Solid Earth Discuss., 7, 2311–2346, 2015
www.solid-earth-discuss.net/7/2311/2015/
doi:10.5194/sed-7-2311-2015

Solid Earth
Discussions
Open Access

Geometry of the inverted Cretaceous Chañarcillo Basin based on 2-D gravity and field data. An approach to the structure of the western Central Andes of northern Chile

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Received: 14 July 2015 – Accepted: 18 July 2015 – Published: 17 August 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This paper discusses an integrated approach that provides new ideas about the structural geometry of the NNE-striking, Cretaceous Chañarcillo Basin located along the eastern Coastal Cordillera in the western Central Andes of northern Chile (27–28° S). The results obtained from the integration of two transverse (E–W) gravity profiles with previous geological information, show that the architecture of this basin is defined by a large NNE–SSE-trending and east-vergent anticline ("Tierra Amarilla Anticlinorium"), which is related to the positive reactivation of a former Cretaceous normal fault (Elisa de Bordos Master Fault). Moreover, intercalations of high and low gravity anomalies and steep gravity gradients reveal a set of buried, west-tilted half-grabens associated with a synthetic normal fault pattern. These results, together with the uplift and folding style of the Cretaceous syn-rift recognized within the basin, suggest that their complete structural geometry could be explained by an inverted fault system linked to the shortening of pre-existing Cretaceous normal fault systems. Ages of the synorogenic deposits exposed unconformably over the frontal limb of the Tierra Amarilla Anticlinorium confirm a Late Cretaceous age for the Andean deformation and tectonic inversion of the basin.

1 Introduction

The NNE-trending Chañarcillo Basin is located along the eastern Coastal Cordillera over the western Central Andes flat-slab subduction segment in northern Chile, between latitudes 27 and 28° S (Fig. 1). This basin corresponds to one of the five discrete, Early Cretaceous back-arc basins identified by Aguirre-Urreta (1993) in the southern Central Andes. Its Origin is related to the progressive stretching and extension of the western continental margin developed during the Mesozoic, from the break-up of the Pangea–Gondwana super continent (Coira et al., 1982; Mpodozis and Ramos, 1990, 2008; Viramonte et al., 1999; Franzese and Spalleti, 2001). This Cretaceous back-arc

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extension allowed the establishment of several intra-plate, elongated NE–NW-trending rift systems and volcanic arcs, broadly distributed in Argentina and Chile (Fig. 2). However; in northern Chile both the Tarapacá and Chañarcillo Basins represent the first-order features related to this process.

In northern Chile the extensional basins were positioned adjacent to the Mesozoic volcanic arc with a preferential NNE-strike, being largely affected by extended volcanism (Fig. 2). In contrast, a NE–NW-striking intra-plate rift pattern developed on the Argentinean side (Fig. 2). The original geometry and architecture of many of these rift and extensional basins were later modified by successive episodes of tectonic shortening during the growth of the Central Andes (Mpodozis and Ramos, 1990; Ramos, 2009, 2010). However, this later situation has been well documented in only a few Mesozoic basins on the Argentinean side of the eastern Central Andes (e.g., Salta Rift, Cuyo Basin, and Neuquén Basin), where both subsurface information (2-D and 3-D seismic profiles and oil well information) and field data indicate that Cenozoic compressional thrust systems have affected the Mesozoic syn-rift deposits (Manceda and Figueroa, 1995; Cristallini et al., 1997, 2006; Carrera et al., 2006; Giambiagi et al., 2009; Grimaldi and Dorobek, 2011).

Analogues of syn-rift deposits have also been recognized in some Mesozoic basins along the present day fore-arc of northern Chile, such as the Tarapacá Basin, Chañarcillo Basin, Salar de Atacama Basin and Lautaro Basin, (Jensen, 1976; Soffia, 1989; Mpodozis et al., 2005; Amilibia et al., 2008; Amilibia, 2009; Martínez et al., 2012, 2013). In these places, the current compressive deformation pattern overprinted over the Jurassic and Early Cretaceous syn-rift successions, is considered to be a result of continuous Late Cretaceous and Cenozoic horizontal shortening (Jensen, 1976; Soffia, 1989; Mpodozis and Allmendinger, 1993; Mpodozis et al., 2005; Arévalo, 2005a, b; Arévalo et al., 2006; Arriagada et al., 2006; Amilibia et al., 2008; Amilibia, 2009; Martínez et al., 2012, 2013). In most of them, however, the geological interpretations are supported only by field data.

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The Chañarcillo Basin is a region of special interest for analyzing the effects of the Andean deformation over the western slope of the Central Andes, mainly related to horizontal shortening over the previous extensional systems, because of the coexistence of preserved extensional and compressional structures. The structure of this basin has been explained using different models, as is illustrated in Fig. 5.

The tectonic models include: extensional domino systems (Mpodozis and Allmendinger, 1993; Arévalo, 2005b; Fig. 5a), a west-vergent fold and thrust belt (Arévalo and Mpodozis, 1991; Arévalo, 2005b; Arévalo and Welkner, 2008; Fig. 5b), sinistral and transpressional fault systems (Arévalo and Grocott, 1997), and the most recent, positive tectonic inversion model (Amilibia, 2009; Martínez et al., 2013; Fig. 5c and d). Such differing interpretations suggest that the architecture of the basin as well as the eastern Coastal Cordillera is not yet fully understood in terms of geometry and deformation styles, and therefore it has not allowed a full understanding of the structure for the western segment of the Central Andes along the flat-slab subduction segment. The reason is fundamentally associated with the lack of subsurface information. It is difficult to interpret what happens in the basin using only the geological information derived from the main exposures illustrated in Fig. 2. Thus, detailed structural analyses of the deep structure of this basin are necessary to understand both the subsurface geometry and the main mechanisms of deformation related to the crustal evolution of this Andean segment.

In order to better constrain the geometry of the basin during its evolution and to resolve the aforesaid problem, we carried out a new gravity survey through the central region of the basin (Martínez et al., 2013) and added some new geological data supported mainly by structural measurements (strike and dips) (Fig. 3). We used gravity signals with the aim of delineating buried master faults and determining density changes related to the interface between the basement and the syn-rift infill of the basin. Based on these new geological data and geophysical constraints, we analyze the geometry of the Chañarcillo Basin and propose a new tectonic model for the structure of the western Central Andes of northern Chile.

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2 Geological setting

During the Mesozoic, the western continental margin of Gondwana was characterized by a tectonic scenario composed of volcanic arcs and back-arc extensional basins (Fig. 2); however, these were later modified during the Andean deformation responsible for the current anatomy of the Central Andes (Daziel et al., 1987; Moscoso and Mpodozis, 1988; Mpodozis and Ramos, 1990; Scheuber et al., 1994; Charrier et al., 2007; Amilibia et al., 2008; Ramos, 2010). In northern Chile, the Chañarcillo Basin, which extends to the east of the Chilean Coastal Cordillera nearly 200 km from the Copiapó River valley to the Vallenar region (Fig. 1), is a special case for analyzing this interaction.

