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Geomorphological markers of faulting and neotectonic activity along the western Andean margin, northern Chile

LAURENCE AUDIN,[1]* GÉRARD HERAIL,[1] RODRIGO RIQUELME,[1,2] JOSÉ DARROZES,[3] JOSEPH MARTINOD[1,3] and ERIC FONT[3]
[1] IRD-Université P. Sabatier, Dept. Géologie, 38 rue des 36 ponts, 31400 Toulouse, France
[2] DGF, Departamento de Geologia, Facultad de Ciencias Fisicas y Matematicas, Universidad de Chile, Chile
[3] LMTG, Université P. Sabatier, Toulouse, France

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ABSTRACT: In the Atacama Desert, northern Chile, some ephemeral channels are developed in the Plio-Quaternary alluvial sequence that caps the Neogene Atacama Gravels Formation. Geomorphological studies and high-resolution digital elevation data (GPS) along a structural transect in the Central Depression are used to document modern growth history of subtle folding and faulting in the fore-arc region. Outcrop data of the most recent deposits are combined with observations of warped and faulted late Quaternary pediments, alluvial fans and terrace surfaces to propose unsuspected neotectonic processes on the western flank of the Domeyko Cordillera. Neotectonic process recognition is here based largely upon the interpretation of alluvial landforms, drainage organisation and evolution as the intermittent river network shows systematic patterns of course deflections, successive incisions or deposition processes as it encounters the fault scarps or folds in the superficial deposits. This area presents both N–S-trending active vertical faults in the topographically higher pampas, and N–S-trending active folding in the lower pampas. These faults seem to accommodate E–W extension and compression that could be related to uplift of the western Andean margin within a compressive context. Uplift may have taken place unevenly over the past few million years after the deposition of the superficial alluvial surfaces that cap the Neogene Atacama Gravels. Copyright © 2003 John Wiley & Sons, Ltd.

KEYWORDS: neotectonics; geomorphology; drainage network; intracontinental basin.

Introduction

Rivers and their alluvial fans in arid environments are very sensitive to topographic changes caused by uplift or subsidence and are thus ideal markers to identify recent tectonic activity (Molnar *et al.*, 1994; Holbrook and Schumm, 1999; Formento-Trigilio *et al.*, 2002). In northern Chile, Neogene debris flows and alluvial fans are trapped in the Central Depression, also known as the Longitudinal Valley. This depression trends N–S with an average E–W width of 70 km (Fig. 1) and is part of the southern Atacama Desert.

On its western flank, the Central Depression is bounded by the Coastal Cordillera and the Atacama Fault system (Arabasz, 1971; Armijo and Thiele, 1990; Brown *et al.*, 1993). The Atacama Fault system (AFS) is a N–S-trending fault zone extending over 1000 km in the coastal range of northern Chile. Various studies established initial activity of the AFS as Jurassic to Early Cretaceous, i.e. contemporaneous with the period of magmatic activity in the Coastal Cordillera (Naranjo and Puig, 1984; Scheuber and Andriesen, 1990; Scheuber and Reutter, 1992). The AFS appears in some places to have reactivated during Tertiary and recent times, from north of Antofagasta (about 20°S; Delouis *et al.*, 1998) to the western structural border of the Central Depression (26°S, Fig. 1; Riquelme *et al.*, 2003).

In contrast, recent tectonic activity along the eastern border of the Central Depression has not been documented. The Domeyko fault zone, draw along the eastern flank of the Central Depression and is N–S-trending fault system that controls much of the structure of the Chilean Precordillera (Mortimer, 1973). The Cenozoic was characterised by important magmatic activity along N–S-trending volcanic arcs that migrated step by step towards the east up to its present-day location along the Western Cordillera in Argentina. Although the timing and kinematics of the Domeyko fault system is poorly constrained, studies suggest that it was active during the lifespan of the Eocene to early Oligocene magmatic arc, showing both important strike-slip and shortening components (Fig. 1;

* Correspondence to: Dr L. Audin, IRD-Université P. Sabatier, Dept. Géologie, 38 rue des 36 ponts, 31400 Toulouse, France. E-mail: Laurence.Audin@ird.fr

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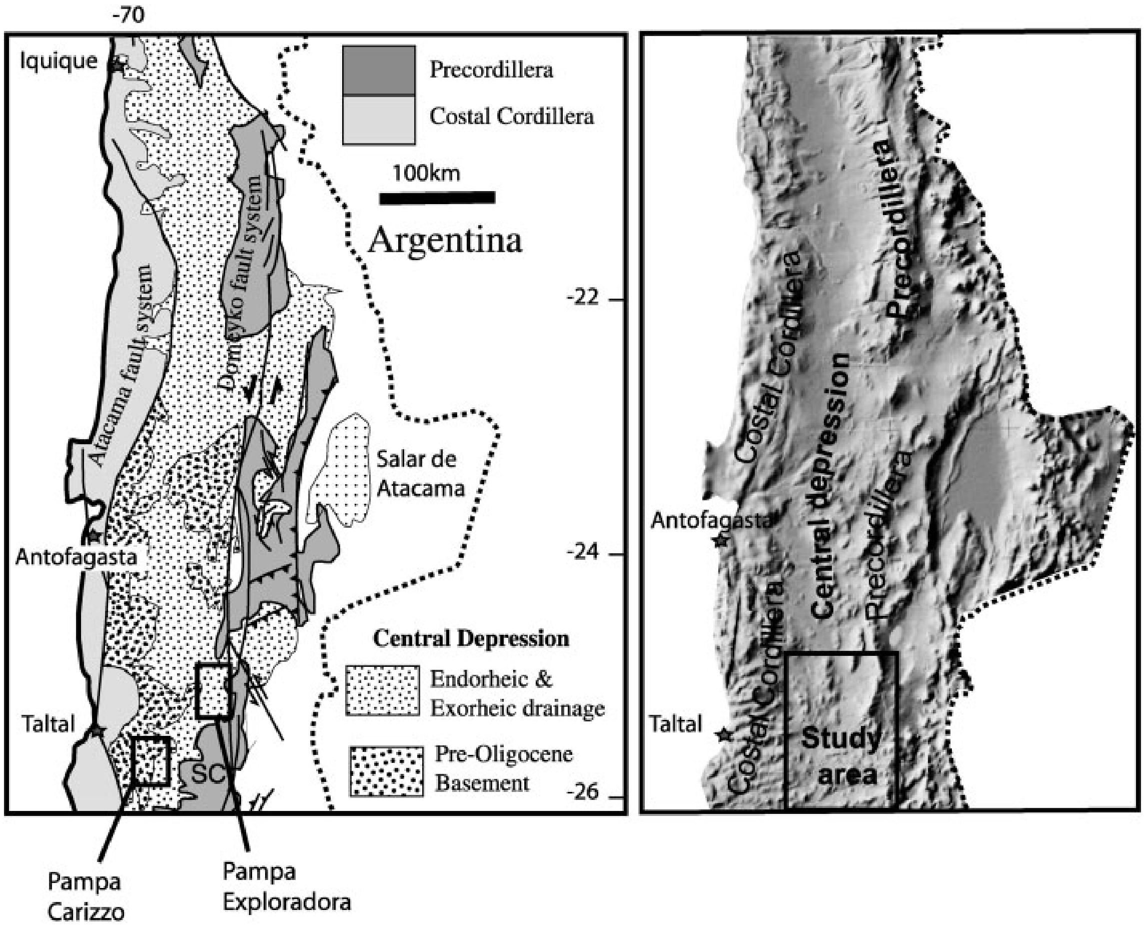


Figure 1 Tectonic framework of northern Chile. Location of the area studied in the Central Depression along the western flank of the Precordillera. SC: Sierra Castillo fault system

Reutter *et al.*, 1991; Niemeyer, 1999; Tomlinson *et al.*, 1999). These deformation episodes induced localised rotations of small-scale crustal blocks (palaeomagnetically constrained) during Eocene activity of the Precordillera fault system (Arriagada *et al.*, 2000; Randall *et al.*, 2001), reported east of our study area along the eastern border of a major N–S-trending strike-slip fault zone. Once again, however, no neotectonic activity has been reported along the Domeyko Fault zone.

Based on relationships between tectonics and morphology, this paper aims to demonstrate the presence of Pliocene to Quaternary active faulting and folding along the piedmont of the Precordillera in the Central Depression, bisecting Pliocene to Quaternary alluvial deposits (Fig. 1). We concentrate particularly on geomorphological aspects. As is commonly the case, it is difficult to find datable markers that would constrain slip rates. However, this zone in the Central Depression contains some remarkable geomorphology that provides insight into how drainage systems in arid areas respond to tectonics. Thus this paper also discusses the relative chronology between the intermittent rivers and the tectonic scarps.

Basin history and infilling morphology

Throughout the Neogene, the Central Depression acted as a significant drainage basin for water input from the east that flowed into the area (Sáez *et al.*, 1999; Hartley and Chong, 2002). From the Upper Paleogene to Pliocene (Mortimer, 1973; Riquelme *et al.*, 2003), the Central Depression was an endorheic area (Fig. 1; Mortimer, 1980; Chong *et al.*, 1999). Pedimentation followed drainage incision and the resulting pediplain constitutes a single surface throughout the southern Atacama desert (Fig. 2).

