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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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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 synextensional deposits recognized within the basin, suggest that its structure 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 current 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 basins identified by Aguirre-Urreta (1993) in the southern Central Andes. Its origin is related to the negative rollback subduction geodynamic setting established along the western margin of South America over-riding plate during the Late Jurassic–Early Cretaceous time, which was coeval with the Mesozoic break-up of the Pangea–Gondwana supercontinent. This tectonic scenario caused extension in the upper continental crust and contributed to the development of a NE–NW-trending magmatic arc with back-arc extensional basins on the eastern side (Coira et al., 1982; Mpodozis and Ramos, 1990; Viramonte et al., 1999; Franzese and Spalleti, 2001; Mpodozis and Ramos, 2008), which were broadly distributed in Argentina and Chile (Fig. 2). In northern Chile the Tarapacá and Chañarcillo basins represent the first-order features related to this process.

In northern Chile, the Early Cretaceous extensional back-arc basins (Tarapacá and Chañarcillo basins) were positioned adjacent to the Mesozoic magmatic arc with a preferential NNE strike, being largely affected by extended volcanism (Fig. 2). Different to this back-arc tectonic scenario, a series of NE–NW-striking intra-plate rift basins were established on the Argentinean side being mainly associated with intra-continental extension or rifting (e.g., Salta Rift) (Fig. 2). The original geometry of these and other ancient (Triassic and Early Jurassic) extensional systems located in the western margin of Chile and Argentina was 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,

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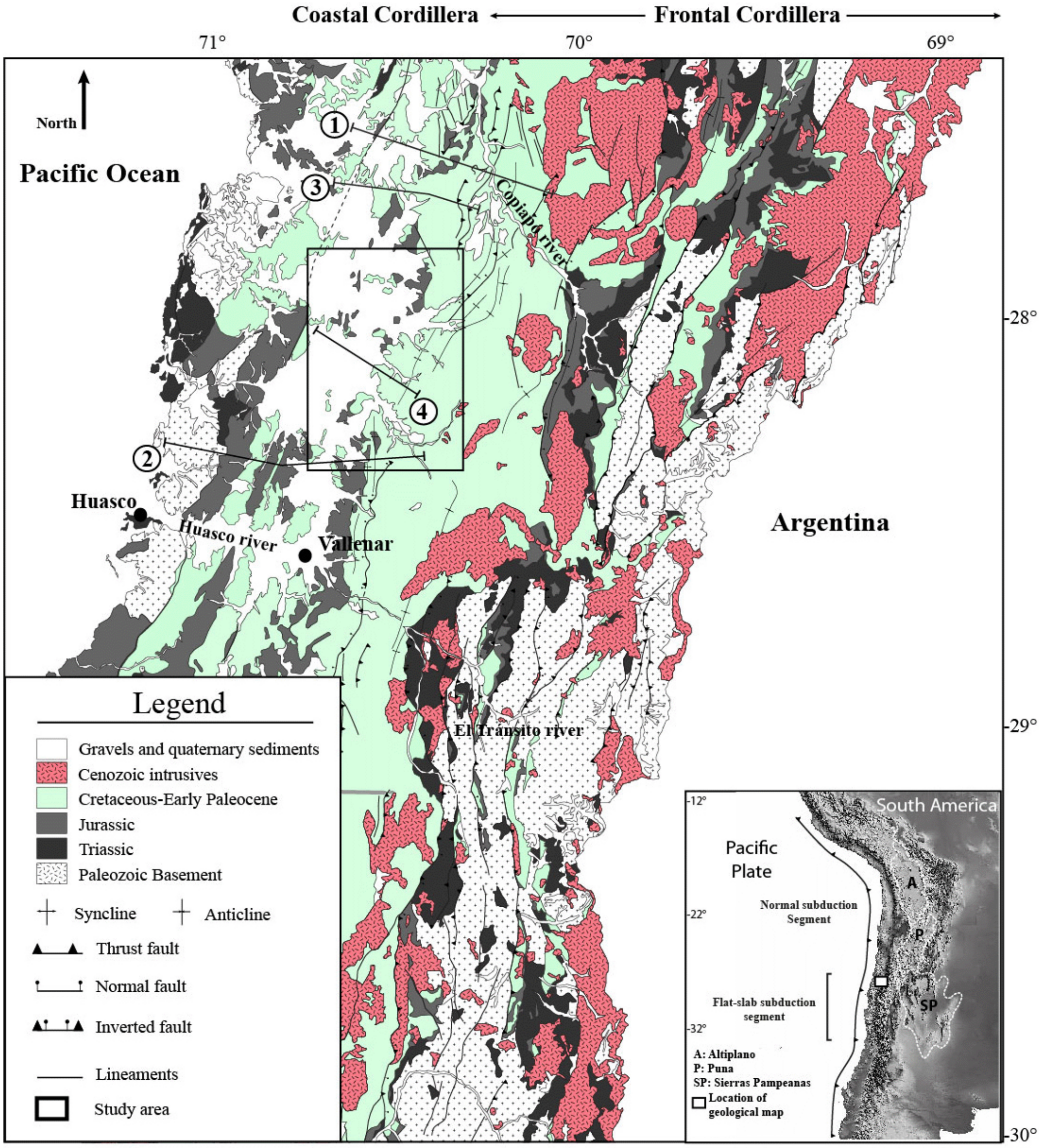

