasz, 1971; Okada, 1971; Mortimer, 1980; Naranjo, 1987; Hervé, 1987; Armijo and Thiele, 1990; Delouis et al., 1998). Most of these authors suggest a predominantly normal-vertical movement, responsible for the uplift of the western side of the AFS. In the southern Atacama Desert, in the El Salado segment (26°–28°S), no evidence of Neogene activity has been reported. The AFS in this segment comprises faults and lineaments that have a clear expression on Landsat images. These faults and lineaments cut the Mesozoic substratum but, in the field, it is not possible to observe important fault escarpments or tectonic displacements where Neogene and Quaternary rocks outcrop along the fault trace.

Extremely arid Neogene climatic conditions in the Atacama Desert are responsible for well-preserved and well-exposed topographic forms that reflect the geomorphologic evolution of the area. In this paper, we analyze the impact of tectonic activity along the AFS in the Neogene geomorphologic evolution of Coastal Cordillera from the area of the El Salado segment (26°–28°S). This analysis considers both qualitative and quantitative approaches to the relief development for the whole Coastal Cordillera. We study also the principal drainage and watershed systems that cross this Cordillera. These analyses are complemented by specific geomorphologic observations from key areas. Finally, we study the Neogene deposits exposed in the area and we discuss the relationship between regional tectonic activity and geomorphologic evolution.

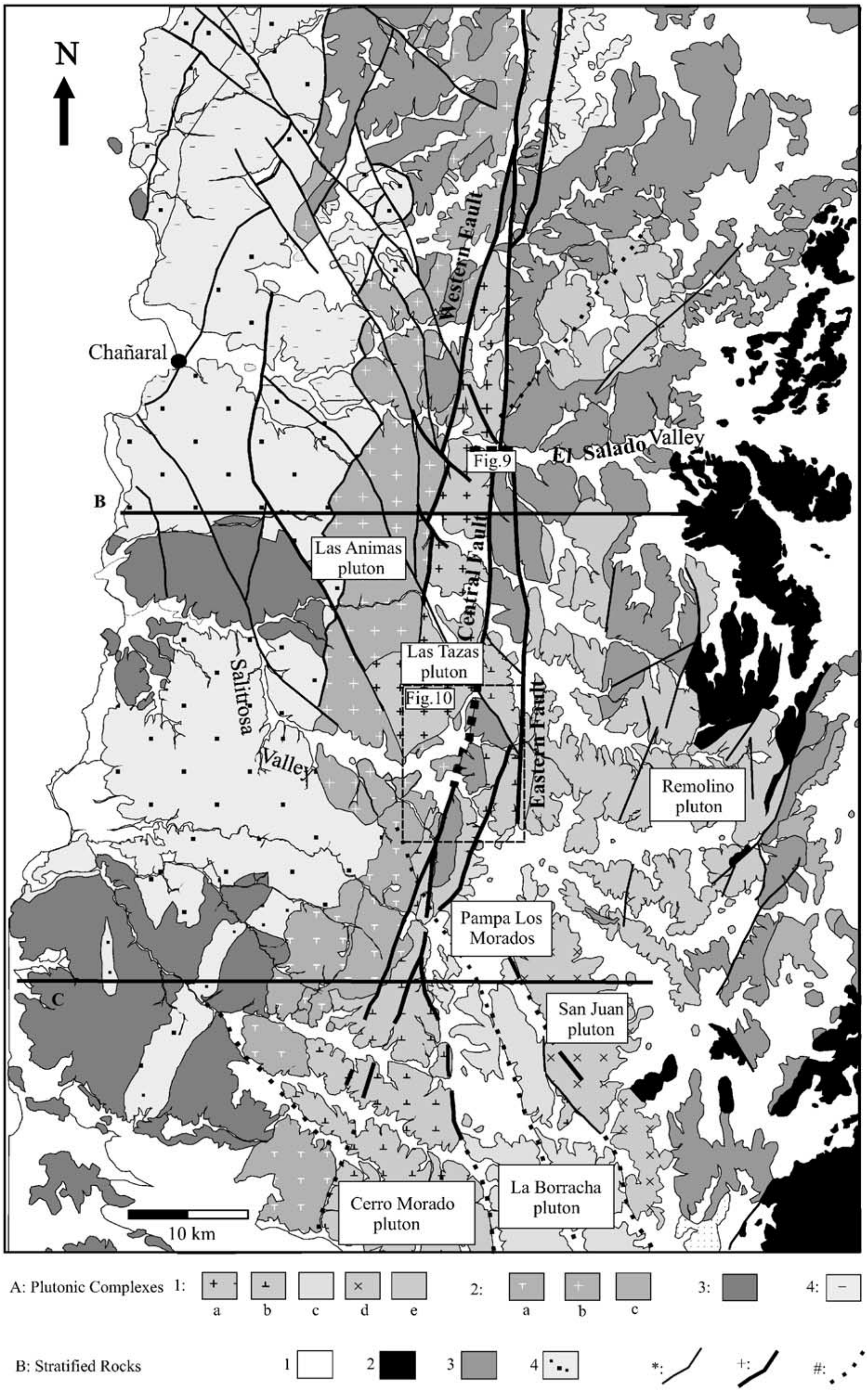
2. Geological background

2.1. Mesozoic evolution of the costal cordillera

Subduction at the active continental margin has played a major role in the structural and magmatic evolution of the Central Andes since the beginning of the Jurassic (Coira et al., 1982). The Andean Cycle is characterized by a systematic eastward migration through time of the magmatic arc towards the interior of the continent (Reutter and Scheuber, 1988). The Coastal Cordillera, located today in a forearc position is the realm of the Jurassic–early Cretaceous magmatic arc. This magmatic arc reveals a complex multiphase evolution. Fault systems, magmatic, volcanic and basin development are arc-parallel and show an episodic decrease in age from west to east (Brown et al., 1993; Grocott et al., 1994; Dallmeyer et al., 1996; Taylor et al., 1998). The dominant structure during the Jurassic–early Cretaceous evolution of the magmatic arc was the AFS, located in the center of the present-day Coastal Cordillera (e.g. Taylor et al., 1998).

Within the study area (Fig. 2), the Jurassic–early Cretaceous magmatic arc includes several north–south trending and elongated plutons, which are parallel to the AFS branches. Higher structural levels of the arc are represented by an extensive andesitic volcanic sequence exposed in most of the studied area (La Negra Formation, García, 1967), and by volcanic–volcanoclastic sequences and intercalated marine sedimentary rocks exposed in the eastern part of the studied area. The latter have been attributed to an Upper Jurassic–Early Cretaceous back-arc basin fill succession and are included in the Punta del Cobre Group (Lara and Godoy, 1998). The lithologies of the Jurassic–early Cretaceous plutons include gabbros, diorites, tonalites/granodiorites, and minor granites (Dallmeyer et al., 1996; Lara and Godoy, 1998; Godoy and Lara, 1998). The textural characteristics of the plutons reflect relatively shallow levels of emplacement and associated rapid post-magmatic cooling (Dallmeyer et al., 1996). Detailed studies carried out on the mylonitic borders of these plutons show that they were emplaced during the movement of the AFS (Brown et al., 1993; Grocott et al., 1994; Dallmeyer et al., 1996; Taylor et al., 1998).

The basement to the Jurassic–early Cretaceous magmatic arc is a penetratively deformed late Paleozoic–Triassic metasedimentary sequence, dominated by turbiditic facies (Bell, 1987), exposed along the western margin of the Coastal Cordillera. This basement is intruded by Triassic plutonic complexes mainly comprising monzogranite to syenogranite, which outcrop immediately north of Chañaral (Godoy and Lara, 1998). The contact between the basement and the Jurassic–early Cretaceous plutonic complexes has been described as a ramp-flat extensional fault system. This fault system corresponds to the oldest


N
Chañaral
Western Fault
Central Fault
Eastern Fault
El Salado Valley
Fig.9
Fig.10
B
C
Las Animas pluton
Las Tazas pluton
Salitrosa Valley
Remolino pluton
Pampa Los Morados
San Juan pluton
Cerro Morado pluton
La Borracha pluton
10 km
A: Plutonic Complexes 1: a b c d e 2: a b c 3: 4:
B: Stratified Rocks 1 2 3 4 *: +: #:

record of a wide, flower-like, extensional structure developed in the Coastal Cordillera, and where the AFS probably acted as the locus for magma ascent during much of the Jurassic to earliest Cretaceous (Grocott et al., 1994). This extensional fault system has been related to a retreating subduction boundary (Taylor et al., 1998). Plutonic complexes that were emplaced in this period correspond to the Early Jurassic Flamenco pluton exposed at the river mouth of the Salitrosa river valley (Grocott et al., 1994) and the Middle–Upper Jurassic Las Animas pluton, exposed immediately west of El Salado (Brown et al., 1993).

During the Early Cretaceous, although the kinematics of the extensional system changed to left-lateral transtension, the AFS continued to be the principal fault system along which plutons were emplaced (Taylor et al., 1998). Ductile kinematic indicators show that the Las Tazas pluton, exposed in the El Salado area, was emplaced at the time of this change from extension to left-lateral transtension (Wilson, 1996). This left-lateral transtension has been interpreted as a consequence of the oblique subduction of the oceanic plate (Scheuber and Andriessen, 1990). Following this initial phase of ductile, left-lateral transtension, a period of brittle, left-lateral strike-slip is recorded along the AFS, indicating that the magmatic arc had abandoned the Coastal Cordillera region (Scheuber and Andriessen, 1990; Brown et al., 1993; Taylor et al., 1998). The brittle, left-lateral, strike-slip movements have been detected in the eastern branch of the AFS (Fig. 2) where they overprint ductile, left-lateral, kinematic indicators from the Remolino pluton (Hervé, 1987; Colley et al., 1990). Furthermore, the geometry of the three north–south trending and overlapping principal branches of the AFS exposed south of El Salado has been related to represent the development of left-lateral sidewall rip-outs (Swanson, 1989) or a left-lateral strike-slip duplex (Woodcock and Underhill, 1986). In the Middle–Late Cretaceous, the magmatic activity was established in the Central Valley Zone, on a new fault system located east of the study area, along the present-day Central Depression (Scheuber and Reutter, 1992). In the Coastal Cordillera in the northwest part of studied area, a set of NW–SE trending brittle faults appears to be linked to Middle–Late Cretaceous activity in the Central Valley Zone, the Coastal Cordillera being deformed as a large strike-slip duplex (Taylor et al., 1998).

