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The role of inherited tectono-sedimentary architecture in the development of the central Andean mountain belt: Insights from the Cordillera de Domeyko

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ABSTRACT

The structure of the Cordillera de Domeyko is dominated by a number of elongated N–S-trending basement ridges. These ridges were uplifted by steep reverse N–S faults that deformed the Mesozoic–Cenozoic cover. The vergence of the fault system varies along strike, conferring an apparent doubly vergent “pop-up” geometry to the axial zone. Two Mesozoic pre-compressional extensional events were recorded in the area. New structural data presented in this paper indicate that most of the generated N–S-trending thrusts and related folds were controlled by the inversion of the pre-existing Mesozoic extensional faults. Thin-skin structures in the Mesozoic–Cenozoic cover are genetically linked to major basement upthrusts, which could be interpreted as basement short-cuts formed during inversion rather than as uplifted blocks associated with major Cenozoic strike-slip faults. Growth-strata geometries date the beginning of the Andean compressional event, which generates the Chilean Precordillera, as far back as 90 Ma ago; the resulting structural architecture is strongly controlled by inherited pre-Andean extensional structures. The association of porphyry intrusives with major reverse faults suggests that the emplacement of the Eocene–Oligocene porphyry Cu–Mo deposits in Northern Chile can be explained by an oblique-inversion Tectonics Model. The upper Eocene–lower Oligocene giant porphyry copper bodies (Chuquicamata, La Escondida, El Salvador) located in the Cordillera de Domeyko show an adakitic affinity. This magma affinity, together with structural evidence presented in this work, indicates that porphyry emplacement occurred at the end of the basement-involved contractional stage that generates the anomalous thickened crust needed to generate these magmas. This tectonic evolution is coherent with the existence of a flat-slab subducting beneath the Central Andes (22°–26° S) during early Cenozoic, that will also produce the eastward migrating of the compressional regime in the upper plate since Late Cretaceous.

1. Introduction

The Central Andes, between 22° and 25° south latitude, occupies the smooth transition between a nearly flat subduction to the south and a 30° east dipping subduction to the north. It includes several N–S-trending morphostructural units between the present-day subduction margin and foreland (Fig. 1). From west to east these units are: (1) Coastal Cordillera, (2) Longitudinal Valley, (3) Chilean Precordillera and pre-Andean Depression, (4) Western Cordillera (magmatic arc), (5) Altiplano – Puna, (6) Eastern Cordillera and (7) Sub-Andean Ranges (deformed foreland).

The studied area is located in the Cordillera de Domeyko, which belongs to the northern part of the Chilean Precordillera (Figs. 1 and 2). The Precordillera structure consists of several N–S-trending basement ridges parallel to the trench. These basement ridges are uplifted by high-angle reverse to oblique faults (Fig. 2). The deformation in the Mesozoic to Cenozoic cover is characterized by folds and low angle reverse faults.

Most of the major porphyry copper deposits in northern Chile are located within or adjacent to the Cordillera de Domeyko (Fig. 2) and present similar ages (40–30 Ma). This N–S alignment of contemporaneous deposits has given rise to the hypothesis that the emplacement of these Eocene–Oligocene intrusive complexes was controlled by an N–S strike-slip fault system called West Fault System (WFS) (Astudillo et al., 2007; Hoffmann et al., 2006; Reutter et al., 1996; Richards et al., 2001). According to previous authors, these faults developed in a transtensional regime as a result of the strain-partitioning expected along the margin, due to the oblique subduction of the Nazca plate beneath the South American plate (Fig. 3). Other authors consider that NW–SE lineaments also play

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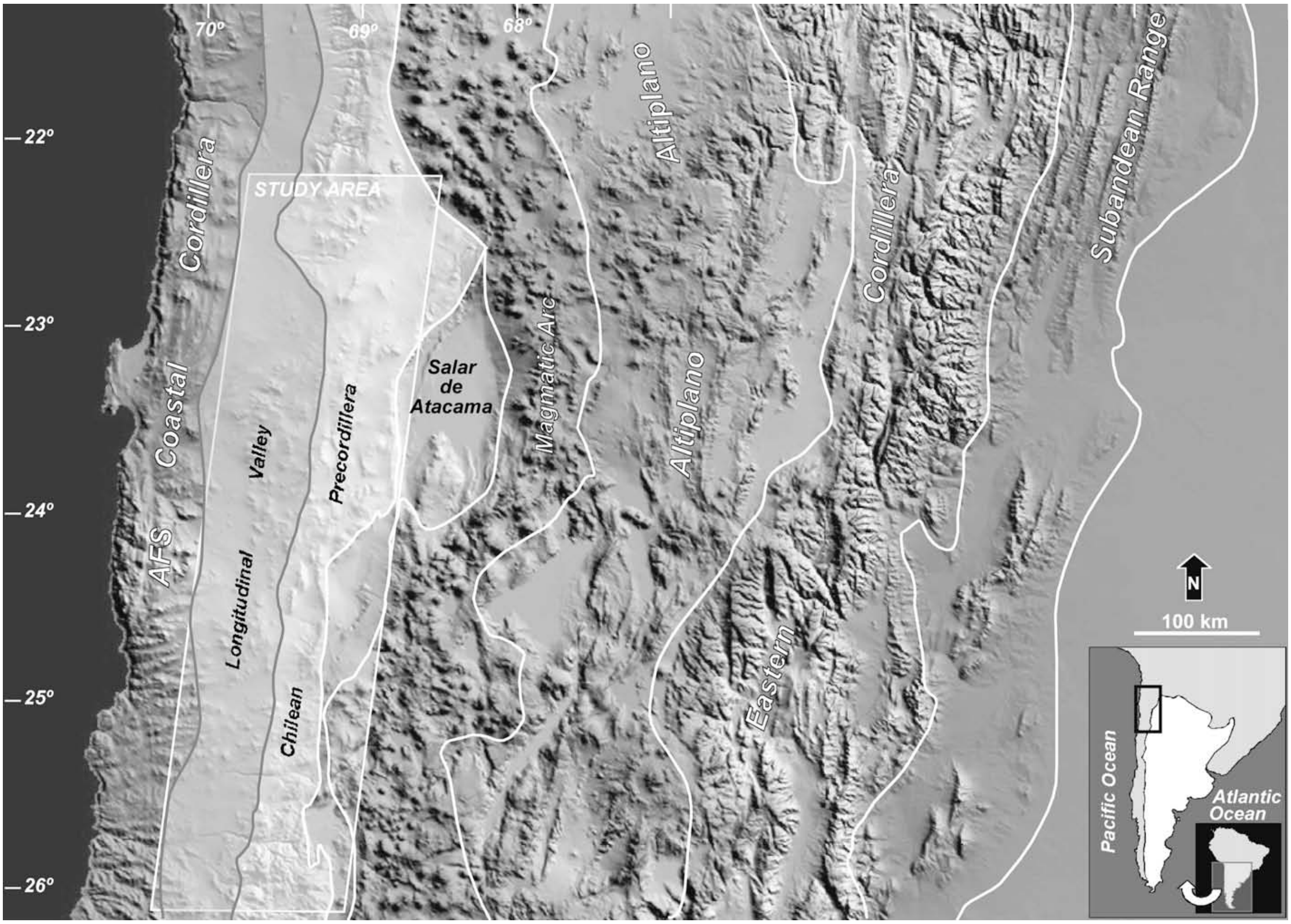

Fig. 1. Northern Chile and Argentina DEM base on Nasa SRTM dataset. The principal morphostructural units of the Central Andes are represented. The study area is located along the Chilean Precordillera morphostructural unit.

a role in the porphyry copper emplacement, especially when intersecting the N–S ones (Salfity, 1985; Chernicoff et al., 2002; Richards, 2003).

The aims of this work are: (1) to evaluate the influence of the pre-Andean structures in the structural style and evolution of the Cordillera de Domeyko and, (2) to validate the influence of the previously described mayor strike-slip faults in the area. Structural inheritance in mountain belts has been extensively described in the Alps, Apennines, Canadian Rocky Mountains as well as in the Argentinian Andes (Gillcrist et al., 1987; Butler, 1989; McClay et al., 1989; Grier et al., 1991; Buchanan and Buchanan, 1995; Uliana et al., 1995; Scisciani et al., 2002; Ramos et al., 2004; Tavarnelli et al., 2004; Butler et al., 2006; Carrera et al., 2006; Hongn et al., 2007). Previous work in the area (Mpodozis and Ramos, 1990; Amilibia et al., 2000; Amilibia, 2002) already suggested an important control on the geometry and localization of the newly developed contractional structures by the pre-existing Mesozoic extensional faults.

2. Geological background

2.1. Tectonic setting

The present-day structure architecture of the Cordillera de Domeyko is the result of the geodynamic evolution of the South American Plate west margin, in which two major stages can be differentiated. A pre-Early Jurassic stage, prior to Nazca subduction, and a Early Jurassic to present stage coeval with the subduction of this plate beneath South American plate.

2.1.1. Pre-subduction stage

During the first stage, the tectonic regime was characterized by: (1) Early to Late Paleozoic accretion and collision of terrains associated with the subduction along the Proto-Pacific plate boundary (Ramos, 1988), which resulted in the final assemblage of Gondwana; and (2) the development of an aborted continental rift between the Early Triassic and Early Jurassic (Figs. 4 and 5A), interpreted as the prolongation of the opening of the North Atlantic towards the south within the South American plate (Uliana et al., 1989; Suarez and Bell, 1992; Mpodozis and Cornejo, 1997; Franzese and Spalletti, 2001).

This continental rift, developed in the present-day western margin of the South American plate, was characterized by a set of NW–SE-trending Triassic half-graben basins arranged in an en-echelon pattern. They have been extensively described in the foreland ranges of south and central Argentina (Alvarez and Ramos, 1999; Franzese and Spalletti, 2001), disappearing under the present-day magmatic arc and reappearing to the west in selected outcrops along the Cordillera de Domeyko. The pre-existing Paleozoic suture zones controlled the location as well as the NW–SE orientation of the newly developed half-graben basins (Günther et al., 1997), as testified by the different geochemical signatures and independent magmatic evolution shown by the Paleozoic

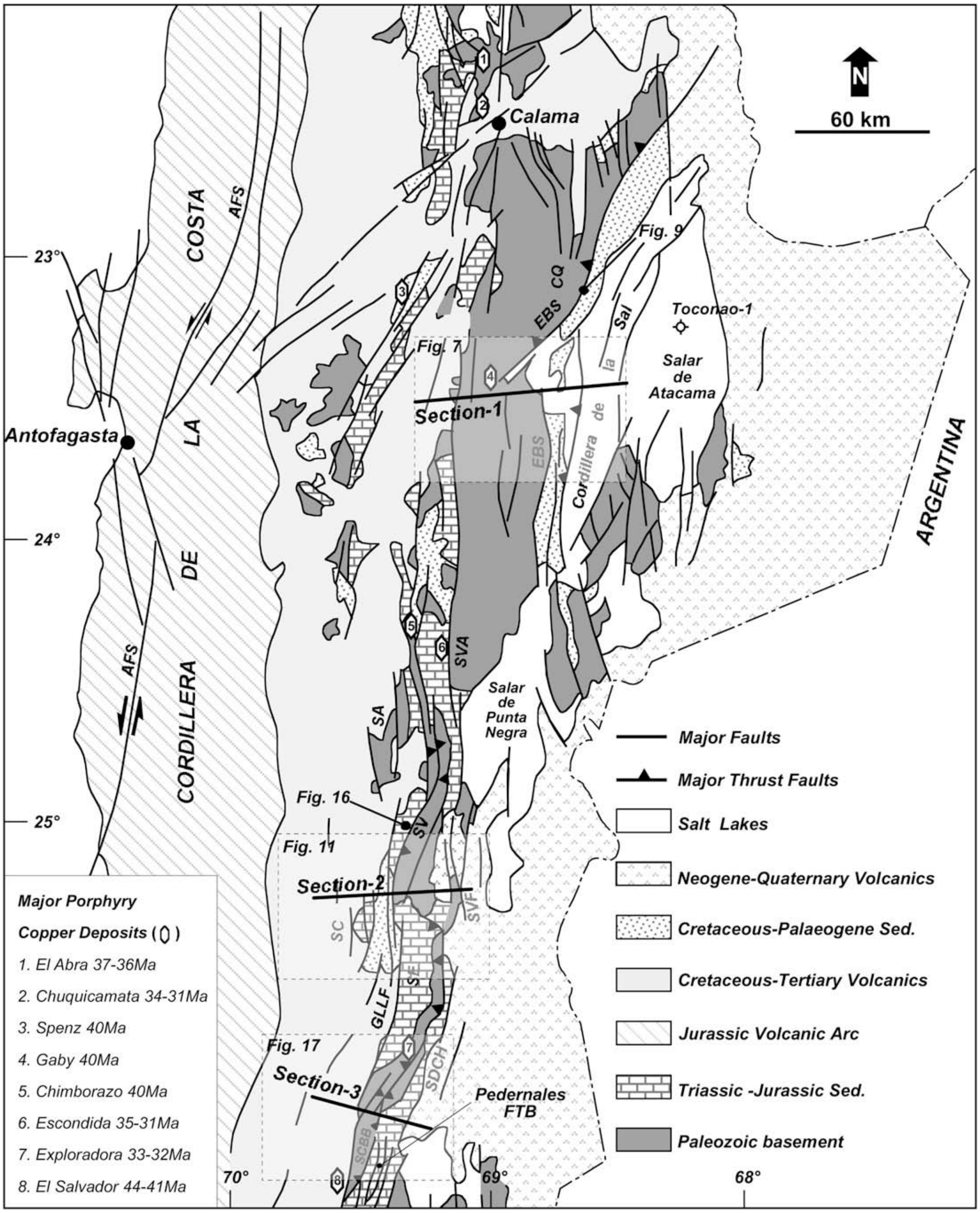

Fig. 2. Simplified geological map of Cordillera de Domeyko. Location of regional cross-sections and Figures. Diamonds show location of major Porphyry Copper Deposits. (AFS, Atacama Fault System; CQ, Cerro Quimal; EBS, El Bordo Scarpment; GLLF, Gran Llano Fault; SA, Sierra Argomedo; SC, Sierra Candeleros; SCBB, Sierra Castillo Basement Block; SDCH, Sierra Doña Inés Chica; SE, Sierra Exploradora; SV, Sierra Vaquillas; SVA, Sierra de Varas; SVF, Sierra de Varas Fault).

basement ridges bounding the Triassic grabens in the Cordillera de Domeyko (Mpodozis and Cornejo, 1997).

2.1.2. Subduction stage

During the Early Jurassic, the initiation of the subduction of the Pacific plate beneath the South American plate, coinciding with the break-up of Gondwana, results in a dramatic change in the geodynamic evolution of the area. The kinematics of this subduction includes two well differentiated periods which resulted in a different tectonic scenario affecting the area.