Figure 1. Simplified geological map of northern Chile (27°30′–30°00′ S), showing the distribution of the main tectonic provinces (Coastal Cordillera and Frontal Cordillera), stratigraphic units, regional structures and the location of the study area (modified from Sernageomin, 2003, Scale: 1 : 1.000 000).

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 synrift deposits (Manceda and Figueroa, 1995; Cristallini et al., 1997, 2006; Carrera et al., 2006; Giambiagi et al., 2009; Grimaldi and Dorobek, 2011).

Analogues of synrift 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 back-arc basin 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.

The Chañarcillo Basin is a region of special interest for analyzing the effects of the Andean deformation along the western slope of the Central Andes, mainly related to horizontal

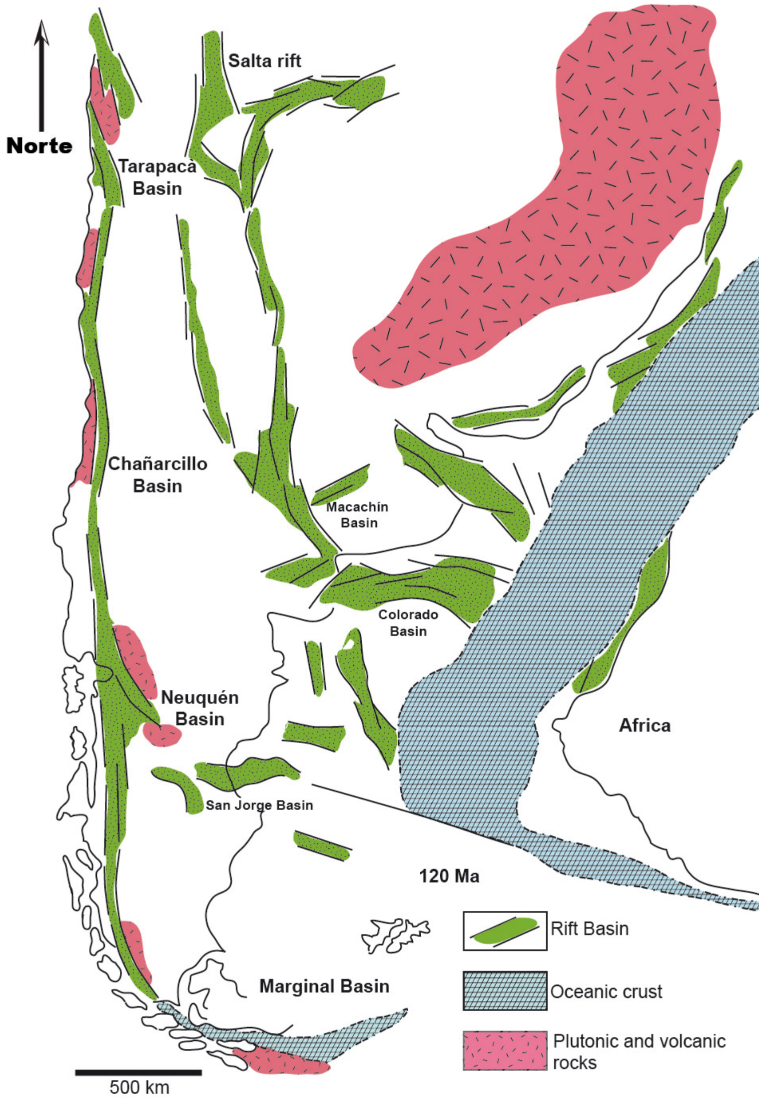

Figure 2. Main rift systems developed in southern South America during the Gondwana–Pangea break-up (Ramos and Aleman, 2000).

