

Mechanisms and Episodes of Deformation Along the Chilean–Pampean Flat-Slab Subduction Segment of the Central Andes in Northern Chile

Fernando Martínez, César Arriagada and Sebastián Bascuñán

Abstract The knowledge of the tectonic architecture, timing, and the mechanisms of deformation that affected the western slope of the Chilean–Pampean flat-slab subduction segment of the Central Andes in northern Chile are a key to understand the complete evolution of this Andean segment. In Chile, this segment is composed of two tectonic provinces: The Coastal and the Frontal Cordilleras. Traditionally, this broad intracontinental deformation zone that characterized this segment has been compared with the Rocky Mountains, in terms of structural styles and age of deformation, although the complex interaction between extensional Mesozoic structures and different styles of contractional structures suggest that this segment resulted from multiple episodes of deformation. We present the results of a study developed along the Coastal and Frontal Cordillera of northern Chile (27°–28° S), based on regional fieldwork, structural analysis, and geochronological dating of synorogenic deposits. Our results have revealed that the structure of this region consists of NNE-striking inverted and basement-involved contractional structures. The occurrence of these structural styles suggests that a hybrid tectonic mechanism dominated by tectonic inversion and basement-involving thrusting was responsible of its current configuration. On the other hand, the U–Pb ages determined in the synorogenic deposits exposed on the footwall of the main faults indicate that the Andean deformation could have initiated during the Late Cretaceous in the Coastal Cordillera associated with tectonic inversion and then this migrated to the east as basement-involved thrusting during the Paleocene–Miocene times.

Keywords Chilean–Pampean flat subduction zone • Cretaceous deformations
Cenozoic deformations • Tectonic inversion • Basement-involved structures
Northern Chile

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1 Introduction

The Chilean–Pampean flat-slab subduction segment of the Central Andes between 28° and 33° S (Baraganzi and Isacks 1976; Jordan et al. 1983; Isacks 1988) represents one of the two major flat-slab segments imaged below the continental margin of South America (Martinod et al. 2010) (Fig. 1). This Andean segment is characterized by a gap of active volcanism, a basement-involved deformation style and spread Late Cenozoic arc volcanism in the foreland area (Ramos et al. 2002). Between 27°–28° S, this segment consists of three morphotectonic units that include the Coastal and the Frontal Cordillera along the Chile–Argentina border, and the Precordillera and Sierras Pampeanas on the Argentinean side (Fig. 1). At these latitudes, the Frontal Cordillera, the Precordillera, and the Sierras Pampeanas reach elevations between 2 and 4 km and locally 6 km a.s.l., with intervening flat plains at less than 1 km a.s.l. (Jordan et al. 1983; Moscoso and Mpodozis 1988; Martínez et al. 2015b).

Traditionally, the Chilean–Pampean flat-slab subduction segment was considered as a modern analogue to the Rocky Mountain of North America in regards to its structure and age of deformation (Jordan and Allmendinger 1986; Allmendinger et al. 1997; Ingersoll 2012, among others), as it is fundamentally dominated by large and broad crystalline uplifted blocks (Jordan et al. 1983; Narr and Suppe 1994; Ramos 1999; Poblet and Lisle 2011) that resulted from Miocene horizontal compression generated by the shallowing of the Nazca Plate under the continental margin of South America. The knowledge of its tectonic history comes mainly from studies carried out along tectonic provinces and petroliferous basins located on the eastern side, such as the Sierras Pampeanas, the Tucumán Basin, the Méta Basin, the Santa Barbara System, among others. In these regions, previous studies using seismic information combined with field and oil well data have interpreted a thick-skinned structure composed of large and broad, basement-cored folds, and reverse faults intercalated with synorogenic basins related to the reactivation of ancient suture zones and normal faults, which have propagated as reverse faults accumulating around 150 km of minimum crustal shortening during Neogene times (Jordan et al. 1983; Coutand et al. 2001; Kley and Monaldi 2002; Heredia et al. 2002; Ramos et al. 2002; Cristallini et al. 2004; Carrapa et al. 2011; Iaffa et al. 2011).

On the other hand, recent studies developed in the western slope of northern Chile (Fig. 1), based mainly on geological observations, balanced cross sections and radiometric ages, have also documented a remarkable basement-involved deformation style (Moscoso and Mpodozis 1988; Amilibia et al. 2008; Peña et al. 2013; Martínez et al. 2013, 2015b, 2016). However, this has been mainly associated with inversion structures created from the shortening and partial closure of Lower Cretaceous and Jurassic extensional back-arc basins during Late Cretaceous–Paleocene and Miocene contractional pulses (Peña et al. 2013; Martínez et al. 2013, 2016). In contrast to previous interpretations made on the eastern Andean slope, the results obtained recently in northern Chile (Fig. 1) have opened a new debate about:

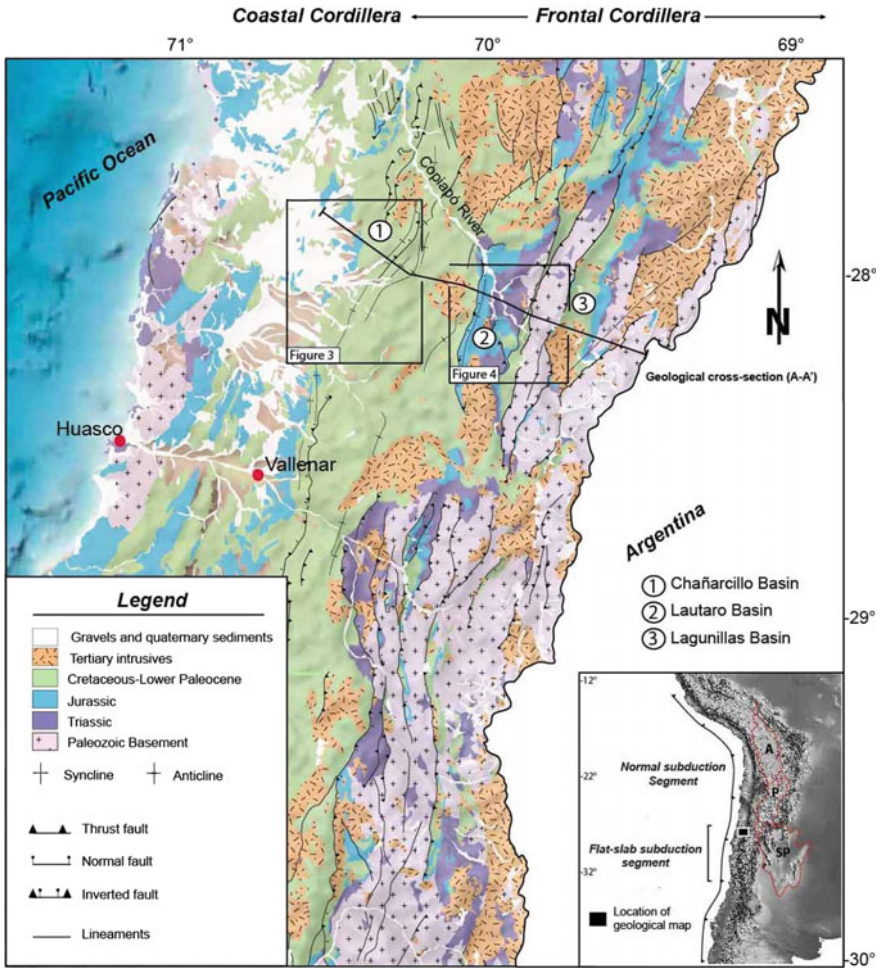


Fig. 1 Generalized geological map of the “Pampean” subduction segment of northern Chile between 28°–30° S, showing the spatial distribution of the main stratigraphic and tectonic units of the region

(a) What tectonic mechanisms are responsible for the current architecture of this Andean segment; (b) how the Mesozoic extensional systems previously established in this region have interacted with younger thrust systems during later Andean deformation; (c) what is the main tectonic control on the basement-involved deformation style; and (d) what are the main episodes of Andean deformation.