Within the study area the oldest rocks are represented by a series of Triassic to Lower Cretaceous intrusions (Fig. 3) (Dallmeyer et al., 1996; Arévalo, 1999). These Mesozoic plutonic complexes consist of granitic rocks that form the pre-rift basement of the Chañarcillo Basin. The main intrusions in the region correspond to a series of Mesozoic intrusives (Fig. 3), such as the Jurassic (152–149 Ma) San Antonio diorite, and other Cretaceous (131 Ma) granodiorite-to-tonalitic rocks defined by Arévalo (1999) and Arévalo and Welkner (2008) (Fig. 3). Along the eastern Coastal Cordillera, a narrow belt of Jurassic volcanic deposits is exposed along the eastern Sierra Loma Negra, as illustrated in Fig. 3. These volcanic deposits consist of at least 150 m of dacitic and calco-alkaline lavas and domes of the La Negra Formation, derived from the Early Jurassic volcanic arc (Fig. 4) (Grocott and Taylor, 2002; Taylor et al., 2007; Arévalo and Welkner, 2008). East of this sector about 1000 m of Jurassic basaltic and basaltic-andesitic lava flows and breccias of the Punta del Cobre Formation crop out, which were interpreted as a basal and continental syn-rift succession of the Chañarcillo Basin (Figs. 3 and 4) (Segerstrom and Ruiz, 1962; Marschik and Fontboté, 2001; Arévalo, 2005b; Arévalo and Welkner, 2008; Martínez et al., 2013). Further, in the easternmost part of the Punta del Cobre Formation, are ~ 2000 m of late Valanginian-Aptian marine and siliciclastic deposits corresponding to the Chañarcillo Group, historically

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interpreted as a syn-rift sequence (Figs. 3 and 4) (Segerstrom and Ruiz, 1962; Arévalo and Grocott, 1997; Arévalo, 1999; Mourgues, 2004, 2007; Arévalo et al., 2006; Martínez et al., 2013; Peña et al., 2013).

In the study area, outcrops of the Chañarcillo Group extend as a NNE-trending belt from north of Los Sapos Creek to south of Algarrobal Creek (Fig. 3). The Chañarcillo Group corresponds to a marine and siciliciclastic syn-rift sequence, which has been divided into four conformable formations according to Biese (in Hoffstetter et al., 1957). The Abundancia Formation is composed of 200 m of well-laminated grey mudstone and arkoses with *Olcostephanus (O)* aff. *atherstoni* (Sharpe), *Olcostephanus (O)* aff. *Densicostatus* (Wegner), *Olcostephanus (V) permolestus* (Leanza) (Segerstrom and Ruiz, 1962; Corvalán, 1973) (Fig. 4). Second, the Nantoco Formation is composed of at least 1200 m of grey mudstones, calcareous breccias and wackestone with *Crioceratites (C)* and *schlagintweiti* (*Giovine*) (Segerstrom, 1960; Mourgues, 2004) (Fig. 4). Third, the Totoralillo Formation consists of about 350 m of laminated marls with chert nodules and volcaniclastic intercalations with *Crioceratites* (*Paracrioceras*) cf. *emerici* Levillé and *Shasticrioceras* cf. *Poniente* of late Barremian age. Finally, the Pabellon Formation includes about 2000 m of volcanic and sedimentary rocks composed of black chert, grey limestone, conglomerates and sands with *Parancyloceras? domeykanus, Prahoplites* gr. *nutfieldiensis,* and *Paulkella nepos* (Paulcke) and other important fauna (Fig. 4) (Perez et al., 1990; Mourgues, 2004, 2007; Arévalo, 2005b).

The Chañarcillo Group is unconformably covered by nearly 2000 m of volcano-sedimentary deposits well exposed to the northeast of the study area, and defined as the Cerrillos Formation (Fig. 3) (Segerstrom and Parker, 1959). The Cerrillos Formation is a Late Cretaceous continental wedge composed of red conglomerates, para-conglomerates, sandstones, and thick intercalations of tuffs, andesitic lava flows and breccias (Segerstrom and Parker, 1959; Arévalo 2005a, b; Maksaev et al., 2009), which mark clearly an abrupt change from previous marine sedimentation (Fig. 4). Previous chronological and stratigraphic studies carried out in this region by Maksaev et al. (2009) suggest a synorogenic character for these continental deposits. However,

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others have defined this succession as sag or post-rift deposits of the Chañarcillo Basin (Martínez et al., 2013).

To the east of the study area, thicker, Upper Cretaceous-Paleocene successions are exposed, which are composed of sedimentary rocks, lavas, and ignimbrites. These successions were recently defined as the Viñitas Formation (Peña et al., 2013) and unconformably overlie the upper section of the Cerrillos Formation (Figs. 3 and 4). Compressive growth strata have been recognized within these successions, eliciting their assignment to a contractional tectonic setting (Peña et al., 2013). Finally, the Viñitas Formation exhibits intrusions of different Paleocene and Eocene plutonic complexes composed of granodiorites, monzogranites, granites, and tonalities (Fig. 2) with U-Pb ages ranging from ~ 70 to 50 Ma (Fig. 2) (Peña et al., 2013).

3 Structural background

A large NNE–SSW-striking anticline initially called the Tierra Amarilla Anticlinorium by Segerstrom (1960) defines the main structure of the Chañarcillo Basin. This structure lies well exposed over the eastern section of the basin from northeast of Los Sapos Creek to south of Algarrobal Creek, extending nearly 53 km (Fig. 3). The Tierra Amarilla Anticlinorium mainly involves the Upper Jurassic and Early Cretaceous syn-rift successions of the Punta del Cobre Formation and Chañarcillo Group, as well as the Upper Cretaceous post-rift deposits of the Cerrillos Formation (Fig. 3). The structure is an east-vergent asymmetrical anticline of long wavelength, characterized by an inclined frontal limb with a dip varying between 40–70° E (Figs. 3 and 6). It is composed of the sedimentary and volcaniclastic deposits of the upper section of the Chañarcillo Group (Pabellón Formation) and Cerrillos Formation, as well as a flat back-limb composed entirely of volcanic rocks of the Punta del Cobre Formation (Figs. 3 and 6). Large changes of thickness occur along the syn-rift deposits of the Chañarcillo Group between the frontal and back limbs, forming a characteristic syn-rift wedge geometry (Figs. 3 and 6). This geometry was achieved by the compressive deformation of this syn-rift wedge

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and it is mostly associated with an inversion anticline, which shows an "arrowhead" shape. Similar geometries have been reproduced by some analogue models of inverted structures (McClay and Buchanan, 1991; Yamada and McClay, 2003, among others) and are illuminated by seismic surveys developed in many inverted basins around the world (e.g, The North Sea, Viking Graben, Morroco Atlas, Appenines Chain).

On the other hand, internally, the Chañarcillo Group shows some mesoscale, planar normal faults, which have accumulated some metric throws and show growth strata in the hanging walls indicating an extensional tectonic regime during deposition (Fig. 7). Other structures such as thin-skinned thrusts also have been recognized on the frontal limb of the anticline; however, they were considered to be minor accommodation structures (Amilibia, 2009).

To the east of the basin, the frontal limb of the Tierra Amarrilla Anticlinorium is truncated by a NNE–SSW-trending fault named the Elisa de Bordos-Agua de los Burros Fault System (Arévalo, 2005b; Arévalo and Welkner, 2008; Martínez et al., 2013; Peña et al., 2013) (Figs. 3 and 6d). The NNE–SSW-trending Elisa de Bordos-Agua de los Burros Fault System marks the eastern limit of the Chañarcillo Basin (Fig. 3), and represents the first-order fault in the region, being easily recognized toward the north of the Los Sapos Creek and toward the southern part of Algarrobal Creek (Fig. 3) for nearly 30 km. Only in the intermediate section between both creeks the fault is not exposed. In contrast, at this locality the correct position of the fault is speculative because it is truncated by an angular unconformity (Fig. 8). This fault corresponds to an east-vergent high-angle fault (70°), which puts in contact deposits of the Chañarcillo Group and Cerrillos Formation, with the Upper Cretaceous-Paleocene synorogenic deposits of the Viñitas Formation (Figs. 3 and 6d). Along this structure, the deposits of the Chañarcillo Group and Cerrillos Formation form an important positive structural relief, which is continuous along the eastern flank of the Coastal Cordillera, being clearly observed along different streams that cut transversely into this structure (Fig. 6). The hanging-wall fault is mostly composed of the sedimentary deposits of the Chañarcillo Group and the overlying Cerrillos Formation, although some Tertiary intrusive bodies are localized along the trace fault. In contrast, there are some places where the frontal limb of the Tierra Amarilla Anticline is unconformably covered by the synorogenic deposits of the Viñitas Formation (Figs. 3 and 8). In this last case, the contact between the syn-rift and synorogenic deposits is marked by an angular unconformity, which is best observed along the Chuschampis and Algarrobal Creeks (Fig. 8).