During the first period, subduction kinematics are characterized by a retreating subduction boundary which in turn generates an extensional regime in the western margin of the South American over-riding plate. In this scenario, the study area records both: (1) the development of a post-rift back-arc basin, known as the Domeyko-Tarapacá thermal basin (Figs. 4 and 5B) (Arcuri and Brimhall, 2002; Ardill et al., 1998; Gröschke et al., 1988; Prinz et al., 1994; Scheuber and Gonzalez, 1999; Scheuber et al., 1994); (2) the genesis of a new Late Jurassic and Early Cretaceous extensional stage, affecting the South American plate by developing a new N–S-trending rift system over-imposed on the pre-existing Triassic one (Fig. 5C). This extensional stage seems to be the inland response to the variations in the Atlantic opening, and it is closely related to the Salta Rift event in Argentina. This Late Jurassic–Early Cretaceous rift system was controlled by N–S normal faults such as the Gran Llano Fault (GLLF) or the Sierra

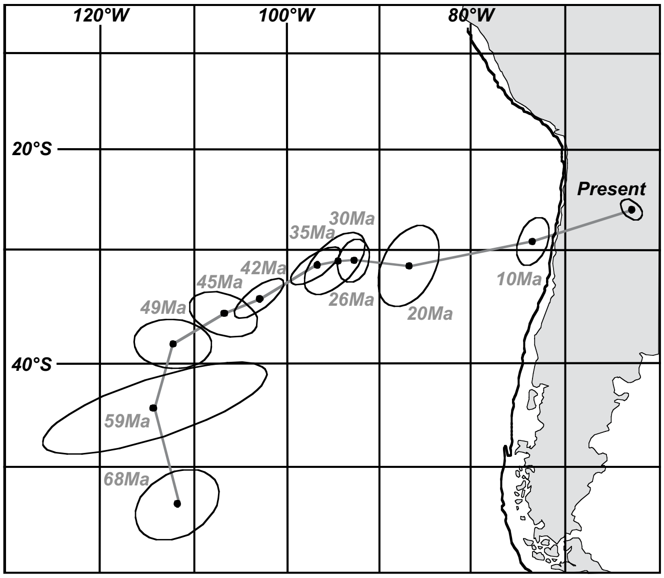

Fig. 3. Plate convergence vector between the Nazca and South American plates for the last 68 Ma, modified from Pardo-Casas and Molnar (1987).

Candeleros Fault (SCAF) as evidenced by the considerable changes in thickness and lithology. The structural features that developed during these extensional periods as well as the associated deposits are crucial to the understanding of the geometry and evolution of the Cordillera de Domeyko.

In the second period, a major plate reorganization associated with the fast opening of the South Atlantic Ocean during the Late Cretaceous changed the tectonic scenario. The South American plate stopped rotating clockwise and started to drift westward towards the Nazca plate at high convergence rates. This produced a change in the subduction kinematics, i.e. from a retreating subduction boundary to an advancing one, which established a compressional regime in the upper plate. During this second tectonic scenario the Andean Orogeny developed (Figs. 4 and 5D) (Royden, 1993; Scheuber et al., 1994). Shortening and uplifting of the Tarapacá-Domeyko Basin, combining thick and thin-skinned tectonic styles occurred (Amilibia et al., 2000). Also, as a result of this subduction change, the magmatic arc shifted eastward as far as its present position in the Western Cordillera. The tectonic erosion of the fore-arc (Stern, 1991) and the shallowing of the subducting slab (Kay et al., 1999) could account for this magmatic arc shift (Fig. 5).

2.2. Stratigraphy of the Cordillera de Domeyko

The rocks cropping out in the Cordillera de Domeyko can be grouped into three major assemblages: (1) the paleozoic–early triassic basement; (2) the late triassic–early cretaceous syn-extensional cover; and (3) the syn-orogenic late cretaceous up to present sediments.

2.2.1. Basement

The outcropping basement is made up of a thick succession of volcanosedimentary rocks intruded by Carboniferous–Permian granitoids. The volcanosedimentary rocks are mainly made up of Permian to lower Triassic siliceous volcanic series and subordinate andesites of the El Bordo (*PzTeb*) and La Tabla (*Pzlt*) Formations, which uncomformably overlie Devonian marine siliciclastic rocks exposed in the Sierra Argomedo (Fig. 2).

2.2.2. Triassic to lower Cretaceous syn-extensional cover

This unit shows strong thickness variations along the Cordillera de Domeyko, such that it can be absent in some areas or be kilometers thick in the basin depocenters. Its basal boundary is usually not so well exposed and when present can correspond to both a regional uncomformity (low angle) or to a paraconformity. According to the tectonic setting in which they were sedimented, these upper Triassic–lower Cretaceous deposits can be subdivided into three major stratigraphic units contemporaneous to the development of the Late Triassic–Early Jurassic rift, the Jurassic thermal back-arc basin and the Late Jurassic–Early Cretaceous back-arc rift.

2.2.2.1. Upper triassic–Hettangian syn-rift unit. Associated with the development of the upper Triassic–Hettangian NW–SE rift basins two major mega-sequences were deposited (Fig. 4). The lower one, coeval to major fault activity, corresponds to the Barrancos (*Trbr*) and Agua Dulce (*Trjad*) Fms. It is made up of a thick sequence of basic, intermediate and acid volcanic, volcanoclastic and subaerial siliciclastic rocks, as well as inter-bedded conglomerates, predominant at the basin margins, and some carbonates (Fig. 4). The upper mega-sequence is Hettangian in age and rests unconformably on top of the volcanic sequence of Barrancos Fm. locally affected by minor syn-depositional faulting, this non-volcanic unit is conformed by the bioclastic calcarenites of the Tinieblas Formation (*Jrti*) and the overlying upper Quebrada del Salitre (*Jrqs*) Fm.

2.2.2.2. Sinemurian–Kimmeridgian back-arc unit. In the Cordillera de Domeyko the development of a back-arc thermal subsiding basin, that records the beginning of the subduction of the Nazca plate beneath South American plate, is recorded by the sedimentation of up to 1500 m thick marine sediments forming the Profeta Formation (*Jpf*). This fauna rich formation consists of well-stratified unit integrated by thick levels of sandstones, mudstones, black clays, limestones and gypsums (Ardill et al., 1998; Prinz et al., 1994). This unit has a very widespread distribution lying uncomformably on top of all the previous described units.

2.2.2.3. Late Jurassic (post Kimmeridgian)–Early Cretaceous syn-rift unit. The sediments of this age filled an "aborted continental rift", and overlie the back-arc basin deposits. The subsidence of the basin was controlled by N–S normal faults, e.g. the Gran Llano Fault and the Quebrada Chaco Fault, as evidenced by the considerable changes in thickness and lithology across them (Figs. 2, 4 and 5C). The sequences deposited in this stage are mainly composed of volcanic rocks. Their geochemistry shows that they are not a typical subduction related volcanism series (Cornejo and Mpodozis, 1996; Morata and Aguirre, 2003), evidencing continental crustal thinning (Sierra Candeleros Fm., Punta del Cobre Group and Sierra Fraga Fm.). These sequences also comprise conglomerates and sandstones, like the ones described in Cerrillos, Llanta and Santa Ana Formations (Fig. 4).

2.2.3. The syn-orogenic Late Cretaceous up to present-day sediments

2.2.3.1. Late Cretaceous–Oligocene syn-orogenic unit. During the Late Cretaceous and the Paleogene, the magmatic arc migrated to the east locating along the western margin of the proto-Cordillera de Domeyko. The volcanic activity was associated with the development of enormous calderas and with the emplacement of granodioritic intrusions (Cornejo and Mpodozis, 1996). Andesites, rhyolites and dacites of the Chile-Alemania Fm. (*Tcha*) make up this Late Cretaceous–Eocene magmatic arc. These rocks are part of the syn-inversion sequence, being synchronous with the clastic continental sediments (Purilactis Group, Orange Fm., and Loma

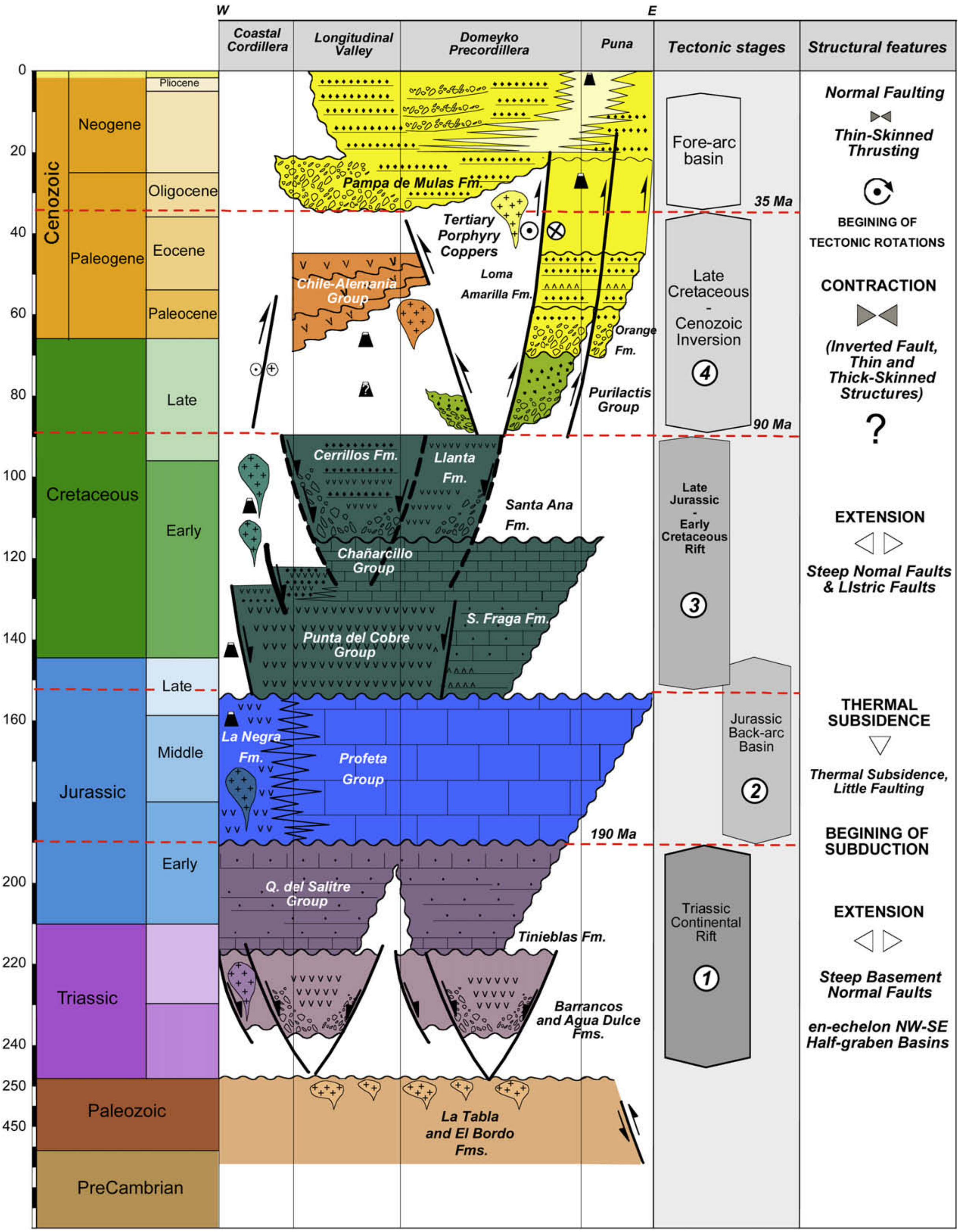

Fig. 4. Chronostratigraphic chart of the Cordillera de Domeyko showing the mega-sequences for the different morphostructural units, tectonic stages and dominant structural features. (Little black/white volcano marks the position of the magmatic arc. Notice its migration towards the E since late Cretaceous time.)

Amarilla Fm.) deposited in the Salar de Atacama Foreland Basin during the uplift of the Cordillera de Domeyko. They show internal angular unconformities typical of growth-strata syn-orogenic sequences (Hartley et al., 2000; Mpodozis et al., 2005; Charrier and Reutter, 1994).

During the Middle Eocene–Oligocene, which was the last stage of shortening in the Cordillera de Domeyko, a general lull in volcanic arc activity coincided with the emplacement of some acid porphyries along the range. The giant porphyry copper ore deposits – Chuquicamata, La Escondida, El Teniente, El

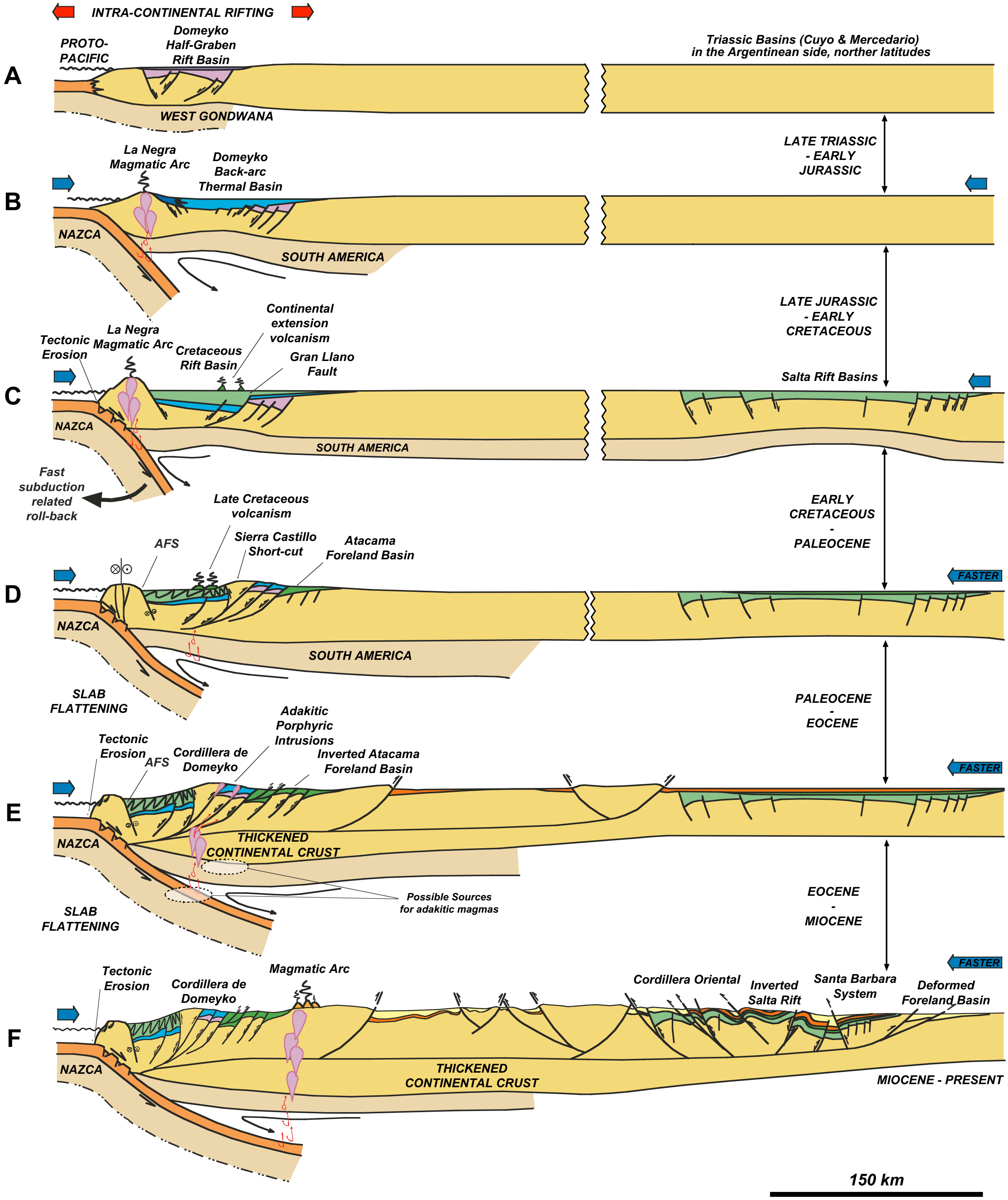

Fig. 5. A tectonic evolutionary model for the Cordillera de Domeyko since Triassic times, and its relationship with the evolution of the adjacent Salta Rift of Northern Argentina. Arrows show plates sense of displacement, and intensity.