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 it 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, d). Such different 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 Chañarcillo 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

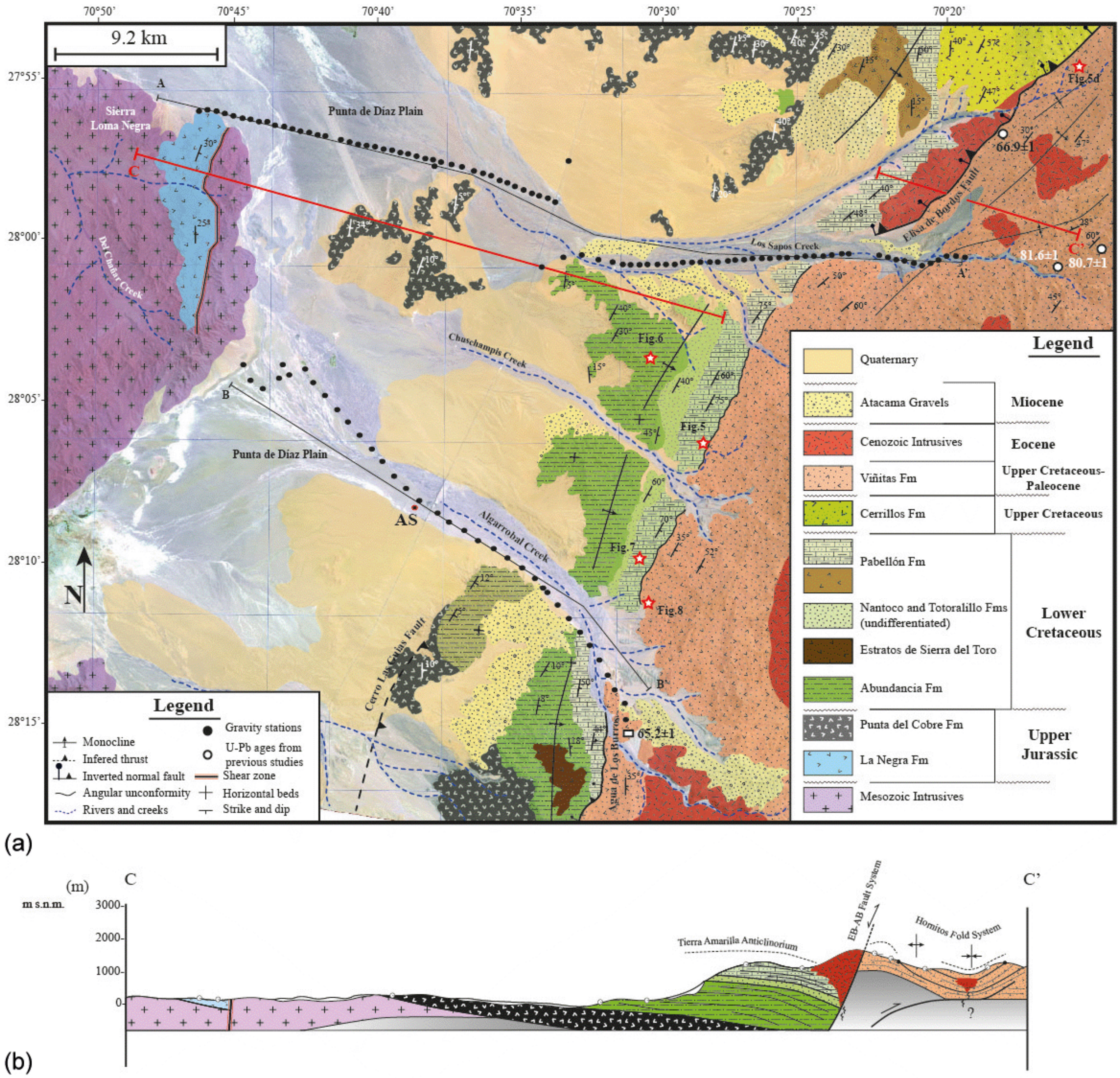

Figure 3. **(a)** Geological map of Chañarcillo Basin (Martínez et al., 2013, scale: 1 : 1.000 000) and the distribution of the gravimetric transects (A–A′, B–B′) acquired in this study; **(b)** schematic geological cross section showing the surface structures recognized along profile A–A′.

density changes related to the interface between the basement and the synextensional 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.