In order to discuss these topics, we present here the results of a recent study developed along the Coastal and Frontal Cordilleras of northern Chile (Fig. 1), which is based on regional geological mapping, field observations, structural analysis, and geochronological dating of synorogenic deposits. Finally, we compare

these data with previous tectonic models proposed for the neighboring regions on the Argentinean side, highlighting the main tectonic mechanism and episodes of deformation that took place in these regions, showing that timing of development of the Chilean–Pampean flat subduction segment includes more than one phase of deformation and then that important sectors of the fold and thrust belt were constructed previously to the slab shallowing achieved in the last 17 Ma.

2 Regional Geological Context

Two tectonic provinces compose the present-day architecture of the Chilean–Pampean flat subduction segment in northern Chile: the Coastal Cordillera and the Frontal Cordillera, as illustrated in Fig. 1. The stratigraphic successions exposed along them comprise at least five major sequences (Fig. 2; Martínez et al. 2016). The oldest units correspond to Paleozoic and Lower Triassic rocks that include metasedimentary (Naranjo and Puig 1984; Grocott and Taylor 2002; Scheubert and Reutter 1992) and granitic plutonic complexes (245–250 Ma; Mpodozis and Ramos 1990; Martínez et al. 2015b; Del Rey et al. 2016, among others). They lie well-exposed both in the western Coastal Cordillera and the Frontal Cordillera (Fig. 1) and form the pre-rift basement of the Jurassic and Cretaceous extensional back-arc basins developed in this region after the breakup of Gondwana (Pindell and Dewey 1982; Mpodozis and Ramos 1990; Aguirre-Urreta 1993; Mpodozis and Ramos 1990, 2008; Ramos 2009; Del Rey et al. 2016).

These rocks are unconformably covered and flanked by a thick cover of volcanic and sedimentary sequences that vary laterally from the Coastal to the Frontal Cordillera, forming part of the infill of the Mesozoic, inverted Chañarcillo, Lautaro, and Lagunillas basins (Martínez et al. 2016; Figs. 1 and 2). These basins correspond to a series of NNE-oriented, former half-grabens that were created during the fragmentation of western Gondwana during the Late Triassic–Early Cretaceous periods (Aguirre-Urreta, 1993; Mpodozis and Ramos 1990, 2008; Martínez et al. 2016) (see Chap. “[The Early Stages of the Magmatic Arc in the Southern Central Andes](#)”). Within this cover, the oldest sequences correspond to around 2,100 m of Upper Triassic volcanic and sedimentary deposits (La Ternera Fm; Segerstrom 1960; Suárez and Bell 1992) that are mainly exposed along valleys and rivers cutting the Frontal Cordillera (Figs. 1 and 2). These deposits have been associated with a continental syn-rift sequence accumulated during early episodes of stretching and crustal extension, previous to the establishment of the Jurassic and Cretaceous back-arc basins in this region (Jensen 1976; Charrier 1979; Mpodozis and Cornejo 1997; Martínez et al. 2012). The Jurassic sequences can be divided into two sections, the westernmost deposits exposed along the eastern Coastal Cordillera which consist predominantly of Upper Jurassic volcanic successions (Punta del Cobre Fm; Fig. 2) related to intra-arc deposits (Lara and Godoy 1998; Marschik and Fontboté 2001), and the eastern, marine, and continental Jurassic deposits that crop out in the Frontal Cordillera, corresponding to intercalations of limestones, shale and volcano-sedimentary successions (Lautaro and Lagunillas formations;

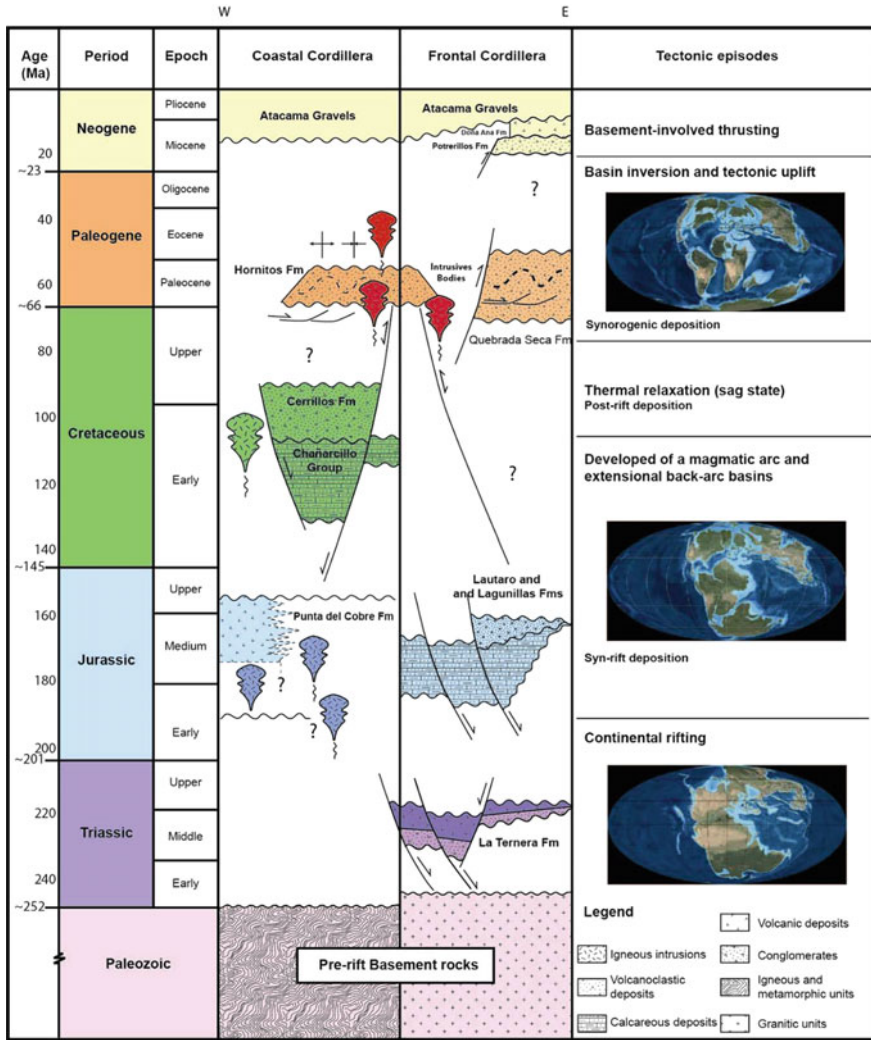


Fig. 2 Chronostratigraphic chart indicating the main sequences recognized on the western Andean slope of the northern Chilean–Pampean flat subduction zone and the tectonic stages proposed to the evolution of this Andean segment

Fig. 2), with remarkable variations of thickness, progressive unconformities, and internal normal faults, which have been interpreted as syn-rift deposits (Segerstrom 1960; Jensen 1976; Arévalo 2005; Martínez et al. 2012).