Salvador – are found in these intrusions (Ballard et al., 2001; Richards et al., 2001).

2.2.3.2. Miocene–present-day slightly deformed unit. Erosion and denudation of the range due to its uplift resulted in the deposition of Neogene alluvial and coalluvial sediments (Pampa de Mulas Fm.) on top of the deformed basement and Mesozoic–Cenozoic cover. The deformed sequences are also overlain by volcanic rocks from the present magmatic arc located in the Western Cordillera.

3. Structure of Cordillera de Domeyko

The Cordillera de Domeyko is a well-defined 500 km long tectonic unit striking N–S. The range is arranged in several sub-ranges that reflect along strike changes in structural style and polarity of the structures. From north to south these sub-ranges are the western margin of the Salar de Atacama, Sierra Vaquillas Altas, Sierra Exploradora, Sierra Doña Inés Chica and Sierra Castillo (Fig. 2). The cores of these sub-ranges are composed of N–S oriented, elongate basement ridges. These basement blocks are limited by high-angle reverse faults, which exhumed the basement, thrusting it on top of Triassic to Cenozoic cover rocks, which in their turn are deformed by thin-skin structures (Fig. 2).

The Cordillera de Domeyko is cut by a number of transverse NW–SE and subordinated NE–SW lineaments that have been previously interpreted as major strike-slip faults, e.g. the Sierra de Varas Fault (Scheuber et al., 1994) (Fig. 2). Nevertheless, some of these morphological lineaments do not show clear strike-slip fault features.

Basement ridges mark a limit between the Cretaceous rift basin to the west and the Cenozoic foreland basins to the east, which is currently occupied by the “Salares”. The structural vergence undergoes a dramatic change along the strike and this fault arrangement confers an apparent doubly verging “pop-up” geometry to the axial zone of the range, which has a complex three-dimensional geometrical structure.

This paper summarises the results obtained from fieldwork in the Cordillera de Domeyko. Field mapping and LANDSAT interpretation were used to construct a detailed geological map of the region with special emphasis on structural geometries. More than 2000 structural data points were collected to study the Cordillera de Domeyko structure which is described on the basis of constructed geological cross-sections. In order to construct them, we used the 2DMove programme (Midland Valley Exploration©) to project data on the cross-section and to draw the dip domains. The cross-sections are oriented west–east, approximately in the direction of the tectonic transport and are perpendicular to the regional structural strike. The most representative cross-sections (see location in Fig. 2) of the Cordillera de Domeyko are described below. Data used on these cross-sections is plotted in Fig. 6.

3.1. Northern Cordillera de Domeyko

This region is of particular interest owing to the outcrop of major basement blocks along the El Bordo Scarpment (EBS) in the western margin of the Salar de Atacama (Fig. 7). The relationship between these blocks and the folded and thrusted Mesozoic–Cenozoic cover at Llanos de la Paciencia (LLP) and Cordillera de la Sal can be observed to the east of the El Bordo Scarpment. In this area it is possible to observe growth-strata geometries of Late Cretaceous–Oligocene age (Purilactis Group, Orange Fm. and Loma Amarilla Fm.), which are associated with the uplift of the Cordillera de Domeyko. Basement uplifted blocks also show Late Cretaceous–Cenozoic porphyries, some of which host giant Cu–Mo deposits such as the Chuquicamata and Gaby ore deposits (Fig. 2).

3.1.1. Section A–A′: Cerro Negro–Salar de Atacama

This cross-section runs perpendicular to the regional structural strike (Fig. 6a), from Cerro Negro in the west to the Salar de Atacama in the east (Figs. 7 and 8). Cerro Negro is an isolated Triassic outcrop located in the northern segment of the Cordillera de Domeyko and is mainly made up of syn-rift andesitic lavas, pelites and conglomerates of Agua Dulce Fm. (*TrJad*, Late Triassic–Early Jurassic). These rocks lie in angular unconformity on the sedimentary rocks of El Bordo Fm. (*PzTeb*, Permo-Triassic), and describe an asymmetric east-verging open anticline. This anticline shows a very long and gently dipping back-limb and a short and steep, east dipping, frontal-limb. This hanging-wall asymmetric anticline is consistent with the presence of a related deep thrust involving the basement. The regional syn-rift nature of the Late Triassic rocks outcropping in the hanging-wall, as well as the absence of them to the east, observed along Cordon del Lila outcrops and on the Toconao-1 exploratory well (Fig. 2) (Muñoz and Townsend, 1997), suggests that this anticline geometry is consistent with the reactivation of a pre-existing Triassic normal fault, the Cerro Negro Fault (CNF) (Fig. 8, Structure 1). Later on, as the shortening increases, the uplifted Triassic syn-rift sequence was transported eastwards by a gently dipping by-pass thrust, thrusting over the Oligocene–Eocene sandstones and conglomerates of the Orange and Loma Amarilla Fms. (*Tor* and *Ela*), transferring the deformation towards the east (Fig. 8, Structure 2). Further north, along Cerro Quimal Transect (Fig. 2), the basement blocks thrust on top of the Cretaceous red sandstones of the Purilactis Group. Thin-skinned structures (thrust and related folds) are observed to the east in the Mesozoic–Cenozic cover of the Llanos de la Paciencia. These structures have been interpreted as detached in the gypsum of the lower Purilactis Group, owing to the uplift and transport of the Cerro Negro rigid block eastwards. Thin-skin structures are commonly observed in the cover sequences adjacent to the major high-angle basement-involved thrusts all along the Cordillera de Domeyko. They have been interpreted as produced by a “bulldozer mechanism” and illustrate

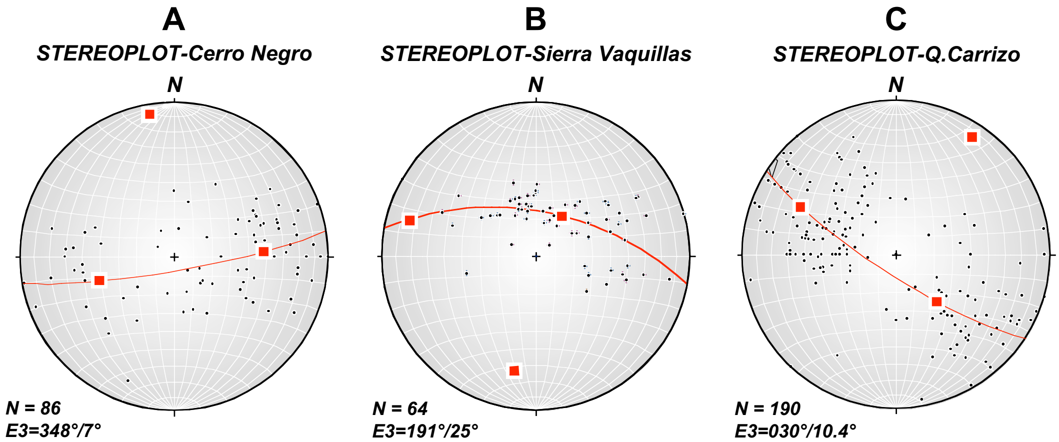

Fig. 6. Stereoplots of pols to bedding for each transect. Eigen values are calculated. The E3s values have been used as projection vector when projecting the structural data into the cross-section planes (*N* = number of measurements; E3 = Eigen vector minimum).

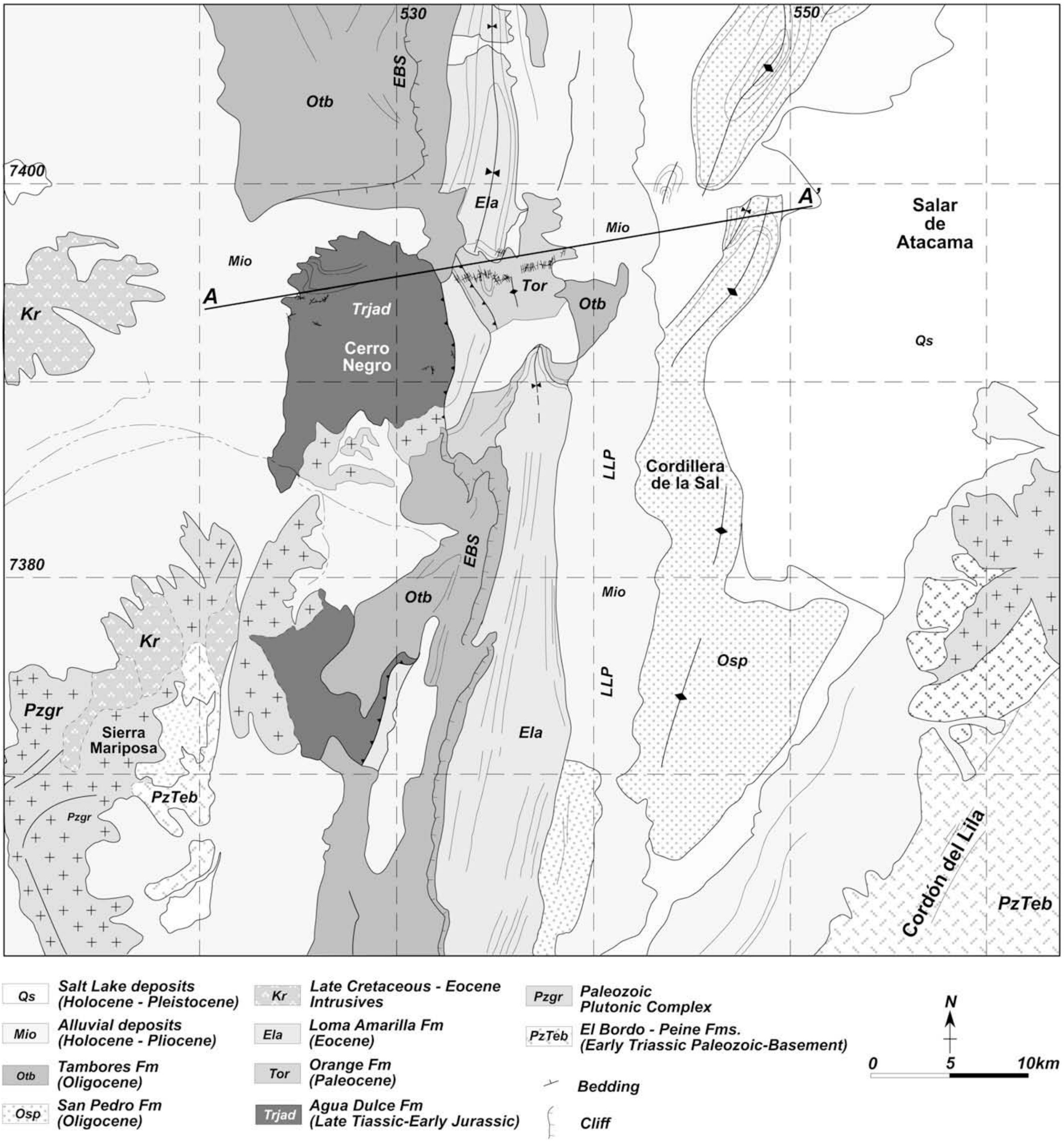

Fig. 7. Detailed geological map of the western margin of Salar de Atacama, showing the main structural features of the Cordillera de Domeyko across the Cerro Negro transect (modified from Ramírez and Gardeweg, 1982). See location on Fig. 2. See section A–A′: Cerro Negro in Fig. 8. (EBS, El Bordo Scarpment; LLP, Llanos de la Paciencia).

how thick-skinned basement structures induced thin-skinned structures in the cover.

The conglomerates of the Loma Amarilla Fm. unconformably overlie the folded red beds of the Orange Fm. Moreover, these conglomerates describe an open syncline (enlargment in Fig. 8) with a thick eastern limb and a thinner western limb. These changes in thickness together with the uncomformity allow us to interpret these sediments as last syn-inversion sequence observed in the area, coeval with the development of the by-pass thrust. The Late Cretaceous red sandstones of the upper member of the Purilactis Group also show internal angular relationships that can be interpreted as growth-strata geometries (Mpodozis et al., 2005). These angular relationships together with thermochronological and geochemical data (Amilibia and McClay, 2004; Maksaev and Zentilli, 1999; Haschke et al., 2002) enable us to date the deformation and uplift of the Cordillera de Domeyko. As deformation migrated eastwards, the thin-skin fold and thrust system was uplifted and deformed by a new lower basement structure called Llanos de la Paciencia Fault (LLPF) (Fig. 8, Structure 3).