2.2. Previous evidence for Neogene to Recent activity on the AFS

Activity on the AFS during the Neogene to Recent is remarkably well preserved between Taltal, Antofagasta and Mejillones latitudes (23° to 24°S, see Fig. 1), to the north of our study area. In these areas, Arabasz (1971) and Okada (1971) first stated that slip on the AFS must have been predominantly vertical during late Cenozoic times. Faulting along the Paposo segment produced uplift on the western side of the fault and closure of west-flowing river valleys (Arabasz, 1971; Okada, 1971; Mortimer, 1980; Hervé, 1987; Naranjo, 1987). This extensional activity began in the Lower Miocene and probably ended near Paposo in the Upper Miocene, with no evidence of post-Miocene activity (Naranjo, 1987; Hervé, 1987). However, young normal faulting in marine terraces marking E–W extension has been recognized farther north in the Mejillones Peninsula (Armijo and Thiele, 1990; Delouis et al., 1996, 1998). Armijo and Thiele (1990) also described strike-slip drainage offsets and surface breaks east of the Mejillones Peninsula, along faults nearly parallel to the coastline, interpreting them as evidence for recent left-lateral movements along the AFS. Most authors, however, consider that the large-scale Neogene to Recent deformation in the

Fig. 2. Geological map of the Chañaral region showing the major faults and the distribution of the main lithological units, compiled after the Servicio Nacional de Geología y Minería maps, Brown et al. (1993), Grocott et al. (1994), Dallmeyer et al. (1996) and Taylor et al. (1998). (A) Plutonic Complexes, (1) Early Cretaceous Plutons; (a) Las Tazas Pluton, (b) Cerro Morado Pluton, (c) La Borracha Pluton, (d) San Juan Pluton, (e) Remolino Pluton; (2) Upper Jurassic Plutons, (a) Cerro Moradito Pluton, (b) Las Animas Pluton, (c) Undifferentiated Upper Jurassic plutonic complexes; (3) Undifferentiated Lower Jurassic plutonic complexes; (4) Undifferentiated Upper Triassic plutonic complexes. (B) Stratified Rocks, (1) Neogene to Recent sedimentary deposits, (2) Lower Cretaceous volcanic and calcareous rocks, (3) Jurassic volcanic rocks (La Negra Fm.), (4) Upper Paleozoic–Triassic sedimentary and metasedimentary rocks. *: Principal Faults, +: Principal AFS branches, #: Landsat and DEM lineaments.

outer forearc of Mejillones is characterized by vertical uplift resulting from the activity of east-dipping normal faults (Delouis et al., 1996; Niemeyer et al., 1996). Moderate strike-slip offsets in the AFS vary coherently with the fault azimuths and are compatible with E–W extension (Delouis et al., 1998). Delouis et al. (1998) and Harltey et al. (2000) also suggest that active tectonic erosion and underplating along the Andean margin is responsible for a broad-scale flexure, resulting in the observed extensional features. Most authors (Delouis et al., 1998) noted that evidence for Recent activity in the AFS diminishes toward the south. At the latitude of Chañaral (26°–27°S, Fig. 1), evidences for Neogene to Recent activity has not been yet recognized.

In this study, we looked for evidences of Neogene to Recent activity on the AFS in the Coastal Cordillera of the Chañaral area. We used a Digital Elevation Model (DEM) to carry out a geomorphologic study which integrates the analysis of the large-scale landscape features analysis, as well as analysis of the principal morphometric characteristic of the topographic forms. The DEM has been generated by interpolation of digitized contour lines of 1:50.000 topographic Chilean maps, resulting in a 35-m horizontal DEM ground resolution. The morphometric analysis has been done in order to point out variations in the landscape characteristics between both sides of the AFS. This analysis was based on the drainage and basin watershed structure. Both, watershed basins and watershed drainage networks have been extracted from the DEM using the D8 algorithm described in O'Callaghan and Mark (1984). Strahler's (1952) hierarchization has been carried out in order to establish the watershed organization. This organization is necessary in order to be able to compare the morphometric parameters. In addition, we studied in the field and using aerial photographs (at scale 1:60.000) the Neogene sedimentary deposits and their relationship to the geomorphological landscape characteristics, as well as their relationship to the principal faults exposed in the studied area. The morphological and morphometric data presented here, combined with field data, permit us to characterize the Neogene to Recent morphological and tectonic evolution of a region were this tectonic activity has been weak and is difficult to recognize.

3. Geomorphological evidence of topographic effects of tectonic activity on the AFS

3.1. Large-scale geomorphology

The Coastal Cordillera of Chañaral is a north–south oriented mountain range, about 60 km wide, with a mean altitude of 1100 m above sea level and maximum altitudes of around 2000 m above sea level recorded in the southeastern part of our study area. The Coastal Cordillera is separated from the Pacific Ocean by an irregular and inactive Coastal scarp. There is an abrupt increase in the mean altitude, passing from 0 to 500 or 700 m above sea level in less than 5 km. The foot of the scarp is a narrow littoral zone generally less than 1 km wide. The eastern limit of the Coastal Cordillera is transitional and comprises a series of northeast-oriented ranges that penetrate into the Central Depression.

The main structural feature of Coastal Cordillera in the Chañaral region is the AFS (Fig. 3). Here, the AFS is composed of three north–south trending and overlapping branches, located along the axis of Coastal Cordillera, that define two large-scale northward trending lenses (Fig. 3B). In the El Salado area, these branches have been named, the Western, Central and Eastern faults (Lara and Godoy, 1998; Godoy and Lara, 1998). A gradual north–south to northwest change in the orientation of the Central and Eastern faults, south of the Salitrosa watershed basin, can be inferred from the lineaments interpreted from the DEM (Fig. 3B).

The AFS does not only represent the main structural feature of the Coastal Cordillera. It also corresponds to a N–S-oriented geomorphologic disruption in the large-scale topography. Fig. 4 shows the E–W variation of the mean altitude, calculated for 10-km-wide strips. The strips are located along the El Salado river valley, 20 km south of the El Salado valley, and 60 km south of the El Salado valley (Fig. 4A,B,C, respectively). In all the profiles, branches of the AFS are marked by an abrupt decrease in the mean altitude to the east of the faults. These decreases cannot be attributed to contacts between lithologic units, because they are always observed whatever the lithology of rocks exposed on both side of the fault. In the northern and central profiles (Fig. 4A and B), the mean altitude diminishes to 200 m east of the Western

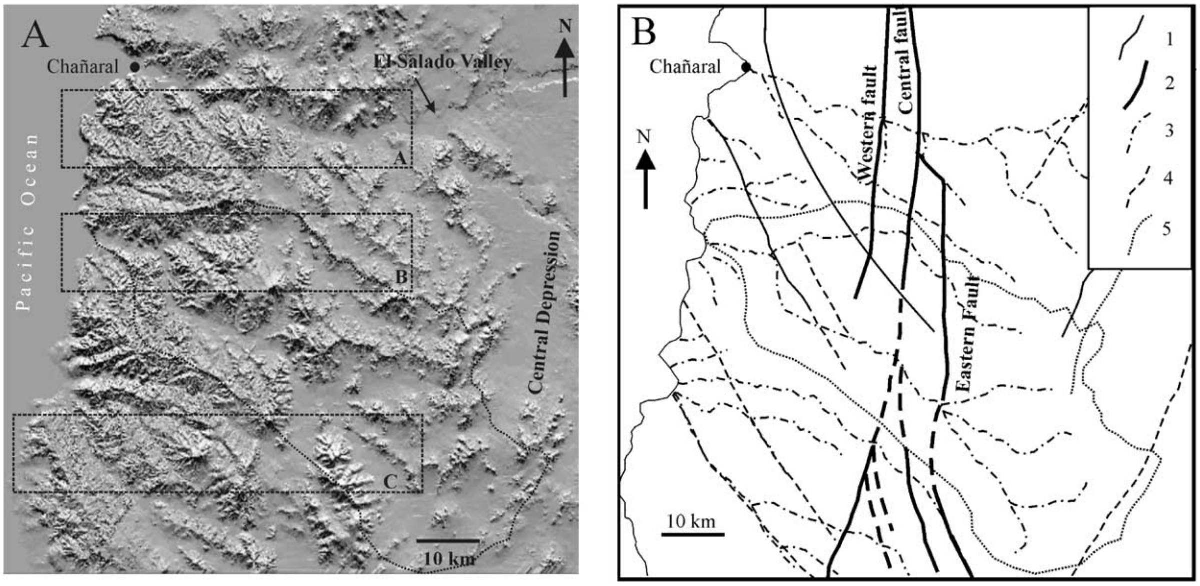


Fig. 3. (A) Digital Elevation Model (DEM) of the Coastal Cordillera in the Chañaral area. Boxes indicate the location of the profiles A, B, C in Fig. 4. (B) Principal structural features obtained from the geological maps, from the DEM and Landsat image interpretation. (1) Principal fault branches, (2) Principal AFS branches, (3) Principal drainage systems, (4) DEM and Landsat interpreted fault lineaments, (5) Salitrosa Watershed basin divide.

Fault of the AFS. This fault corresponds to the contact between the Las Animas pluton and the Las Tazas pluton (Figs. 2 and 4B). In contrast, in the southern profile (Fig. 4C), the decrease in the mean altitude occurs across the southern extension of the Central Fault and on a minor NNW–SSE subsidiary fault of the AFS. In this profile, the decrease is more than 400 m, and occurs across lithologic units that are different to those exposed along profiles A and B (Fig. 4). In profile C (Fig. 4), the Central Fault partly forms the contact between the Cerro Moradito and the Cerro Morado plutons, and the subsidiary fault forms the contact between the Cerro Morado and the La Borracha plutons (Figs. 2 and 4C).

We calculated the standard deviation of the altitude as a function of the longitude, for each of the 10-km-wide strips, in order to visualize variations in the regional degree of incision (Fig. 4). Coinciding with the decrease of the mean altitude, drops of the standard deviation of altitude are registered across the same faults. The standard deviation of the altitude is larger west of the westernmost fault in each profile (the Western Fault in profile 4b and the Central Fault in profile 4c), and diminishes abruptly to the east. In Fig. 4A, the standard deviation shows larger values east and west of the Western Fault, but it is null at the intersection with this fault. In fact, the reason why we observe large standard deviations in the eastern part of this strip is because it covers the El Salado river valley. This valley is deeply incised both in the Central Depression and in the Coastal Cordillera. In addition, it is the only valley in our study area that comes from the highest summits of the main Cordillera, and its stronger erosive potential has resulted in incision of not only the Coastal Cordillera (as have the other regional rivers), but also the Central Depression.