Major post-Neogene deposition zones in the area studied, between 25°30S and 26°30S, are, from east to west, Pampas Exploradora, Dona Ines Chica and Carrizo (Fig. 2). In these plains, overlying the Atacama Gravels Formation large coalescing and dissected alluvial fans, deposited by streams coming directly from the Precordillera, cap the Atacama Gravels and cover the valley floor (Figs 2 and 3). The basin fill in Pampas Exploradora and Carrizo (Figs 1 and 2) comprises series of Neogene to Pliocene continental deposits, locally more than 300 m thick, defined as the 'Atacama Gravels' (Fig. 2C and D).The Neogene Atacama sequence corresponds to fluviatil econglomerates (Mortimer, 1969, 1973). The lower series (17–15 Ma in the Precordillera; Cornejo and Mpodozis, 1996) covers an erosional palaeotopography that developed in the Tertiary deformed layers (Fig. 2C and D). Around 26°21′S, in the valley flanks of Rio Salado, an ignimbrite interbedded within the lower part of the Atacama Gravels Formation provides a radiometric age of 12.6 ± 0.5 Ma (Clark *et al.*, 1967; Mortimer, 1973). At the base of the pediplain (26°55′S) on the flanks of San Andres valley, two samples provide the youngest radiometric age (9.15 ± 0.25 Ma) for a marker interstratified in the upper Atacama sequence (another ignimbrite; Clark *et al.*, 1967; Mortimer, 1973). Riquelme *et al.* (2003) concluded that deposition of the San Andres ignimbrite marks the end of the aggradation episode before the beginning of a new phase of incision.

In previous studies, Alpers and Brimhall (1988, 1989) suggest that desertification in the Atacama region began at

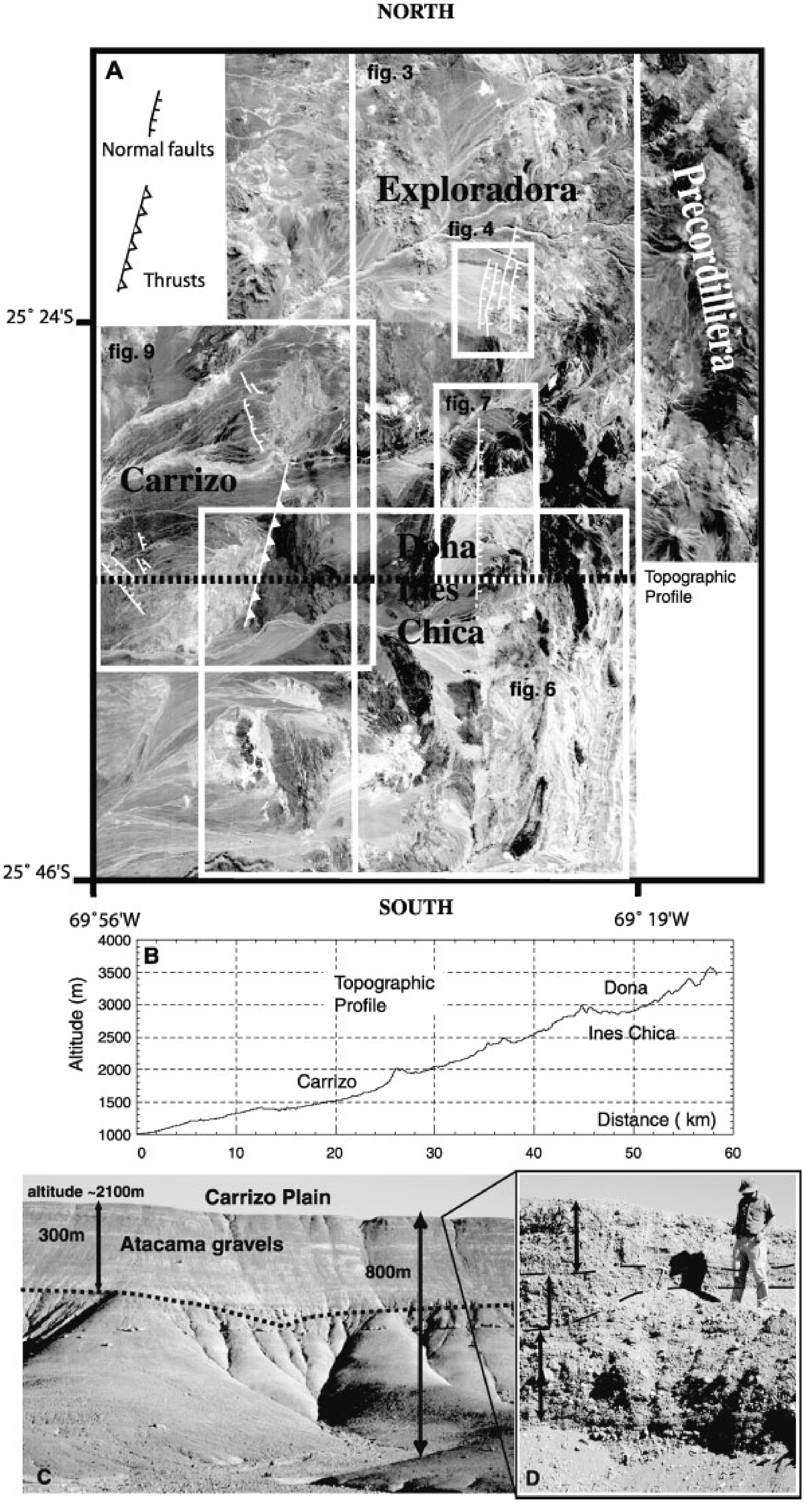


Figure 2 (A) Aster Satellite image, and locations of the following figures. White boxes represent field surveys. (B) Topographic profile. (C) Photograph of Carrizo Canyon, looking from the bottom towards the southern flank of the canyon. Cliffs are composed of multiple debris flow series within the Atacama Gravels, with the whole formation lying on a palaeosurface. (D) Pampa Exploradora alluvial deposits, lying in a secondary valley along the intermittent river network, on the top of the Atacama Gravel Formation. They consist of distinct nested fill terraces showing more rounded stream gravel with sandy matrix (see Fig. 4 for location)

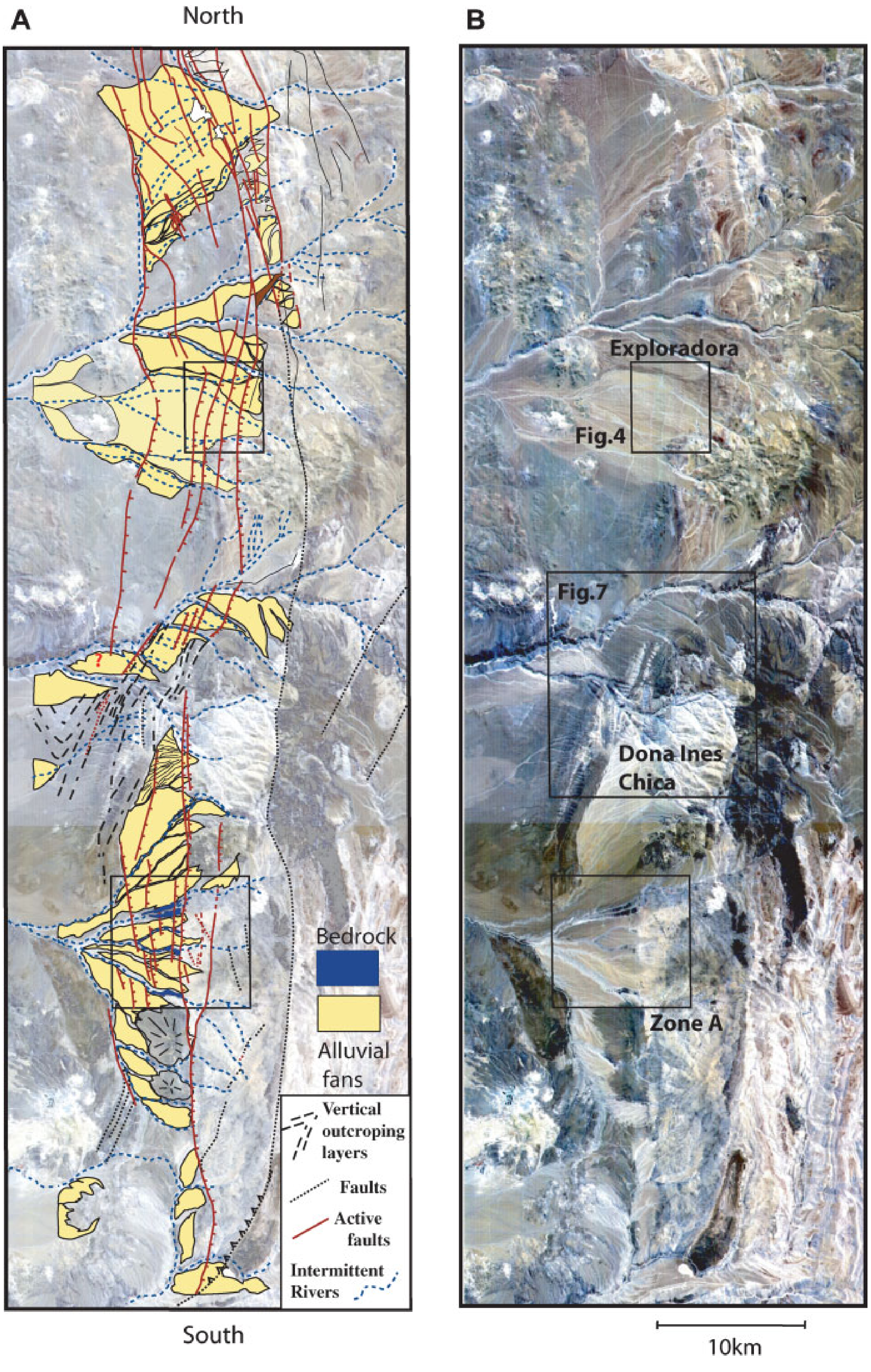


Figure 3 (A) Morphotectonic interpretation. (B) Aster Satellite image. Alluvial fans affected by active normal faults in Pampa Exploradora and Pampa Dona Ines Chica. In Zone A, the bedrock is uplifted and appears darker