3.2. Central Cordillera de Domeyko

Between 25°15′ and 25°30′S, the vergence of the structures varies from west in the Sierra Vaquillas (SV) basement thrust to east along the Sierra Exploradora (SE) thin-skinned thrust system (Figs. 2 and 9). In this accommodation area, the basement structure

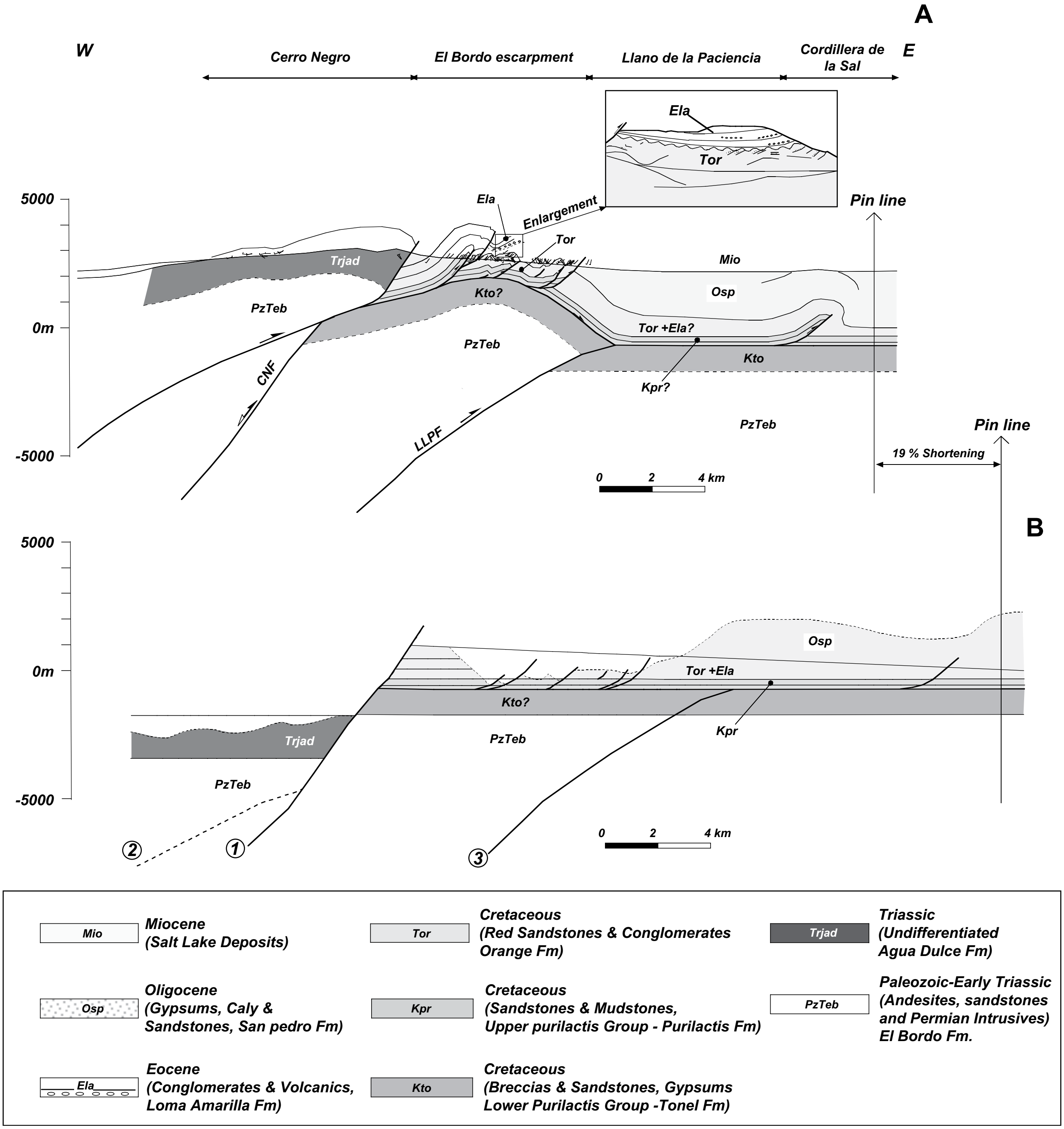

Fig. 8. (a) Regional cross-section A–A′ trough Cerro Negro and llanos de la Paciencia (location in Figs. 2 and 7). The enlargement shows a detail of the angular uncomformity between the folded red-beds sequence of Orange Fm. (Tor) and the conglomerates of Loma Amarilla Fm. (Ela). (b) Restored A–A′ cross-section to its pre-contractional stage (CNF, Cerro Negro Fault; LLPF, Llanos de la Paciencia Fault; numbers mark the relative chronology of the structures).

disappears under the Triassic cover, developing an overturned anticline verging to the west and plunging to the south. To the southeast of this structure, the Triassic and Sinemurian rocks are folded and faulted without involving the basement. The cross-sections of this area provide evidence of inversion tectonics, accounting for the uplift and deformation of the Triassic and Cretaceous syn-rift sequences.

3.2.1. Section B–B′: Sierra Candeleros–Sierra Vaquillas

This section runs parallel to the tectonic transport direction of the basement thrust at Sierra Vaquillas deduced from the thrust strike (Figs. 6b and 9). The cross-section was constructed along the exceptional outcrops of Quebrada Vaquillas (Figs. 11 and 12). In this cross-section a large syncline is prominent, which is the northern expression of the Sierra Candeleros (SC) syncline. The syncline shows contrasting limbs under the Cretaceous conglomerates and sandstone beds. The western limb contains a Kimmeridgian–Bathonian sequence of east dipping fossiliferous limestones and andesitic lavas, thrusting to the west on the flat lying Cretaceous volcanic rocks (Fig. 10, Structure 2). The eastern limb of the syncline is totally different, containing a very thick, up to 5000 m, steeply dipping monoclinal sequence of Kimmeridgian–Oxfordian

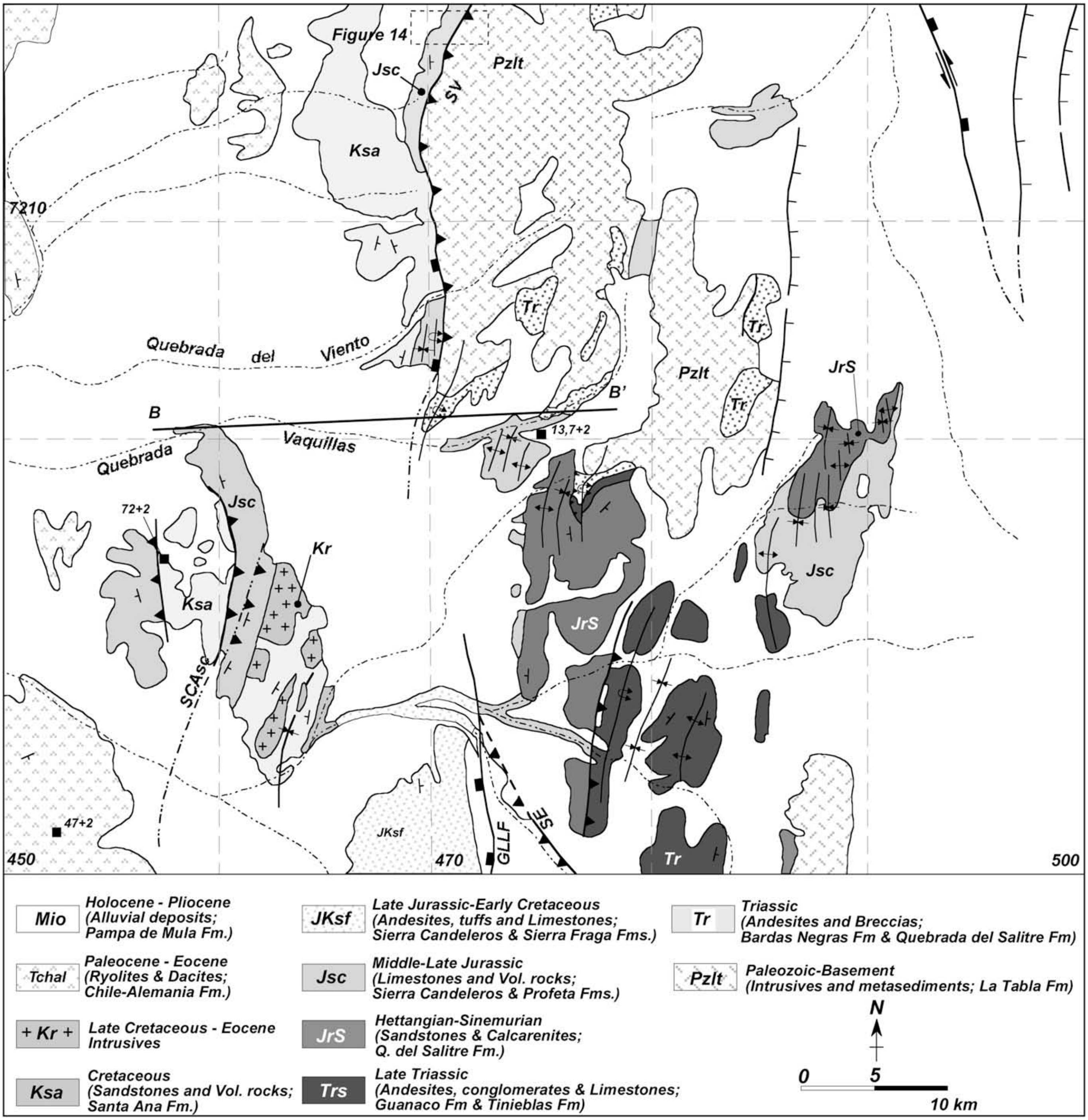

Fig. 9. Detailed geological map of Sierra Vaquillas Altas (SA) (Central Domeyko Range), showing the main structural features of Cordillera de Domeyko along Quebarada Vaquillas outcrop, see location in Fig. 2 (modified from Marinovic et al., 1992). See section B–B′: Q. Vaquillas–Sierra Candeleros in Fig. 10 (GLLF, Gran Llano Fault; SCAsc, Sierra Candeleros short-cut; SE, Sierra Exploradora; SV, Sierra Vaquillas Fault). Fig. 14 showing Punta del Viento panoramic is also located.

andesitic lavas (equivalent to S. Fraga Fm.). Under this sequence lies the typical Oxfordian sequence of the Profeta Fm. composed of gypsum and fossiliferous marls (ammonites rich). This anomalous thick eastern limb is interpreted as a syn-extension sequence related to a Late Jurassic–Cretaceous normal fault which location coincides with the axial plane of the syncline. We call it the Sierra Candeleros Fault (*SCAF*), and can be interpreted as an antithetic fault of the Gran Llano (*GLLF*) master fault, that delimitates the Late Jurassic–Early Cretaceous rift basin to the east (Figs. 2 and 9).

Further east, a basement block is thrusting towards the west over the synclinal mega-limb. At this transect, the basement structure is represented at surface by a Triassic anticline verging to the west. The anticline involves a thick Triassic succession which is affected by a normal fault outcropping in the core of the anticline. This fault coincides with the axial plane of the anticline (Fig. 11). Further east, a back-thrust and fold system verging to the east developed in the Triassic syn-extensional cover. The Triassic syn-rift sequence of Barrancos and Acantilado Fms. overthrusted Late Triassic–Hettangian post-rift sequences of the Tinieblas and Quebrada del Salitre Fms. towards the east. The angular unconformity at the bottom of the Tinieblas Fm. limestones marks the end of the main Triassic rifting event and the beginning of the Early Jurassic

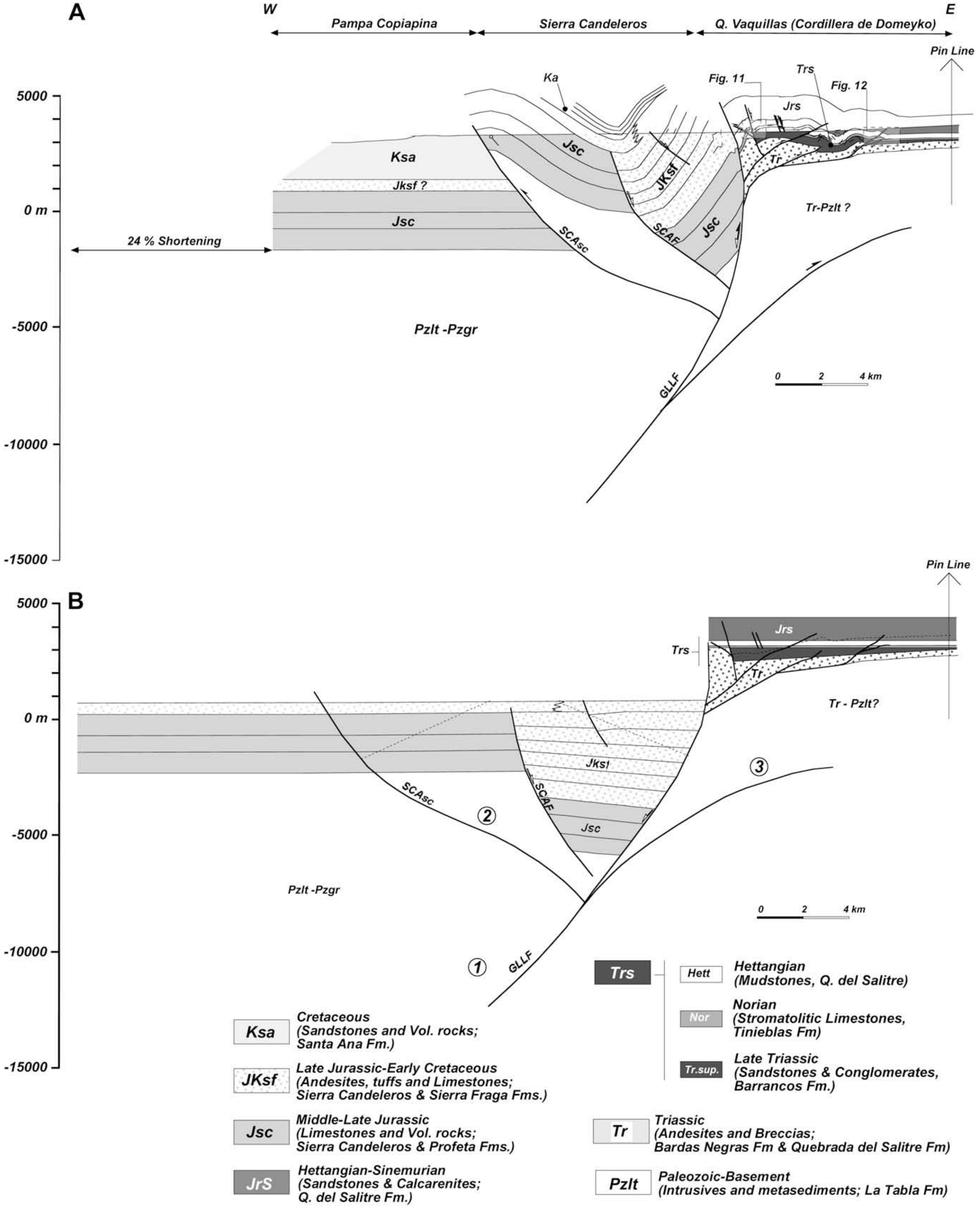

Fig. 10. (A) Regional cross-section B–B′ through Q. Vaquillas and Sierra Candeleros (Location in Fig. 9). (B) Restored B–B′ cross-section to its pre-contractional stage. (GLLF, Gran Llano Fault; SCAF, Sierra Candeleros Fault; SCAsc, Sierra Candeleros short-cut; numbers mark the relative chronology of the structures).

sag phase (Fig. 12). However, some extensional structures were active until Sinemurian times as shown in Fig. 11. All this thin-skin back-thrust system could be interpreted as a detached system that resulted from the ejection of the syn-rift sequence towards the east via a newly generated short-cut thrust of the GLLF (Fig. 10, Structure 3) as the deformation evolves (Figs. 12 and 13). All the thin-skinned structures plunge to the south, reflecting the end of the Sierra Vaquillas basement block.