In conclusion, topographical data show that the AFS marks the only abrupt N–S disruption to the large-scale geomorphology of the Coastal Cordillera. This N–S disruption, which can be systematically visualized by the easterly decrease in the mean altitude, is independent of the lithologies present on either side of the branches of the AFS. South of the El Salado river valley (Fig. 4B and C), the N–S geomorphologic disruption can also be seen by analyzing the E–W variation in the standard deviation of the altitude. This value is higher west of the AFS

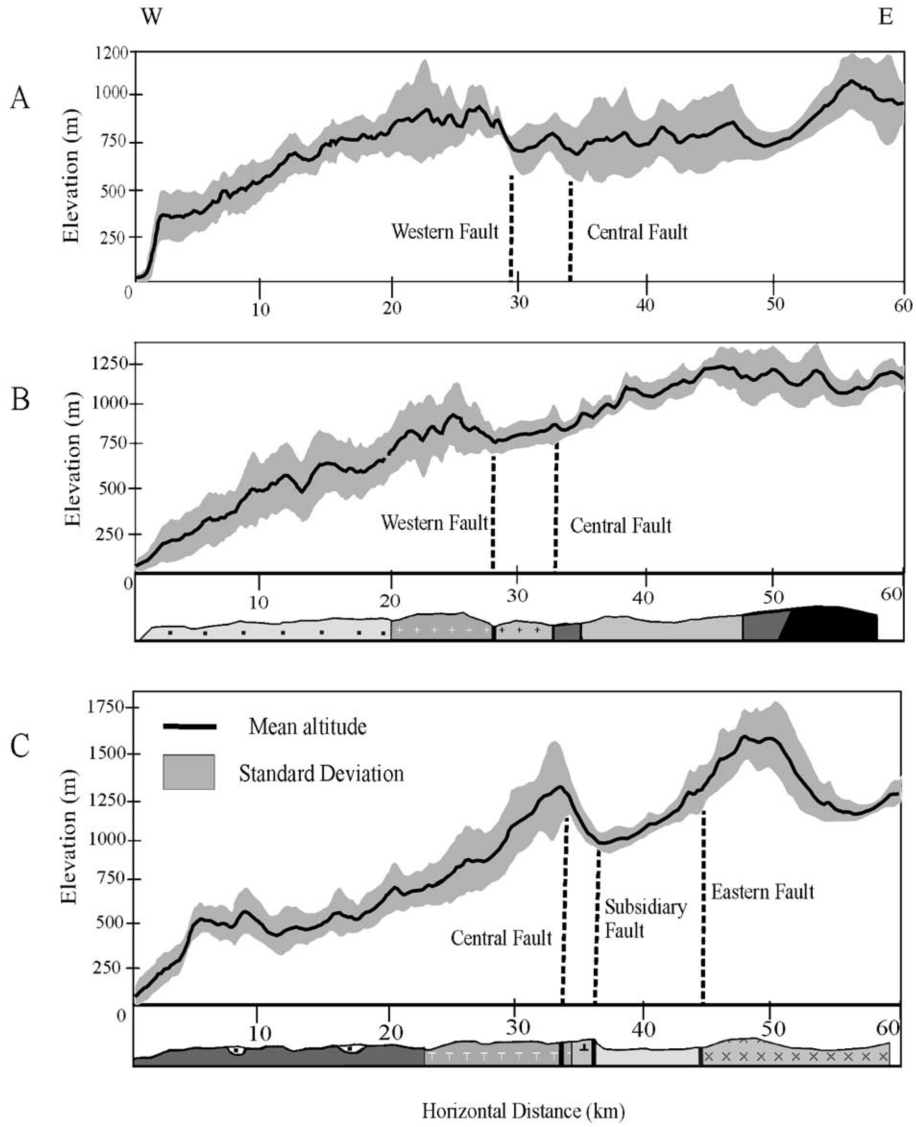


Fig. 4. Profiles showing the mean altitude and the standard deviation of altitudes for 10-km-wide E–W orientated strips. See Fig. 3 for the location of the strips, and Fig. 2 for the location and legend of the geological cross-sections.

where the valleys are deeply incised into basement, while east of the AFS, valleys form large plains (up to 3 km wide) filled by Neogene to Recent sediments (see below). Therefore, the difference in the standard deviation is the consequence of a more incised landscape west of the AFS. The decrease in mean altitude east of the AFS, and the difference in the degree of incision degree west and east of this fault system suggest that the AFS accommodated the relative uplift of the western part of the Coastal Cordillera in the Chañaral area.

3.2. Present-day longitudinal valley profiles (thalweg profiles)

River valleys provide the primary linkage between tectonic deformation and landscape response (Howard et al., 1994). In particular, anomalies in thalweg profiles can be used together with other evidences as indicators of recent tectonic deformation (Holbrook and Schumm, 1999). In the case of the Chañaral area, to study the effects of the recent tectonic activity of the AFS on thalweg profiles, two additional parameters should be taken into account: the effects of relative fluctuation of sea level and any lithological control related to the substratum.

Two main observations can be made on the thalweg profiles of the principal valleys that cross the AFS in the Chañaral region. The first one corresponds to changes in the slope of the longitudinal profiles of the valleys, which are exactly and systematically located at the intersection between the valleys and branches of the AFS (valleys 1, 3 and 4, Fig. 5). This suggests that recent activity on the AFS has controlled the changes in the slopes of the longitudinal valley profiles (valleys 1, 3 and 4 in Fig. 5). Change in the base level (ocean level) or lithologic variations cannot explain the coincidence of these slope breaks. Slope breaks are systematically located exactly at the intersection of valleys with the AFS branches, and are independent of lithology (Fig. 5B).

In profile 1, the slope break coincides with the Central Fault, where this fault places the Las Tazas Pluton (western side) in contact with the volcanic La Negra Formation (eastern side, Fig. 2). In profiles 3

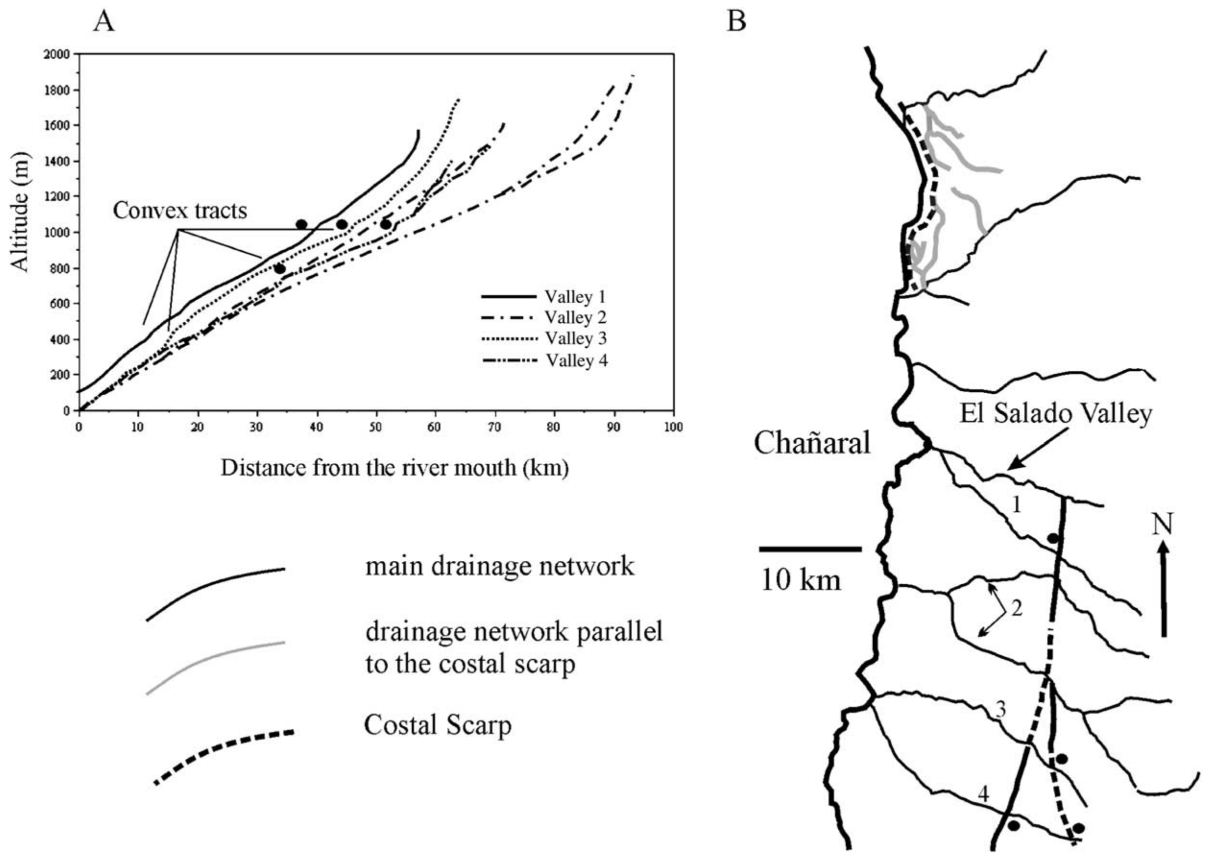


Fig. 5. (A) Longitudinal topographic profiles of the principal valleys of the Coastal Cordillera that cross the AFS. Black points indicate where the profiles intersect branches of the AFS. (B) Localization of the principal valleys: north of Chañaral, the main river valleys are ENE–WSW orientated. Many of their tributaries are parallel to the Costal Scarp, suggesting this scarp formed in its present-day position after the formation of the drainage network. South of Chañaral the main river valleys are ESE–WNW oriented. Black points show the branches of the AFS that affect the longitudinal profiles.

and 4, the slope breaks are coincident with a NW–SE-oriented lineament that splays off the Central Fault. For both profiles, the lineament crosses the homogeneous La Borracha granite (Fig. 2). The lineament, well marked in the DEM and Landsat images, corresponds to the rectilinear western limit of a large plain (Pampa Los Morados). This plain is limited to the west by the Central Fault, suggesting that it represents an AFS-controlled depression.

The second important observation in some of the thalweg profiles is the presence of a marked convex tract, clearly registered in valley 3 and, to a minor degree, in valley 1 (Fig. 5A). Studies of river valleys show that most thalweg profiles can be described by exponential, power and/or logarithmic functions (e.g. Ohomori, 1991). These studies assume that equilibrium in sediment transport has been achieved without morphological changes. The convexity exposed in the thalweg profile of valley 3 is unusual. It may mark an uplift of the western part of the Coastal Cordillera. It could also, however, be a consequence of relative changes in river base level, which in turn may result from the combined effect of changes in sea level, continent-wide uplift and/or eastward retreat of the Chilean coast. The coastal scarp is particularly spectacular north of Chañaral, where its crest reaches 800 m above sea level. It rose to its present-day position when parts of the modern Coastal Cordillera drainage network had already formed. This is evident from the geometry of the drainage network north of Chañaral, where a number of tributary valleys flow eastward from the coastal cliff, to reach the main valleys that connect to the ocean (Fig. 5B). The relatively late development of the coastal cliff is also marked by the presence of minor hanging valleys that arrive at the coastal scarp at altitudes of up to 300 m above sea level.