14 Ma during global climate desiccation. Sedimentological data from middle Miocene to upper Pliocene formations in the modern Atacama desert, however, indicate that a semi-arid climate persisted from 8 to 3 Ma, with a peak of aridity around 6 Ma (Hartley and Chong, 2002). Together with new cosmogenic ages ranging between 5.5 and 6 Ma (neon ages; Manuel Moreira, IPG Paris, personal communication, 2003), This suggests that the major alluvial fans are related to this hyperarid period (Hartley and Chong, 2002). This is consistent with detailed studies in the northern part of the Central Depression (20°S to 23°S), north of our study area, which proposed that between 6 and 3 Ma, Precordillera-derived sediments formed extensive alluvial fan deposits in the Central Depression (Saez *et al.*, 1999; Kober *et al.*, 2002). Moreover this strongly suggests that the alluvial fans in Pampas Exploradora, Dona Ines Chica and Carrizo comprise such typical Pliocene deposits and, as well, younger Quaternary deposits.

Alluvial fan morphology and interaction with fault scarps

For the past few millions of years, continued incision (see discussion on uplift) in the arid environment led to the development of rills and gullies that dissect the surface of the Plio-Quaternary deposits. Major canyons can reach up to hundreds of metres deep (Quebrada Carrizo, Fig. 2C and D), but minor streams that dissect major alluvial fans (Fig. 3) entrench in some places up to 20 m into the alluvial surfaces (Fig. 4).

Most of these gullies are interrupted by N–S striking structures well developed on either side of the scarps, as can be seen on Fig. 4. They are in places continuously disposed from one side to the other of the scarps and no lateral offset is observed. Some of them are disconnected from upstream water inflow by the escarpment (Fig. 4), and thus mark the existence of the drainage network prior to the development of the topographic relief. As the pale lineaments on the images are systematically associated with escarpments (Fig. 4), this strongly suggests tectonic origin of the scarps after the development of the intermittent network. On Fig. 4, as the rivers encounter the scarps, they either stop, traverse or are deflected. From place to place, the stream response to growing scarps is either an increase of erosion or deposition at the base of the fault scarp. The intermittent river will tend to cross the facing fault scarps if the rate of stream incision is equivalent or greater than the growth rate. This is possible particularly if the river course is established before tectonic deformation occurs.

Indeed only major streams are able to entrench the newborn relief, incise and cross again tectonic active scarps in order to reconnect with their pre-existing bed downslope. Figures 4 and 5 demonstrate that minor streams are not able to do this. As the faults grow, temporary sag ponds (up to several metres across) develop, showing distinctive shapes at the base of the scarps (Figs 4 and 5). The term 'sag pond' is used here to describe the small shallow enclosed flat basins in this desertic area. These basins flood after storms and then they rapidly dry out through evaporation and infiltration of the water into the surrounding substrate. The rounded sag ponds are smaller and indicate small inflows (on Fig. 4), whereas the triangular larger ones may be associated with larger inflows (Fig. 4). The ponding results in the deposition of fine material at the base of the active fault scarps. These process interactions lead to the preservation of a series of nested surfaces along the major streams (Figs 4 and 5). Kober *et al.* (2002) proposed an erosion rate of about 20 cm Myr^{-1} in the northern Atacama Desert (average rate between 17 and 23 cm Myr^{-1}, from the alluvial deposits to the Neogene bedrock, using ^{21}Ne and ^{10}Be analyses), where higher degrees of erosion are suspected. It follows that the smallest scarps in our region, of about 1 m high, should be younger than 5 Ma, or they would not be preserved and visible to do.

Vertical faulting and geomorphology along the western flank of the Precordillera (Pampa Exploradora and Dona Ines Chica)

In the eastern Pampas, the relief is the results of a series of escarpments, cutting vertically through the alluvial deposits at relatively high angles (Figs 4 and 5). In plane view, the scarps are continuously distributed parallel to older tectonic structures. The Exploradora fault segments are located north of the Dona Ines Chica segments and of the Sierra Castillo Fault that lies lying parallel to the Domeyko fault system on its western side (Figs 3 and 6; Cornejo, 1993). The Exploradora and Dona Ines Chica segments form vertical and sometimes composite scarps about 5–10 m high, the dip direction of which (towards the east) never changes along strike (Figs 3–8). Such constant dip direction (Fig. 3) is commonly associated with surface normal fault throws (Philip and Meghraoui, 1983).

Mapped from an aerial photograph enlargement and field work, Fig. 4 focuses on some of the vertical faults in Pampa Exploradora. The successive surface deposits are cut by three main fault scarps, parallel, east-dipping, nearly perpendicular to the dry 'river' runoff that dissects the fan surfaces (Fig. 5). Figure 4, based on analysis of aerial photographs and satellite images shows that the fault segments offset at least three alluvial fan generations (four nested surfaces, Fig. 4) deposited on the piedmont of the Precordillera. The vertical throws become smaller as the offset surface becomes younger (Fig. 5). The faults also affect the most recent sediments deposited inside the intermittent valleys. This attests to repeated activity of the faults during fan emplacement and dissection phases (Fig. 5). There are four main surface levels at the site: S4 is the active floodplain, S3 is the surface last abandoned by the stream, S2 and S2′ are intermediate upper levels and S1 is the highest level corresponding to the ancient fan surface (Fig. 4). On Figure 4, the nested young surfaces are clearer than the oldest ones and in the field no dark varnished pebbles can be identified on the former in contrast to what is observed on the oldest ones. Surface S2 and S2′ are incised by the most recent gullies or rills (Fig. 4). Two main channels on each side of the cone-shaped landform supply the floodplains with fine sediments that accumulate along fault scarps (Fig. 4). The intersection of major streams and normal scarps delimits V-shaped foci of deposition (ponding) as in zones on Fig. 4 in marked 1. This is the main indication of interaction between active faulting and erosion in this area.

To the south of the Exploradora fault system extends a domain of ancient fault systems trending N25°E (Figs 3 and 6). The Sierra Castillo fault has been described as a subvertical strike-slip fault, trending N–S, juxtaposing Palaeozoic rocks on the east against Cretaceous volcanic sequences on the west (Fig. 6; Tomlinson *et al.*, 1993). South of the Sierra Castillo Fault, the Agua Amarga fault is a high-angle west-dipping reverse fault, placing the same Jurassic volcanic formations on the west over Palaeocene to Lower Eocene volcanic units on the east (Fig. 6; Mpodozis *et al.*, 1995). Despite the different nature of the fault segments, both belong to the Domeyko fault system (Fig. 6). The timing and nature of movement of these