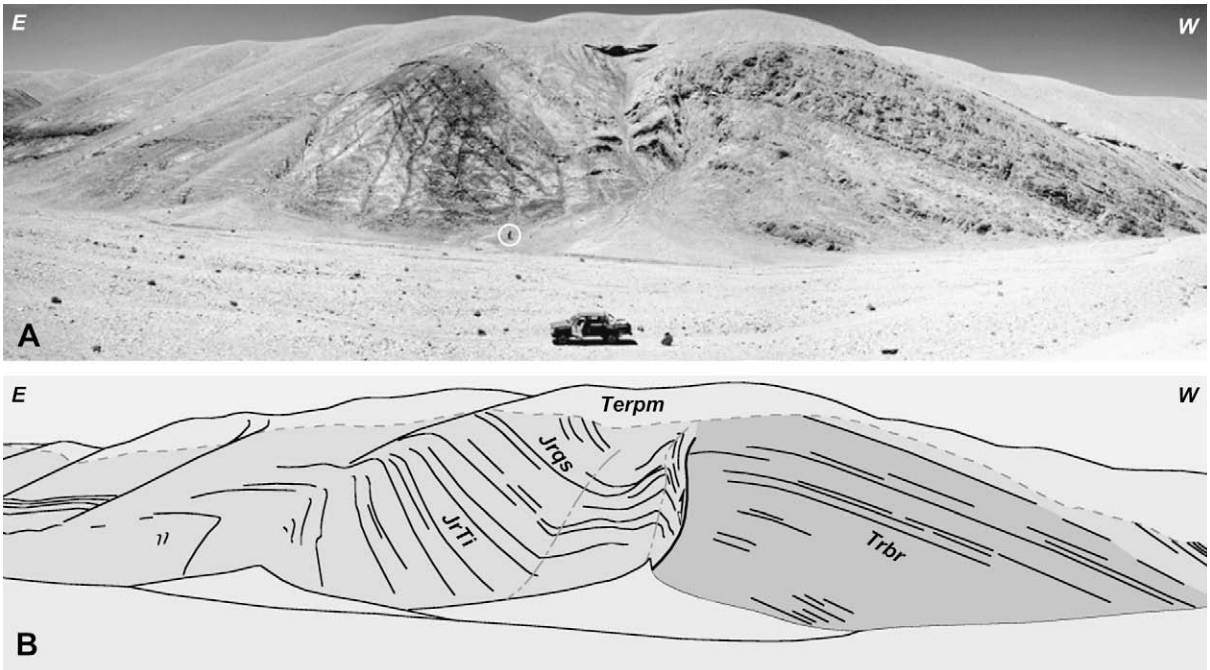

Fig. 11. (A) Quebrada Vaquillas inverted normal fault (south view). (B) Picture line-drawing intrepretation. This, 60° east dipping Triassic normal fault was partially inverted as the anticline drag fold shows. This fault placed in contact Early Jurassic Tinieblas Fm. limestones (JrTi) and Quebrada del Salitre Fm. sandstones (Jrqs) in its hanging-wall, with Early Triassic Barrancos Fm. volcanic conglomerates (Trbr). Oligo-miocene alluvial deposits of Pampa de Mulas Fm. (Terpm) lie unconformably on top of the inverted fault. The circle shows a geologist as scale.

To the north of Quebrada Vaquillas, the southern slope of the E–W Quebrada Punta del Viento (Figs. 9 and 14) also shows well-exposed and beautiful inversion structures where several east dipping Triassic normal faults were reactivated in subsequent contractions during the Cenozoic. These faults exhibit a normal net displacement in the lower levels whereas they show a net reverse displacement in the upper structural levels, placing Triassic syn-rift andesitic breccias and sandstones over the Late Triassic limestones (Tinieblas Fm.). The Triassic extensional faults were partially inverted and controlled the location and orientation of the newly formed contractional structures.

3.3. Southern Cordillera de Domeyko

In Sierra Doña Inés Chica contractional structures are mainly basement-involved thrusts (thick-skinned) that deform the Triassic syn-extensional sequence. The dominant vergence of the structure is to the west, contrasting with the vergence to the east, which occurs both further south at Sierra Castillo (SCBB), and further north at Sierra Exploradora (SE) (Figs. 2 and 15). The area shows a slightly deformed thick sequence of Lower Cretaceous volcanic rocks to the west, and a strongly deformed, thinner Triassic–Early Jurassic syn-rift sequence, to the east. The boundary

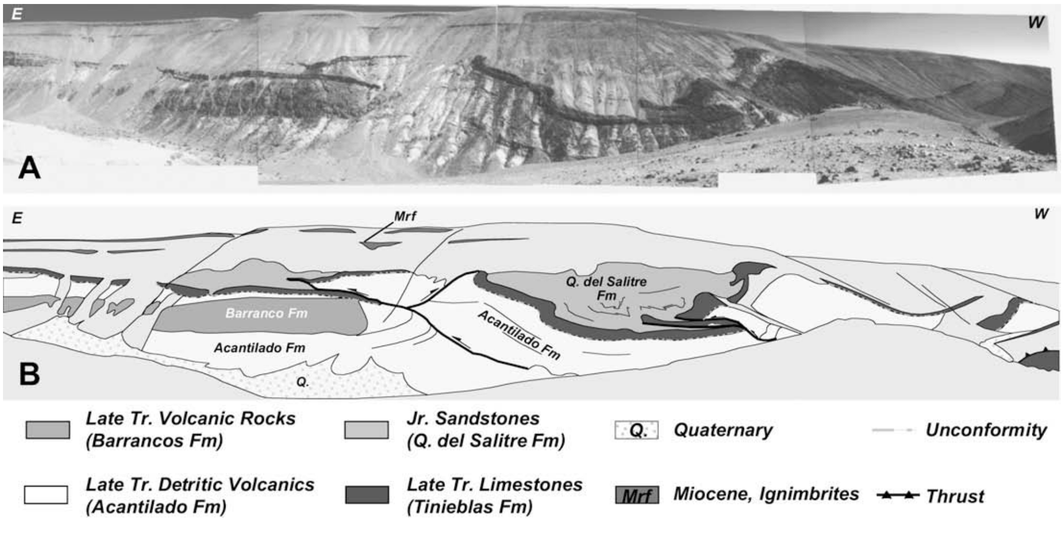

Fig. 12. (A) Back-thrusting in Quebrada Vaquillas (south view). (B) Outcrop interpretation. The Triassic syn-rift sequence of Barranco and Acantilado Fms is thrusting on top of Hettangian post-rift sequence of Q. del Salitre Fm. towards the east. The angular unconformity between Late Triassic Tinieblas Fm. limestones and the Late Triassic Barranco Fm. andesitic lavas is clearly visible in the eastern part of the outcrop. It marks the end of the, fault controlled, syn-rift sedimentation and the beginning of the Early Jurassic post-rift phase.

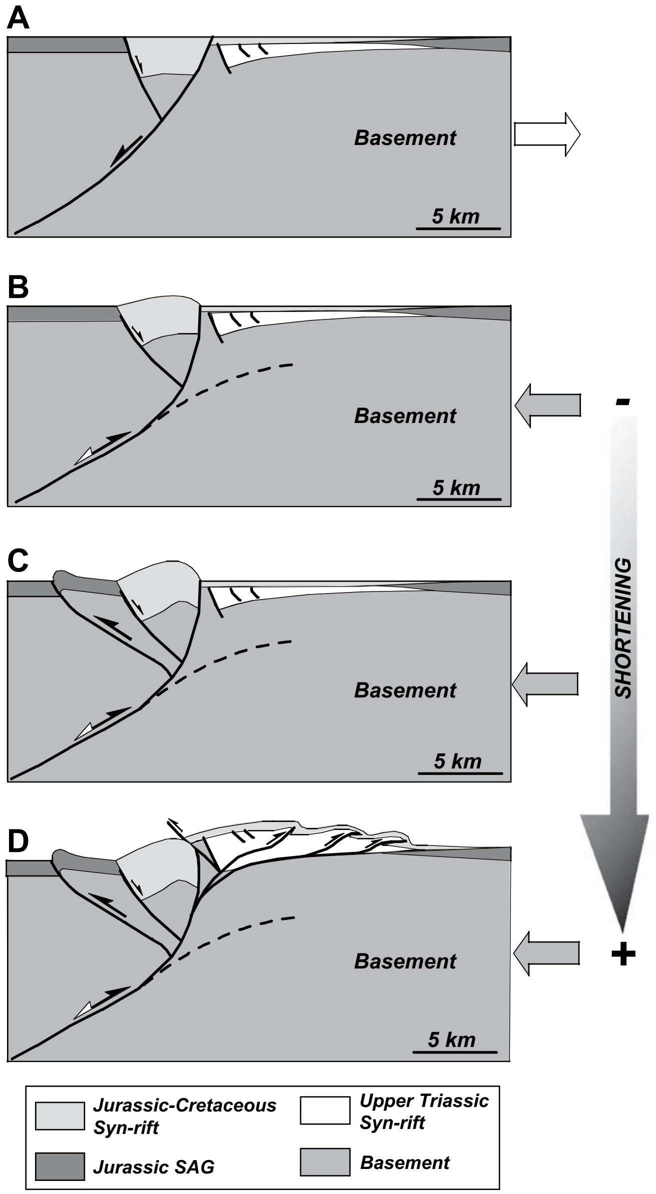

Fig. 13. Quebrada Vaquillas section evolutionary structural model. (A) Two phases of extension were over-imposed in the area (Triassic and Late Jurassic–Early Cretaceous). (B) The contractional phase during Late Cretaceous times results in E–W shortening, tilting and inversion of the extensional structures.

between both areas is the Gran Llano normal fault (GLLF). Intrusions, some of them emplaced parallel to the bedding (sills), are aligned along this Fault. The GLLF is a well-preserved N–S-trending Cretaceous normal Fault. The interaction between the newly formed contractional faults and these N–S-trending extensional faults play a major role in the structural geometries observed in Cordillera de Domeyko, as well as the location of the Range itself. From north to south the GLLF changes from been partially reactivated to non-reactivated. These changes in the character of the fault, control by the interaction with other pre-existing structures (Triassic NW–SE faults), results in changes of structural style and vergence of the compressional structures along strike.

3.3.1. Section C–C′: Quebrada Carrizo

This cross-section runs across the eastern limb of a wide syncline of Late Jurassic–Early Cretaceous syn-extension volcanic rocks of Sierra Fragua Fm. and conglomerates of Llanta Formation (Fig. 16). This limb shows very steep to overturned dips in contact with the Sierra Castillo Fault (SCF). This E-dipping reverse fault places Paleozoic basement and Triassic andesitic rocks of its hanging-wall, on top of Jurassic volcanic rocks. The Sierra Castillo Paleozoic rocks disappears northwards across Quebrada La Perra beneath Triassic rocks, describing a complex anticline plunging towards the north (Fig. 15). Two large antiformal structures (Fig. 16, Structures 2) outcrop to the east of the Sierra del Castillo Fault. Both of these structures present steep, complex frontal-limbs and longer and gently dipping to the E back-limbs. Whereas the frontal-limbs consist of Triassic–Jurassic quartzite sandstones (Quebrada del Salitre Fm., *Tqv(2)*), the back limbs contain a thick Late Triassic syn-extensional volcanic sequence (*Tqv(2)*) (Fig. 17). The complexity of the frontal limbs, the asymmetry of the folds and, mainly, the differences in thickness and lithology between the two limbs strongly suggest that these structures resulted from inversion of Triassic normal faults. At the easternmost anticline, the fault reaches the surface as an inverse fault and the hanging-wall Triassic sequence exhibit sills. These sills could be Late Triassic or Cenozoic. In any case, these intrusions followed the fault to ascent, either during the extensional stage or during inversion. Along the Pedernales Fold and Thrust Belt syn-contractional porphyries can also be observed. They probably used the already existing basement reverse fault to reach upper structural levels. Once they reach the weaker and brittle sedimentary cover they emplace within the fault related anticline, deforming them and conferring an anomalous amplitude and high to these anticlines. Pluton emplacement along reverse faults under contractional regimes has been extensively documented in orogens like the Rocky Mountains (Kalakay et al., 2001). The shortening across this section was mainly absorbed by two major structures, the Sierra del Castillo thrust Fault (SCF) and the Carrizo inverted normal Fault (CF) (Fig. 16).

4. Discussion

4.1. Domeyko structural style

Illustrated balanced cross-sections and the overall tectono-sedimentary architecture of the area enable us to postulate that the majority of the Cordillera de Domeyko basement-involved thrusts, orientation and distribution, were controlled by pre-existing extensional structures (e.g. Amilibia et al., 2005). Most of the observed basement-involved anticlines of Cordillera de Domeyko, such as the one described at Cerro Negro (Fig. 8, Northern Cordillera de Domeyko), resulted from the inversion of Mesozoic extensional faults, preserving Triassic syn-rift sequences in their hanging-walls.

Due to the complex 3D structural configuration resulting from two superimposed extensional systems (Triassic and Late Jurassic–Early Cretaceous), the influence of the pre-existing structures during subsequent contraction is not just represented by simple inversion geometries and reactivation of extensional faults. As observed in some of the Domeyko transects (Figs. 8, 10 and 16), changes in the vergence of the compressional system as well as the development of basement short-cuts were strongly controlled by the interaction between the two sets of extensional faults. An example is the previously described Gran Llano Fault (GLLF). Along C–C′ cross-section (Fig. 16) the GLLF was not reactivated, acting as a buttress to the E–W shortening and transferring the deformation into the basement of its footwall, were the pre-existing Triassic structures were reactivated. However, further south, the Late Jurassic–Early Cretaceous GLLF was partially reactivated, changing the vergence of the system to the east and giving rise to a typical short-cut of its footwall (Fig. 2). The transported Sierra Castillo basement block over-thrust the pre-rift Mesozoic cover to the east, developing the east-verging Pedernales Thrust and Fold Belt, being another clear example of the interrelation between thick

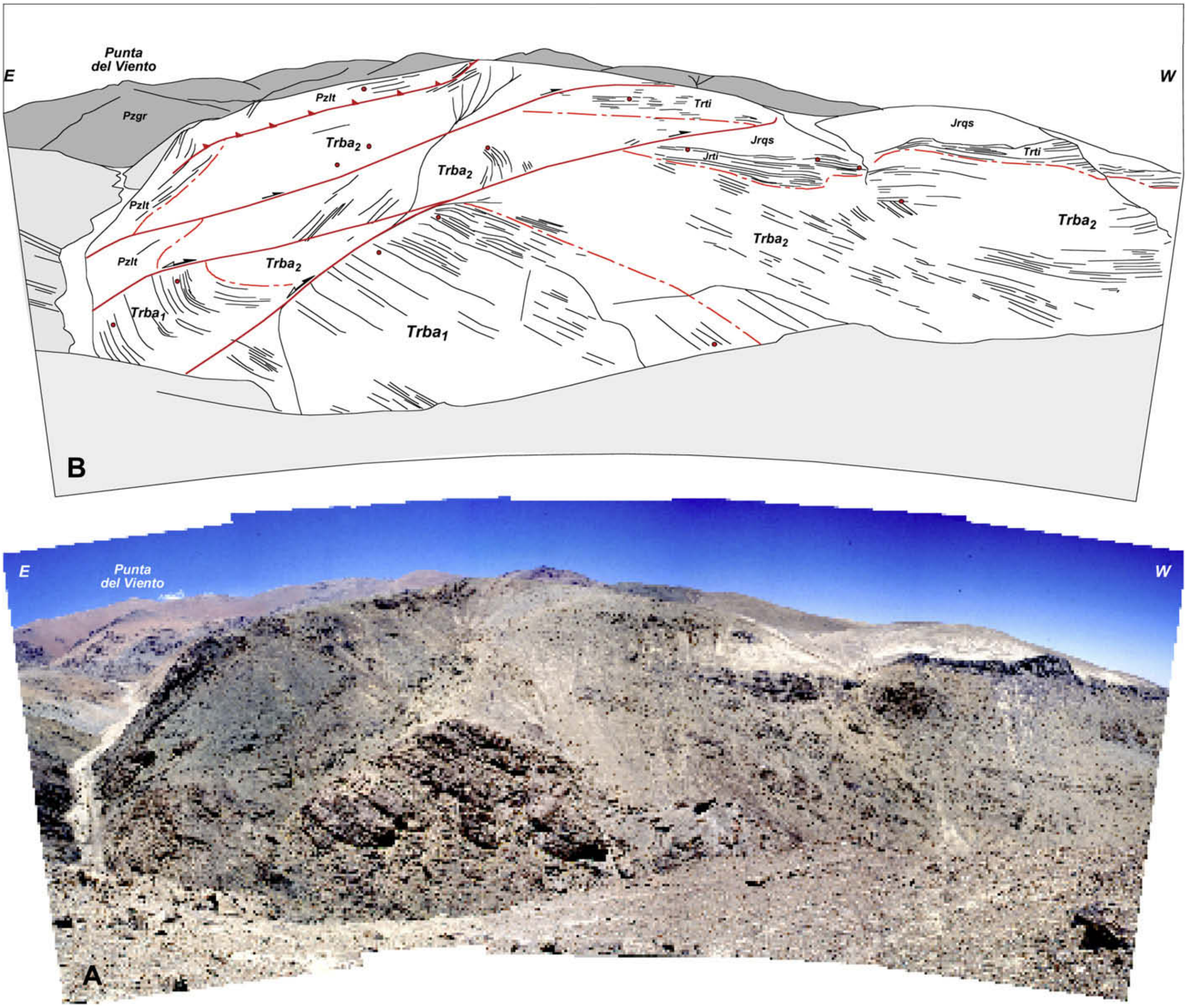

Fig. 14. (A) Quebrada Punta del Viento Triassic outcrop (south view). In this view is possible to observe the relationships between pre-existing Triassic extensional faults and their syn-tectonic sequence with the newly developed Late Cretaceous contractional ones. (B) Picture line-drawing interpretation. This outcrop shows the relationships between the pre, syn and post-rift Triassic sequences as well as the positive inversion of some Triassic extensional faults. The observed Triassic faults keep a normal fault net displacement at lower structural levels, but show a reverse fault geometry at upper structural levels. This observation allowed us to interpret them as partly inverted normal extensional faults. (Trba$_1$, Triassic syn-rift Barrancos Fm lower member; Trba$_2$, Triassic syn-rift Barrancos Fm upper member; Trti, Late Triassic post-rift Tinieblas Fm; Jrqs, Jurassic post-rift Q. Del Salitre Fm; Pzlt, Paleozoic basement La Tabla Fm; Pzgr, Permian Intrusive complex) (red dots mark field-measurements).