The Lower Cretaceous deposits in this region are exposed along the eastern Coastal Cordillera (Fig. 2). Here, they crop out as a NNE-oriented belt of almost 4,000 m of calcareous and siliciclastic rocks, forming a stratigraphic wedge internally affected by syn-extensional faults. These deposits have been interpreted as the

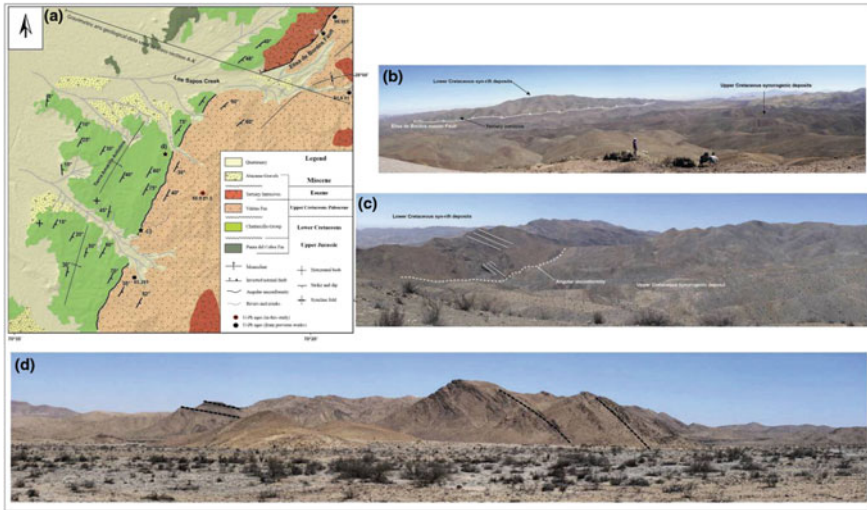


Fig. 3 **a** Geological map of the central region of the Lower Cretaceous Chañarcillo Basin (see location on Fig. 1), **b** frontal view of the Tierra Amarilla Anticline and the Elisa de Bordos Fault marking the eastern limit of the Chañarcillo Basin (see position in Fig. 3a), **c** aspect of the angular unconformity between the Lower Cretaceous syn-rift deposits of the Chañarcillo Group and the Upper Cretaceous synorogenic deposits of the Viñitas Formation observed along the frontal limb of the Tierra Amarilla Anticline (see positions on Fig. 3a), **d** panoramic and transversal view of the Tierra Amarilla Anticline, showing a typical geometry related to an inversion anticline. Note the lateral variations of thickness of the Lower Cretaceous (Chañarcillo Group) syn-rift deposits along the structure (see positions on Fig. 3a)

syn-rift deposits of the Chañarcillo Basin (Fig. 3) and they are called the Chañarcillo Group (Segerstrom 1960; Arévalo 1999; Mourgues 2004). This sequence is locally overlapped by Mid-Cretaceous volcanic and sedimentary successions (Cerrillos Fm; Segerstrom 1960; Arévalo 1994, 2005; Fig. 3) that are related to the sag deposits associated with thermal relaxation of the Chañarcillo Basin subsequent to crustal extension (Martínez et al. 2013, 2015a).

The transition from the Mesozoic to the Cenozoic cover is marked by the Upper Cretaceous and Paleocene sequences (Viñitas and Quebrada Seca formations; Figs. 3 and 4), which correspond to thick continental synorogenic deposits exposed along intramontane depressions in the eastern Coastal Cordillera (Viñitas Formation) and the eastern Frontal Cordillera (Quebrada Seca Formation; Figs. 3 and 4). They are composed of red sandstones, conglomerates, ignimbrites, and different volcanic flows with growth strata and progressive unconformities (Martínez et al. 2016), which in turn are intruded by kilometric, intrusive bodies (Figs. 3 and 4). The accumulation of these deposits has been related to regional contractional pulses associated with tectonic inversion and thrusting processes, as well as with the eastward displacement of the magmatic arc (Mpodozis and Ramos 1990; Cornejo et al. 1993; Martínez et al. 2013). Miocene continental and unconsolidated sediments (Atacama Gravels; Mortimer 1973) unconformably overlie the latter sequences.

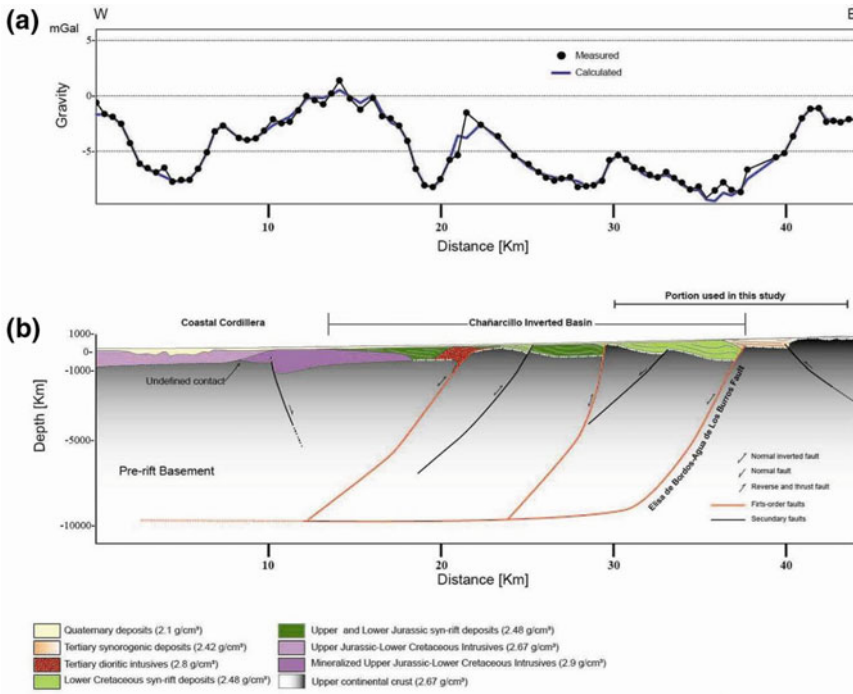


Fig. 4 **a** Gravity profile through the central section of the Chañarcillo Basin used in this study showing the Bouguer anomaly and the regional anomaly, **b** structural interpretation of the gravity profile supported by geological data (see position of this profile in Fig. 3) (modified from Martínez et al. 2015a)

3 Tectonic Framework and Mechanisms of Deformation

Two main structural styles have been recognized along this Andean segment: inversion and basement-involved structures (Jensen 1976; Moscoso and Mpodozis 1988; Arévalo 2005; Peña et al. 2013; Martínez et al. 2016). Their occurrence and distribution vary along the complete segment. Inversion structures are preferentially located at the edges of the Mesozoic basins forming the major limits between the Coastal and the Frontal Cordillera (Figs. 3 and 4), while basement-involved structures are specifically distributed along the Frontal Cordillera (Fig. 1). In order to document the mechanisms of deformation that took place in this region, we have constructed a regional cross section from the Coastal Cordillera to the Frontal Cordillera at 28° S (Figs. 1 and 5). We have constrained the surface structure by field work and geological maps (Moscoso et al. 2010; Peña et al. 2013) and the subsurface structure by gravimetric data (Martínez et al. 2015a). The cross section was constructed using Move software (@Midland Valley). Major detachments in this region are unknown, and they have been inferred by area-balanced methods,