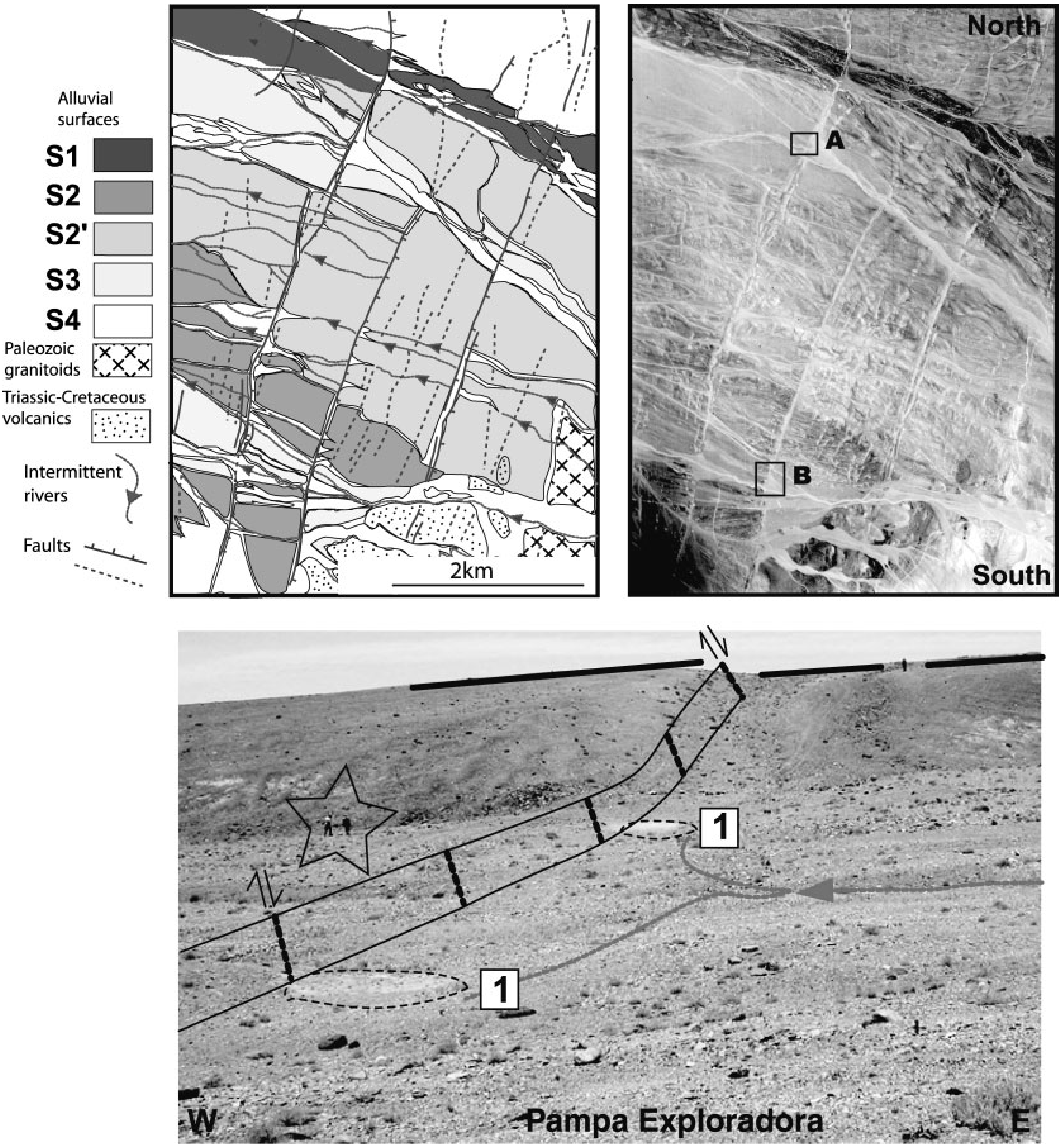
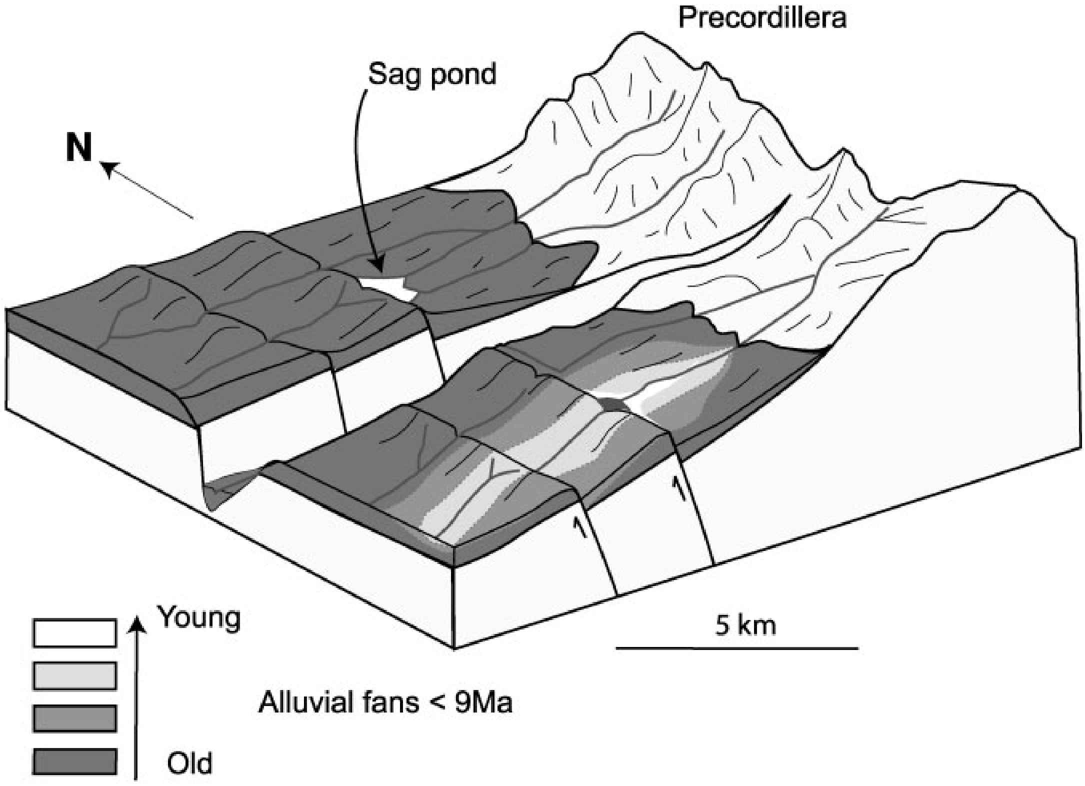


Figure 4 Aerial photography and interpretation of the normal fault zone, in Pampa Exploradora around 3500 m. Boxes A and B show the location of Fig. 2C and Fig. 5b, respectively. S1 to S4: successive nested alluvial surfaces. The scarps are linear and continuous. The Exploradora segments form small vertical and composite scarps about 5–10 m high, the dip direction of which (towards the east) never changes along strike. No lateral offset can be identified along these fault traces. The scarps are coupled with neighbouring secondary synthetic faults that create small half-graben where Quaternary sediments are trapped. Photograph of modern stream-cut and deposition in Pampa Exploradora. Sag ponds are preserved on the present-day river bed along the fault throw. The valley walls are about 30 m above the modern channel and show a larger (cumulative) vertical throw. 1: small recent sag ponds

fault segments are poorly constrained. They cut Cretaceous rocks in a sinistral transpressional movement, show some transpressional movement in Eocene–Oligocene times and are partly overlain by the Miocene to Neogene Atacama Gravels (Tomlinson *et al.*, 1993). Nothing more recent has been reported.

In Pampa Dona Ines Chica, lying west of the Sierra Castillo (SC) fault, a linear normal fault cuts through the most recent surfaces that cap the Atacama Gravels (Figs 3 and 6). This fault segment is aligned with the Pampa Exploradora fault system (Fig. 3). Secondary parallel scarps dipping to the east cut through the same alluvial fans. Mapped from aerial photograph enlargement and in the field, Fig. 7 focuses on the SC fault zone and recent normal faults. The pale uniform surface deposits are cut by numerous gullies running downslope to the west that dissect the fan surfaces (Fig. 7). The fault scarp is rather continuous and trends N–S perpendicular to the gullies and the average slope (Figs 3 and 7b). Most of the streams are intercepted by



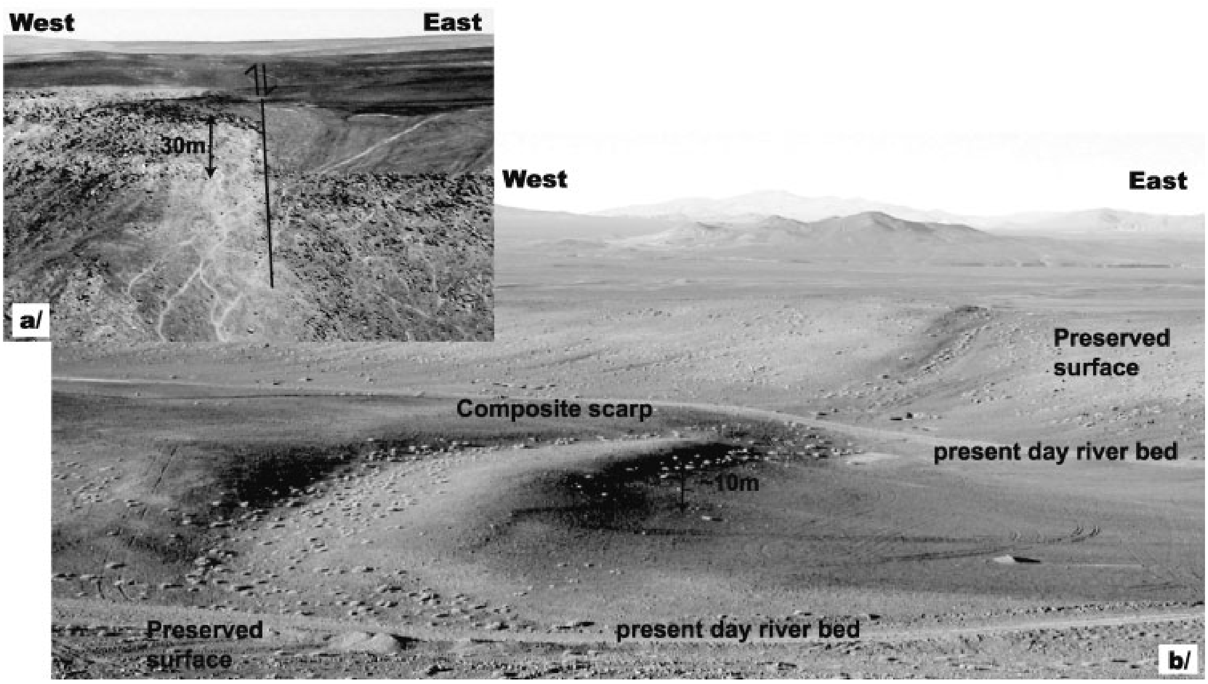


Figure 5 Block diagram showing the interaction of the pre-existing intermittent river network and the development of normal fault scarps in the Exploradora Fault zone. Interpreted after Fig. 4. Photographs: (a) type example of a major normal fault scarp, 30 m throw, cropping out in the Carrizo canyon (looking north to the flank of the Pampa Exploradora). (b) View north across river cut cross-section of a fault scarp at Dona Ines Chica site (see Fig. 4 for location)

the fault scarp, and are then deflected downslope at the base of the scarp (Figs 7 and 8). As the streams cross the scarp, the stronger degree of incision toward the west is clear (Fig. 8). This typical increase in incision from one side of the fault to the other can be related to the progressive uplifting and tilting of the western block toward the west (Fig. 8; Jackson *et al.*, 1996). Topographic profiles were surveyed with two fixed receivers and one mobile receiver of ASHTEC type. Cross-cutting profiles generate a relative resolution of about 10 mm on average. In order to assess varying vertical throws reported in the nested surfaces, we measured both flanks of a type example valley (Fig. 8c) where we identified a terrace. Figure 8b