Previous structural interpretations (Fig. 5) have related the growth of the Tierra Amarilla Anticlinorium with different geometries and kinematics of the Elisa de Bordos Fault-Agua de Los Burros Fault System. Some models suggest that this fault system must be interpreted as a west-vergent inverted normal fault (Fig. 5a; Arévalo 2005b); however, it is a difficult geometry from which to reproduce the Tierra Amarilla Anticlinoriun. Other interpretations define the Elisa de Bordos Fault as an east-tilted normal fault (Fig. 5b; Arévalo and Welkner, 2008), which suggests a tectonic collapse or rapid tectonic subsidence of the Tierra Amarilla Anticlinorium (for which there is no structural evidence). However, recent models based on balanced cross-section techniques (Fig. 5c and d; Amilibia, 2009; Martínez et al., 2013) have defined the Tierra Amarilla Anticlinorium as an east-vergent inversion anticline related to the positive reactivation of the Elisa de Bordos Fault-Agua de Los Burros Fault System. This last interpretation is now the most accepted, and suggests that the Elisa de Bordos Fault-Agua de Los Burros Fault System was initially a west-tilted normal fault that controlled sedimentation both for the Chañarcillo Group and the overlying Cerrillos Formation.

4 Methodology

4.1 Gravity data and rock densities

In order to obtain a density-depth model constrained by the geological information we carried out a gravity survey in June 2013, through the central section of the Chañarcillo Basin (Fig. 9). This method was chosen, because we could examine the conformity between the calculated gravity response of modelled bodies in a vertical geological cross

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section, and the gravity effect measured in the field. Ground measurements were made along existing roads using a Lacoste and Romberg (Model G-411) gravity meter, which has a resolution of 0.01 mGal. A total of 121 gravity stations were distributed along two NNW–SSE profiles orthogonal to regional-scale structures: a north profile (44 km length) including 84 gravity stations spaced every 500 m, and a south profile (30 km length) including 36 gravity stations spaced every 1000 m. These profiles extended beyond the western and eastern limits of the Chañarcillo Basin (Fig. 9). The coordinates and elevations were measured using a Topcon-Hiper V D-GPS system. The gravity and D-GPS base station (Algarrobal Station) was located inside the studied area (point AS in Fig. 9).

Standard gravity reduction processes were applied in order to obtain the Complete Bouguer Anomaly (Blakely, 1995) and a density of 2.67 $gr\,cm^{-3}$ (Hinze, 2003) for Bouguer correction was considered. Furthermore, the gravity data were corrected for effects caused by variations in latitude, elevation, topography, instrumental drift and earth tides caused by the sun and moon. The location of each station was recorded for 1 min with a mobile antenna, and then adjusted with a secondary antenna that was fixed for the entire gravity survey at the base station (AS, see Fig. 9). To ensure consistency between the different gravity profiles measured and to control for temporal instrumental drift, we used the Algarrobal Station (Fig. 9) as a gravity reference station, where systematic measurements were carried out before and after daily surveys. After this process, tidal, geographical latitude-dependent normal gravity corrections, elevation-dependent free-air gravity, and Bouguer gravity corrections, as well as, topographic corrections were applied to the gravity values.

Rock densities were determined for eleven samples (corresponding to different geological units exposed in the region) using the Archimedes Principle, the results of which are shown in Table 1. However, in this process the values obtained were considered as maximum values, because we determined densities for unfractured rocks. However, this situation rarely occurs in nature, because on a regional scale the geological units have fractures, pores, and saturated water levels, among others features. In this study, we have assigned a density of $2.67 \mathrm{gr\,cm^{-3}}$ to the pre-rift basement (Mesozoic granitic rocks) in the region, considering that it is also a standard density used to model the upper continental crust. The other density values used are shown in the Table 1 (see reference values).

5 Gravity and structural modeling

In order to better constrain the model, the gravity profiles were interpreted in terms of the previous geological information (shown in Fig. 3), as well as the density distribution (Reference values shown in Table 1). We used ModelVision v. 10.0 software and assumed that the major gravity features (long wavelength) represent the contrast between the pre-rift basement rocks and the volcano-sedimentary cover. This situation was better constrained at the western extreme of the northern profile, where the contact between the pre-rift basement rocks ant the syn-rift cover is exposed. Another part of the geological modeling was constrained mainly by the geometry of the syn-rift and post-rift deposits, field structural measurements (Fig. 3) and by more regional measured gravity (scale: 1 : 500 000; Vivallos et al., 2008).

The complete residual gravity-anomaly values ranged from 4 to −9 mGal (Figs. 10a and 11a) showing many short wavelength anomalies that can be related to second-order structures and superficial and intrusive bodies. These occasionally corresponded to Fe-mineralized intrusive bodies. The local gravity maxima observed along the northern and southern profiles have been modeled as structural highs, while the gravity lows were associated with buried depocenters. As observed in Figs. 10a and 11a, the gravity signal over the Chañarcillo Basin shows wedge shaped anomalies probably caused by the syn-rift infill, which were modeled with an average density of $2.48 \mathrm{g\,cm^{-3}}$ (see Figs. 10b and 11b).

The northern profile was extended perpendicular to the NNE-trending central section of the Chañarcillo Basin (Figs. 9 and 10). This profile shows four gravity lows, the three lows located at the eastern side of the profile are interpreted as three west-tilted

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half-grabens, the easternmost being better developed. The fourth gravity low located near the western limit is interpreted as Quaternary deposits over Jurassic-Cretaceous intrusives. The steep gravity gradients allowed us to define three west-dipping first-order faults that limit these half-grabens. These faults involve the Elisa de Bordos-Agua de los Burros Fault Systems, and two synthetic buried faults; moreover, other second-order faults and very small half-grabens were identified (Fig. 10).

According to this interpretation the gravity highs match with the hanging wall faults (Fig. 10) and could correspond to pre-rift basement blocks; however, in the central part of the modeled profile a small intrusive body was included (using a density of $2.8\,g\,cm^{-3}$, Table 1) emplaced along the faults, as have been observed in neighboring sectors (Arévalo and Welkner, 2008). Based on geological observations of the folding style described previously (see Sect. 4), and the high angles of the fault systems illustrated by the steep gravity gradients, we propose that most of these structures correspond to east-vergent inverted normal faults. This interpretation agrees with previous descriptions by Amilibia (2009) and Martínez et al. (2013) who suggested an array of inverted structures to explain the structural framework of the basin.