The formation of the coastal scarp in its present-day position must have modified the longitudinal profiles of the rivers and could explain their convexity, although this convexity also partly results from the uplift of the Coastal Cordillera West of the AFS. The fact that changes in the longitudinal slope of the valleys are observed where the valleys cross the AFS shows that recent activity on the fault system is, in part, responsible for the convexity of the river profiles.

4. Effects of AFS tectonic activity on watershed basin development

In this section, we analyze the characteristics of minor tributary basins within the Salitrosa watershed basin (Fig. 3). The 1943 km^2 NW–SE trending Salitrosa basin is the largest drainage basin developed in the studied region. Two principal valleys form this basin, the Las Animas river valley to the north, and the Salitrosa river valley to the south (Fig. 6). The three principal faults of the AFS cut the Las Animas river valley and the Central and Eastern Fault cut the Salitrosa river valley. Although both valleys display a rectilinear longitudinal profile, some small perturbations are visible where the valleys cross the AFS (profile 2, Fig. 5A). We show below that the relative uplift of the western side of the Coastal Cordillera can be inferred from the morphometry of the minor tributary basins within the Salitrosa watershed basin.

4.1. Drainage basin organization

We considered the DEM extracted drainage network in order to study the morphometric characteristics of the Salitrosa basin. To establish an organization of the drainage network and that of the minor tributary basins, we used Strahler's (1952) hierarchization of the drainage network. This organization shows a major NW–SE oriented stream of order 5, corresponding to the Salitrosa river valley (Fig. 6). All streams of order 4 and corresponding minor tributary basins are developed on the northeastern side of the main Salitrosa river valley, showing the strong morphological dissymmetry of the basin.

The statistical relationships for the morphometry of the sub-watershed basins (Strahler, 1954) show a normal trend (geometric progression) for both the stream number and their mean area, for each tributary basin order (Fig. 7). However, statistical relationships show that the mean length of the streams of order 4 is smaller than the mean lengths of streams of order 3, indicating that the drainage network is not hierarchized.

4.2. Hypsometric analysis

Hypsometric curves of the watershed basins, as proposed by Strahler (1952) and have sometimes been

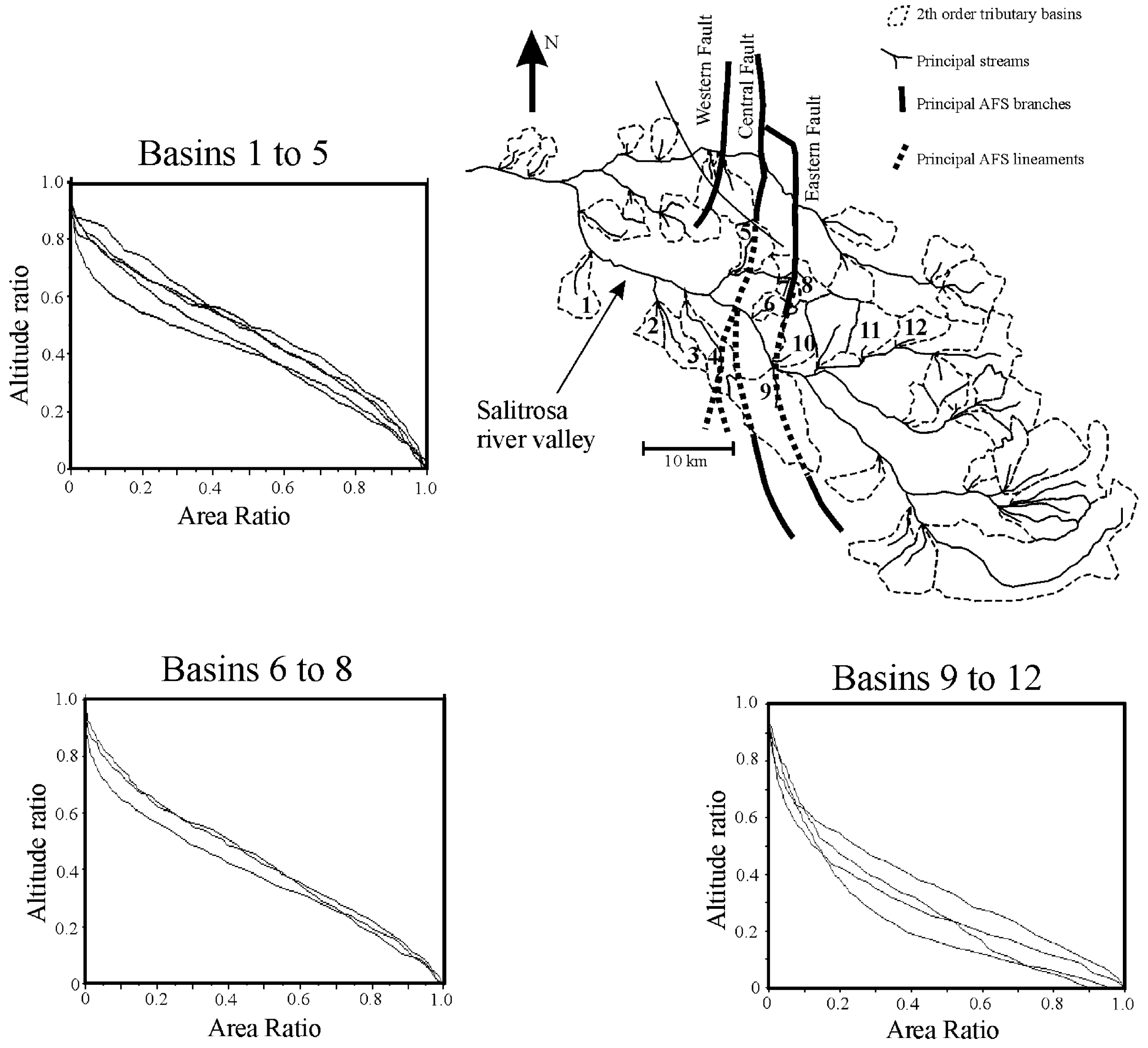


Fig. 6. Hypsometric curves of the order 2 tributary basins of the Salitrosa River. Basins located west of the AFS (basins 9 to 12) show concave hypsometric curves, very different from the convex curves of the basins located immediately east of the AFS (basins 1 to 5). Hypsometric curves of the basins located between the branches of the AFS (basins 6 to 8) show intermediate characteristics.

used as a basis to determine geomorphic development stages resulting from concurrent tectonic and denudation processes (Strahler, 1952; Ohmori, 1993; Bonnet, 1998; Carozza and Delcaillau, 2000). The integral of those curves (hypsometric integrals) permits to summarize the morphology of a drainage basin in a single value (Summerfield, 1991, p. 211). Convex hypsometric curves with high values of hypsometric integrals reflect watershed basins with an important proportion of their surface located at high altitudes, i.e. incised watershed basins, whereas concave curves with low values of hypsometric integrals indicate watershed basins with an important proportion of their surface located at low altitudes.

In the Salitrosa basin (Fig. 6), we observe differences in the hypsometric curves and integrals of the tributary basins of order 2 on both sides of the AFS. To point out these differences, we represent the value

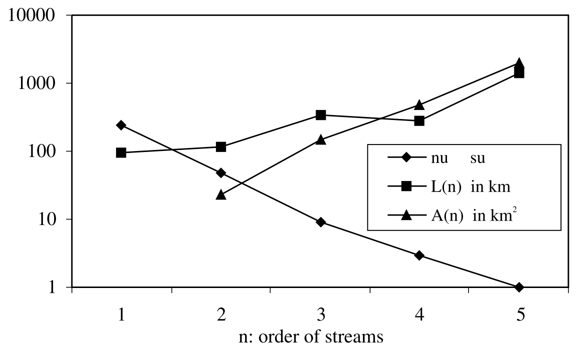


Fig. 7. Strahler's statistical relationships for the drainage basins of the Salitrosa watershed basin, nu is the number of streams of order n, $L(n)$ is the mean stream length for streams of order n, and $A(n)$ is the mean area of the basins of streams of order n.

of hypsometric integrals as a function of the minimum altitude of each tributary basin (Fig. 8). Tributary basins of order 2 located west of the AFS branches have large hypsometric integrals (>0.37), independent of the minimum altitude of the basin (i.e., its position relative to the coast). Tributary basins located immediately east of the AFS branches display small values of hypsometric integrals (< 0.3) that increase with the minimum altitude (i.e. from the AFS branches eastward). Detailed hypsometric analysis for the tributary basins of order 2 located where the Central and Eastern faults of the AFS cross the Salitrosa river valley shows (Fig. 6): (1) on the western side of the Central Fault, convex-to-S-shaped hypsometric curves with a corresponding integral value varying from 0.4 to 0.5 (basins 1 to 5), and (2) on the eastern side of the Eastern Fault concave curves and very low integral values (0.23–0.28, basins 9 to 12) are present. The tributary basins of order 2 located between the branches of the AFS (basins 6 to 8) show convex hypsometric curves and integral values intermediate between those recorded west and east of the AFS branches. These tributary basins also cover anomalously small areas.