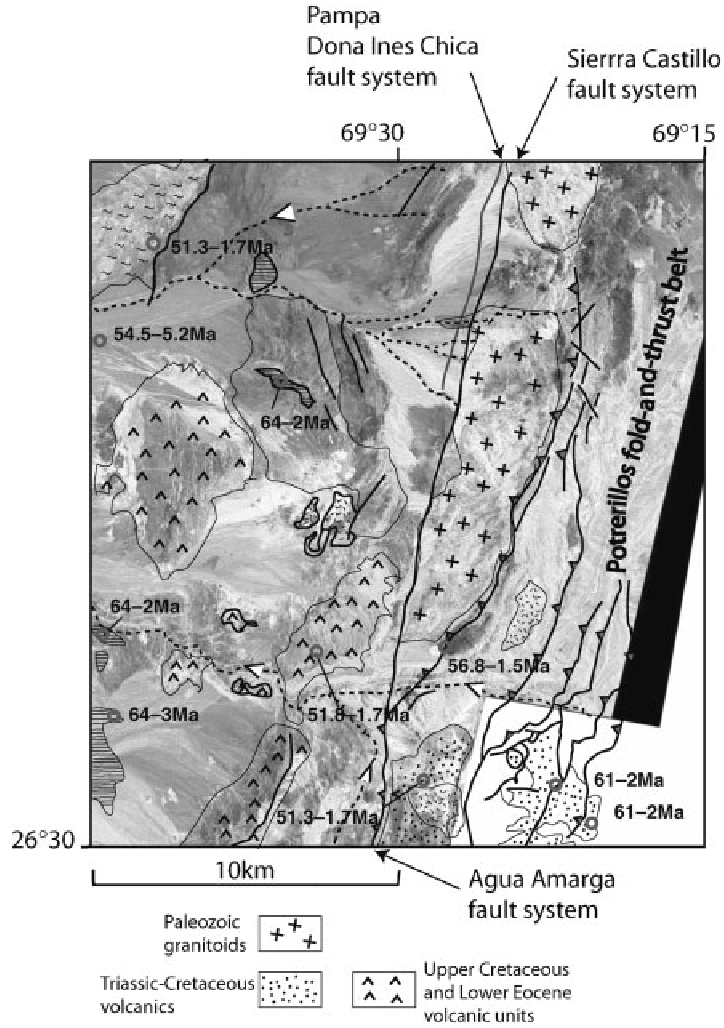


Figure 6 Simplified geological map of the Dona Ines Chica area, showing fault of Eocene age superimposed on the Aster satellite image of the area. The Sierra Castillo system operated as a strike-slip fault at this time (ages after Tomlinson *et al.* (1993) and Mpodozis *et al.* (1995))

indicates that the valley flanks show about 8 m of vertical displacement versus 5 m for the terrace. Moreover, no convexity of the uplifted surface that would be induced by folding and thrusting can be observed (Fig. 8b). This strongly suggests that these vertical throws are associated with surface normal faulting. This surficial normal faulting can be identified in places in the older volcanic and underlying bedrock (Niemeyer, 1999; Figs 5 and 6). In one particular locality (see Frame A on Fig. 3) the bedrock is uplifted on the hanging wall and appears dark blue on the satellite image in the main valleys on the western side of the normal fault zone.

No lateral offset can be identified systematically along these fault traces, thus the deformation pattern in eastern Pampas is not linked to any strike-slip system. The scarps are coupled with neighbouring secondary synthetic faults that create small half-grabens or fault-angled depressions (Figs 4 and 5). This particular morphology is also typical of normal fault sets (Burbank and Anderson, 2001). These arguments, coupled with field studies, enable the characterisation of the Exploradora and Dona Ines Chica fault (Fig. 3) as a network of more or less N–S striking, parallel vertical faults (Fig. 5). Once kinematic evidence is available in these conglomerates, however, it may be these vertical throws could be associated either to normal faults or to overturned thrusts, deflected along bedding and showing a normal sense of displacement (Philip and Meghraoui, 1983).

Reverse faulting and folds in the Central Depression (Pampa Carrizo)

To the west, in the topographically lower (<2000 m) Pampa Carrizo, the Central Depression shows the same sedimentary infill, the Atacama Gravels and the same surficial alluvial deposits (Fig. 2C and D). Some sparse evaporitic deposits (paler than the neighbouring alluvial fans) also can be recognised cropping out on top of the alluvial deposits (Fig. 9). These are not dated and have barely been described.

The Carrizo fault zone comprises short (tens of metres long), parallel synthetic (Fig. 9, frame B and Fig. 9c) and antithetic normal fault scarps (Fig. 9, frames A and C), with very different patterns from those observed in the Exploradora area, and a major thrust (Fig. 9b). The small normal scarps show a N170°E trend. The normal faults consist of graben and tension cracks that represent extensional deformation at the top of a fold. They are disposed en échelon with respect to the main thrust fault (Figure 9b) and thus could be associated to the strike-slip component of a blind thrust, as no vertical throw can be identified at the surface linked to this fault set. This obliqueness of the grabens with respect to the main thrust reveals a left lateral component of compressive deformation.

These extensional structures are developed in the major alluvial surfaces and interact with the intermittent network that

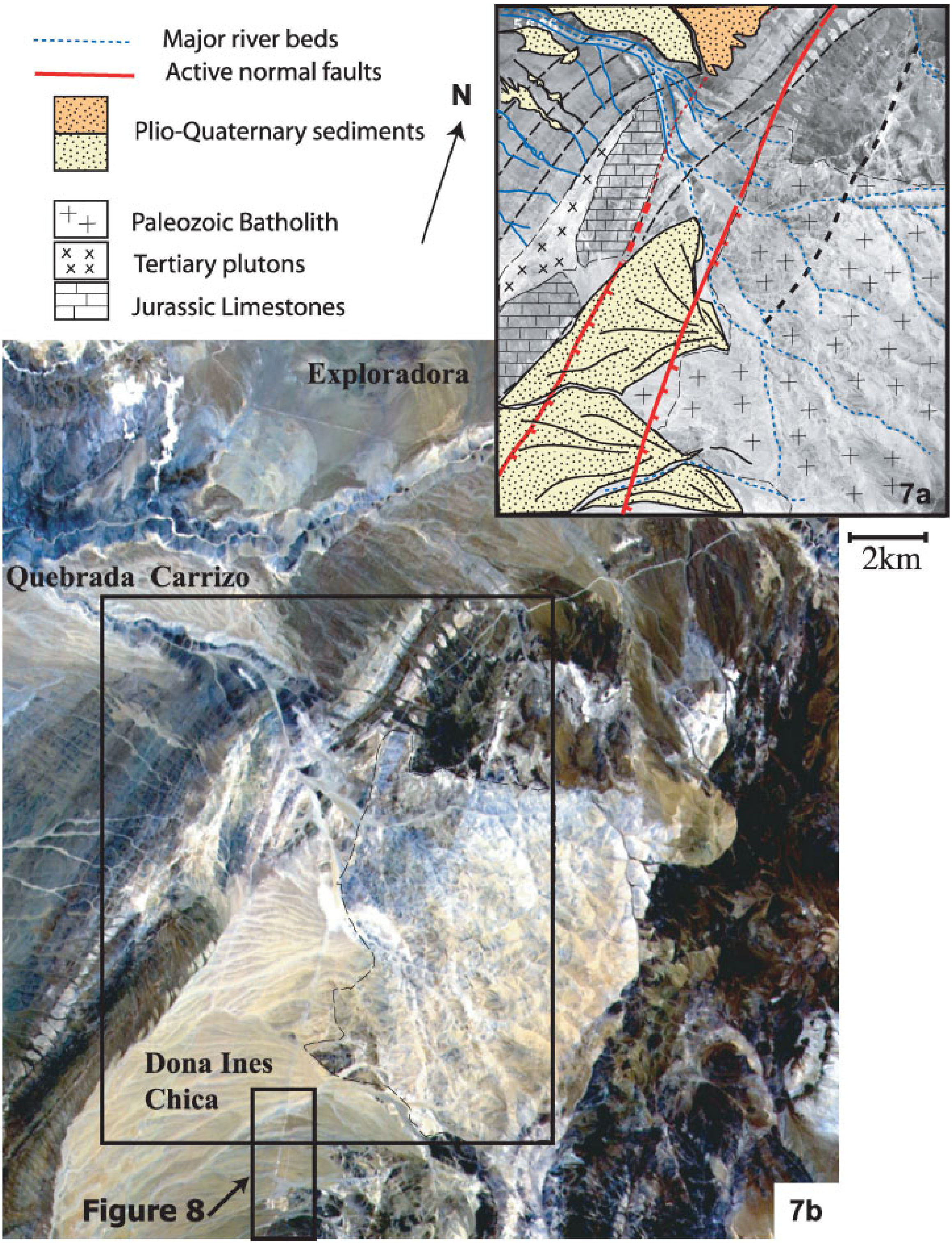


Figure 7 Aster satellite image and aerial photography. Morphotectonic interpretation of the normal fault zone that connects the Exploradora and Pampa Dona Ines Chica fault sets. Geological map after Niemeyer (1999) and Cornejo *et al.* (1993)

dissects the fan surfaces (Fig. 10). The most recent deposits are sometimes captured inside the graben, as in Figs 9 (frame C) and 10 (frames A and C), in which case the course of the rivers is deflected towards the edges of the faults where the scarps decrease in height (Fig. 10c and d). A recent field trip has identified a number of these graben and tension cracks (Fig. 9, frame C) that cross the intermittent channels. Indeed such antithetic normal faults are expected to form along the top surface of a folded area, where the tensile stresses accumulate along the convex region of the folded surface (Philip and Meghraoui, 1983). The edges of the small grabens are eroded by the gully networks, implying that they do not show any sign of repeated activity in the present-day floodplain (Fig. 10).