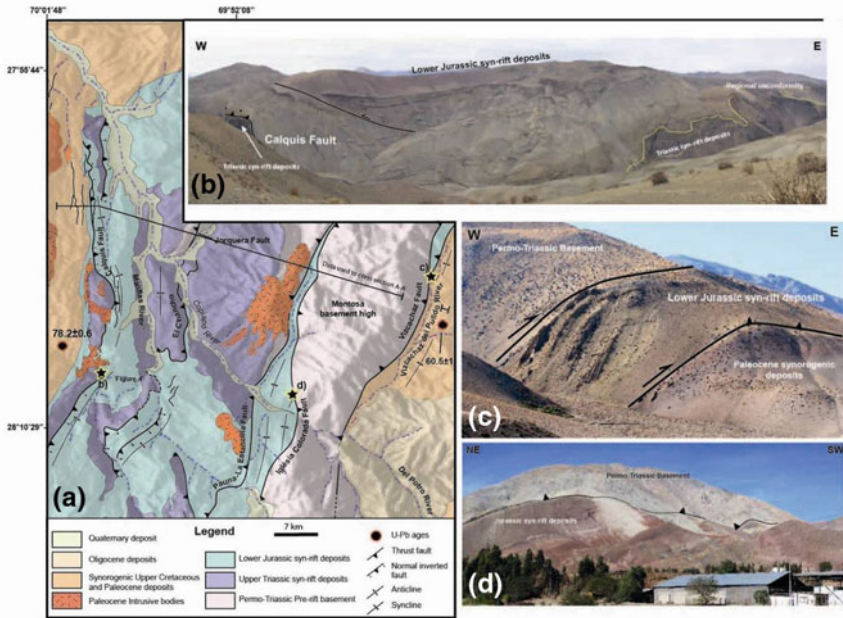


Fig. 5 **a** Geological map of the Lower Jurassic Lautaro Basin (see positions on Fig. 1), **b** panoramic view of the west-vergent inversion anticline recognized along the western edge (Calquis Fault) of the Lautaro Basin (see position on Fig. 4a), **c–d** structural expression of the basement-involved thrusts limiting the west **d** and east **c** sections of the Montosa Horst along the Frontal Cordillera (see location on Fig. 4a)

so this section is only an approximation held to illustrate the tectonic evolution of this region. Below, we describe the main characteristics of the observed deformation style.

3.1 Inversion Structures

The inversion structures correspond to two NNE-striking anticlines exposed along the eastern edge of the Chañarcillo Basin and the western edge of the Lautaro Basin, respectively (Figs. 3 and 4). These structures consist of large and asymmetrical anticlines with a long wavelength and arrowhead geometry (Figs. 3 and 4), similar to those reported from analogue models of inversion anticlines (Bonini et al. 2012 and works cited). Along the eastern edge of the Chañarcillo Basin (Fig. 3), the main structure is represented by the east-vergent Tierra Amarilla Anticline (Segerstrom 1960; Arévalo, 2005, among others), which involves the Jurassic–Lower Cretaceous syn-rift deposits and the Mid-Cretaceous post-rift deposits of the

basin (Martínez et al. 2013; Fig. 3). The Tierra Amarilla Anticline shows along-strike variations in its geometry. For example, to the north of the basin, only the frontal limb is mostly exposed and the back limb is obscured by intrusive bodies, but to the southern region both limbs lie exposed. In the study area, the frontal limb and the hinge of the anticline form the most prominent relief along the eastern Coastal Cordillera (Fig. 3). Previous works have related the growth of this structure with partial reactivation of the NNE-striking Elisa de Bordos Fault (Fig. 3), which is interpreted as the master fault of the Chañarcillo Basin (Arévalo 2005; Martínez et al. 2013; Peña et al. 2013). Recent geophysical data have confirmed this interpretation, as well as the subsurface projection of these structures (Fig. 4; Martínez et al. 2015a).

The other inversion structure consists of a west-verging asymmetrical anticline located at the eastern edge of the Lautaro Basin (Fig. 5). This anticline is composed of a sub-horizontal back limb and an overturned frontal limb facing the NNE-striking Calquis Fault. This fault corresponds to the master fault of the Lautaro Basin (Fig. 4), mainly affecting the Triassic and Lower Jurassic syn-rift deposits (Fig. 5). Along this anticline, the Lower Jurassic marine syn-rift deposits are elevated over its regional level, shortened and buttressed against the footwall of the Calquis Fault (Fig. 5). Based on these geometric characteristics, previous studies (Martínez et al. 2012) have interpreted these as a result of the tectonic inversion and partial closure of the Lautaro Basin. Accordingly, we conclude that tectonic inversion is a fundamental process during the growth of this Andean segment, which took advantage of the former extensional Mesozoic structures established in this region. On the other hand, the inversion structures lie separated by a narrow NNE-striking belt composed of minor thin-skinned thrust (Fig. 6), associated with anticlines and synclines, which have been interpreted as secondary structures formed from the propagation of deformation into the footwall of both inverted faults (Elisa de Bordos and Calquis faults).

3.2 *Basement-Involved Structures*

Basement-involved structures are mostly located along the Frontal Cordillera, as illustrated in Fig. 1. Along this system, they consist of large, NNE-striking, doubly verging (west and east) reverse faults, and basement-cored anticlines (Fig. 1). These structures mainly affect the infill of the Lautaro (Fig. 5) and Lagunillas basins (Martínez et al. 2015b), and frequently place large, lower Triassic granitic blocks of the pre-rift basement of the basins over Mesozoic syn-rift and Cenozoic synorogenic deposits (Fig. 5). The faults predominantly form large east-verging ramps intercalated with west-verging backthrusts (Fig. 6), which have accumulated a minimum shortening of 18 km (Martínez et al. 2015b). On the other hand, the footwall faults generally form narrow and asymmetrical footwall synclines with

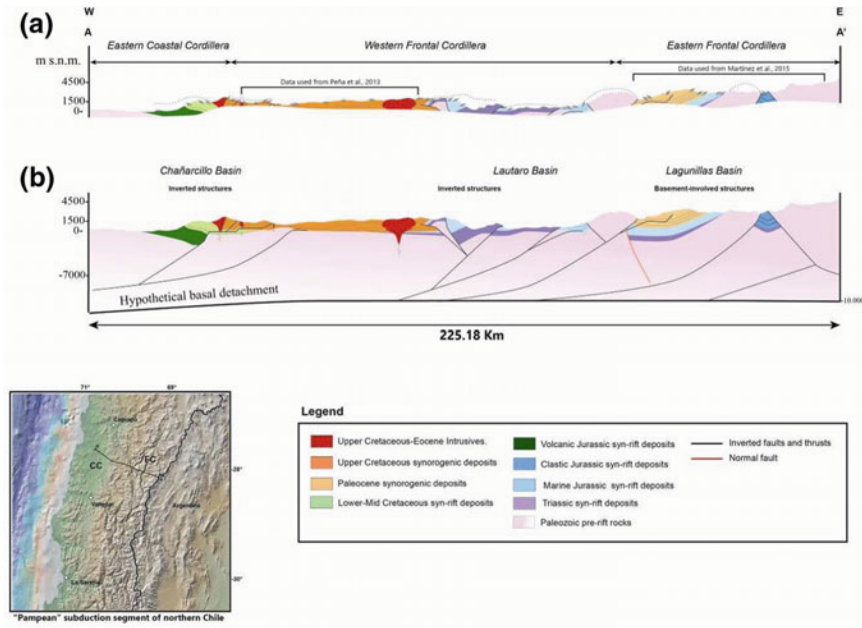


Fig. 6 **a** Geological data used to construct the regional cross section used in this study, **b** structural and semi-balanced cross section along the Chilean–Pampean flat subduction segment in northern Chile (see location of Fig. 1)

minor accommodation structures that involve synorogenic deposits. Previous works interpreted the basement-involved faults in this region as simple high-angle faults along which the basement blocks were uplifted and tilted (Jensen 1976; Godoy and Davidson 1976; Moscoso and Mpodozis 1988). However, recent studies based on balanced cross-sectional techniques and structural restoration have suggested that the geometry of the faults and folds are better related to moderate-angle faults and thrusts (Martínez et al. 2015b, 2016), which would have resulted from the faulting and folding of former basement paleohighs (e.g., Montosa Horst; Godoy and Davidson 1976) preserved in the inverted basins of this sector (Lautaro and Lagunillas basins).