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 calc-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 outcrop, which were interpreted as a basal and continental synextensional back-arc succession of the Chañarcillo Basin (Figs. 3, 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 basin outcrop $\sim$ 2000 m of late Valanginian–Aptian marine and siliciclastic deposits corresponds to the Chañarcillo Group, historically interpreted as a synextensional back-arc sequence (Figs. 3, 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 siliciclastic synextensional sequence associated with a subtidal and supratidal environment, which has been divided into four conformable formations according to Biese (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), and *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)* aff. *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 Pabellón Formation includes about 2000 m of volcanic and sedimentary rocks composed of black chert, grey limestone, conglomerates and sands with *Parancyloceras domeykanus*, *Parahoplites* g. *nutfieldiensis*, and *Paulckella nepos* (Paulcke) and other important fauna (Fig. 4) (Pérez 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 tuff, 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, based on its structural and stratigraphic relationships, other authors have defined this succession as sag facies of post-rift deposits of the Chañarcillo Basin (e.g., Martínez et al., 2013). The deposits associated with this formation only are exposed in the main depocenter of the basin and have shown a change in the geometry of the basin fill; on other hand, their sedimentary section has important levels of reworked clasts derived from the Chañarcillo Group.

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 $\sim$ 70 to 50 Ma (Fig. 2) (Peña et al., 2013).

3 Structural background

A large NNE-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 synextensional successions of the Punta del Cobre Formation and Chañarcillo Group, as well as the Upper Cretaceous post-rift or sag deposits of the Cerrillos Formation (Fig. 3). The structure is an east-vergent asymmetrical anticline of long wavelength, characterized by an inclined frontal