As the stream encounters an obstacle, it is deflected inside the tectonically created grabens (Fig. 10), toward a lower local base level (i.e. the bounding stream). This causes the stream to develop temporarily to the north along the fault scarps (Fig. 10a), which deflects the flow pattern of the southern river towards the bounding northern river that displays a lower or equivalent stream (Fig. 10c, Jackson *et al.*, 1996).

In frame B (Fig. 9), the graben structure shows a distinctive map pattern expressed by older alluvial fan deposits. The

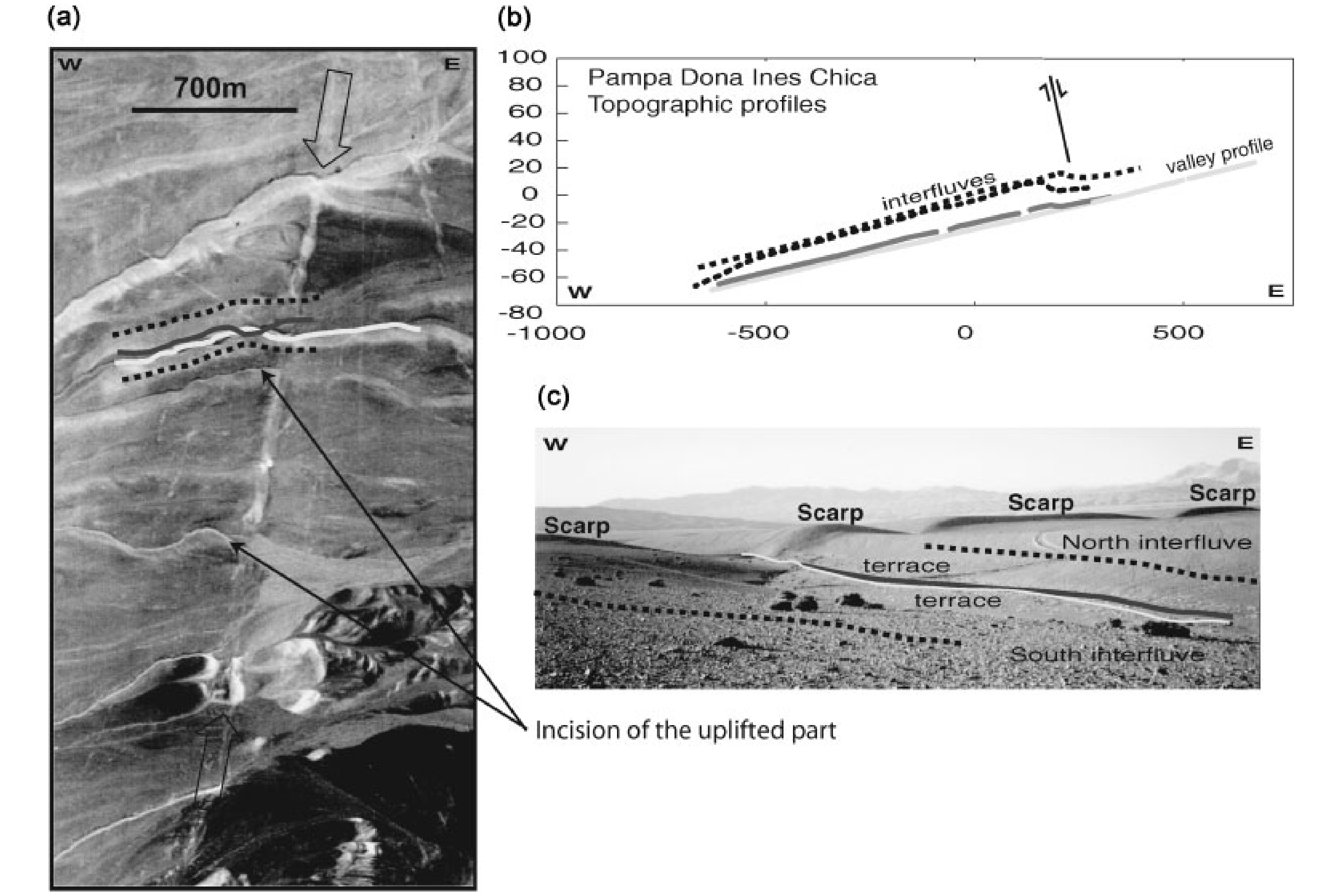


Figure 8 Aerial photograph and close-up view to the northwest of the Dona Ines Chica fault system. Profiles in (b) are reported from the topographic profiles across the scarp (projection 85°N) in (a), following the river bed

darker, older fan is preserved and tilted by warping and locally forms a triangular pattern (frame B, Fig. 9c), with the eastern side of the triangle marked by the normal fault throw.

Surface deformation above blind reverse faults or a fold is often characterised by these typical small graben, cracks and short normal faults. Those small graben look like extrados fault sets, parallel to the direction of the fold axis and in this case showing a slight angle with the direction of the major regional thrust that reaches the surface (Figs 9 and 10). In this case, they most probably represent the surface expression of a broad warp along an anticlinal crest.

The presence of an emergent thrust fault (Fig. 9) in this same area supports the hypothesis that the surperficial folding is the result of possible blind thrusting. Indeed surface mapping using aerial photographs together with field work indicate that this emergent thrust trends N20°E and dips to the east with a high vertical angle that intersects the ground surface. It is 10 km in length and appears to die out to north and south (Fig. 9). The fault plane crops out and this structure is marked along much of its length by a topographic escarpment several metres in height. Folded volcanics crop out on the eastern side of the linear scarp. The outcropping layers are vertical and do show some differential erosion patterns that disrupt the downslope course of the intermittent rivers. On the western side of the scarp (Fig. 9) this suggests that only evaporites and subhorizontal recent alluvial formations are preserved from erosion. The age of movement of these NE–SW-trending reverse faults thus can be constrained to be younger than the coalescing surficial alluvial fans. The trend relationship between graben (Fig. 10) and the reverse fault (Fig. 9) suggests that they are kinematically related to movements on some underlying old reactivated thrust. This implies that the Plio-Quaternary alluvial surfaces could be affected by a NNE–SSW fold system (Figs 9 and 10).

Conclusions

We report the recent deformation history of a part of the southern Atacama Desert that is characterised by folding and faulting neither seismic activity nor clear-cut signs of neotectonics during the Plio-Quaternary timespan have been reported previously from this region. Despite the seismically disrupted morphology, there are no historical or instrumental records of recent superficial earthquakes in the area. Two contrasting tectonic styles can be distinguished in the study area, as observed previously in the north of Chile (Victor, 2000). We propose here a new hypothesis to explain neotectonic activity during the Plio-Quaternary period in the Central Depression. North-south-trending and high-angle dipping faults are active in the upper part of the Central Depression. Vertical throws identified on the surface of coaslescing alluvial fans, vary between 1 m in the present-day river beds to 30 m recorded on the top of the Atacama Gravels sequence. These appear at the surface to be normal faults most probably corresponding to old reactivated overturned thrusts or strike-slip vertical faults (Fig. 11). Folds and thrusts trending NNE–SSW are active in the lower part of the Central Depression. We can distinguish cracks and normal faults on the top of the fold and a major thrust (Fig. 11). The major problem in the analysis of the surface morphology and deformation is to infer the presence of a tectonic feature at