The differences that can be established using hypsometric curves and integrals between the eastern and western side of the AFS branches, suggest that the AFS controls the morphometry of the tributary basins. West of the branches of the AFS, the high values of the integral and the convex-to-S-shaped curves indicate that tributary basins have most of their surface in the higher parts of the basin. On the other hand, immediately east of the AFS branches, the small value of the hypsometric integrals and the concave curves indicate that the tributary basins have most of their surface in the lower parts of the basin. This indicates the presence of more incised tributary basins west of the AFS branches, while east of the AFS, tributary basins that are filled by Neogene to Recent sediments are only slightly dissected. The large incision west of the AFS branches can be attributed to uplift of the western side of the Coastal Cordillera, which is accommodated in the Salitrosa river valley by the Central and Eastern Faults of the AFS. The simulta-

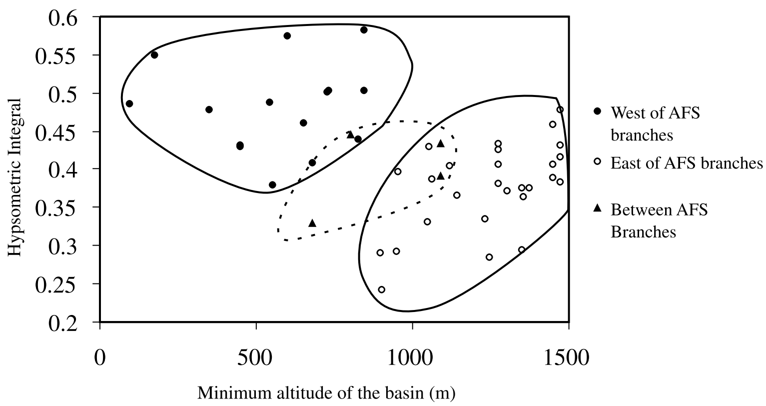


Fig. 8. Hypsometric integral values as a function of the minimum altitude of the basins. Basins are differentiated depending on their relative position with respect to branches of the AFS. Basins located west of the AFS branches show high hypsometric integral values, while basins located east of the fault system have smaller hypsometric integrals, particularly when they lie at low altitudes (i.e. when they are close to the AFS). Basins located between the branches of the AFS show intermediate values.

neous activity of these two faults results in a perturbation in the organization of the tributary basins and explains the convex curves, the intermediate value of the hypsometric integrals and the anomalously small area covered by the basins located between these faults. As we will show later (site 2, Fig. 10), the Central and Eastern faults bound a perched valley, in which the watershed basins 7 and 8 (Fig. 6) are partially developed. Therefore, the morphometric characteristics registered by basins 6 to 8 could be attributed to disorganization of the drainage network induced by activity on the AFS. This disorganization could also be reflected in the lack of hierarchized drainage network as suggested by Strahler's statistical relationships for mean stream lengths (Fig. 7).

5. Field geomorphological evidence for recent activity on the AFS

5.1. Site 1

The north–south-oriented Central Fault of the AFS intersects the main El Salado river valley immediately west of the El Salado village (Fig. 11). A major tributary of the main valley follows this fault on the southern side of the El Salado river valley. In this tributary valley, 15 m of Neogene sediments composed mainly of clay deposits alternating with thin calcareous layers are exposed (Fig. 9). These deposits grade upward into gravels. The basal fine-grained deposits are cut by a set of approximately N160E-oriented normal faults. The major faults have a north–east downthrow of about 2 m and antithetic faults record a downthrow of less than a meter. No evidence for cross-cutting relationships between the normal faults and the gravel layer could be recognized in the field. However, gravel deposits exposed to the south, upstream of the southern tributary, show lineaments parallel to the AFS, suggesting that this branch was active following gravel deposition (Fig. 11).

5.2. Site 2

Evidence for recent activity on the Central and Eastern AFS faults can be observed where these faults cross the Salitrosa river valley. A difference in the sedimentary depositional record is observed on both sides of the Eastern Fault. West of the fault, two sedimentary depositional events can be differentiated. An older event is represented by incised gravel deposits that form a terrace. Terraces are exposed along the Salitrosa river valley, and reach the higher parts of its tributary basins. A maximal vertical incision of 35 m is recorded for terraces of the Salitrosa river valley (Fig. 12A). A second depositio-

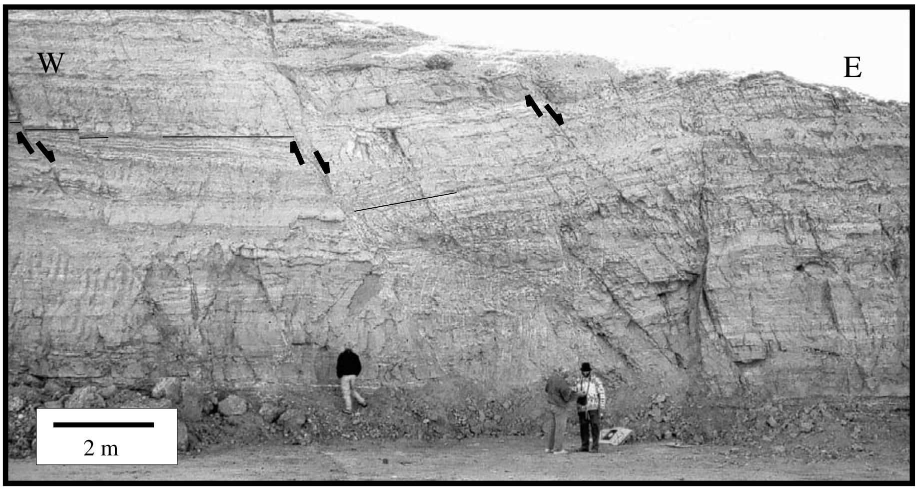


Fig. 9. (Site 1 of paragraph V): Normal faults exposed in the El Salado valley, near El Salado village. Faults cut units of fine-grained sediments composed of alternating calcareous and clay layers. This site is located on the central fault of the AFS. See Fig. 2 for location.

nal event present west of the fault corresponds to weakly incised alluvial fans, restricted to the outlet of the tributaries of the Salitrosa river valley. East of the Eastern Fault, only one depositional event is recorded. This event corresponds to extensive alluvial fans that are weakly incised.

The southern extension of the Central Fault of the AFS is marked by a series of parallel lineaments on terrace surfaces developed on the relatively older gravel depositional event. These lineaments show evidence for opposite senses of relative uplift between the eastern and western side of the fault. North of the Salitrosa river valley, the lineaments are parallel, and they correspond to a scarp and a slope break on the surface of the terraces (Fig. 10B). Both scarps and slope breaks indicate the relative uplift along the eastern side of the fault. In contrast, evaporite deposits overlain by the weakly incised alluvial fan are exposed over 5 km along the Salitrosa river valley, east of the lineament of the Central Fault. This could suggest that uplift on the western side of the fault trapped sediments in the valley resulting in evaporite deposition.

In the block delimited by the Central and Eastern faults of the AFS, an anomalous 5-km-long, NW–SE-oriented valley is present. This valley that partially

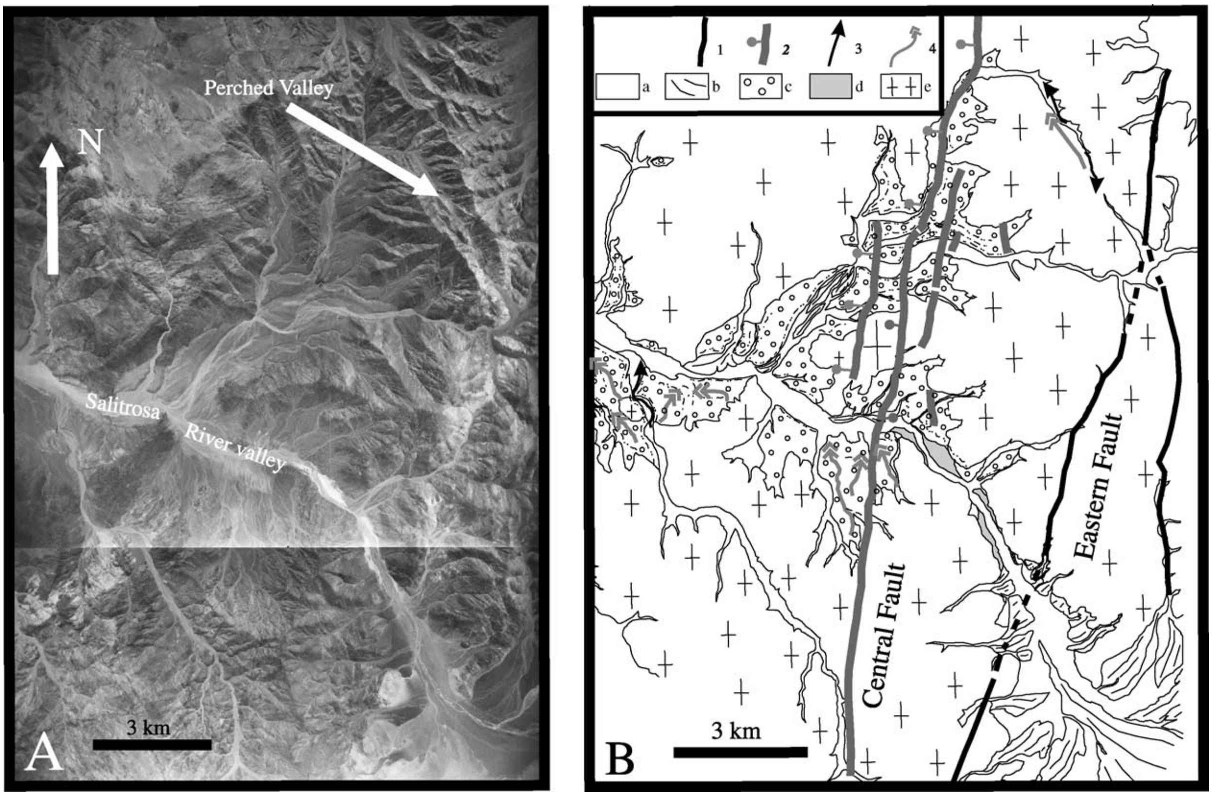


Fig. 10. (Site 2 of paragraph V): (A) Aerial photo of the Salitrosa river valley where the Central and Eastern faults of the AFS cross it. The faults have been recognized in the field although they are not clearly visible on the scanned photo. The southern continuation of the Central Fault can be recognized, crossing the Salitrosa river valley, as a series of lineaments developed on incised gravel deposits. Note in the upper right corner, a perched valley located between the two faults of the AFS. (B) Interpretative map of the area, showing different kinds of Neogene to Recent sedimentary deposits: (a) present-day alluvial fan and flood plain deposits, (b) weakly incised alluvial fans whose morphology is preserved, and that are exposed over the whole mapped area, (c) older deposits, composed of incised gravel which are exposed only west of the Eastern Fault, and in which old hanging paleo-channels are preserved, (d) evaporite deposits exposed only east of the Central Fault, and (e) Upper Jurassic–Lower Cretaceous granites. (1) AFS branches, (2) AFS-related faults cutting Neogene to Recent units, (3) present-day active stream direction, and (4) hanging ancient stream direction. See Fig. 2 for location.

comprises the watershed basins 7 and 8 (Fig. 6) has two outlets, one at its northwestern end and another at its southeastern end. The valley is considered to originally to have been part of a single watershed basin. Movements accommodated by the Central and Eastern faults considered to have left it as a perched valley, in which two basins have developed with opposed runoff directions. This valley shows an example of the disorganization of the watershed drainage systems induced by activity on the AFS. The initial flow of the river was SE–NW oriented. The uplift of the block located west of the eastern fault resulted in the capture by active headward erosion of the upper southeastern part of the valley (Fig. 10).