Modeling of the southern profile shows two important gravity lows within the Chañarcillo Basin (Fig. 11). Both gravity anomalies could indicate a continuity of the west-tilted half-grabens identified in the central section of the basin (Fig. 11). Similar to the northern profile, the steep gravity gradients were interpreted as west-dipping first-order faults that correspond to the Elisa de Bordos master-Agua de Los Burros Fault System and another synthetic buried fault (Fig. 11). The flat gravity signal (−3.5 mGal) registered to the west of the Elisa de Bordos Faults, allowed us to define a planar position at the base of the syn-rift infill (Fig. 11). On the other hand, the folded shape of the gravity anomaly observed in the central section (approximately 20 km from the western extreme of the profile), was modeled as a buried inversion anticline (Fig. 11). The geological observations described previously also indicate a folding style linked to an inverted structure. Based on this, we have interpreted the structures as an east-vergent, inverted normal fault like those identified in the northern profile.

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The high-gravity anomaly observed to the west of the Chañarcillo Basin, matches the occurrence of igneous bodies of the Coastal Cordillera; however, the steep gravity gradients registered along the westernmost part of this section (Fig. 11) could be modeled as east-dipping normal faults, following previous models proposed by Grocott and Taylor (2002) to explain the structural styles of the western Coastal Cordillera.

6 Discussion

6.1 Geometry and internal architecture of the Chañarcillo Basin

The internal structure of many Cretaceous rift systems in the Central Andes has been well determined by integrating field and geophysical information. Particularly, the combination of geological mapping, 2-D and 3-D seismic profiles, and gravity data have resulted in key insights for understanding the geometry and kinematics of the fault systems of some regions (e.g., the Salta Rift and the Neuquén, Cuyo and Metán Basins, as well as the Golfo de San Jorge) (Giambiagi et al., 2005; Kley et al., 2005; Grimaldi and Dorobek, 2011; Iaffá et al., 2011; Mescua and Giambiagi, 2012). However, in other regions of northern Chile, the structural geometry of the former Cretaceous rift systems has been inferred from indirect evidence such as the distribution of marine deposits, huge volumes of tholeiitic and calcalkaline magmatic rocks, or by syn-extensional structures, which are generally obscured by superimposed compressive deformation (Mpodozis and Allmendinger, 1993; Arévalo 2005b; Charrier et al., 2007; Mourges, 2007; Amilibia et al., 2008; Martínez et al., 2013).

The structural systems in the eastern present-day Coastal Cordillera in northern Chile (27–29°) have long been known, and are associated with the Cenozoic compressive and transpressive deformation of the Early Cretaceous Chañarcillo Basin infill (Arévalo and Mpodozis, 1991; Arévalo and Grocott, 1996; Arévalo et al., 2006; Amilibia, 2009; Martínez et al., 2013). However, the new geological and field observations documented in this work have shown that the superficial deformation pattern in this region is mainly characterized by inversion structures that include a large east-vergent asymmetrical anticline and other minor folds linked to the positive reactivation of inherent Cretaceous normal faults. Similar observations of this structural style have also been described in neighboring regions in the north (Tarapacá and Salar de Atacama Basins) (Muñoz et al., 2002; Arriagada et al., 2006b; Jordan et al., 2007), as well as in the Jurassic Lautaro Basin located east of the Chañarcillo Basin (Muñoz et al., 2002; Jordan et al., 2007; Amilibia et al., 2008; Martínez et al., 2009, 2012). This allowed us to recognize that this structural inheritance has played an important role, and exert strong control over the Andean deformation in northern Chile.

In the study area, this mechanism has produced long NNE- and east-vergent folds (the Tierra Amarilla Anticlinorium; Segerstrom, 1960) that exposed the marine and syn-rift deposits of the Chañarcillo Basin (Mourgues, 2007). The Tierra Amarilla Anticlinorium represents a first-order structure in the region, and its geometry is very similar to that reproduced by analogue models of basin inversion. These generally show prominent, asymmetrical, long-wavelength anticlines or "harpoon structures" linked to fault reactivations (McClay and Buchanan, 1992; Keller and McClay, 1995; Bonini, 1998; Yamada and McClay, 2003). Furthermore, the gravity profiles obtained in this study have defined a subsurface structural array in the Chañarcillo Basin characterized by a set of wedge-shaped geometries and west-tilted faults, with a pattern typical of an intra-plate rift system.

These include a series of gravity lows inside the Chañarcillo Basin, associated with narrow internal sub-basins separated by synthetic faults and ridges, which may be former Mesozoic structural highs. These results confirm the previous hypothesis proposed by Martínez et al. (2013), who, based on field data, concluded that the current architecture of the Chañarcillo Basin could be explained by the shortening of former Cretaceous extensional faults. Based on these results, we also conclude that the geometry of the basin is broadly dominated by previous rift architecture, which is associated with the early Cretaceous stretching of the continental margin.

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Previous studies (Martínez et al., 2011, 2013) also have indicated that the Elisa de Bordos-Agua de Los Burros Fault System corresponds to an inverted east-vergent fault, which marks the eastern edge of the basin. Even the Tierra Amarrilla Anticlinorium is geometrically associated with this structure, indicating that it has accumulated a considerable shortening. However, although there is good structural evidence of tectonic inversion in this structure, it is possible that some other former faults extended into the basin, the structures of which were determined by gravity modeling. These may also have absorbed compressional deformation considering the positive relief linked to the present-day position of the Mesozoic syn-rift deposits along the eastern Coastal Cordillera (Fig. 3).

Currently the deeper sections of the basins are unknown, but it is possible to speculate about the geometry of the faults, taking into account the results indicated previously. The geometry of the Tierra Amarilla Anticlinorium is best reproduced by a reactivated listric fault due to the drastic wedging of the syn-rift infill toward the west of the basin (Figs. 6 and 8). Moreover, the Elisa de Bordos-Agua de Los Burros Fault Systems, as well as the synthetic faults, may have reused a previous rift detachment during the shortening phase.

On the other hand, notorious gravity lows were not found to the east of the Elisa de Bordos Fault-Agua de los Burros Fault System, therefore it is not as easy to interpret this as Tertiary extensional basins, as have been proposed by Arévalo and Grocott (1996), Arévalo et al. (2006), and Arévalo and Welkner (2008) to explain the accumulation of synorogenic deposits in the footwall of the Elisa de Bordos Fault-Agua de Los Burros Fault System. The other structural systems proposed in this area and related to the west-vergent thrust and folds (Arévalo and Mpodozis, 1991), are also difficult to interpret from the gravity profiles obtained here. Therefore, we emphasize that these west-vergent thrust and folds could only be interpreted as local and secondary thin-skinned deformation.

Considering the recent U-Pb age (~ 80 Ma) reported by Peñ a et al. (2013) for the synorogenic deposits located over the frontal limb of the Tierra Amarilla Anticlinorium

(Viñitas Formation), we suggest a Late Cretaceous-Paleocene time for the partial reactivation of the Early Cretaceous normal faults. This age does not match with those proposed by Maksaev et al. (2009), who determined younger deformation ages of 66–65 Ma for the successions of the Chañarcillo Group and Cerrillos Formation from the middle section of the Viñitas Formation. However, we believe that these data recorded the propagation of the inversion structures during their evolution.

7 Conclusions and remarks

This work presents an integrated analysis of the Chañarcillo Basin, supported by gravity and field data, in order to obtain better knowledge of its architecture. The results presented and discussed previously allow the following conclusions.

1. The predominant structural style printed in the syn-rift infill of the Early Cretaceous Chañarcillo Basin corresponds to large a NNE- and east-vergent asymmetrical inversion anticline (Tierra Amarilla Anticlinorium), which developed upon and along the previous master fault of the basin (Elisa de Bordos-Agua de Los Burros Fault System).