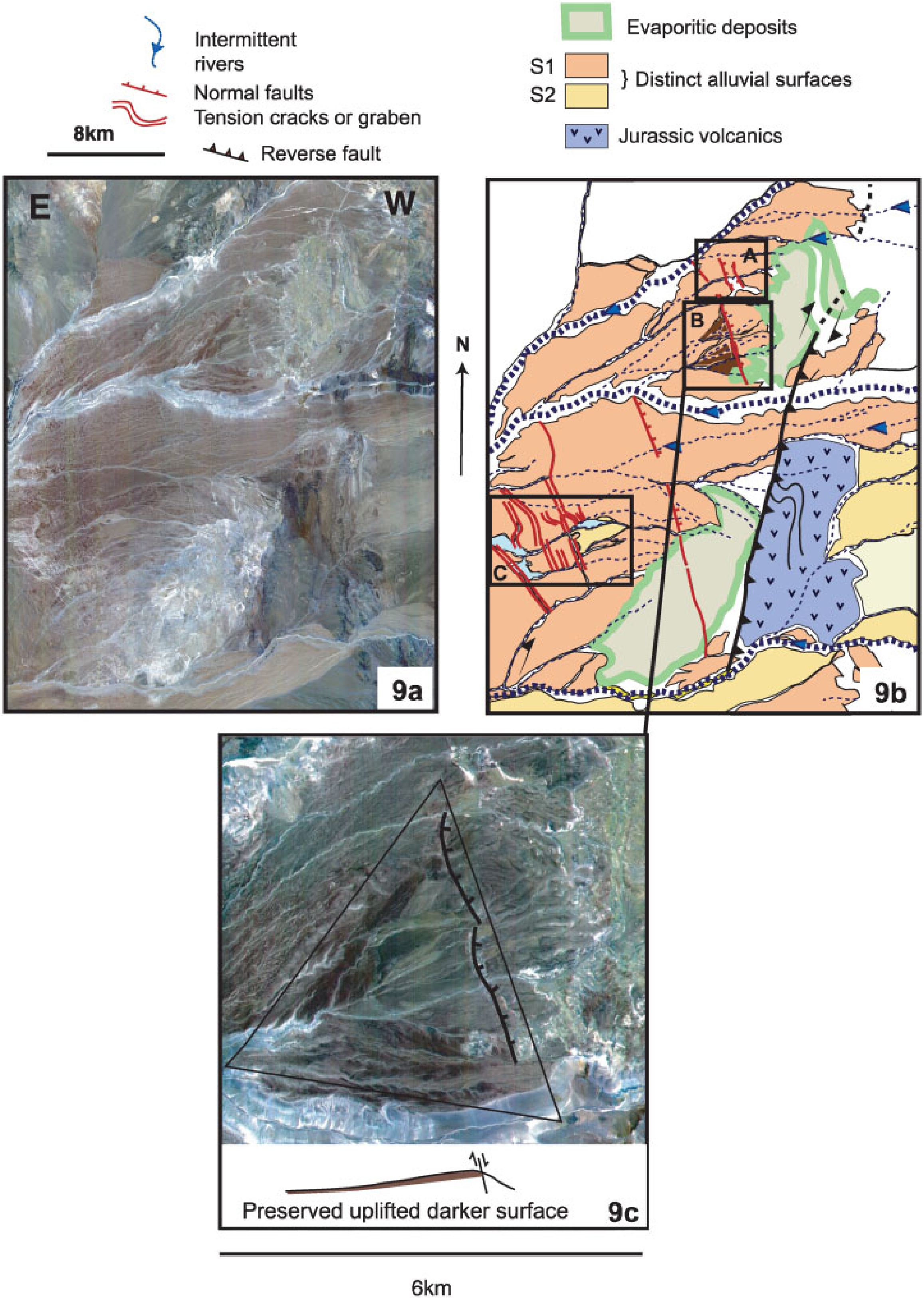


Figure 9 (a) Aster view of Pampa Carrizo. (b) Tectonic interpretation of the Pampa Carrizo area. Tension cracks define small graben. Zone A: some recent deposits are captured inside the axial depression in the small graben. Zone B: darker and probably older preserved fan deposits are tilted and form a triangular parttern. Zone C is detailed on Fig. 10

depth, but it is possible to propose an interpretation (Fig. 11) because these surficial geomorphological markers help to define a regional compressive deformation.

Some questions remain considering the reactivation of major tectonic features in relation to the Neogene Domeyko fault system. Since 10 Ma an E–W compressional regime in the lower part of the Central Depression (Pampa Carizzo) seems to have coexisted with evidence of an extensional regime (Pampa Exploradora), currently active, in the upper part of the Central Depression and Precordillera. The observation of synchronous

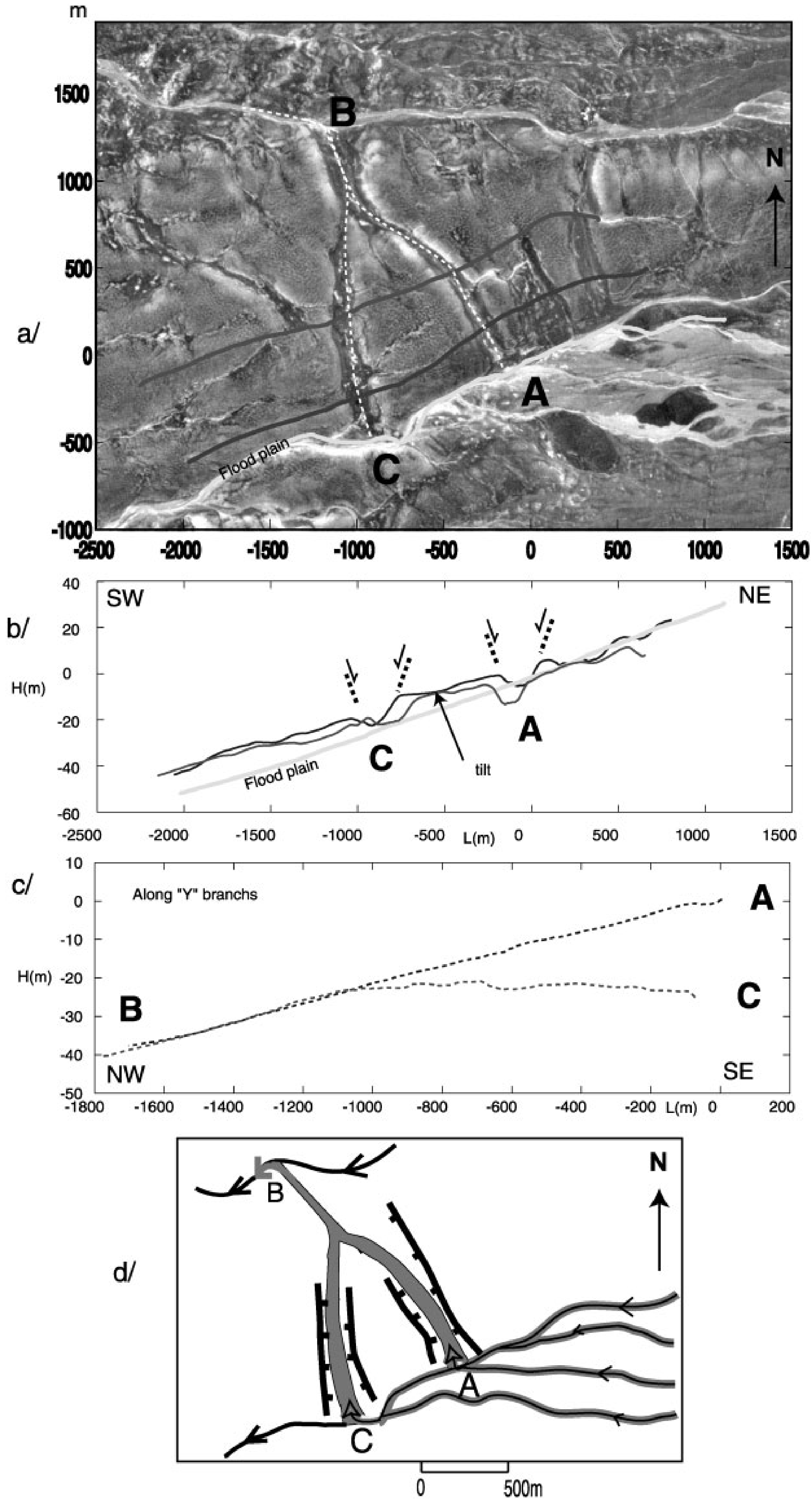


Figure 10 (a) Aster close-up view of Pampa Carrizo. (b) Downslope topographic profiles. (c) Topographic profiles following the 'Y' branches and the path of captured deflected old river courses. (d) Sketch interpretation of the temporary river catchment

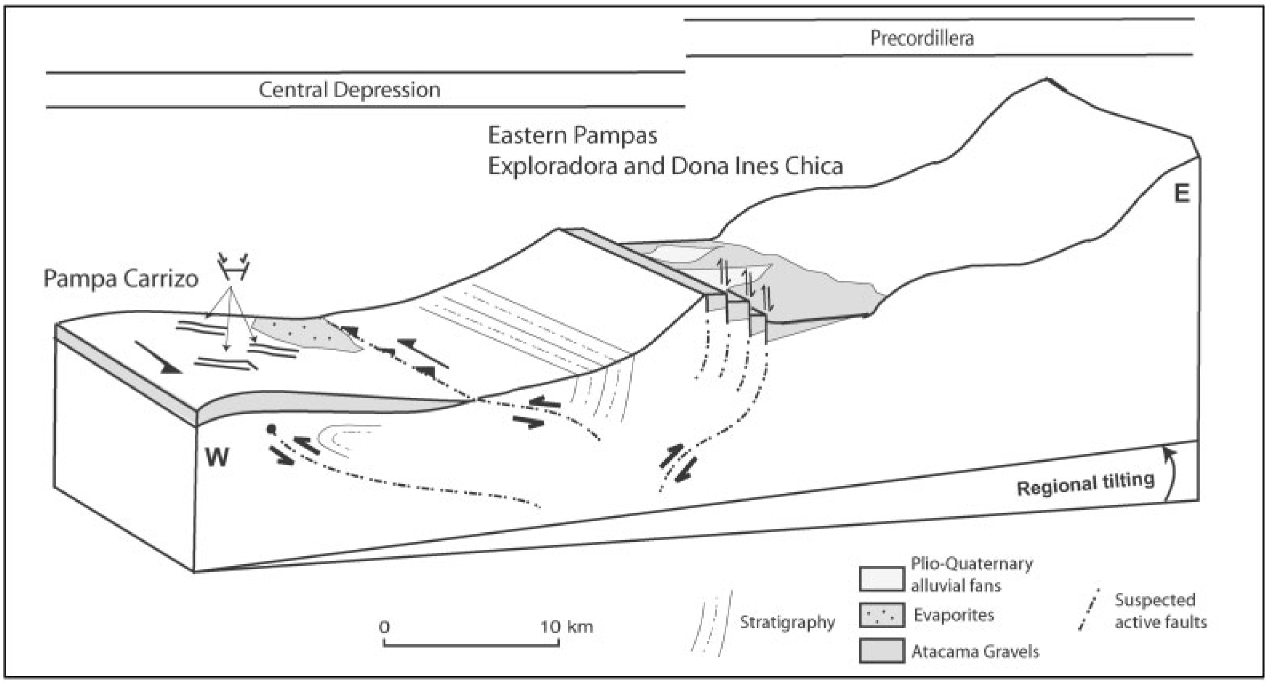


Figure 11 Regional relative location of Plio-Quaternary tectonic activity recorded in the Neogene sediments and Quaternary alluvial fans. Proposed schematic cross-section at 26°S illustrating southern Atacama neotectonics

Plio-Quaternary extensional and compressional tectonics reported in the Central Depression area may result from a combination of several factors.