6. Neogene sediments preserved in the Coastal Cordillera and their tectonic and geomorphologic significance

The watershed basin of the El Salado river valley is one of the major drainage systems in the Southern Atacama Desert and it is the only one that cuts across the Coastal Cordillera and the entire Central Depression in the studied area (Figs. 2 and 3). From the Precordillera, and through the Central Depression, the El Salado river valley cuts a series of continental gravels and conglomerates (Atacama Gravels of Mortimer, 1969). In the Precordillera, the age of the Atacama Gravels can be attributed to the Middle–Upper Miocene: ash layers in the lower and middle part of those gravels yielded ages of 17 and 15 Ma (Cornejo and Mpodozis, 1996). On the other hand, a 10-Ma-old ignimbrite seals a pedimentation surface that marks the top of the gravels (Cornejo et al., 1993).

The Atacama Gravels have a thickness that may reach several hundreds of meters and grade laterally near to the western margin of the Central Depression into mainly fine-grained sediments. These sediments are continuously exposed along the El Salado river valley and its main tributaries in the Coastal Cordillera, east of the intersection of the Central Fault of the AFS with the valley. West of the Central Fault, in contrast, the El Salado river valley cuts Mesozoic rocks, and only the present-day alluvial fan and floodplain deposits are preserved there (Fig. 11). These observations show that the AFS, at least partially, controlled the Neogene depositional and morphological evolution of this part of the Coastal Cordillera.

6.1. Neogene depositional and geomorphological evolution of the El Salado river valley

It is possible to distinguish three stages in the Neogene depositional and morphological evolution of the part of the Central Depression crossed by the El Salado river valley, east of the Central Fault of the AFS (Fig. 11).

(1) The first stage is marked by the deposition of the fine-grained Neogene succession. These sediments were deposited over a very irregular basal surface, which suggests a pre-existing deeply incised landscape surface was present (Figs. 11 and 12B). The sediments comprise alternating tabular, flat lying and massive beds, one to several meters thick, composed mainly of silt, clay, and gypsum. Coarse-grained gravel and conglomerates are exposed only along the axes of the main tributaries, and in areas close to steep paleo-slopes. The sediments, near El Salado, comprise clay deposits, alternating with thin calcareous layers (Fig. 9). They grade upwards into continuous thick evaporitic level containing a large proportion of gypsum and presenting paleo-dessications features (Fig. 12C). These represent flood plain and playa deposits. The thickness of this level may have reached several hundred meters near El Salado, and decreases upward to several tens of meters near Diego de Almagro.

(2) Above the fine-grained sediments, a pedimentation surface and related gravel deposits record a second stage in the evolution of the El Salado river valley. This surface is well exposed near Diego de Almagro (Fig. 11), where it is in continuity with a surface of regional extent that corresponds to the top of most of the Central Depression. The age of this episode of pedimentation is poorly constrained. If we suppose that the process of pedimentation above the Atacama Gravels occurred synchronously from the Precordillera (where the pedimentation surface has been dated) to the Coastal Cordillera, we can suggest an age of about 10 Ma for the pediment-associated gravel deposits. An age of 6 Ma has also been recorded for deposits that have been correlated with this pedimentation surface, in the Coastal Cordillera 40 km north of the El Salado valley (Godoy and Lara,

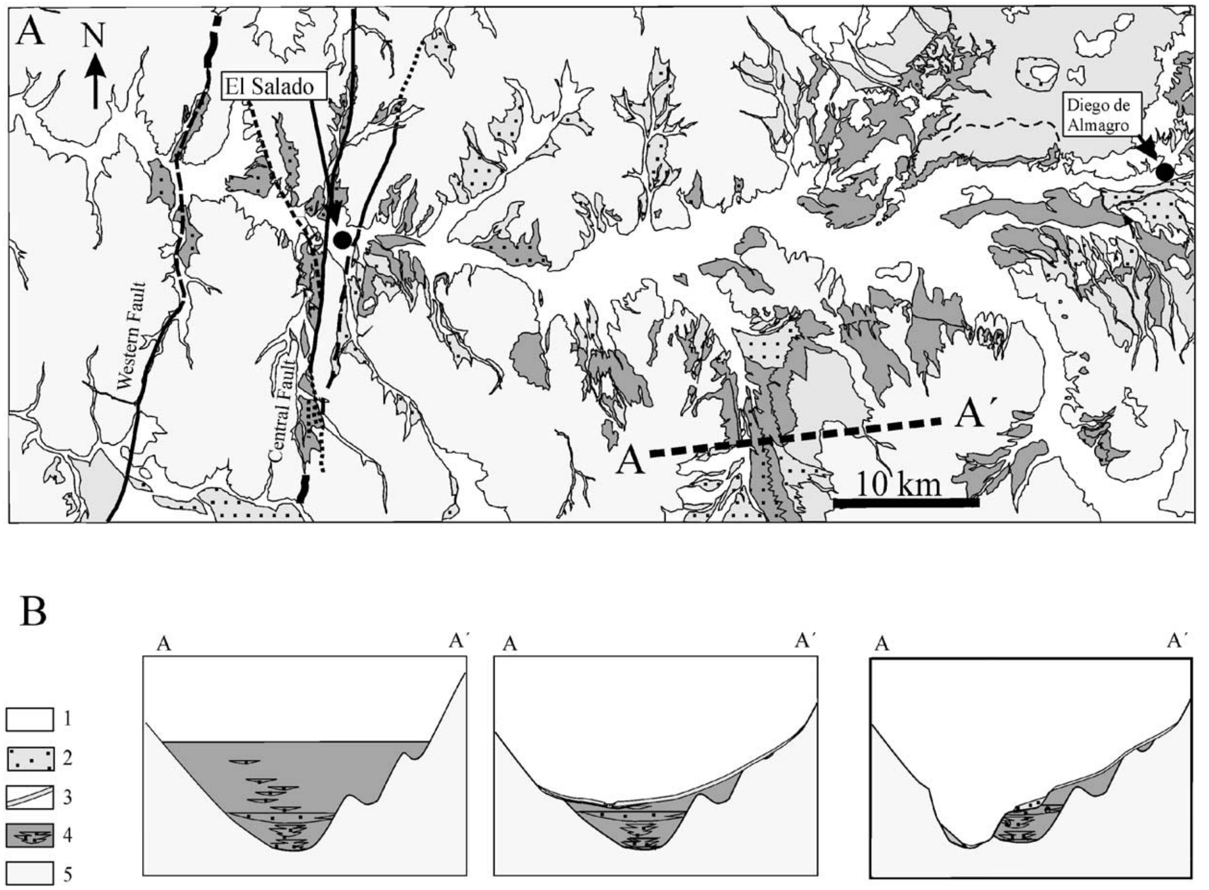


Fig. 11. (A) Distribution of the Neogene deposits in the El Salado river valley, between Diego de Almagro and El Salado. (1) Modern alluvial fans and flood plain deposits, (2) alluvial fan deposits incised into older units, and dissected by modern drainage systems, (3) post-Atacama Gravel pediment deposits, (4) Atacama Gravel related deposits, and (5) Jurassic–Cretaceous substratum. (B) Schematic profile showing the stratigraphic relation between the different Neogene deposits and their morphologic characteristics.

1998). These ages suggest that the pedimentation episode occurred in the Coastal Cordillera in the Upper Miocene.

(3) Later episodic incision into the Atacama Gravels and related fine grained sediments, and into the pedimentation surface, is restricted to the present-day fluvial valleys. Alluvial fan deposits that cut and are incised into the pediment deposits mark the end of a first episode of incision. A terrace surface is developed on the fine-grained Neogene sediments near Diego de Almagro, and corresponds to a surface that is exposed to the west and which truncates the alluvial fan deposits (Fig. 11). A final incision cutting all previous units is responsible for the present-day drainage configuration, and corresponds to the last stage of the El Salado river valley evolution.

6.2. Tectonic significance

The fine-grained sediments mark a particular episode of valley development. The sediments are interpreted as playa-related deposits that fill a previously deeply incised landscape surface, indicating that the El Salado valley existed prior to Neogene deposition. This sedimentation phase terminated with deposition of an evaporite unit in a valley that was much wider than the present-day one. Fine-grained sediments are absent west of the eastern branch of the AFS. There are two possible explanations for this: (1) Neogene