Palinspastic restorations carried out along the Frontal Cordillera (Martínez et al. 2015b) have associated this structural style with large ramps that resulted from the shortening of previous extensional systems during different deformation phases that took place after the previous tectonic inversion events. If we consider that the previous extensional systems established in this region were composed of synthetic normal faults separated by basement highs (Martínez et al. 2016), then it is possible that some of these ramps could have truncated older, normal, or inverted faults (Fig. 6).

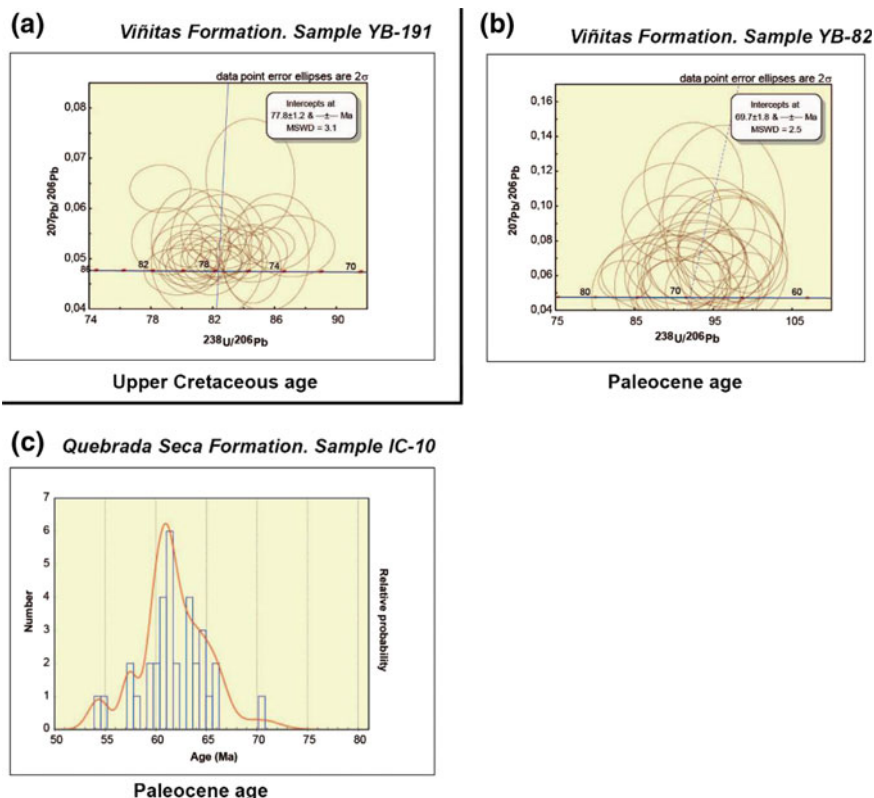


Fig. 7 a–b Concordia plots of LA-ICPMS U–Pb analyses of zircons from synorogenic deposits of the Viñitas Formation, c U–Pb frequency plot ages from detrital zircons of the Quebrada Seca Formation

4 Timing of Deformation

In order to obtain a constraint on the age of deformation in our study area, a series of U–Pb datings were performed using a LA-ICP Mass Spectrometer, which were then compared with previously reported ages. We obtained samples of detrital and igneous zircons from the continental red sandstone beds and ignimbrites belonging to synorogenic deposits (Viñitas and Quebrada Seca formations; Figs. 3, 5, and 7) exposed in the eastern Coastal Cordillera and the Frontal Cordillera, respectively. The samples were prepared applying the standard methods at the Geology Department of the University of Chile. The zircon selection was made by hand with a binocular microscope. The analytical work was carried out at the Laboratorio de Estudios Isotópicos of the Universidad Autónoma de México (UNAM), using a M50 193 nm laser excimer connected to a Thermo Xii Series Quadrupole Mass Spectrometer, applying the technical details described in Solari et al. (2010). The mean ages were calculated using Isoplot v. 3.7 (Ludwig 2008).

Sedimentary and volcanic rocks of the middle and upper section of the Viñitas Formation, exposed over the angular unconformity formed in the frontal limb of the Tierra Amarilla Anticline in the eastern section of the Chañarcillo Basin, have reported ages that range between 65 and 68 Ma (sample YB-82) (Figs. 3 and 6). Older ages of $81,6 \pm 1$ Ma were also determined by Peña et al. (2013) from the basal section of this succession (Fig. 3). These age groups coincide with those previously reported by Maksaev et al. (2009), which have allowed us to place the tectonic inversion of the Chañarcillo Basin and the onset of the Andean deformation in the eastern Coastal Cordillera between the Upper Cretaceous–Paleogene ranges. Other stratigraphic features recognized in these deposits, such as internal progressive unconformities and growth strata, have confirmed their syn-kinematic character acquired during the interplay between tectonic uplift and continental accumulation. On the other hand, younger ages (Eocene; Peña et al. 2013; Martínez et al. 2016) obtained from syntectonic intrusive bodies located east of the Chañarcillo Basin have also suggested that the Andean deformation could have continued here during Eocene times.

Similar ages have been determined from the synorogenic deposits that rest unconformably over the frontal limb of the inversion anticline formed in the hanging wall block of the Calquis Fault in the Lautaro Basin (Fig. 5). Here, the ignimbrites and tuffs of the basal section have ages of 78 Ma (Fig. 5), indicating that this structure grew from the Upper Cretaceous onwards, at least in this sector. On the other hand, a younger Paleogene age of 60.5 Ma (IC-10) was obtained from the continental synorogenic successions of the Quebrada Seca Formation exposed to the east of the east-verging Viscachas Fault, in the Frontal Cordillera (Figs. 5 and 7). Here, Martínez et al. (2015b, 2016) also reported similar ages that range between 60 and 65 Ma. These ages have been frequently associated with propagation and uplift of the basement structures, which appear to be younger and subsequent to the creation of the inversion structures (Martínez et al. 2016; Rossel et al. 2016; Moscoso and Mpodozis 1988, among others). Lower Miocene ages have also been reported from basement-involved structures found in the easternmost portion of the Frontal Cordillera (Moscoso et al. 2010), which also confirm this interpretation. Based on the data reported here, we propose that the Andean deformation at these latitudes could have started during the Late Cretaceous, at least along the eastern Coastal Cordillera, and then migrated to the eastern regions in the Paleocene.