(1) A very important fault system, the Domeyko fault system, in particular the older Sierra Castillo strike-slip structures, orientated roughly parallel to the Plio-Quaternary extension, is inherited from the Palaeogene.
(2) It is usually considered that old strike-slip or thrust structures could be reactivated in a set of vertical normal faults as we observe here along the Precordillera piemont.

These active fault sets, however, could not result from a giant landslide in view of the repeated activity on the Exploradora fault sets that reflect clear recurrent neotectonics. Moreover, normal east-dipping faults are not associated with a major antithetic west-dipping normal fault that should accompany any giant landslide initiated along the piedmont of the Precordillera. Consequently these vertical faults must result from the reactivation of older structures and overturned thrusts. In the lower area, the en échelon pattern of the graben indicates that the regional shortening direction is oblique to the pre-existing fault trend. To conclude, we propose that the significant normal and reverse faults described here may be derived from the uplift of the Central Depression in relation to the Precordillera mountain range. The deep (800 m) and narrow valleys that run from the Precordillera south of 25°S would have formed as a result of the change in base level following regional uplift of the western side of the Precordillera (Riquelme *et al.*, 2003). This can be reconciled in a single model: the vertical faulting, the fold and thrusts could result from regional uplift and tilting west of the Andean system (Victor, 2000).

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References

Alpers C, Brimhall GH. 1988. Middle Miocene climatic change in the Atacama Desert, northern Chile: evidence from supergene mineralization at La Escondida. *Geological Society of America Bulletin* **100**: 1640–1656.

Alpers C, Brimhall GH. 1989. Paleohydrologic evolution and geochemical dynamics of cumulative supergene metal enrichment at La Escondida, Atacama Desert, northern Chile. *Economic Geology* **84**: 229–255.

Arabasz WJ. 1971. *Geological and geophysical studies of the Atacama Fault Zone in Northern Chile*. PhD thesis, California Institute of Technology, Pasadena, CA.

Armijo R, Thiele R. 1990. Active faulting in northern Chile: ramp stacking and lateral decoupling along a subduction plate boundary. *Earth and Planetary Science Letters* **98**: 40–61.

Arriagada C, Roperch P, Mpodozis C. 2000. Clockwise block rotations along the eastern border of the Cordillera of Domeyko, northern Chile. *Tectonophysics* **326**: 153–171.

Brown M, Diáz F, Grocott J. 1993. Displacement history of the Atacama fault system 25°S–27°S, northern Chile. *Geological Society of America Bulletin* **105**: 1165–1174.

Burbank DW, Anderson RS. 2001. *Tectonic Geomorphology*. Blackwell Science: Oxford.

Chong G, Mendoza M, Garcia-Veigas J, Pueyo JJ, Turner P. 1999. Evolution and geochemical signatures in a Neogene forearc evaporitic basin: the Salar Grande (Central Andes of Chile). *Palaeogeography, Palaeoclimatology, Palaeoecology* **151**: 39–54.

Clark A, Mayer A, Mortimer C, Sillitoe R, Cooke R, Snelling N. 1967. Implications of the isotopic ages of ignimbrotoc flows, Southern Atacama, Chile. *Nature* **215**: 723–724.

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

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

Delouis B, Philip H, Dorbath L, Cisternas A. 1998. Recent crustal deformation in the Antofagasta region (northern Chile) and the subduction process. *Geophysical Journal International* **132**: 302–338.

Formento-Trigilio ML, Burbank DW, Nicol A, Shulmeister J, Rieser U. 2003. River response to an active fold-and-thrust belt in a convergent margin setting, North Island, New Zealand. *Geomorphology* **49**(1–2): 125–152.

Hartley AJ, Chong G. 2002. Late Pliocene age for the Atacama Desert: implications for the desertification of western South America. *Geological Society of America Bulletin* **30**: 1, 43–46.

Holbrook J, Schumm SA. 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. *Tectonophysics* **305**(1–3): 287–306.

Jackson J, Norris R, Youngson J. 1996. The structural evolution of active fault and fold systems in central Otago, New Zealand: evidence revealed by drainage patterns. *Journal of Structural Geology* **18**: 217–234.

Kober F, Schlunegger F, Wieler R, Ivy-Ochs S, Simpson G. 2002. Determination of erosion rates in a decoupled river and pediplain system in the Central Andes, Northern Chile. *Fifth International Symposium, Andean Geodynamics*, Toulouse, France; 347–349.

Molnar P, Brown ET, Burchfiel BC, Qidong D, Xianyue F, Jun L, Raisbeck GM, Jianbang S, Zhangming W, Yiou F, Huichuan Y. 1994. Quaternary climate changes and the formation of river terraces across growing anticlines on the north flank of the Tien Shan, China. *Journal of Geology* **102**: 583–602.

Mortimer C. 1969. *The geomorphological evolution of the southern Atacama desert, Chile*. PhD thesis, Department of Geology, University College of London.

Mortimer C. 1973. The Cenozoic history of southern Atacama Desert, Chile. *Journal of the Geological Society, London* **129**: 505–526.

Mortimer C. 1980. Drainage evolution of the Atacama desert of northernmost Chile. *Revista Geologica de Chile* **11**: 3–28.

Mpodozis C, Cornejo P, Kay S, Tittler A. 1995. La Franja de Maricunga: sintesis de la evolucion del Frente Volcanico Oligoceno–Mioceno de la zona sur de los Andes Centrales. *Revista Geologica de Chile* **21**: 273–313.

Naranjo JA, Puig A. 1984. *Hojas Taltal y Chanaral, Regiones de Antofagasta y Calama*. Carta Geologica de Chile, N°62–63, escala 1:250.000, Servicio Nacional de Geologia y Mineria: Santiago.

Niemeyer H. 1999. Nuevos datos cinematicos para la faille Sierra Castillo en Quebrada del Carrizo, Precordillera de la Region de Atacama, Chile. *Revista Geologica de Chile* **26**: 159–174.

Philip H, Meghraoui M. 1983. Structural analysis and interpretation of the surface deformations of the El Asnam earthquake of October 10, 1980. *Tectonics* **2**: 17–49.

Randall DE, Tomlinson AJ, Taylor GK. 2001. Paleomagnetically defined rotations from the Precordillera of northern Chile. *Tectonics* **20**: 235–254.

Reutter KJ, Scheuber E, Helmcke D. 1991. Structural evidence of orogen-parallel strike slip displacements in the Precordillera of Northern Chile. *Geologische Rndschau* **80**: 135–153.

Riquelme R, Martinod J, Hérail G, Darrozes J, Charrier R. 2003. Neogene tectonics of the Central Depression and Precordillera (Andes of northern Chile) from the analysis of a drainage basin evolution. *Tectonophysics* **361**(3–4): 255–275.

Sáez A, Cabrera L, Jensen A, Chong G. 1999. Late Neogene lacustrinerecord and palaeogeography in the Quillagua Llamara basin, Central Andean fore-arc (northern Chile). *Palaeogeography, Palaeoclimatology, Palaeoecology* **151**(1–3): 5–37.

Scheuber E, Andriessen AM. 1990. The kinematics and geodynamic significance of the Atacama fault zone, northern Chile. *Journal of Structural Geology* **132**: 243–257.

Scheuber E, Reutter K-J. 1992. Magmatic arc tectonics in the Central Andes between 21° and 25°S. *Tectonophysics* **132**: 127–140.

Tomlinson AJ, Cornejo P, Mpodozis C, Ramirez C. 1993. Structural geology of the Sierra Castillo-Agua Armaga fault system, Precordillera of Chile, El Salvador Potrerillos. *Second International Symposium on Andean Geodynamics*, Editions de l'Orstom, Colloques et Séminaires: Paris; 259–262.

Tomlinson AJ, Cornejo P, Mpodozis C. 1999. *Hoja Potrerillos, Region de Atacama, Mapas Geol., 14, 1:100000 scale*. Servicio Nacional de Geologia y Mineria: Santiago.

Victor P. 2000. *Die Entwicklung der Altiplano Westflanke und ihre Bedeutung fur die Plateaubildung und Krustenverdickung in N-Chile (20–21°S)*. PhD thesis, Freie Universität, Berlin.