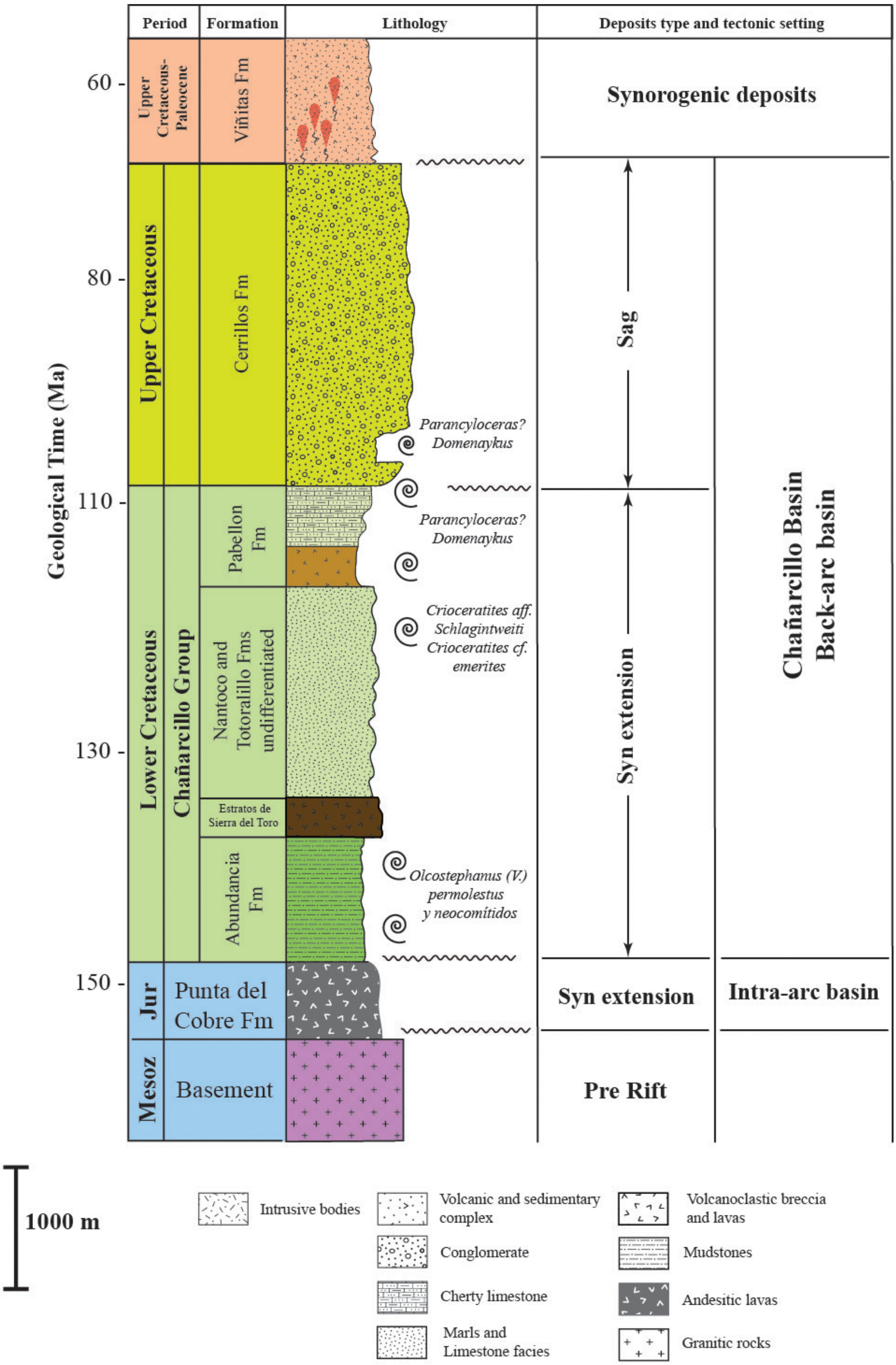

Figure 4. Simplified stratigraphic column of the Chañarcillo Basin (modified from Mourgues, 2004).

limb with a dip varying between 40 and 70° E (Figs. 3, 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 synextensional deposits of the Chañarcillo Group between the frontal (3000 m) and back limbs (300 m), forming a characteristic synextensional wedge geometry (Figs. 3 and 6). This geometry was achieved by the compressive deformation of this synextensional wedge, 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, North Sea, Viking Graben, Morocco Atlas, Apennines 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 Amarilla Anticlinorium is truncated by a NNE-trending contractional fault named the Elisa de Bordos–Agua de los Burros Fault (Arévalo, 2005b; Arévalo and Welkner, 2008; Martínez et al., 2013; Peña et al., 2013) (Figs. 3, 6d). This fault 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 and lie buried. 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 synextensional 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. Some models suggest that this fault 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 Anticlinorium. 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). On the other hand, recent models based on balanced cross-section techniques (Fig. 5c, 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. This last interpretation is now the most accepted and suggests that the Elisa de Bordos Fault–Agua de Los Burros Fault was initially a west-tilted normal fault that controlled sedimentation both for the Chañarcillo Group and the overlying Cerrillos Formation.

4 Methodology

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. 3). This method was chosen because we could examine the conformity between the calculated gravity response of modeled bodies in a vertical geological cross 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. 3).

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. 3). The location of each station was recorded for 3 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. 3). To ensure consistency between the different gravity profiles measured and to control for temporal instrumental drift, we used the Al-