2. Preexisting extensional systems have exercised primary control over the structural geometries formed along the eastern Coastal Cordillera (27–28° S) during the Andean deformation in northern Chile. In this context, the Elisa de Bordos-Agua de Los Burros Fault System represents a good example of reactivated normal faults from the shortening of former normal faults.

3. The large-scale features determined from gravity profiles show that the geometry of the Chañarcillo Basin, in particular, is composed of a subdivision of narrow west-tilted half-grabens separated by synthetic faults and ridges, which are clearly expressed by intercalations of gravity highs and lows inside the basin.

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4. A partial closing of the Chañarcillo Basin was at least initiated during a shortening phase in Late Cretaceous times. The first contractional stage in the region was determined by U-Pb ages to be related to the volcanic synorogenic successions deformed and located over the frontal limb of the Tierra Amarilla Anticlinorium.

5. Finally, we conclude that the above analysis of the Chañarcillo Basin from detailed gravity data constrained by geological data provides information useful for understanding the tectonic evolution and the subsequent structure of the basin. This may have potential impact on our comprehension of the main mechanisms of the Andean deformation along the continental margin in northern Chile (27–28° S), and on future mineral exploration.

Acknowledgements. The authors are thankful to Emilio Vera, as well as to the Geophysical Department of the University of Chile, for supplying D-GPS and gravity meter equipment. This work was supported by a grant from the National Fund for Scientific and Technological Development (FONDECYT grant no. 3 140 557), "The crustal structure and timing of deformation along the Chilean flat-slab subduction segment (27–29°), Central Andes". We gratefully acknowledge the support of Reynaldo Charrier for this research project, as well as to our colleagues at the Laboratorio de Tectónica y Paleomagnetismo of the University of Chile.

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Table 1. Sampling and density measurements.

Geological units	Lithologies	Density		
		Number of samples used	Measured	Reference
Quaternary deposits	Sand and grabels	–	–	2.1 (1)
Viñitas Formation	Laves, sandstones and tuffs	3	2.81	2.42 (1, 2)
Tertiary Intrusives	Diorites	2	–	2.8 (1)
Chañarcillo Group	Limestone	5	2.69	2.48 (1)
Mesozoic Intrusives	Granodiorites, diorites and tonalites	1	2.74	2.67 (3)
La Negra Formation	Andesites	2	2.75	2.48 (2)
Punta del Cobre Formation	Andesites	2	2.75	2.48 (2)

Referece values based on: (1) Jacoby and Smilde (2009), (2) Aguirre (1999), (3) Hinze (2003).

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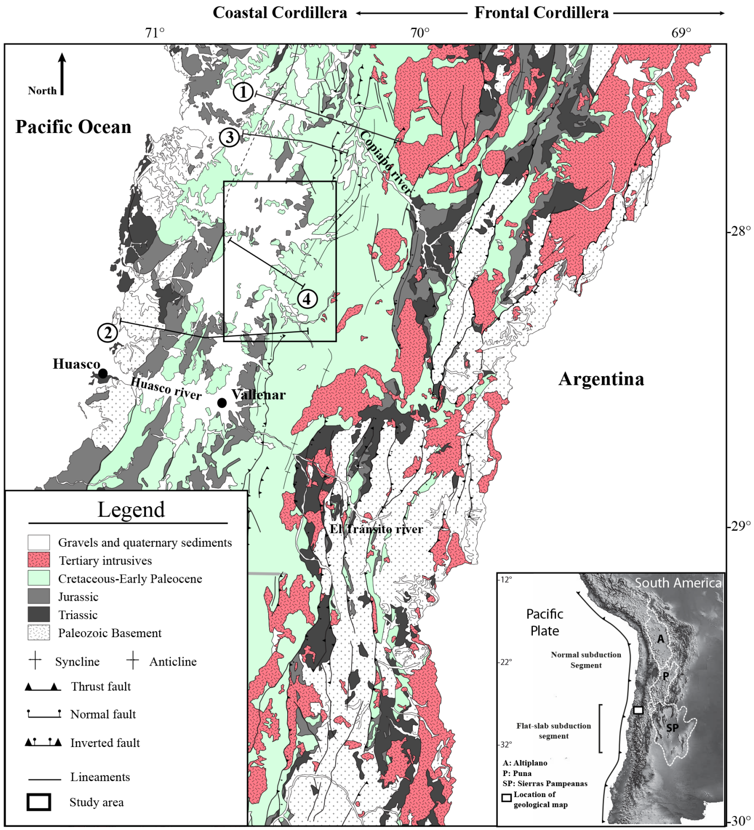

Figure 1. Simplified geological map of northern Chile (27°30′–30°00′), showing the distribution of the main tectonic provinces (Coastal Cordillera and Frontal Cordillera), stratigraphic units, regional structures and the location of the study area (modified from Sernageomin, 2003. Scale: 1 : 1 000 000).

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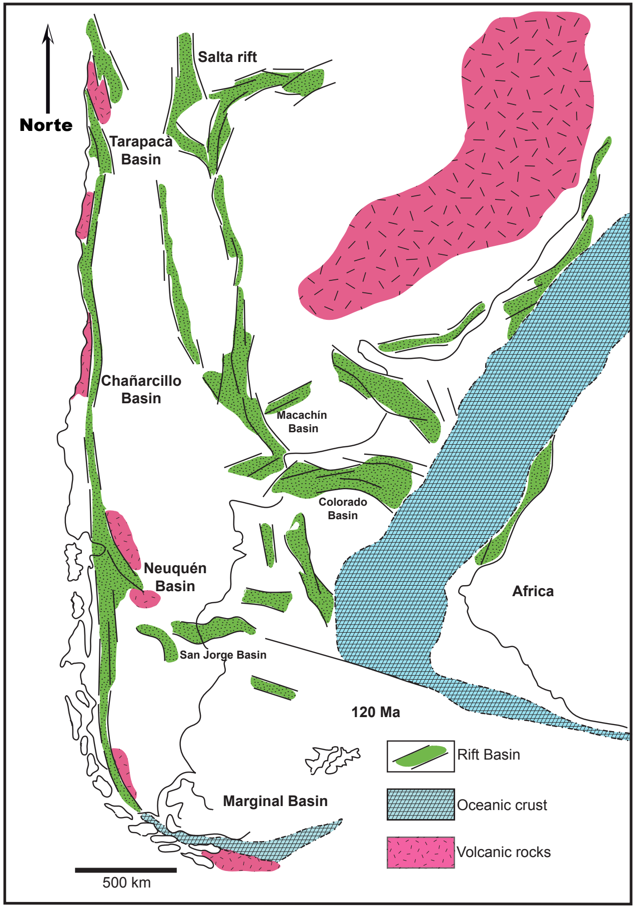

Figure 2. Main rift systems developed in southern South America during the Gondwana-Pangea break-up (Ramos and Aleman, 2000).