and thin-skinned structures. The influence of the pre-existing extensional faults is not only consistent with the inversion features and the structural style of the Cordillera de Domeyko described above, but also with the location of the range itself. Thus, the Cordillera de Domeyko is located along the Late Jurassic–Early Cretaceous east rift margin (Fig. 18).

The resulting N–S-trending reverse faults show little evidence of major strike-slip movement, and are crosscut by some NW–SE sinistral strike-slip faults. Both set of structures possibly accommodate the basement deformation and rotation owing to along strike differential shortening (Fig. 18) since 35 Ma (Fig. 4). This relationship between the N–S basement faults and the NW–SE sinistral faults has been described in the eastern margin of the Cordillera de Domeyko (Arriagada et al., 2000, 2003, 2006; Amilibia, 2002). Moreover, previous Domeyko strike-slip models (i.e. WFS: West Fissure Zone) does not account for: (a) the fact that there was insufficient obliquity in the convergence to allow strain-partitioning (Schreurs and Colleta, 1998; Casas et al., 2001; Amilibia, 2002) and for (b) the fact that the strike-slip displacements observed in the Cordillera de Domeyko are small and mainly described as left-lateral. This sense of displacement is in sharp contrast with those expected under dextral oblique convergence regimes (Fig. 3). On the other hand, our model relates the basement tectonics with the inversion of pre-existing extensional faults due to an increase in the convergence rate and to the existence of a subducting flat-slab.

All cross-sections have been restored to their pre-contractional stage. The absence of subsurface data and the poor quality of stratigraphic data increased the uncertainties when constructing balanced cross-sections. Sedimentary thickness was deduced from field data as well as from earlier stratigraphic works and was assumed to be constant except for the Triassic and Jurassic–Cretaceous syn-rift sequences as well as for the Purilactis Group where changes were considered. A 10–15 km deep detachment

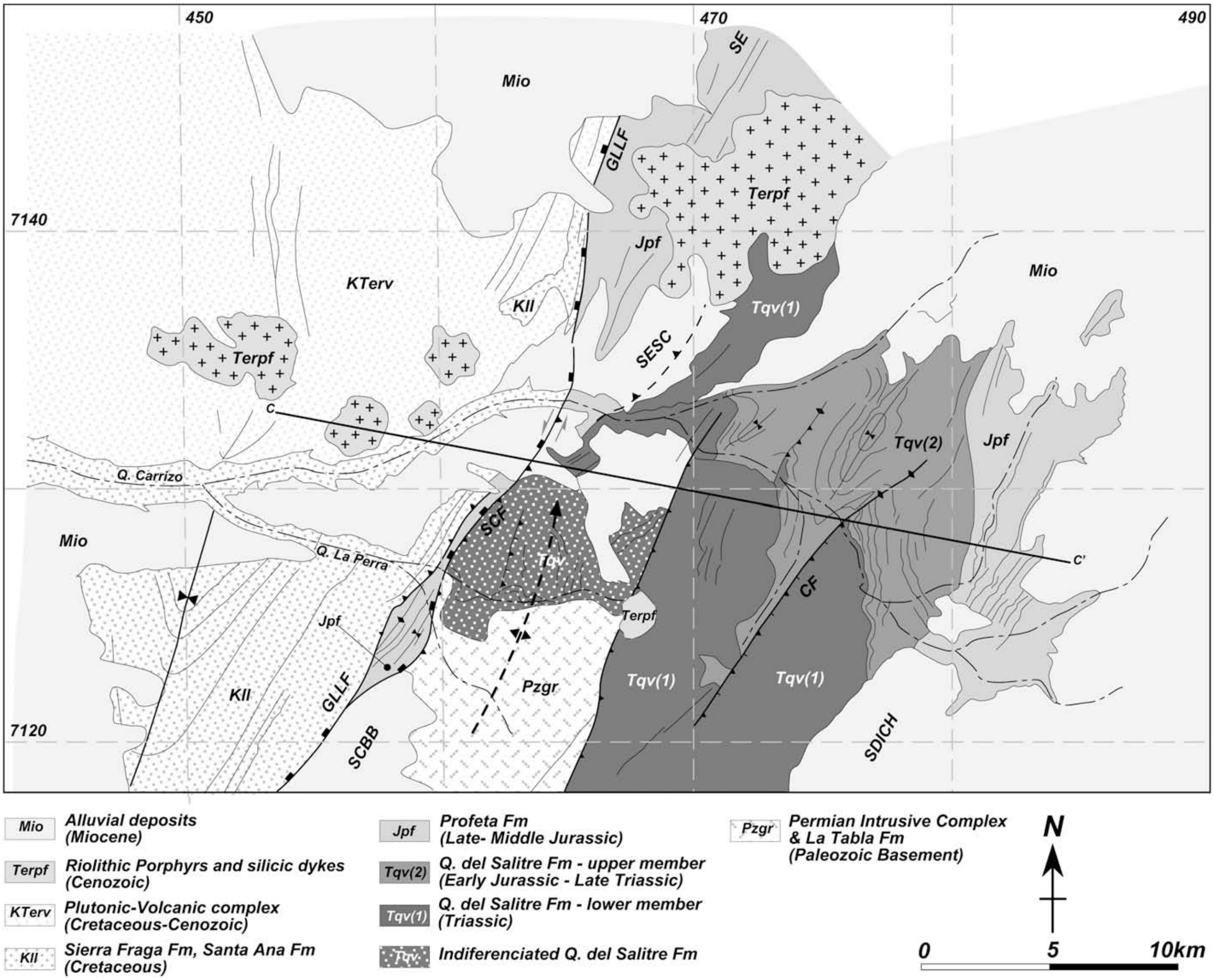

Fig. 15. Detailed geological map of Sierra Doña Inés Chica (Southern Domeyko Range) showing the main structural features of Cordillera de Domeyko along Quebarada Carrizo outcrops. Location of section C–C′: Q. Carrizo (Fig. 16). CF, Carrizo Fault; GLLF, Gran Llano Fault; SDICH, Sierra Doña Inés Chica; SE, Sierra Exploradora; SESC, Sierra Exploradora short-cut; SCF, Sierra Castillo Fault; SCBB, Sierra Castillo basement block.

was used for the basement structures. A similar detachment depth has been used for the extensional faults and for inverted basement structures in Argentina, where the basement structures were linked to the brittle–ductile transition in the middle crust (Ramos et al., 1996; Giambiagi et al., 2003). This level is a classic detachment for basement-involved structures and is consistent with the expected detachment depth deduced from these cross-sections. Comparison between present and restored cross-sections show shortening of around 20% (Figs. 8, 10 and 16). Local shortening of up to 40%, obtained for the thin-skinned part of the range (Pedernales Thrust and Fold Belt, Cordillera de la Sal thrust belt) is not representative of the total shortening of the range and cannot be extrapolated.

Taking into account all these observations we concluded that the Mesozoic extensional faults as well as Proterozoic and Paleozoic structures exerted a strong control over the structural style in different areas of the Central Andes during contractional Andean events. This control of earlier structures over the Andean structural style has been reported in the Andes of Argentina (Uliana et al., 1995; Ramos et al., 1996; Cristallini and Ramos, 2000; Giambiagi and Ramos, 2002; Giambiagi et al., 2003; Carrera et al., 2006; Oncken et al., 2006). Kley et al. (1999) also explained how different modes of continental extension produce different styles of foreland deformation under subsequent contractional stages.

These studies also showed how the structural style along the Central Andes foreland changes more often due to inversion tectonics, than factors such as the slab dipping angle or convergence obliquity of the subduction. The onset of the contractional stage also varies from place to place along the Central Andes foreland (Jordan et al., 1997). It may be concluded that variations in the pre-existing sedimentary cover and the basement structures account for the marked segmentation of the Central Andes and of the Cordillera de Domeyko with the result that the deformational style of the Andean foreland is essentially controlled by inherited crustal features (Grier et al., 1991; Jacques, 2003a,b).

4.2. Age of the deformation

A change in the deformational regime from extensional to contractional, coincident with a magmatic gap, can be associated with a major plate reorganization during the Late Cretaceous (between 100 and 70 Ma). Scheuber et al. (1994) concluded that during this time span the spreading centre between the Aluk and

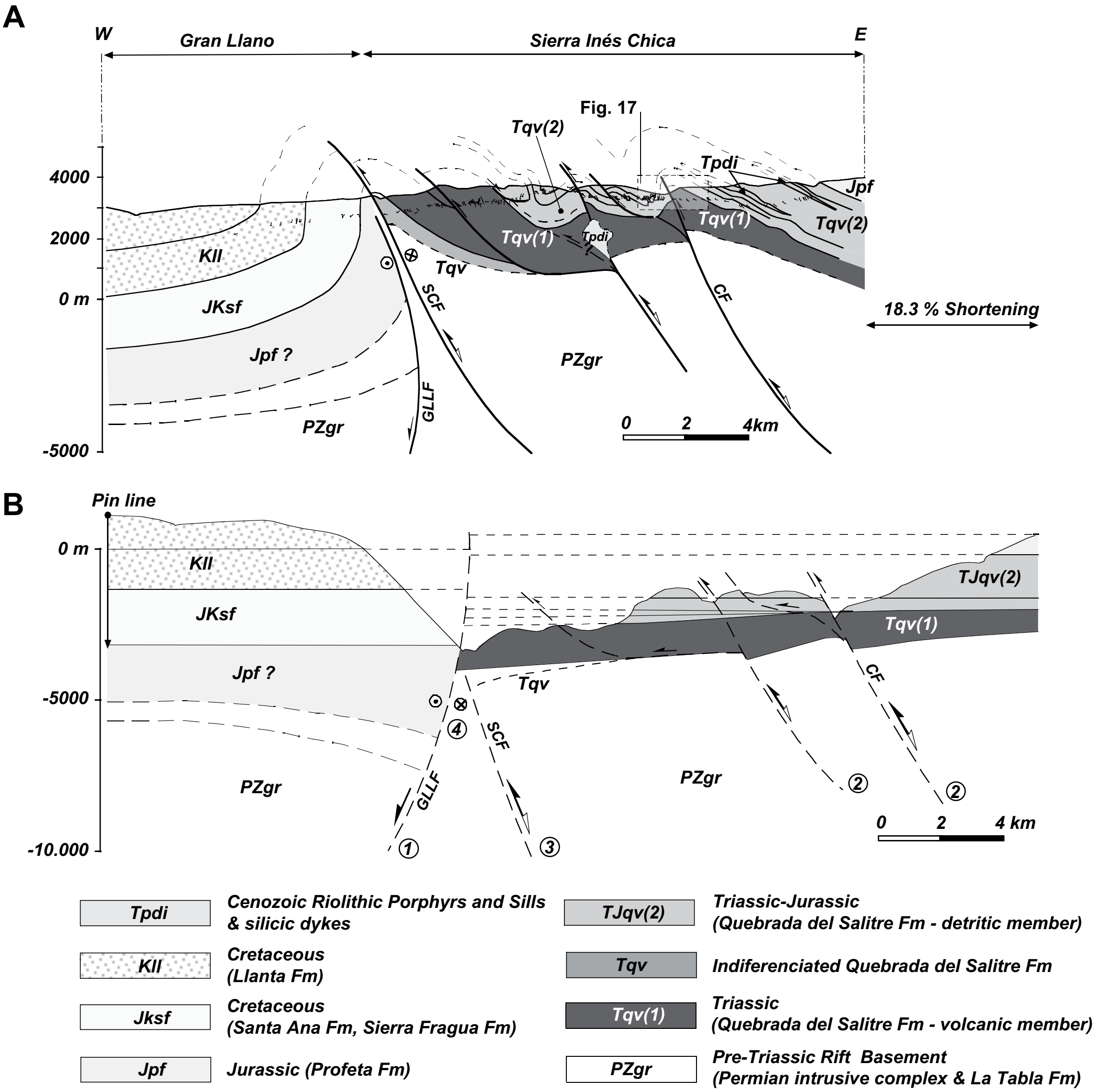

Fig. 16. (a) Regional cross-section C–C′ along Q. Carrizo (location in Fig. 15). (b) Restored C–C′ cross-section to its pre-contractional stage. (CF, Carrizo Fault; GLLF, Gran Llano Fault; SCF, Sierra Castillo Fault). Fig. 17 showing Quebrada carrizo panoramic is also located (numbers mark the relative chronology of the structures).

the Farallon plates migrated towards the south and as a result, in the study area, the convergence between the Aluk and South American plates was replaced by the convergence between the Farallon and South American plates. As a consequence of this change, the obliquity of the convergence became smaller and dextral. Orogen-normal extension is assumed to have occurred during the Aluk-South American sinistral convergence, whereas orogen-normal shortening occurred subsequently during the Farallon-South American slightly dextral convergence (see Fig. 3). Moreover, the opening of the Southern Atlantic Ocean 90 Ma ago induced a fast westward displacement of the South American plate, affecting the stress regime of the South American continent. This change of speed and direction of South America transformed the active plate boundary from a retreating subduction (subduction rate faster than convergence rate) to an advancing subduction (convergence rate faster than subduction rate), placing the overriding South American plate under a compressional regime from the Late Cretaceous onward (Scheuber et al., 1994).