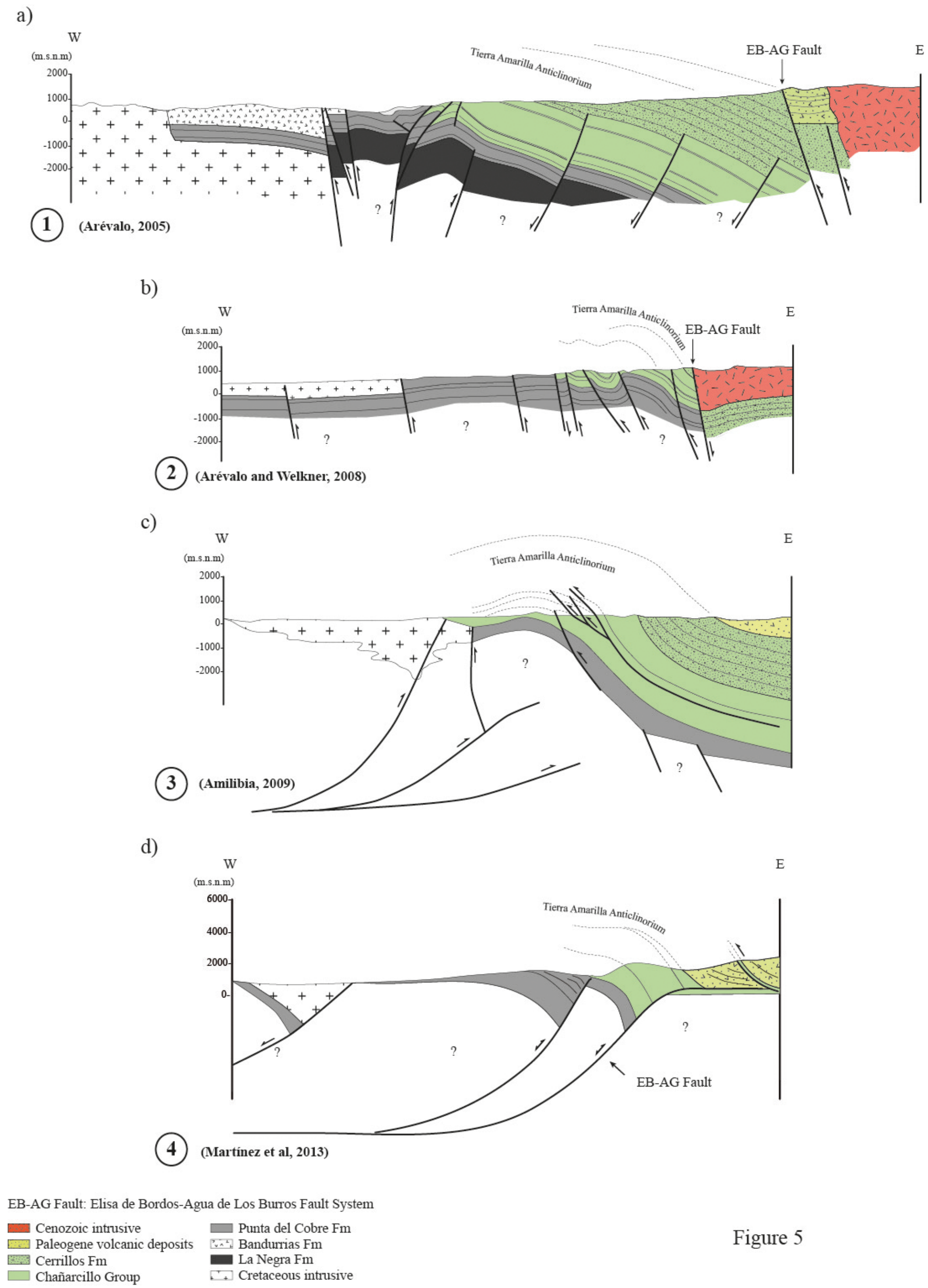

Figure 5. Structural models proposed to explain the architecture of the Chañarcillo Basin, as well as the relationship between the Tierra Amarilla Anticlinorium and the Elisa de Bordos–Agua de Los Burros Fault System (see description in text).

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 synrift 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 Anticlinorium (see location in Fig. 3).

garrobal Station (Fig. 3) as a gravity reference station, where systematic measurements were carried out before and after daily surveys.

Standard gravity reduction process was applied in order to obtain the complete Bouguer anomaly (Blakely, 1995). The process involves the following steps:

- Earth tide correction, applying the algorithm of Longman et al. (1959);
- instrumental drift correction by a time linear interpolation between the daily repetitions in the gravity base (0.02–0.2 mGal h^{-1} for this study);
- latitude correction according to the WGS84 ellipsoid;
- free-air anomaly and simple Bouguer corrections with the D-GPS elevations and a background density of 2.67 g cm^{-3} (Hinze, 2003);
- Finally, the complete Bouguer anomaly was obtained after the application of an accurate terrain correction performed in the Oasis Montaj Software with a 92 m × 92 m high-resolution SRTM digital elevation model (DEM) grid (Jarvis et al., 2008). The DEM grid extension was about 75 km × 75 km in order to remove the far and near effects of the topographic masses.