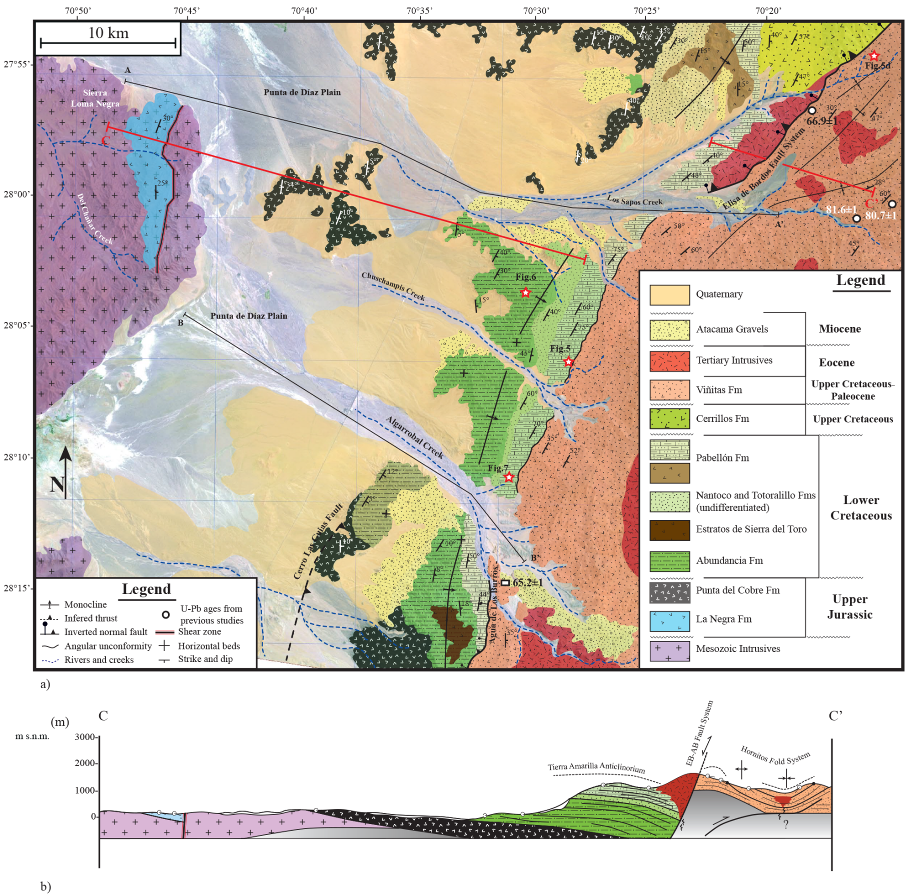

Figure 3. (a) Geological map of Chañarcillo Basin (Martínez et al., 2013, scale: 1 : 1 000 000) and the distribution of the gravimetric transects (A-A', B-B') acquired in this study; **(b)** schematic geological cross-section showing the surface structures recognized along profile A-A'.

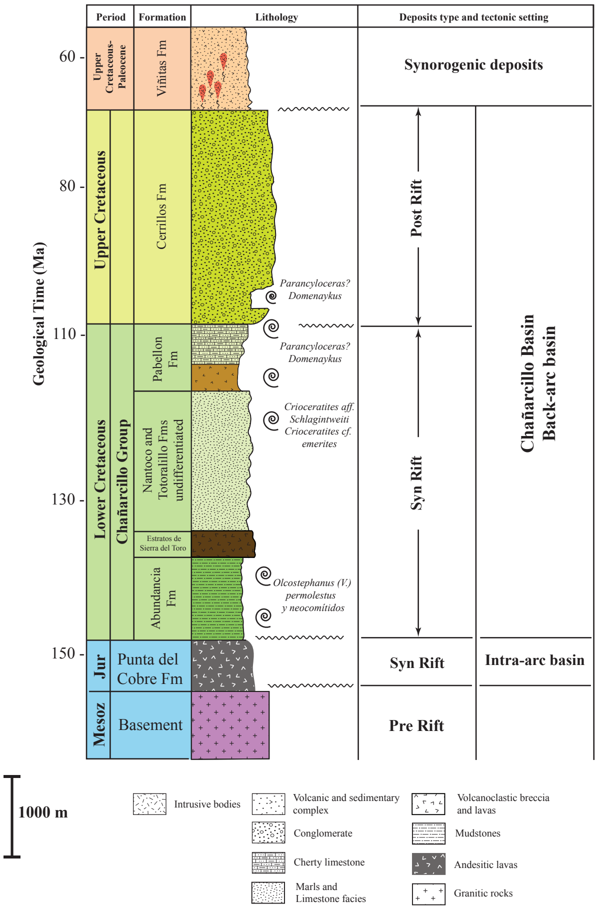

Figure 4. Simplified stratigraphic column of the Chañarcillo Basin (modified from Mourgues, 2004).

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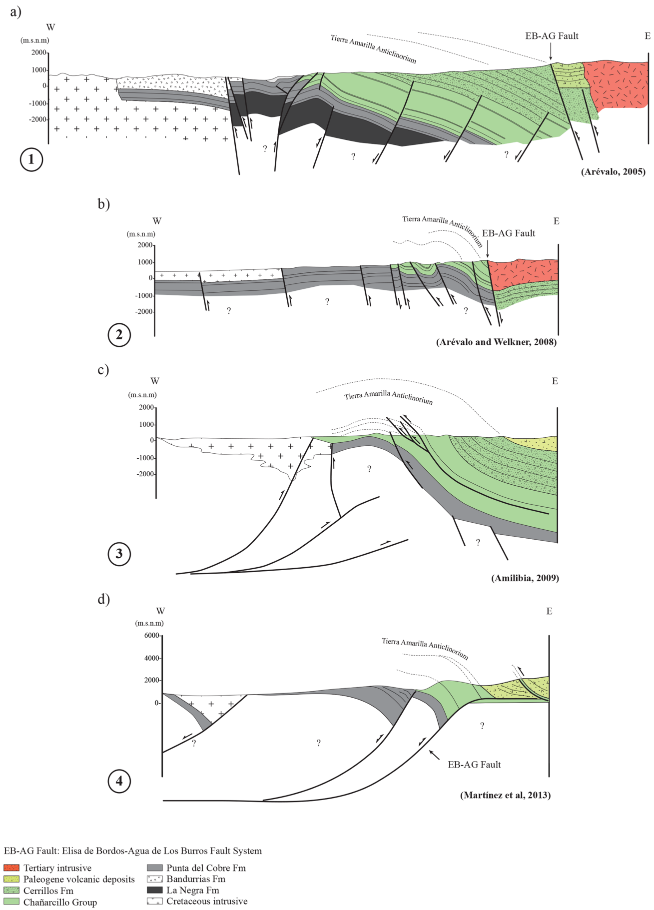

Figure 5. Structural models proposed to explain the architecture of the Chañarcillo Basin, as well as the relationship between the Tierra Amarilla Anticlinorium and the Elisa de Bordos-Agua de Los Burros Fault System (see description in text).

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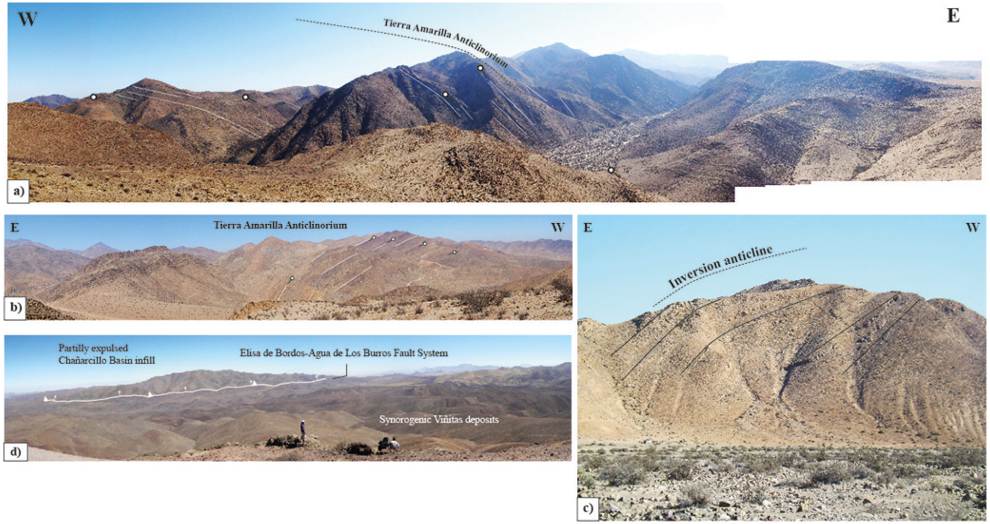

Figure 6. (a, b) W–E panoramic views of the east-vergent and long-wavelength Tierra Amarilla Anticlinorium involving the Chañarcillo Group (see location in Fig. 3); **(c)** oblique view of the Elisa de Bordos-Agua de Los Burros Fault System showing the contact between the syn-rift deposits of the Chañarcillo Group and the synorogenic deposits of the Viñitas Formation (see location in Fig. 3); **(d)** detail of the frontal limb of the Tierra Amarilla Anticinorium (see location in Fig. 3).