5 Discussion

5.1 *The Chilean–Pampean Flat-Slab Segment of Northern Chile as a Result of a Hybrid Tectonic Mechanism*

The structure of the Pampean–Chilean flat subduction segment of northern Chile is characterized by a complex interaction between inverted and basement-involved folds and faults (Fig. 6), or a hybrid mechanism. In this segment, the west and east

variations of the structural styles are related to important differences of the previous structural configuration of the region. As recognized in other sectors of the Central Andes, the variations of the Andean structures appear to be influenced by the Mesozoic architecture inherent to former extensional tectonic episodes. In adjacent localities (e.g., Sierras Pampeanas, the Santa Barbará System, or the Salta Rift among others), the reactivation of previous normal faults and basement anisotropies is responsible for the final configuration of the Andean structures. In northern Chile, the position of inversion anticlines also allows the interpretation of this mechanism of deformation. Their doubly verging geometries reveal that they resulted from tectonic inversion of westward and eastward master faults separated by basement highs rather than by tectonic inversion of simple graben geometries (Figs. 6 and 8). Based on our field observations, we interpret that the crustal shortening in this region was initially accommodated by the reactivation of normal faults, such as those evidenced along the main edge of the Chañarcillo and Lautaro basins along the Coastal Cordillera and the Frontal Cordillera, respectively. Later shortening, however, was absorbed by large, basement-involved thrusting (Fig. 8).

On the other hand, the ages of the synorogenic deposits obtained here suggest that the Andean deformation in this segment started close to 78 Ma, with tectonic inversion of the Mesozoic basins indicating the occurrence of the Peruvian tectonic phase (Steinman 1929). Other younger, Paleocene ages determined from the synorogenic deposits exposed in the footwall of the basement-involved structures indicate: (a) an eastward migration of the Andean deformation front and (b) basement-involved thrusting occurring after the previous tectonic inversion episodes and during the K-T tectonic phase (Cornejo et al. 2003). Recent analyses of exhumation timings carried out in different regions of Argentina also indicate that the oldest episodes of Andean deformation occurred in the Late Cretaceous (Peruvian tectonic phase) (Balgord and Carrapa 2014; Folguera et al. 2015; Fennell et al. 2015; Echaurren et al. 2016).

In contrast to other regions, where the transition from tectonic inversion to basement-involved thrusting has been developed by shortcut faults, we have seen that the transition in this region could have been achieved by new thrusts that cut through basement highs and the hanging wall of the normal faults that dip away from the advancing thrusts (Figs. 6 and 8). Along the Andes, this mechanism of transition between inverted and basement-involved structures has been identified in the Cordillera de Carabaya in southern Peru (Pérez et al. 2016), in the Metán Basin in northwestern Argentina (Iaffa et al. 2011), in the Santa Barbara System (Kley and Monaldi 2002), the Eastern Cordillera of Colombia (Mora et al. 2009), as well as along other thrust belts located in the Alps, the Apennines, and the Atlas of Morocco (Welbon and Butler 1992; Scisciani et al. 2002; Burkhard et al. 2006, among others). From a point of view more speculative, this hybrid tectonic mechanism could be associated with a transition from tectonic inversion of half-grabens to the creation of basement-involved thrusts. Both geological processes are seen to have a broad wavelength, because both have been recognized in Chile and Argentina. In northern Chile, this hybrid mechanism was initially controlled by the coeval tectonic inversion of the ancient normal faults both in the

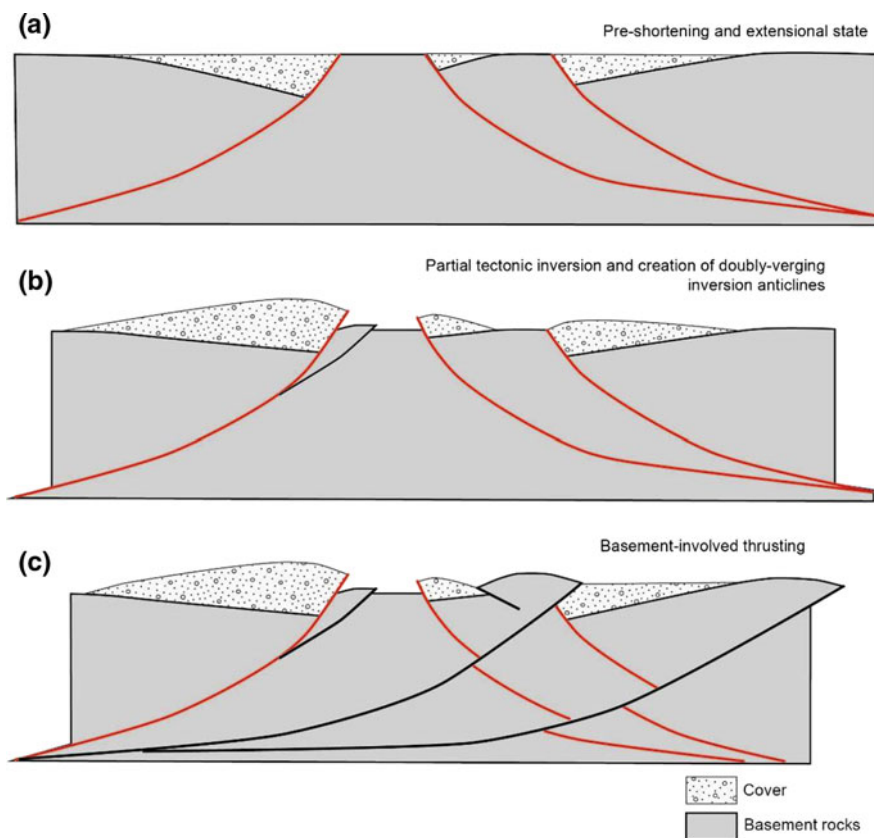


Fig. 8 Schematic cartoon illustrating the tectonic evolution of the Andean structures in the Chilean–Pampean flat subduction segment of northern Chile, as well as the interaction between the different tectonic mechanisms interpreted in this work

Coastal and Frontal Cordilleras; however, during the tectonic inversion is common that some faults are blocked by changes in their physics and therefore, new thrusts are created with a thick-skinned style taking advantage of a continental crust thermal and mechanically weakened. Similar interpretations have been proposed for the Malargüe Thrust and Fold Belt, where an interplay between inverted and basement-involved faults was also observed (Giambiagi et al. 2003; Mescua and Giambiagi 2012), previously established in a weak and thin continental crust.

Other, more regional factors that could have governed this mechanism are the convergence angle with respect to previous structural patterns and the magnitude of shortening; however, the last is most speculative, at least in this study area. Finally, our results indicate that the amplitude of the deformation, the degree of shortening, and the spatial development of contractional structures, as well as their kinematics, are fundamentally influenced by inherited structures in the basement and master normal faults. This was also interpreted by Ramos et al. (2002), who proposed that

the contractional deformation along the Chilean–Pampean flat subduction segment is a product of the successive reactivation of weakness zones in the pre-rift basement of this region.

6 Conclusions

The Chilean–Pampean flat subduction segment of the Central Andes in northern Chile displays two main tectonic styles: inverted structures and basement-involved thrusts confined along the Coastal Cordillera and the Frontal Cordillera, respectively. The occurrence of both structural styles is associated with different tectonic mechanisms, which involve dip-slip reactivation of inherited extensional structures and anisotropies in the basement pre-rift units exposed along the region and basement-involved thrusting. The geological observations described here indicate that this structural interaction has resulted from a hybrid tectonic mechanism, which is marked by the transition from tectonic inversion to thrusting through inherited basement highs (Fig. 7). The first mechanism is mostly associated with the oldest episodes of Andean deformation that affected the continental margin during the Peruvian tectonic phase (~80 Ma), and the second is related to eastward and younger Paleocene tectonic episodes. We conclude that the tectonic evolution of this Andean segment is strongly influenced by the previous configuration of the pre-rift basement and the extensional basins that dominated this region during Mesozoic times, in terms of paleo-positions of normal faults and basement highs, among others. Finally, we suggest taking in consideration these results in order to analyze the tectonic context of northern Chile.