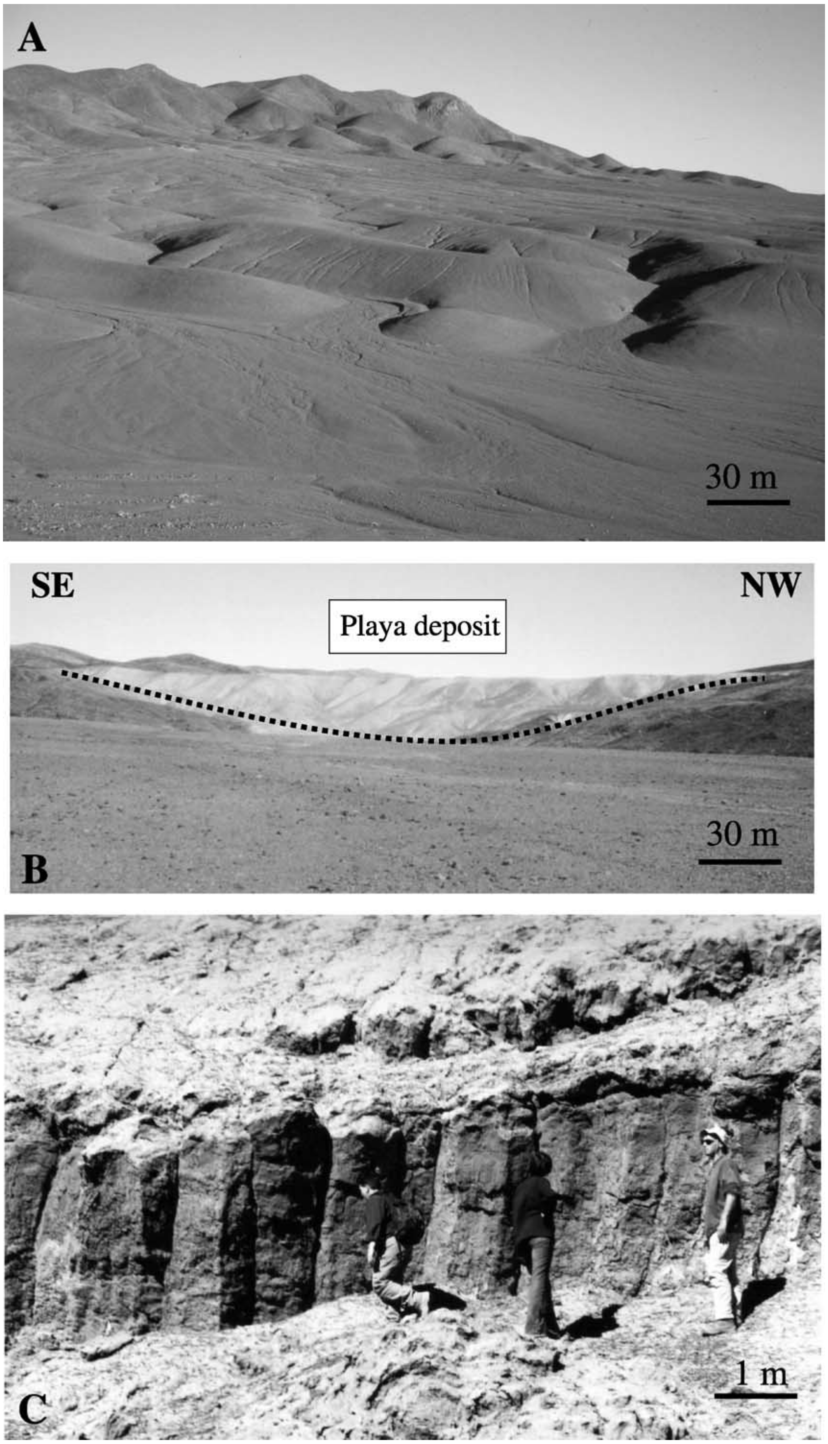


Fig. 12. (A) Incised alluvial fans in the Salitrosa watershed basin, west of the AFS. (B) Playa deposits infilling paleo-valley. The local maximum thickness of deposits is around thirty meters. (C) Paleo-desiccation marks in the playa-related deposits of the El Salado valley.

conditions allowed deposition of fine-grained sediments west of the eastern branch of the AFS, and the subsequent uplift of the western Coastal Cordillera resulted in erosion of these deposits. (2) The fine-grained sediments were never deposited west of the eastern branch of the AFS, because this fault system accommodated the relative uplift of the western part of the Coastal Cordillera at that time. This uplift resulted in the closure of paleovalleys draining from the Andean Cordillera, and deposition of fine-grained playa sediments in the Central Depression and in the El Salado valley, east of the eastern branch of the AFS.

The playa sediments can be recognized high in the present-day relief, indicating that the fine-grained deposits may have been up to 300 m in thickness. Tectonic uplift of the western part of the Coastal Cordillera can account for deposition of these sediments. As uplift is known to have occurred during the Neogene, it is reasonable to assume that it controlled the aggradational episode east of the AFS. After uplift-driven closure of the El Salado valley, dissection across the uplifted block of the Coastal Cordillera resulted in headward-retreat of the valley, eventually reaching the fine-grained sediments and opening the valley to the ocean.

7. Discussion

7.1. Neogene AFS activity

The analyses presented above indicate that the AFS accommodated the relative uplift of the western side of the Coastal Cordillera in the Chañaral area. These analyses consider observations at different scales, which also correspond to different time scales and to different amounts of relative displacements along the AFS.

The playa-related Neogene deposits present along the El Salado valley, east of the AFS, indicate that this system was already accommodating the relative uplift of the western side of the Coastal Cordillera in the middle/upper Miocene. It also shows that the AFS, at least partially, controlled Neogene deposition (Mortimer, 1973), resulting in the infilling of the Central Depression and possibly Neogene deposition in the Precordillera. In the Precordillera, undated gravels fill preexisting valleys whose incision in the basement was as deep as the incision of the present-day valleys: Near Potrerillos for instance, the bottom of the paleo El Salado valley lies 2 km below the highest regional summits, showing that the Precordillera was already a high and deeply incised chain at that time. It is difficult to determine precisely when the AFS activity resulted in the deposition for the playa-related Neogene deposits, since there is not any dated ash layer in the El Salado area. Assuming that the deposition of those sediment occurred simultaneously with the deposition of the Atacama gravel to the east, near Potrerillos, would give an age of 18–10 My for this event (see above).

The control of the AFS on Neogene sedimentation has also been proposed, north of Antofagasta, for the fluvial and lacustrine deposits of the Loa river valley (Naranjo and Paskoff, 1982), and playa-related deposits in the Taltal area (Hervé, 1987). Therefore, the AFS played a fundamental role in the Neogene, between 20° and 27°S, acting as a barrier to sediment transported from the Andean Cordillera.

The analysis of large-scale landscape features shows an abrupt decrease in the mean regional altitude (up to 400 m) across the AFS, and larger standard deviations for altitudes west of the AFS indicating uplift and greater incision in the western part of the Coastal Cordillera. In the valleys located south of the El Salado river valley, the largest incision west of the AFS is also marked by the presence of terraces (Fig. 10). These terraces mark much more modest uplift phases (a few tens of meters), and are considered to represent only the last period of a relatively continuous uplift of the western side of Coastal Cordillera. This resulted in an incision of the tributary basins located west of the AFS, as revealed by the hypsometric curves and integrals. Also related to activity on the AFS is the disorganized nature of the drainage in the Salitrosa watershed basin, which can be regarded as a drainage system that has not yet adapted to the uplift associated with the AFS.

Field evidence shows that activity on the AFS continues to the present-day. This is marked by lineaments in the post-Atacama Gravel pedimentation surface, by scarps that cut the terraces of the Salitrosa river valley, and by an increase in the longitudinal slope of the valleys where they cross the fault system. The tectonic activity subsequent to deposition of the Atacama gravels is, however, less than that reported in the Antofagasta area where it is related predominantly to east-dipping normal faults (Delouis et al., 1996, 1998).

7.2. Neogene forearc morphological evolution

Tectonic activity on the AFS in the Chañaral area partly controlled the morphological and depositional development of the forearc (Fig. 13). We observe that the El Salado river valley already existed prior to the Middle to Upper Miocene aggradation episode, and that it was deeply incised through the entire forearc (Fig. 13A). This indicates that an uplift had occurred before that time, probably in the Eocene as suggested by fission track data obtained from the Precordillera in the Atacama Desert, between Chañaral and Antofagasta (Maksaev and Zentilli, 1999).

From the Middle to Upper Miocene, deposition of the Atacama gravel filled the preexisting incised morphology in the Precordillera, in the Central Depression and the eastern part of the Coastal Cordillera. These sediments consist of gravels in the Precordillera, and pass laterally into playa-related deposits near the AFS (Fig. 13B). We argue that deposition was partly controlled by uplift of the Western part of the Coastal Cordillera along the AFS.

A pedimentation episode followed deposition of the Atacama gravels in the Precordillera and the Central Depression, and marked the end of the playa-related deposition east of the AFS. This indicates that the El Salado river valley had again gained access to the ocean (Fig. 13C). The headward-retreat of the El Salado river valley resulted in dissection of the Atacama Gravels and related deposits in the Central Depression. However, the relative uplift of the western part of the Coastal Cordillera accommodated by the AFS continued, resulting in the incision of the landscape west of the AFS. East of the AFS, extensive deposits of alluvial fans and pedimentation-related deposits continued to accumulate up to present day but only in valleys that do not drain the high Cordillera.

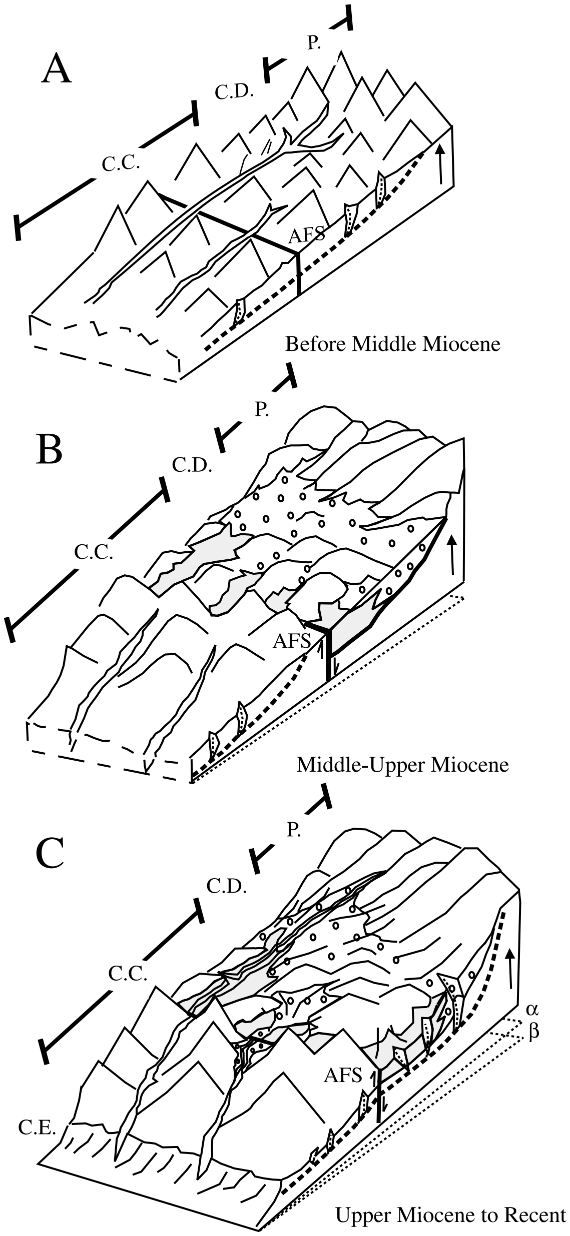


Fig. 13. Schematic block diagrams showing the inferred Neogene morphological and depositional evolution of the Chilean forearc in the Chañaral region. Dashed lines show the longitudinal river valley profiles in each stage of the evolution. (A) Before Middle Miocene: the El Salado valley is deeply incised into basement, in the Precordillera, the Central Depression and the Coastal Cordillera. (B) Middle to Upper Miocene: The AFS accommodated the uplift of the western part of the Coastal Cordillera. Atacama gravels and related playa deposits (light grey) were deposited east of the AFS. (C) Upper Miocene to Recent: Although the relative uplift of the western Coastal Cordillera accommodated by the AFS is still active, the El Salado valley incises into Neogene deposits of the Central Depression. Angles α and β mark a possible progressive tilting of the forearc. C.C., Coastal Cordillera, C.D., Central Depression, P., Precordillera.

To summarize, the El Salado river valley, east of the AFS, experienced three successive morphological phases: Middle to Upper Miocene deposition of the Atacama Gravel-related sediments occurred after a first episode of incision, and was followed by a new episode of incision that continued through the Quaternary. Hartley and Chong (2002) show that the hyper-arid present-day climate of the Atacama Desert definitely established 3 My ago. Alpers and Brimhall (1988) show, however, that since the Middle Miocene the climate has always been arid to extremely arid in the Atacama Desert. We propose that two tectonic phenomena may be responsible for the morphological evolution of this area.