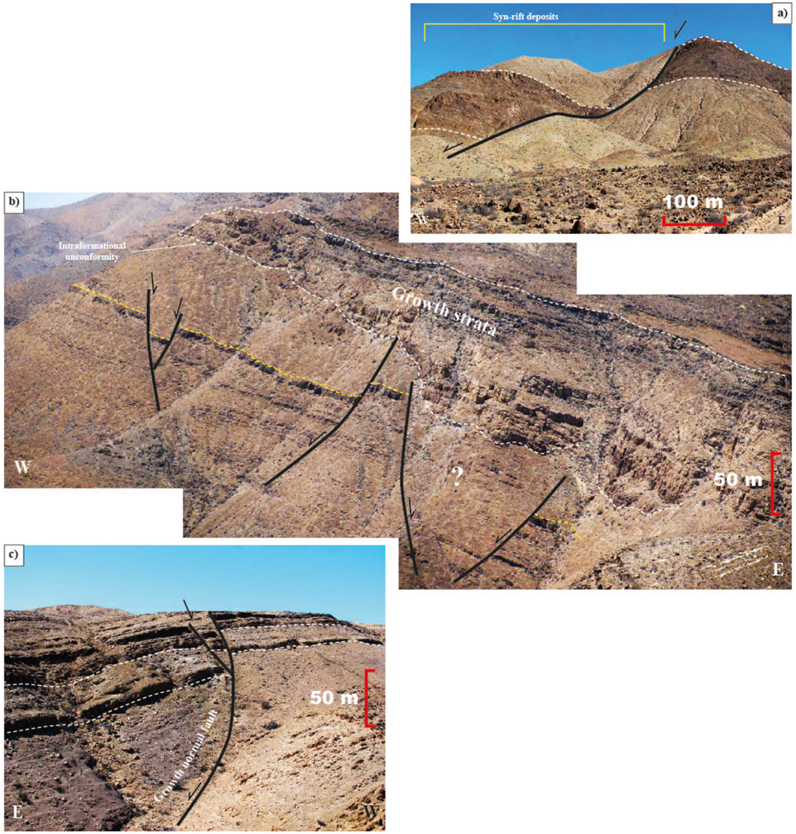

Figure 7. (a) Syn-extensional faults affecting the rocks of the Abundancia Formation (see location in Fig. 3); **(b)** details of the growth strata observed in the basal successions of the Chañarcillo Group (see location in Fig. 3); **(c)** aspect of the listric geometry recognized for the syn-extensional faults in the Chañarcillo Group (see location in Fig. 3).

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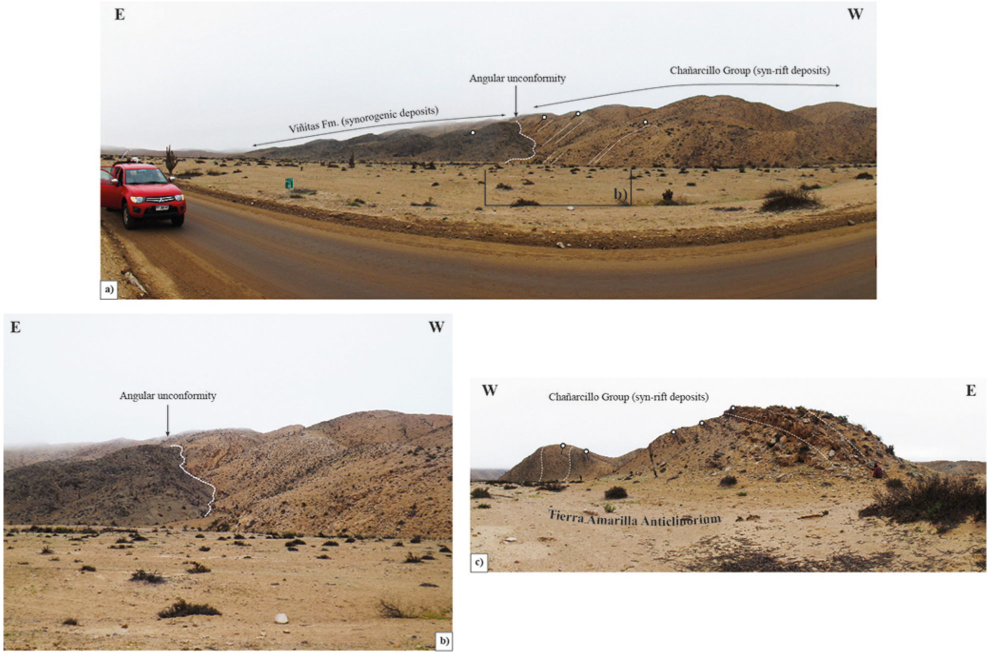

Figure 8. (a) E–W panoramic view of the angular unconformity between the synorogenic deposits of the Viñitas Formation and the Pabellón Formation along the frontal limb of the Tierra Amarilla Anticlinorium (see location in Fig. 3); **(b)** detail of the contact between the syn-rift deposits of the upper section of the Chañarcillo Group and the synorogenic deposits of the Viñitas Formation (see location in Fig. 3); **(c)** aspect of the inclined frontal limb of the Tierra Amarilla Anticlinorium (see location in Fig. 3).

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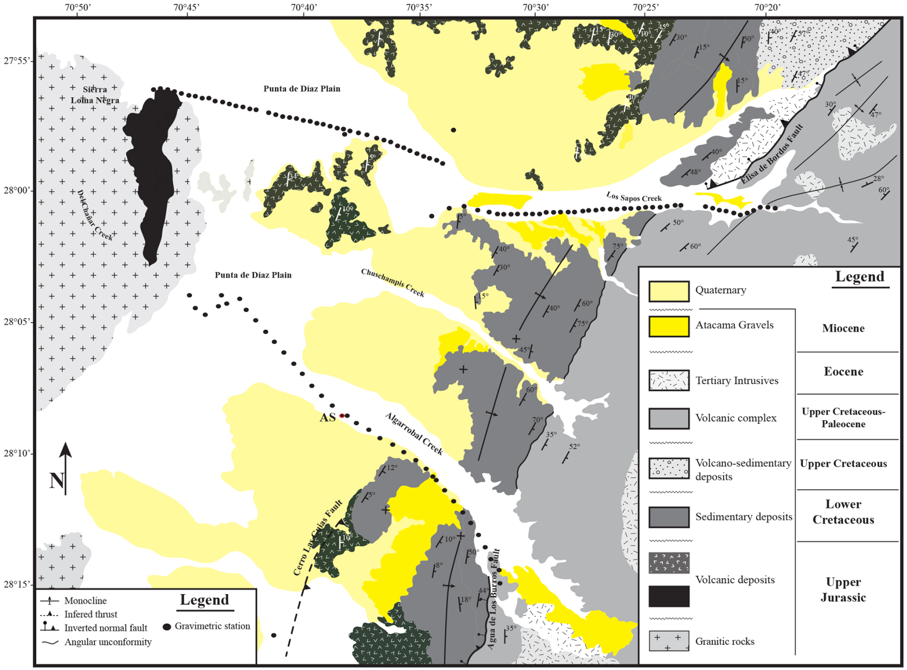

Figure 9. Simplified geological map of the Chañarcillo Basin (scale: 1 : 1 000 000) showing the distribution of the gravity stations used in this study.