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References

- Aguirre-Urreta B (1993) Neocomian ammonite biostratigraphy of the Andean basins of Argentina and Chile. *Rev. Española de Paleontología* 8:57–74
- Allmendinger RW, Jordan TE, Kay SM, Isacks BL (1997) The evolution of the Altiplano-Puna Plateau of the central Andes. *Annu Rev Earth Planet Sci* 25:139–174
- Amilibia A, Sábát F, McClay KR, Muñoz JA, Roca E, Chong G (2008) The role of inherited tectono-sedimentary architecture in the development of the central Andean mountain belt: insights from the Cordillera de Domeyko. *J Struct Geol* 30:1520–1539

- Arévalo C (1994) Mapa geológico de la Hoja Los Loros, Región de Atacama (1:100.000). Servicio Nacional de Geología y Minería, Documentos de Trabajo No 6
- Arévalo C (1999) The Coastal Cordillera–Precordillera boundary in the Copiapó area, northern Chile, and the structural setting of the Candelaria Cu–Au ore deposit. Unpublished Ph.D. Thesis. Kingston University, Kingston-upon-Thames, UK, p. 244
- Arévalo C (2005) Carta los Loros, Región de Atacama, Carta Geológica Básica. Servicio Nacional de Geología y Minería, Santiago 92: 54
- Balgord E, Carrapa B (2014) Basin evolution of Upper Cretaceous–Lower Cenozoic strata in the Malargüe fold-and-thrust belt: northern Neuquén Basin, Argentina. *Basin Res*: 1–24
- Baraganzi M, Isacks BL (1976) Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America. *Geol* 4:686–692
- Bonini M, Sani F, Antonielli B (2012) Basin inversion and contractional reactivation of inherent normal faults: A review based on previous and new experimental models. *Tectonophysics* 522:55–88
- Burkhard M, Caritg S, Helg U, Robert-Charrue C, Soulaïmani A (2006) Tectonics of the Anti-Atlas of Morocco. *CR Geosci* 338:11–24
- Carrapa B, Trimble JD, Stockli D (2011) Patterns and timing of exhumation and deformation in the Eastern Cordillera of NW Argentina revealed by (U–Th)/He thermochronology. *Tectonics* 30:1–30
- Charrier R (1979) El Triásico en Chile y regiones adyacentes de Argentina: Una reconstrucción paleogeográfica y paleoclimática. *Comunicaciones* 26:1–47
- Comejo P, Mpodozis C, Kay S, Tomlinson A, Ramirez C (1993) Upper cretaceous lower eocene potassic volcanism in an extensional regime in the precordillera of Copiapó, Chile. In: *Second IASG (Oxford)*. pp 347–350
- Comejo P, Matthews S, Pérez de Arce C (2003) The K-T compressive deformation event in northern Chile (24°–27°). In: *10° Congreso Geológico Chileno (Concepción)*, Chile
- Coutand I, Cobbold P, Urreiztieta M, Gautier P, Chauvin A, Gapais D, Rossello E, Gamundi O (2001) Style and history of Andean deformation, Puna plateau, northwestern Argentina. *Tectonics* 20:210–234
- Cristallini E, Comínguez A, Ramos V, Mercerat ED (2004) Basement double wedge thrusting in the northern Sierras Pampeanas of Argentina (27° S). Constraints from deep seismic reflection. In: McClay KR (ed) *Thrust Tectonics and Hydrocarbon Systems*. AAPG Mem 82:1–26
- Del Rey A, Dejkart K, Arriagada C, Martínez F (2016) Resolving the paradigm of the late Paleozoic–Triassic Chilean magmatism: isotopic approach. *Gondwana Res* 37:172–181
- Echaurren A, Folguera A, Gianni G, Orts D, Tassara A, Encinas A, Giménez M, Valencia V (2016) Tectonic evolution of the North Patagonian Andes (41°–44° S) through recognition of syntectonic strata. *Tectonophysics* 677–678:99–114
- Fennell L, Folguera A, Naipauer M, Gianni G, Rojas Vera E, Bottesi G, Ramos V (2015) Cretaceous deformation of the southern Central Andes: synorogenic growth strata in the Neuquén Group (35°30′–37° S). *Basin Res*: 1–22. <https://doi.org/10.1111/bre.12135>
- Folguera A, Bottesi G, Duddy I, Martín-Gonzalez Orts D, Sagripanti L, Vera, Rojas, Ramos VA (2015) Exhumation of the Neuquén Basin in southern Central Andes (Malargüe fold and thrust belt) from field data and low-temperature thermochronology. *J S Am Earth Sci* 1–18
- Giambiagi L, Ramos V, Godoy E, Álvarez P, Orts D (2003) Cenozoic deformation and tectonic style of the Andes, between 33° and 34° south latitude. *Tectonics* 22(4):1–18. <https://doi.org/10.1029/2001TC001354>
- Godoy E, Davidson JD (1976) Pilares en compresión de edad Mioceno superior en los Andes del Norte de Chile (22°–30° Latitud Sur). In: *I Congreso Geológico Chileno*. pp 87–103
- Grocott J, Taylor G (2002) Magmatic arc fault systems, deformation partitioning and emplacement of granitic complexes in the Coastal Cordillera, north Chilean Andes (25°30′ to 27°00′S). *J Geol Soc Lond* 159:425–442
- Heredía N, Rodríguez Fernández L, Gallastegui G, Busquest B, Colombo F (2002) Geological setting of the Argentine Frontal Cordillera in the flat-slab segment (30°00′–31°30′S latitude). *J S Am Earth Sci* 15:79–99