The deduced contraction onset is consistent with the plate tectonic evolution described above. Different localities show growth-strata in the Paleocene (70–55 Ma) sedimentary and volcanic sequences of the Chile-Alemania Fm., and the Leoncito Fm. to the south of the Salar de Pedernales basin (Cornejo et al., 1993; Amilibia, 2002). These Paleocene sequences unconformably overlie the deformed Late Jurassic–Early Cretaceous rocks. Growth-strata geometries have also been observed in the Late Cretaceous red sandstones and conglomerates of the upper part of the Purilactis Group to the east of the El Bordo cliff (Fig. 8), (Charrier and Reutter, 1994; Pananont et al., 2004; Mpodozis et al., 2005). These observations indicate that the upper part of the Purilactis Group and the Chile-Alemania and Leoncito Formations are syn-tectonic sequences, giving an age of about 85 Ma for the onset of the contractional thin-skinned structures which continued during the Cenozoic. In line with the structural style discussed above the thin-skin fold and thrust belt in the Mesozoic–Cenozoic cover results from the basement block uplift (thick-skin structures). These relationships, allows us to date the majority of the basement-involved structures as Late Cretaceous as well.

Although tectonic uplift of the 3000–5000 m high Cordillera de Domeyko in northern Chile is assumed to be mainly Miocene in age, fission track thermochronology (Maksaev and Zentilli, 1999)

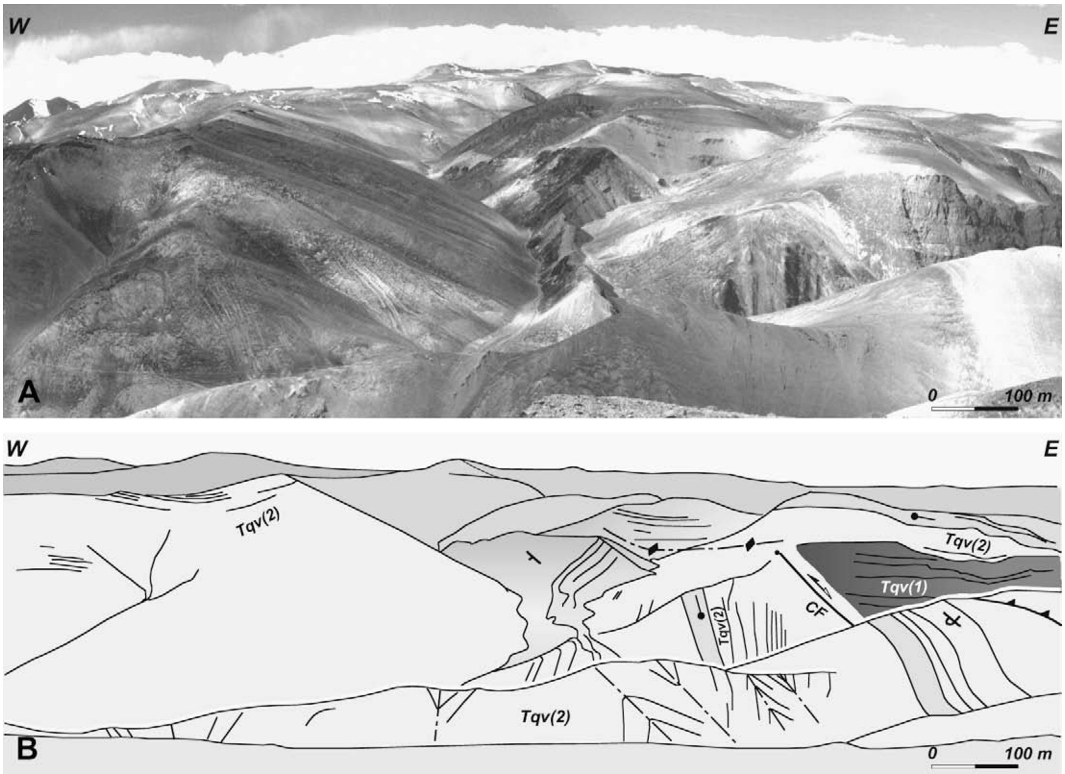

Fig. 17. (a) North view of Quebrada Carrizo inverted normal fault. (b) Line-drawing picture interpretation. The structure describes a complex anticline that shows big stratigraphic and structural differences from the frontal-limb to the back-limb. The long and gently dipping back-limb shows a thick sequence of basalts and andesitic breccias (*Tqv(1)*) that does not outcrop in the frontal-limb. The frontal-limb is steeper and shows a train of chevron folds affecting Late Triassic–Early Jurassic post-rift sedimentary rocks (*Tqv(2)*). The Quebrada Carrizo Fault (CF) is set along the axial plane of the anticline.

indicates that it was mainly active during the Eocene–Early Oligocene (between 45 and 30 Ma), when at least 4–5 km of rocks were eroded during exhumation of tectonic blocks of the Cordillera de Domeyko. Moreover, our preliminary thermochronological results (Amilibia and McClay, 2004) suggest an even older age (70 Ma) for the onset of the denudation of the basement blocks that form the Cordillera de Domeyko axial zone.

In conclusion, the onset of the E–W contractional regime in the Cordillera de Domeyko is assumed to be Late Cretaceous (90–70 Ma) (Amilibia et al., 2000; Amilibia, 2002; Mpodozis et al., 2005). A more precise timing is not constrained by all the available data. However, this time bracket is consistent with the plate tectonics evolution and field observations.

4.3. *Implications for the tecto-magmatic evolution of the area*

This study corroborates the hypothesis presented in previous work (Amilibia, 2002) that located the beginning of the compressional regime in the Chilean back-arc as far as 90 Ma ago, previous to the 45–40 Ma to present so called Andean event. On the other hand, all the shortening resulting of this tectonic event should be taken in account when calculating total shortening across the central Andes, as well as when developing a coherent tectonic evolutionary model of the area (Fig. 5).

At the end of the shortening episode that created the Cordillera de Domeyko around 40 Ma ago the South American crust was already thickened, as a consequence the melted lower crust could already be the most likely source for the adakitic magmas that generates the Eocene–Oligocene Cu rich porphyries (Kay et al., 1999; Haschke et al., 2002).

The study also demonstrates that the basement-involved structures that uplifted the Cordillera de Domeyko (from 90 Ma) already existed as reverse faults when the porphyry copper were emplaced (40–30 Ma), thus it is not necessary to develop a new set of N–S faults across the area that would act as feeders. As a consequence, the already existing Cordillera de Domeyko Fault System was reactivated during the Andean event as sinistral oblique slip structures (Fig. 18), in order to accommodate rotation owing to along strike differential shortening. These structures are the most suitable feeder for the Eocene–Oligocene porphyries to ascent to upper structural level once they reach the brittle–ductile transition zone where these reverse fault detached (Vigneresse, 1995). Minor NW–SE sinsitral strike-slip also developed during this late episode of deformation, facilitating the clockwise rotation of basement blocks accommodating the different E–W shortening rates from North to South.

5. Conclusions

We concluded that the main structural style of the Cordillera de Domeyko is strongly dependent on inherited structures. Inversion Tectonics, where pre-existing normal faults were reactivated as steep reverse faults, produced kilometric scale inversion anticlines, uplifting syn-rift Triassic sequences and transferring the deformation to post-Triassic sedimentary Mesozoic cover. According to this interpretation the Cordillera de Domeyko can be characterized as follows:

1. The Cordillera de Domeyko is an N–S-trending, W–E shortened structural belt, with little evidence of N–S major strike-slip deformation, developed under a gently oblique convergence from the end of the Cretaceous times.
2. No evidence for strain-partitioning in the Precordillera has been observed. Part of the expected parallel to the trench

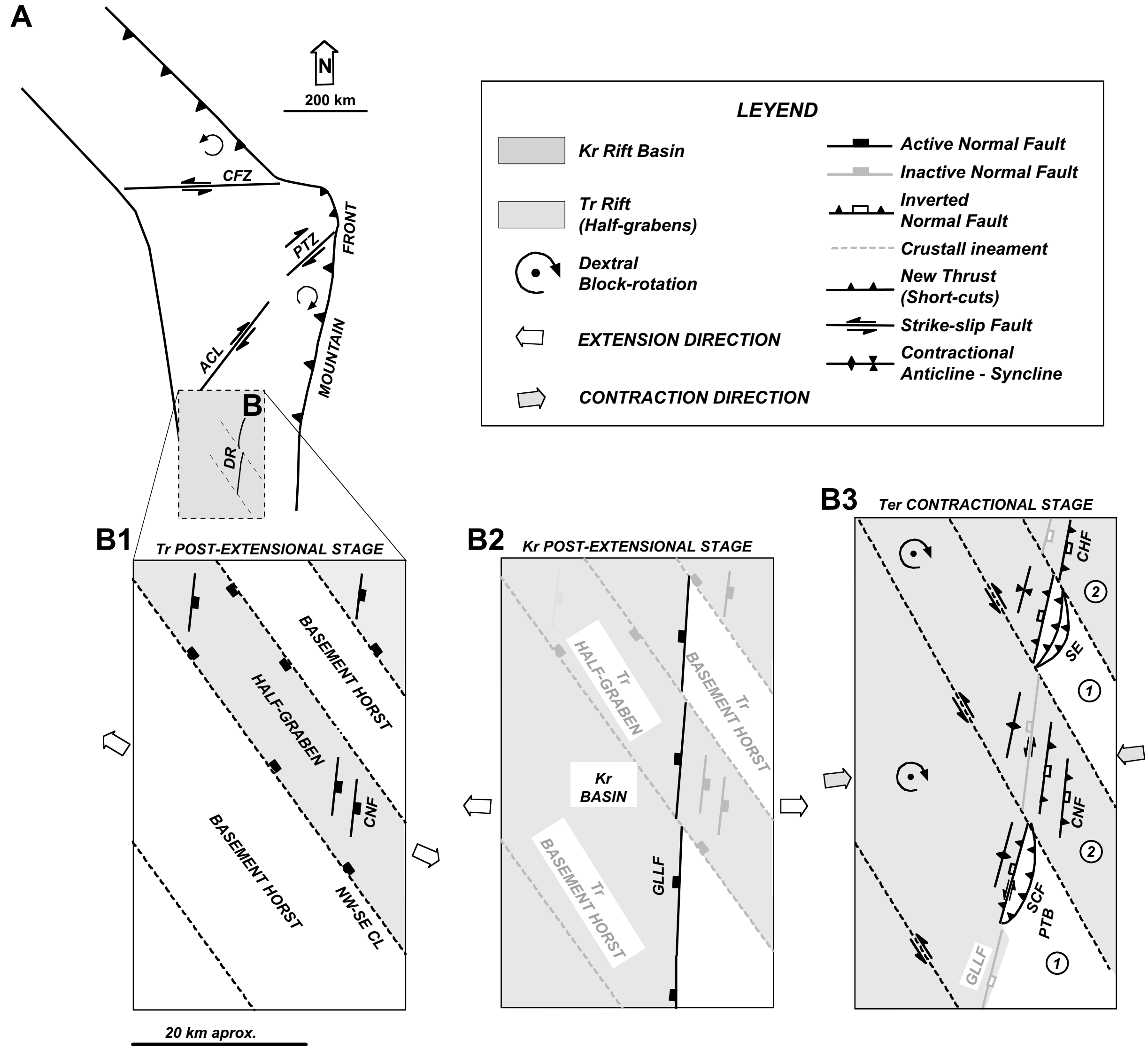

Fig. 18. (A) Strain-partitioning along the Central Andes in order to accommodate the differential shortening along the Bolivia Orocline; CFZ, Cochabamba Fault Zone; PTZ, Padilla Transfer Zone; ACL, Atacama Calama Lineament; DR, Domeyko Range. (B) Synoptic evolutionary model for the Domeyko Range area: (1) Structural framework after Triassic–Late Jurassic Rifting. NW-SE half-grabens were generated. (2) Structural framework after over-imposing the Cretaceous rifting. Extension was dominated by N–S faults. (3) Structural framework after E–W Andean Shortening (1, areas without pre-existing structures in the footwall basement, the shortening is absorbed mainly by new developed short cuts; 2, areas with pre-existing structures in the footwall basement, these structures were reactivated under contraction). (NW–SE CL, Northwest–southeast crustal lineaments; CNF, Carrizo Triassic Normal Fault; GLLF, Gran Llano Cretaceous Normal Fault; CHF, Chaco Inverted Basement Fault; SE, Sierra Exploradora Short-cut complex; SCF, Sierra Castillo Fault; PTB, Pedernales Thrust and Fold Belt).

displacements was absorbed by the Atacama Fault System during the early stages of deformation.

3. Inversion of pre-existing extensional faults, related to the Triassic and Late Jurassic–Early Cretaceous rifts, is the dominant way of absorbing the shortening in the area. Thus, basement uplift is related to inversion tectonics. Thick and thin-skinned contractional structures are genetically related and were developed during the Late Cretaceous–Cenozoic deformational stage.
4. Internal levels of Mesozoic–Cenozoic cover acted as detachments levels, (e.g. Oxfordian gypsums and Middle Jurassic marls by thin-skinned structures).
5. Shortening across the Cordillera de Domeyko is estimated to not exceed 35%.
6. Our evolutionary model is coherent with the genesis of a Porphyry Copper magma source at the end of the compressional stage, coinciding with the existence of a thick lower crust. The resulting Eocene–Oligocene porphyries were emplaced as sills and tabular dykes in the hanging-wall of reverse faults in a regional transpressional stress field.

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References

Alvarez, P.P., Ramos, V.A., 1999. The Mercedario rift system in the principal Cordillera of Argentina and Chile (32° SL). Journal of South American Earth Sciences 12, 17–31.

Amilibia, A., 2002. Inversión Tectónica en la Cordillera de Domeyko, Andes del Norte de Chile. PhD thesis, Universitat de Barcelona.

Amilibia, A., Sàbat, F., Chong, G., Muñoz, J.A., Roca, E., Gelabert, B., 2000. Criterios de Inversión tectónica: ejemplos de la Cordillera de Domeyko (II región de Antofagasta, Chile). In: Proc. IX Congr. Geol. Chileno, vol. 2 548–552.

Amilibia, A., McClay, K., 2004. Structural Evolution of the Cordillera de Domeyko. CODELCO, Informe Registrado, Santiago, Chile, 88 pp.

Amilibia, A., McClay, K.R., Sàbat, F., Muñoz, J.A., Roca, E., 2005. Analogue modelling of inverted oblique rift systems. Geologica Acta 3, 251–271.

Arcuri, T.L., Brimhall, G.H., 2002. Animation Model of West Central South America from the Early Jurassic to Late Miocene, with some oil and gas implications. Search and Discovery Article 10033.

Ardill, J., Flint, S., Chong, G., Wilke, H., 1998. Sequence stratigraphy of the Mesozoic Domeyko Basin, northern Chile. Journal of the Geological Society, London 155, 71–88.

Arriagada, C., Roperch, P., Mpodozis, C., 2000. Clockwise block rotations along the eastern border of the Cordillera de Domeyko, Northern Chile (22°45′–23°30′S). Tectonophysics 326, 153–171.