(1) Activity on the AFS-controlled deposition of the Atacama Gravels and related sediments. Fluctuation in the relative amount of uplift of the western Coastal Cordillera accommodated by this set of faults may explain the renewed ability of the El Salado river to incise into the forearc east of the AFS.

(2) It is important to point out that the renewal of incision within the Central Depression occurred in the Upper Miocene. This period probably corresponds to an important episode of uplift of the Altiplano and Puna (Gregory-Wodzicki, 2000). This uplift was not accompanied by the activation of any major fault west of the volcanic arc. Field data suggest rather that it may have been accommodated by a small tilting ($\approx 3°$) of the entire Chilean forearc (e.g. Lamb et al., 1997). This tilting would have resulted in a larger average slope of the Chilean forearc, which could explain the stronger erosive action of the El Salado river that is now able to incise both the Coastal Cordillera and the Central Depression.

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References

Alpers, C., Brimhall, G., 1988. Middle Miocene climatic change in the Atacama Desert, northern Chile: evidence from supergene mineralization at La Escondida. Geol. Soc. Amer. Bull. 10, 1640–1656.

Arabasz, W.J., 1971. Geological and geophysical studies of the Atacama Fault Zone in Northern Chile. PhD Thesis, Calif. Inst. Technol., Pasadena, CA. 264 pp.

Armijo, R., Thiele, R., 1990. Active faulting in northern Chile: ramp stacking and lateral decoupling along a subduction plate boundary. Earth Planet. Sci. Lett. 98, 40–61.

Bell, C.M., 1987. The origin of the Upper Paleozoic Chañaral mélange of N. Chile. J. Geol. Soc. (Lond.) 144, 599–610.

Bonnet, S., 1998. Le socle Armonicain au Pléistocène. PhD, Université de Rennes I, Rennes, France. 352 pp.

Brown, M., Diáz, F., Grocott, J., 1993. Displacement history of the Atacama fault system 25°S–27°S, northern Chile. Geol. Soc. Amer. Bull. 105, 1165–1174.

Carozza, J.M., Delcaillau, B., 2000. Réponses des bassins versants à l'activité tectonique: l'exemple de la terminaison orientale de la Chaîne pyrénéenne. Approche morphotectonique. Géomorphologie: relief, processus, environnement. Groupe Français Géomorphol. (Paris) 1, 45–60.

Coira, B., Davidson, J., Mpodozis, C., Ramos, V., 1982. Tectonic and magmatic evolution of the Andes of northern Argentina and Chile. Earth-Sci. Rev. 18, 303–332.

Colley, H., Treloar, P.J., Diáz, F., 1990. Gold–silver mineralisation in the El Salvador region, northern Chile. In: Keays, R., Ramsey, R., Groves, D. (Eds.), The Geology of Gold Deposits: The Perspective in 1998. Econ. Geol. Monogr., vol. 6, pp. 208–217.

Cornejo, P., Mpodozis, C., 1996. Geología de la Región de Sierra Exploradora (Cordillera de Domeyko 25°–26° S): Servicio Nacional de Geología y Minería-CODELCO, Informe Registrado IR-96-09. 330 pp., Santiago, Chile.

Cornejo, P., Mpodozis, C., Ramirez, C.F., Tomlinson, A.J., 1993. Estudio Geológico de la Región de Potrerillos y El Salvador (26°–27° Lat.S). Servicio Nacional de Geología y Minería-CODELCO, Informe Registrado IR-93-01, 12 cuadrángulos escala 1:50.000 y texto. 258 pp., Santiago, Chile.

Dallmeyer, R.D., Brown, M., Grocott, J., Taylor, G.K., Treloar, P.J., 1996. Chronology of magmatic and tectonic events in a retreating arc: the Mesozoic evolution of the Andean Plate Boundary Zone, north Chile. J. Geol. 104, 19–40.

Delouis, B., Philip, H., Dorbath, L., 1996. Extensional stress regime in the Antofagasta Coastal Area (Northern Chile). Third International Symposium on Andean Geodynamics, Actas. ORSTOM, Saint-Malo, pp. 169–171.

Delouis, B., Philip, H., Dorbath, L., Cisternas, A., 1998. Recent crustal deformation in the Antofagasta region (northern Chile) and the subduction process. Geophys. J. Int. 132, 302–338.

García, F., 1967. Geología del Norte Grande de Chile. Sociedad Geológica de Chile, Symposium sobre el Geosinclinal Andino. 138 pp., Santiago, Chile.

Godoy, E., Lara, L, 1998. Hojas Chañaral y Diego de Almagro, Región de Atacama. Servicio Nacional de Geología y Minería, Mapas Geológicos N.5, 1 mapa, escala 1:100.000. Santiago, Chile.

Gregory-Wodzicki, K.M., 2000. Uplift of the Central and Northern Andes: a review. Geol. Soc. Amer. Bull. 112, 1091–1105.

Grocott, J., Brown, J., Dallmeyer, R.D., Taylor, G.K., Treloar, P.J., 1994. Mechanism of continental growth in extensional arcs: an example from the Andean plate boundary zone. Geology 22, 391–394.

Hartley, A.J., Chong, G., 2002. Late Pliocene age for the Atacama Desert: implications for the desertification of western South America. Geology 30 (1), 43–46.

Hartley, A.J., Chong, G., Turner, P., May, P., Kape, S.J., Jolley, E.J., 2000. Development of a continental forearc: a Neogene example from the Central Andes, northern Chile. Geology 28, 331–334.

Hervé, M., 1987. Movimiento normal de la falla Paposo, Zona de Falla de Atacama, en el Mioceno, Chile. Rev. Geol. Chile 31, 31–36.

Holbrook, J., Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle apeirogenic deformation in modern and ancient settings. Tectonophysics 305, 287–306.

Howard, A.D., Dietrich, W.E., Seidl, M.A., 1994. Modeling fluvial erosion on regional to continental scales. J. Geophys. Res. 99, 13971–13986.

Lamb, S., Hoke, L., Kennan, L., Dewey, J., 1997. Cenozoic evolution of the Central Andes in Bolivia and northern Chile. Geol. Soc. Spec. Publ. 121, 237–264.

Lara, L., Godoy, E., 1998. Hoja Quebrada Salitrosa, Región de Atacama. Servicio Nacional de Geología y Minería, Mapas Geológicos N.4, 1 mapa, escala 1:100.000. Santiago, Chile.

Maksaev, V., Zentilli, M., 1999. Fission track thermochronology of the Domeyko Cordillera, Northern Chile: implications for Andean tectonics and porphyry copper metallogenesis. Explor. Min. Geol. 8, 65–89.

Mortimer, C., 1969. The Geomorphological Evolution of the Southern Atacama Desert, Chile. PhD Thesis, Department of Geology, University College of London, U.K. 283 pp.

Mortimer, C., 1973. The Cenozoic history of the southern Atacama Desert, Chile. J. Soc. Lond. 129, 505–526.

Mortimer, C., 1980. Drainage evolution in the Atacama desert of northern Chile. Inst. Invest. Geol., Rev. Geol. Chile 13–14, 79–85.

Naranjo, J.A., 1987. Interpretación de la actividad cenozoica superior a lo largo de la Zona de Falla de Atacama, norte de Chile. Rev. Geol. Chile 31, 43–55.

Naranjo, J.A., Paskoff, R., 1982. Estratigrafía de las unidades sedimentarias Cenozoicas de la Cuenca del Río Loa en la Pampa del Tamarugal, Región de Antofagasta, Chile. Rev. Geol. Chile 15, 49–57.

Niemeyer, H., González, G., Martínez-De Los Ríos, E., 1996. Evolución tectónica cenozoica del margen continental activo de Antofagasta, norte de Chile. Rev. Geol. Chile 23, 165–186.

O'Callaghan, J.F., Mark, D.M., 1984. The extension of drainage networks from digital elevation data. Comput. Vis. Graph. Image Process. 28, 323–344.

Ohmori, H., 1993. Changes in the hypsometric curve through mountain building resulting from concurrent tectonics and denudation. Geomorphology 8, 263–277.

Ohomori, H., 1991. Change in the mathematical function type describing the longitudinal profile of a river through an evolutionary process. J. Geol. 99, 97–110.

Okada, A., 1971. On the neotectonics of the Atacama fault zone region—preliminary notes on Late Cenozoic faulting and geomorphic development of the Coast Range of Northern Chile. Bull. Dep. Geogr., Univ. Tokyo 3, 47–65.

Reutter, K.J., Scheuber, E., 1988. Relation between tectonics and magmatism in the Andes of northern Chile and adjacent areas between 21 and 25°S. V Congr. Geol. Chileno, Actas, vol. 1, pp. A345–A363.

Scheuber, E., Andriessen, P.A.M., 1990. The kinematic and geodynamic significance of the Atacama Fault Zone, northern Chile. J. Struct. Geol. 12, 243–257.

Scheuber, E., Reutter, K.J., 1992. Magmatic arc tectonics in the central Andes between 21°S and 25°S. Tectonophysics 205, 127–140.

Scheuber, E., Hammerschmidt, K., Friedrichsen, H., 1995. 40Ar/39Ar and Rb–Sr analyses from ductile shear zones from the Atacama Fault Zone, northern Chile: the age of deformation. Tectonophysics 250, 61–87.

Strahler, A.N., 1952. Hypsometric (area–altitude) analysis of erosional topography. Geo. Soc. Amer. Bull. 63, 1117–1142.

Strahler, A.N., 1954. Statistical analysis in geomorphic research. J. Geol. 62, 1–25.

Summerfield, M.A., 1991. Global Geomorphology. Longman, Singapore. 537 pp.

Swanson, M., 1989. Sidewall ripouts in strike-slip faults. J. Struct. Geol. 11, 933–948.

Taylor, G.K., Grocott, J., Pope, A., Randall, D.E., 1998. Mesozoic faults systems, deformation and fault block rotation in the Andean forearc: a crustal scale strike-slip duplex in the Coastal Cordillera of northern Chile. Tectonophysics 299, 93–109.

Thiele, R., Pincheira, M., 1987. Tectónica transpresiva y movimiento de desgarre en el segmento sur de la Zona de Falla de Atacama, Chile. Rev. Geol. Chile 31, 77–94.

Wilson, J., 1996. Emplacement of the Las Tazas Plutonic Complex, Coastal Cordillera, Northern Chile. PhD Thesis, Kingston University.

Woodcock, N.H., Underhill, J., 1986. Strike-slip duplexes. J. Struct. Geol. 8, 725–735.