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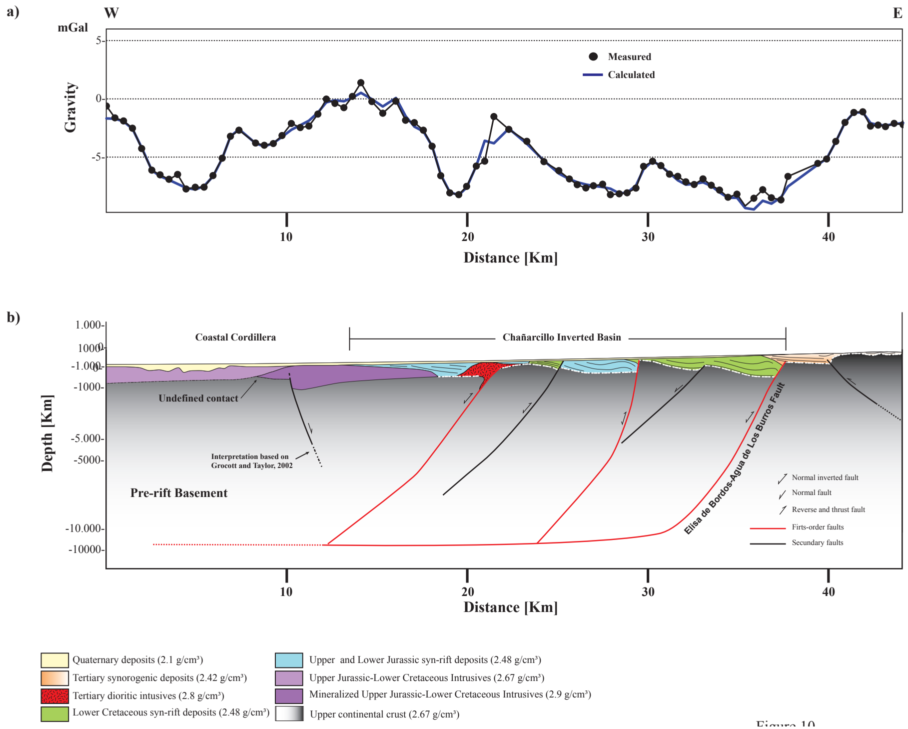

Figure 10. (a) Gravity profile A-A' (see location in Figs. 3 and 9) showing the measured gravity and the calculated gravity; **(b)** structural interpretation constrained with field and gravity data.

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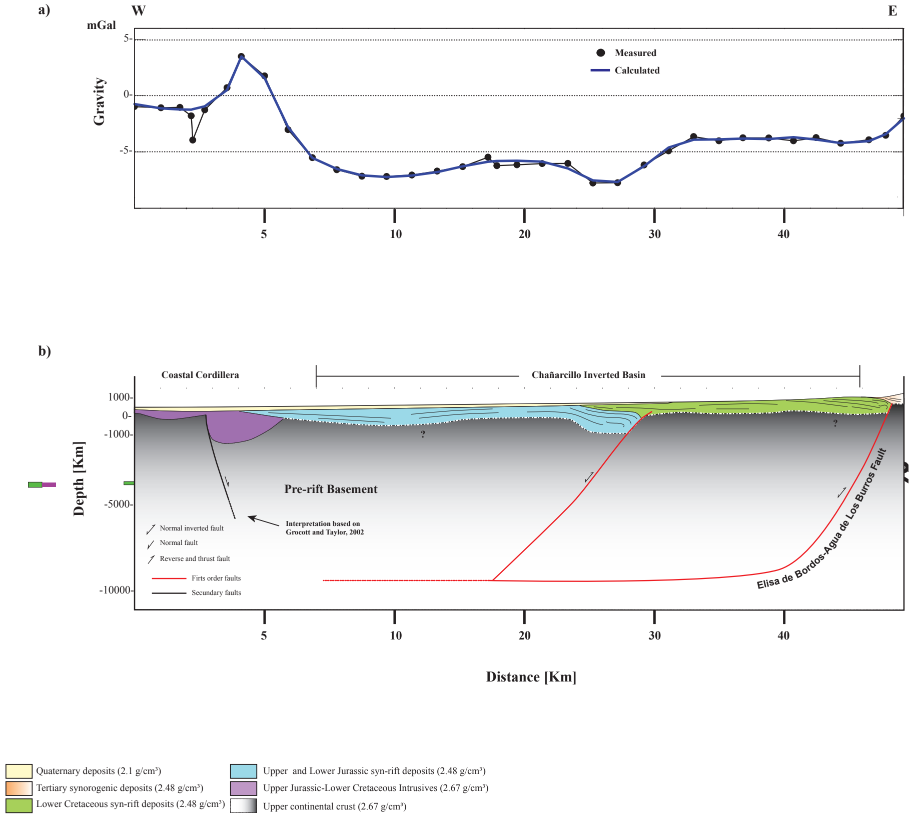

Figure 11. (a) Gravity profile B-B' (see location in Figs. 2 and 8) showing the measured gravity and the calculated gravity; **(b)** structural interpretation constrained with field and gravity data.

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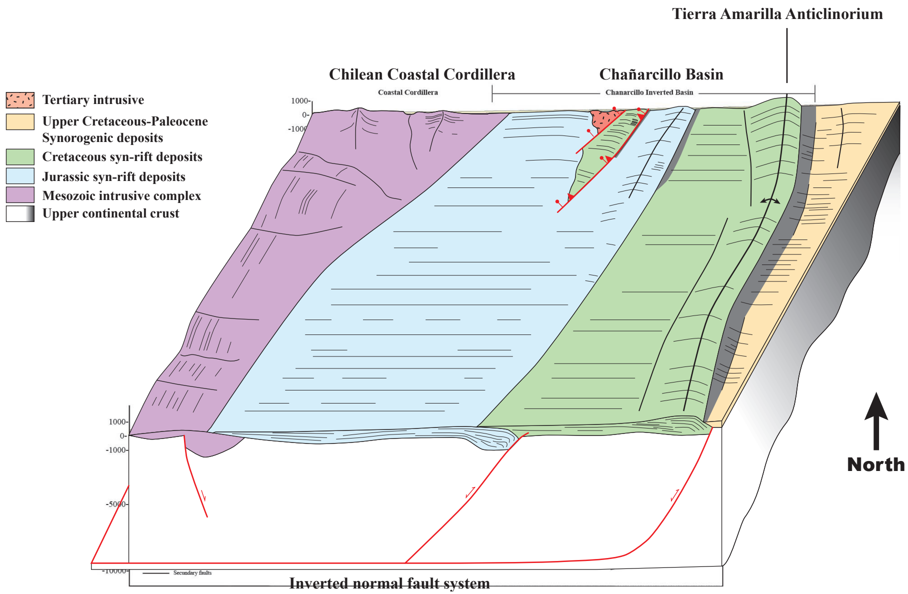

Figure 12. Cartoon illustrating the schematic 3-D architecture of the central section of the Chañarcillo Basin, based on the results obtained.

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