Arriagada, C., Roperch, P., Mpodozis, C., Dupont-Nivet, G., Cobbold, P.R., Chauvin, A., Cortes, J., 2003. Paleogene clockwise tectonic rotations in the fore-arc of Central Andes, Antofagasta region, northern Chile. Journal Geophysical Research 108 (B1), 2032, doi:10.1029/2001JB001598.

Arriagada, C., Roperch, P., Mpodozis, C., Fernandez, R., 2006. Paleomagnetism and tectonics of the soutern Atacama Desert (25–28°), norrthen Chile. Tectonics 25, TC4001, doi:10.1029/2005TC001923.

Astudillo, N., Roperch, P., Townley, B., Arriagada, C., Maksaev, V., 2007. Importance of small-block rotations in damage zones along transcurrent faults. Evidence from the Chuquicamata open pit, Northern Chile. Tectonophysics 450 (1–4), 1–20.

Ballard, J.R., Alin, J.M., Williams, I.S., Campbell, I.H., Faunes, A., 2001. Two ages of porphyry intrusion resolved for the super-giant Chuquicamata copper deposit of northern Chile by ELA-ICP-MS and SHRIMP. Geology 29 (5), 383–386.

Buchanan, J.G., Buchanan, P.G. (Eds.), 1995. Basin Inversion. Geological Society of London, Special Publication, 88, p. 596.

Butler, R.W.H., Tavarnelli, E., Grasso, M., 2006. Structural inheritance in mountain belts: an Alpine–Apennine perspective. Journal of Structural Geology 28, 1893–1908.

Butler, R.W.H., 1989. The influence of pre-existing basins structure on thrust system evolution in the western Alps. In: Cooper, M.A., Williams, G.D. (Eds.), Inversion Tectonics. Geological Society of London, Special Publication, 44, pp. 105–122.

Casas, A.M., Gapais, D., Nalpas, T., Besnard, K., Román-Berdiel, T., 2001. Analogue models of transpressive systems. Journal of Structural Geology 23, 733–743.

Carrera, N., Muñoz, J.A., Sàbat, F., Roca, E., Mon, R., 2006. The role of inversion tectonics in the structure of the Cordillera Oriental (NW Argentinean Andes). Journal of Structural Geology 28, 1921–1932.

Charrier, R., Reutter, K.-J., 1994. The Purilactis Group of Northern Chile: Boundary Between Arc and Backarc from Late Cretaceous to Eocene. In: Reutter, K.-J., Scheuber, E., Wigger, P.J. (Eds.), Tectonics of Southern Central Andes, Structure and Evolution of an Active Continental Margin. Springer-Verlag, Berlin, pp. 189–202.

Chernicoff, C.J., Richards, J.P., Zappettini, E.O., 2002. Crustal lineament control on magmatism and mineralization in northwestern Argentina: geological, geophysical, and remote sensing evidence. Ore Geology Reviews 21 (3), 127–155 (29).

Cornejo, P., Mpodozis, C., Ramirez, C.F., Tomlinson, A., 1993. Estudio Geologico de la Region de Potrerillos y El Salvador (26°–27°S). Servicio Nacional de Geologia y Mineria-CODELCO, Informe Registrado IR-93 01, 12 cuadrangulos escala 1:50,000 y texto, Santiago, Chile, 258 pp.

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

Cristallini, E.O., Ramos, V.A., 2000. Thick-skinned and thin-skinned thrusting in the La Ramada fold and thrust belt: crustal evolution of the High Andes of San Juan, Argentina (32° SL). Tectonopysics 317, 205–235.

Franzese, J.R., Spalletti, L.A., 2001. Late Triassic-early Jurassic continental extension in southwestern Gondwana: tectonic segmentation and pre-break-up rifting. Journal of South American Earth Sciences 14, 257–270.

Giambiagi, L.B., Ramos, V.A., 2002. Structural evolution of the andes in a transtensional zone between flat and normal subduction (33°30́–33°45́S), Argentina and Chile. Journal of South American Earth Sciences 15, 101–116.

Giambiagi, L.B., Alvarez, P.P., Godoy, E., Ramos, V.A., 2003. The control of pre-existing extensional structures on the evolution of the southern sector of the Aconcagua fold and thrust belt, southern Andes. Tectonophysics 369, 1–19.

Gillcrist, R., Coward, M., Mugnier, J., 1987. Structural inversion and its con-trols: examples from the Alpine foreland and the French Alps. Geodinamica Acta 1, 5–34.

Grier, M.E., Salfity, J.A., Allmendinger, R.W., 1991. Andean reactivation of the Cretaceous Salta Rift, northwestern Argentina. Journal of South American Earth Sciences 4, 351–372.

Gröschke, M., Hillebrant, A.V., Prinz, P., Quinzio, L.A., Wilke, H.-G., 1988. Marine Mesozoic paleogeography in northern Chile between 21°–26°S. In: Bahlburg, H., Breitkreuz, Ch., Giese, P. (Eds.), The Southern Central Andes. Lecture Notes in Earth Sciences, vol. 17, pp. 105–117.

Günther, A., Haschke, M., Reutter, K.-J., Scheuber, E., 1997. Repeated reactivation of an ancient fault zone under changing Kinematic conditions: the Sierra de Moreno fault system (SMFS) (N-Chilean Precordillera). In: VIII Congreso Geológico Chileno, Actas, vol. I 85–89.

Haschke, M., Siebel, W., Günther, A., Scheuber, E., 2002. Repeated crustal thickening and recycling during the Andean orogeny in North Chile (21°–26°S). Journal of Geophysical Research 107 (B1), doi:10.1029/2001JB000328.

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

Hoffmann, A., Kukowski, N., Dresen, G., Echtler, H., Onceen, O., Klotz, J., Scheuber, E., Kellner, A., 2006. Oblique convergente along the Chilean margin: partitioning, margin-parallel faulting and force interaction at the plate interface. In: Onceen, O., Chong, G., Granz, G., Giese, P., Götze, H.-J., Ramos, V., Strecker, M., Wigger, P. (Eds.), The Andes, Active Subduction Orogeny, Frontiers in Hearth Sciences. Springer, pp. 1–27. Chap. 1.

Hongn, F., Del Papa, C., Powell, J., Petrinovic, I., Mon, R., Deraco, V., 2007. Middle Eocene deformation and sedimentation in the Puna–Eastern Cordillera transition (23°–26°S): Control by preexisting heterogeneities on the pattern of initial Andean shortening. Geology 35 (3), 271–274.

Jacques, J.M., 2003a. A tectonostratigraphic synthesis of the Sub-Andean basins: implications for the geotectonic segmentation of the Andean Belt. Journal of the Geological Society, London 160, 687–701.

Jacques, J.M., 2003b. A tectonostratigraphic synthesis of the Sub-Andean basins: inferences on the position of South American intraplate accommodation zones and their control on South Atlantic opening. Journal of the Geological Society, London 160, 703–717.

Jordan, T.E., Reynolds III, J.H., Erikson, J.P., 1997. Variability in age of initial shortening and uplift in the Central Andes, 16–33°30′ S. In: Ruddiman, W. (Ed.), Tectonic Uplift and Climate Change. Plenum, New York.

Kalakay, T.J., John, B.E., Lageson, D.R., 2001. Fault/controlled pluton emplacement in the Sevier fold/and/thrust belt of southwest Montana, USA. Journal of Structural Geology 23, 1151–1165.

Kay, S.M., Mpodozis, C., Coira, B., 1999. Magmatism, tectonism, and mineral deposits of the central andes (22°–33°S). In: Skinner, B. (Ed.), Geology and Ore Deposits of the Central Andes. Society of Economic Geology Special Publication 7, pp. 27–59.

Kley, J., Monaldi, C.R., Salfity, J.A., 1999. Along strike segmentation of the Andean foreland: causes and consequences. Tectonophysics 301, 75–94.

Maksaev, V., Zentilli, M., 1999. Fission track thermochronology of the Domeyko Cordillera, Northern Chile: implications for Andean tectonics and porphyry copper metallogenesis. Exploration and Mining Geology 8 (1–2), 65–89.

Marinovic, N.S., Smoje, I.T., Maksaev, V.J., Herve, M.A., Mpodozis, C.M., 1992. Hoja Aguas Blancas, Región de Antofagasta. Nacional de Geología y Minería, Carta Geológica de Chile. 70 (1:250.000)1–122.

McClay, K.R., Insley, M.W., Anderton, R., 1989. Inversion of the Kechika Trough, Northeastern British Columbia, Canada. In: Geological Society, London, Special Publications, vol. 44 235–257.

Morata, D., Aguirre, L., 2003. Extensional Lower Cretaceous volcanism in the Coastal Range (29°30′–30°S), Chile: geochemistry and petrogenesis. Journal of South American Earth Sciences 16, 459–476.

Mpodozis, C., Ramos, V.A., 1990. The Andes of Chile and Argentina. In: Geology of the Andes and Its Relation to Hydrocarbon and Mineral Resources, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series 59–90.

Mpodozis, C., Cornejo, P., 1997. El rift Triásico-Sinemuriano de Sierra Exploradora, Cordillera de Domeyko (25°–26°S): Asociaciones de facies y reconstrucción tectónica. VIII Congreso Geológico Chileno, Antofagasta, Actas-vol. I, Sesión Temática 3, pp. 550–554.

Mpodozis, C., Arriagada, C., Basso, M., Roperch, P., Cobbold, P., Reich, M., 2005. Late Mesozoic to Paleogene stratigraphy of the Salar the Atacama Basin, Antofagasta, Northern Chile: implications for the tectonic evolution of the Central Andes. Tectonophysics 399, 125–154.

Muñoz, N., Townsend, F., 1997. Estratigrafía de la Cuenca Salar de Atacama. Resultados del pozo exploratorio Toconao-1. Implicaciones Regionales. Proc VIII Congr. Geol. Chileno 1, pp. 555–558.

Oncken, O., Hindle, D., Kley, J., Elger, K., Victor, P., Schemmann, K., 2006. Deformation of the Central Andean upper plate system – facts, fiction, and constraints for plateau models. In: Onceen, O., Chong, G., Granz, G., Giese, P., Götze, H.-J., Ramos, V., Strecker, M., Wigger, P. (Eds.), The Andes, Active Subduction Orogeny, Frontiers in Hearth Sciences. Springer, pp. 1–27. Chapter 1.

Pananont, P., Mpodozis, C., Blanco, N., Jordan, T.E., Brown, L.D., 2004. Cenozoic evolution of the northwestern Salar de Atacama Basin, northern Chile. Tectonics 23, TC6007, doi:10.1029/2003TC001595.

Pardo-Casas, F., Molnar, P., 1987. Relative Motion of the Nazca (Farallon) and South American plates since late Cretaceous time. Tectonics 6, 233–248.

Prinz, P., Wilke, H.-G., von Hillebrant, A., 1994. Sediment accumulation and subsidence history in the Mesozoic marginal basin of Northern Chile. In: Reutter, K.-J., Scheuber, E., Wigger, P.J. (Eds.), Tectonics of Southern Central Andes, Structure and Evolution of an Active Continental Margin. Springer-Verlag, Berlin, pp. 219–232.

Ramírez, C.F., Gardeweg, M.C., 1982. Hoja Toconao, Región de Antofagasta. Servicio Nacional de Geología y. Minería, Carta Geológica de Chile. 54 (1:250.000)1–122.

Ramos, V.A., 1988. Late Proterozoic–Early Paleozoic of South America; a collisional history. Episodes 11 (3), 168–174.

Ramos, V.A., Cegarra, M., Cristallini, E., 1996. Cenozoic tectonics of the High Andes of west-central Argentina (30–36°S latitude). Tectonophysics 259, 185–200.

Ramos, V.A., Zapata, T., Cristallini, E., Introcaso, A., 2004. The Andean thrust system – latitudinal variations in structural styles and Orogenic shortening. In: McClay, K.R. (Ed.), Thrust Tectonics and Hydrocarbon Systems. AAPG Memoir 82, pp. 30–50.

Reutter, K.-J., Scheuber, E., Chong, G., 1996. The Precordilleran fault system of Chuquicamata, Northern Chile: evidence for reversals along arc-parallel strike.slip faults. Tectonophysics 259, 213–228.

Richards, J.P., Boyce, A.J., Pringue, M.S., 2001. Geologic evolution of the Escondida Area, Northern Chile: a model for spatial and temporal localization of Porphyry Cu mineralization. Economic Geology 96 (2), 271–305.

Richards, J.P., 2003. Tectono-magmatic precursors for porphyry Cu–(Mo–Au) deposit formation. Economic Geology 98 (8), 1515–1533.

Royden, L.H., 1993. The tectonic expression of slab pull at continental convergent boundaries. Tectonics 12, 303–325.

Salfity, J.A., 1985. Lineamientos transversals al rumbo andino en el noroeste argentino. IV Congreso Geológico Chileno, pp. 2-119–2-137.

Scheuber, E., Bogdanic, T., Jensen, A., Reutter, K.-J., 1994. Tectonic development of the North Chilean Andes in relation to plate convergence and magmatism since the Jurassic. In: Reutter, K.-J., Scheuber, E., Wigger, P.J. (Eds.), Tectonics of Southern Central Andes, structure and evolution of an Active Continental Margin. Springer-Verlag, Berlin, pp. 121–140.

Scheuber, E., Gonzalez, G., 1999. Tectonics of the Jurassic–Early Cretaceous magmatic arc of north Chilean Coastal Cordillera (22°–26°S): a story of crustal deformation along a convergent plate boundary. Tectonics 18 (5), 895–910.

Schreurs, G., Colleta, B., 1998. Analogue modelling of faulting in zones of continental transpression. In: Holdswort, R.E., Strachan, R.A., Dewey, J.F. (Eds.), Continental Transpressional and Transtensional Tectonics. Geological Society, London, Special Publication 135, pp. 59–79.

Scisciani, V., Tavarnelli, E., Calamita, F., 2002. The interaction of extensional and contractional deformations in the outer zones of the Central Apennines, Italy. Journal of Structural Geology 24, 1647–1658.

Stern, C.R., 1991. Role of subduction erosion in the generation of Andean magmas. Geology 19 (1), 78–81.

Suarez, M., Bell, C.M., 1992. Triassic rift-related sedimentary basins in northern Chile (24°–29°S). Journal of South American Earth Sciences 6, 109–121.

Tavarnelli, E., Butler, R.W.H., Decandia, F.A., Calamita, F., Grasso, M., Alvarez, W., Renda, P., 2004. Implications of fault reactivation and structural inheritance in the Cenozoic tectonic evolution of Italy. In: Crescenti, U., D'Offizi, S., Merlini, S., Sacchi, R. (Eds.), The Geology of Italy, Special Volume 1. Societa Geologica Italiana, pp. 209–222.

Uliana, M.A., Biddle, K.T., Cerdan, J., 1989. Mesozoic extension and the formation of Argentine sedimentary basins. In: Tankard, A., Balkwill, H.R. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic Margins. American Association of Petroleum Geologists, Memoir, vol. 46, pp. 599–614.

Uliana, M.A., Arteaga, M.E., Legarreta, L., Cerdán, J.J., Peroni, G.O., 1995. Inversion structures and hydrocarbon occurrence in Argentina. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion. Geological Society Special Publication 88, pp. 211–233.

Vigneresse, J.-L., 1995. Crustal regime of deformation and ascent of granitic magma. Tectonophysics 249 (3–4), 187–202.