- Iaffa D, Sàbat F, Muñoz JA, Mon R, Gutierrez AA (2011) The role of inherited structures in a foreland basin evolution. The Metán Basin in NW Argentina. *J Struct Geol* 33:1816–1828
- Ingersoll R (2012) Tectonic of sedimentary basins, with revised nomenclature, in Tectonic of sedimentary basins recent advances. In: Bushy C and Azor A (ed). Wiley-Blackwell publication, pp 3–47
- Isacks BL (1988) Uplift of the Central Andes Plateau and bending of the Bolivian Orocline. *J Geophys Res* 93:3211–3231
- Jensen O (1976) Geología de las nacientes del río Copiapó, entre los 27°53' y 28°20' de latitud Sur, provincia de Atacama. Memoria de Título (Inédito), Universidad de Chile, Departamento de Geología, p 249
- Jordan T, Allmendinger R (1986) The Sierras Pampeanas of Argentina: a modern analogue of Rocky Mountain foreland deformation. *Am J Sci* 286:737–764
- Jordan T, Isacks BL, Allmendinger R, Brewer J, Ramos V, Ando C (1983) Andean tectonics related to geometry of subducted Nazca plate. *Geol Soc Am Bull* 94:341–361
- Kley J, Monaldi C (2002) Tectonic inversión in the Santa Barbara System of the central Andean foreland thrust belt, northwestern Argentina. *Tectonics* 21:1–18
- Lara L, Godoy E (1998) Mapa Geológico de la Hoja Quebrada Salitrosa, Región de Atacama. Servicio Nacional de Geología y Minería, Santiago, scale: 1:100.000
- Ludwing KR (2008) Isoplot 3.6. 4. Berkley Geochronology Center Special, Publication
- Maksae V, Munizaga F, Valencia V, Barra F (2009) LA-ICP-MS zircon U-Pb geochronology to constrain the age of post-Neocomian continental deposits of the Cerrillos Formation, Atacama Region, northern Chile: tectonic and metallogenic implications. *Andean Geol* 36:264–287
- Marschik R, Fontboté L (2001) The Candelaria-Punta del Cobre iron oxide Cu–Au (–Zn–Ag) deposits, Chile. *Econ Geol* 96:1799–1826
- Martínez F, Arriagada C, Mpodozis C, Peña M (2012) The Lautaro Basin: a record of inversion tectonics in northern Chile. *Andean Geol* 39(2):258–278
- Martínez F, Arriagada C, Peña M, Del Real I, Deckart K (2013) The structure of the Chañarcillo Basin: an example of tectonic inversion in the Atacama region, northern Chile. *J S Am Earth Sci* 42:1–16
- Martínez F, Maksymowicz A, Ochoa H, Díaz D (2015a) Geometry of the inverted Cretaceous Chañarcillo Basin based on 2D gravity and field data—an approach to the structure of the western Central Andes of northern Chile. *Solid-Earth* 6:1–18
- Martínez F, Arriagada C, Valdivia R, Deckart K, Peña M (2015b) Geometry and kinematics of the Andean thick-skinned thrust systems: insights from the Chilean Frontal Cordillera (28°–28.5° S), Central Andes. *J S Am Earth Sci* 34:307–324
- Martínez F, Arriagada C, Peña M, Deckart K, Charrier R (2016) Tectonic styles and crustal shortening of the Central Andes “Pampean” flat-slab segment in northern Chile (27°–29° S). *Tectonophysics* 667:144–162
- Martinod J, Husson L, Roperch P, Guillaume B, Espurt N (2010) Horizontal subduction zones, convergence velocity and the building of the Andes. *Earth Planet Sci Lett* 299:299–309
- Mescua J, Giambiagi L (2012) Fault inversion vs. new thrust generation: A case study in the Malargüe fold-and-thrust belt, Andes of Argentina. *J Struct Geol* 31:51–63
- Mora A, Gaona T, Kley J, Montoya D, Parra M, Quiroz LI, Reyes G, Strecker MR (2009) The role of inherited extensional fault segmentation and linkage in contractional orogenesis: a reconstruction of Lower Cretaceous inverted rift basins in the Eastern Cordillera of Colombia. *Basin Res* 21:111–137
- Mortimer C (1973) The Cenozoic history of the southern Atacama Desert, Chile. *J Geol Soc Lond* 129:505–526
- Moscoco R, Mpodozis C (1988) Estilos estructurales en el Norte Chico de Chile (28°–31° S), regiones de Atacama y Coquimbo. *Rev Geol Chile* 15:155–158
- Moscoco R, Mpodozis C, Nassi C, Ribba L, Arévalo C (Compilador) (2010) Geología de la Hoja El Tránsito, Región de Atacama. Servicio Nacional de Geología y Minería de Chile, Serie Preliminar, 7, scale: 1:250.000, 3 anexos, Santiago

- Mourgues FA (2004) Advances in ammonite biostratigraphy of the marine Atacama basin (Lower Cretaceous), northern Chile, and its relationship with the Neuquén basin, Argentina. *J S Am Earth Sci* 17:3–10
- Mpodozis C, Cornejo P (1997) El rift Triásico- Sinemuriano de Sierra Exploradora, Cordillera de Domeyko (25°–26° S): Asociaciones de facies y reconstrucción tectónica. In: VIII Congreso Geológico Chileno 1:550–554
- Mpodozis C, Ramos V (1990) The Andes of Chile and Argentina. In: Ericksen GE, Cañas Pinochet MT, Reinemud JA (ed). *Geology of the Andes and its relation to hydrocarbon and mineral resources: Circumpacific Council for Energy and Mineral Resources*. *Earth Sci* 11:59–90
- Mpodozis C, Ramos VA (2008) Tectónica jurásica en Argentina y Chile: Extensión, Subducción Oblicua, Rifting, Deriva y Colisiones? *Rev Geol Argent* 63:479–495
- Naranjo JA, Puig A (1984) Hojas Taltal y Chañaral, Regiones de Antofagasta y Atacama. Servicio Nacional de Geología y Minería, Santiago. pp 62–63
- Narr W, Suppe J (1994) Kinematics of basement-involved compressive structures. *Am J Sci* 294:802–860
- Peña M, Arriagada C, Martínez F, Becerra J (2013) Carta Geológica Yerbas Buenas-Tres Morros, Región de Atacama. Servicio Nacional de Geología y Minería, Santiago, scale: 1:100.000
- Pérez N, Horton BK, Carlotto V (2016) Structural inheritance and selective reactivation in the central Andes: Cenozoic deformation guided by pre-Andean structures in southern Peru. *Tectonophysics* 671:264–280
- Pindell J, Dewey J (1982) Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region. *Tectonics* 1:179–211
- Poblet J, Lisle RJ (2011) Kinematic evolution and structural styles of fold-and-thrust belts. In: Poblet J, Lisle RJ (ed) *Kinematic evolution and structural styles of fold-and-thrust belts*. *Geol Soc Spec Pub* 349:1–24
- Ramos V (1999) El segmento de Subducción Subhorizontal de los Andes Centrales Argentino-Chilenos. *Acta Geol Hisp* 32(7):5–16
- Ramos VA (2009) Anatomy and global context of the Andes: main geologic features and the Andean orogenic cycle. In: Kay SM, Ramos VA, Dickinson WR (ed) *Backbone of the Americas: shallow subduction, plateau uplift, and ridge and terrane collision*. *Geol Soc Am Mem* 204:31–65
- Ramos VA, Cristallini EO, Pérez DJ (2002) The Pampean flat-slab of the Central Andes. *J S Am Earth Sci* 15:59–78
- Rossel K, Aguilar G, Salazar E, Martinod J, Carretier S, Pinto L, Cabré A (2016) Chronology of Chilean Frontal Cordillera building from geochronological, stratigraphic and geomorphological data insights from Miocene intramontane-basin deposits. *Basin Res*. <https://doi.org/10.1111/bre.12221>
- Scheubert E, Reutter KJ (1992) Magmatic arc tectonics in the Central Andes between 21° and 25° S. *Tectonophysics* 205:127–140
- Scisciani V, Tavarnelli E, Calamita F (2002) The interaction of extensional and contractional deformations in the outer zones of the Central Apennines, Italy. *J Struct Geol* 24:1647–1658
- Segerstrom K (1960) Cuadrángulo Quebrada Paipote, Provincia de Atacama, Carta Geológica de Chile. Instituto de Investigaciones Geológicas, Santiago de Chile. p 35
- Solari LA, Gómez-Tuena A, Bernal JP, Pérez-Arvizu O, Tanner M (2010) U-Pb zircon geochronology by an integrated LAICPMS microanalytical work station: achievements in precision and accuracy. *Geostand Geoanal Res* 34(1):5–18
- Steinman G (1929) *Geologie von Peru*. Carl Winters Universitäts-Buchhandlung. p 448
- Suárez M, Bell CM (1992) Triassic rift-related sedimentary basins in northern Chile (24°–29° S). *J S Am Earth Sci* 6:109–121
- Welbon AI, Butler RWH (1992) Structural styles in thrust belts developed through rift basins: a view from the western Alps, in *Structural and Tectonic Modelling and its Application to Petroleum Geology*. In: Larsen RM, Brekke H, Larsen BT and Talleras E (ed) *Spec publ Norw Petrol Soc*:464–479