Rock densities were determined for 11 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 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 other features. This difference between the densities of the laboratory samples and the corresponding in situ bulk densities becomes evident for the limestones of the Chañarcillo Group. In this study, we have assigned a density of 2.67 g cm^{-3} to the 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 basement rocks and the volcano-sedimentary cover. This situation

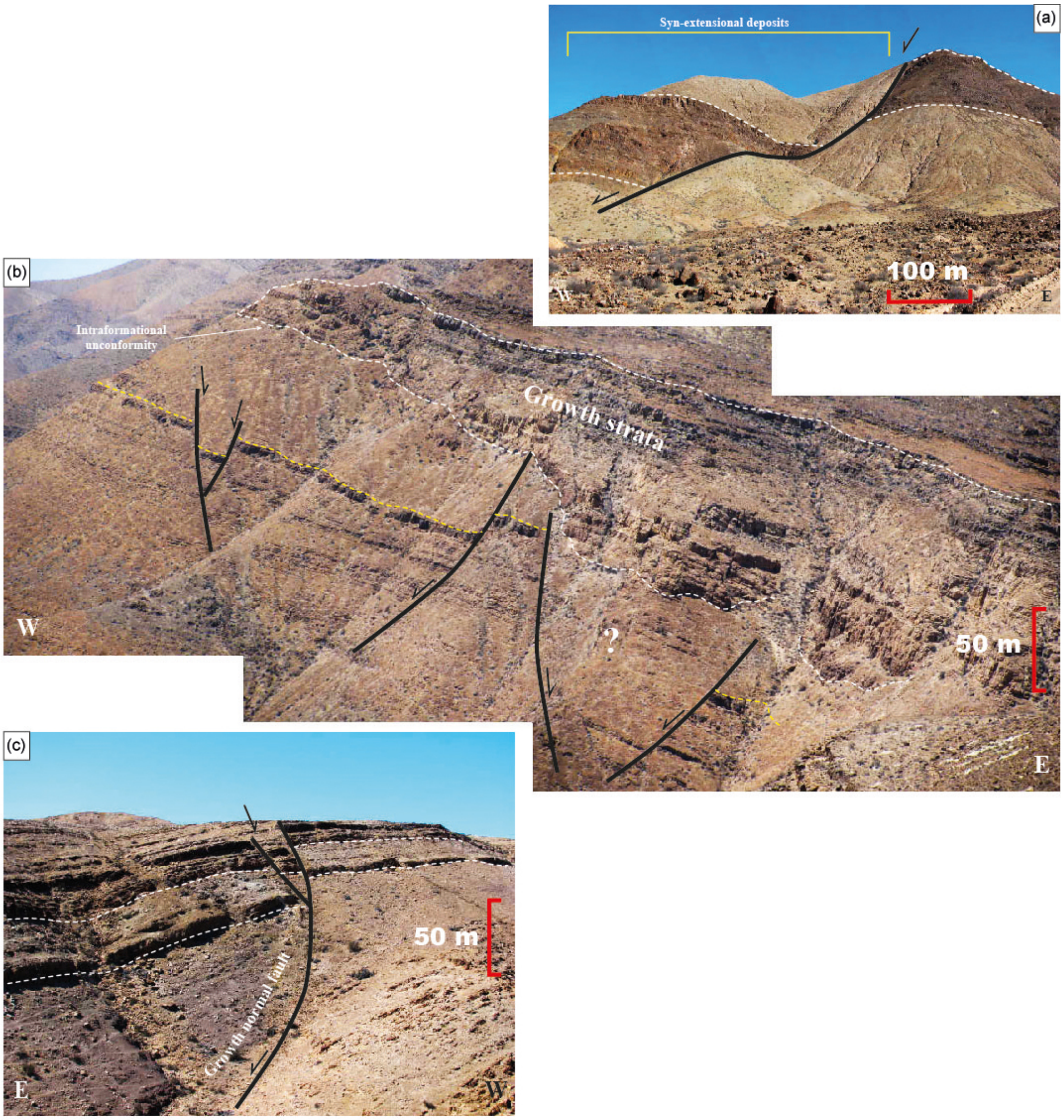

Figure 7. (a) Synextensional faults affecting the rocks of the Abundancia Formation (see location in Fig. 3); **(b)** details of the growth strata observed in the basal successions of the Chañarcillo Group (see location in Fig. 3); **(c)** aspect of the listric geometry recognized for the synextensional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

Table 1. Sampling and density measurements.

		Density		
Geological units	Lithologies	Number of samples used	Measured	Reference
Quaternary deposits	Sand and gravels	–	–	2.1
Viñitas Formation	Lava, sandstone and tuff	3	2.81	2.42
Cenozoic intrusives	Diorites	2	–	2.8
Chañarcillo Group	Limestone	5	2.69	2.48
Mesozoic intrusives	Granodiorite, diorite and tonalite	1	2.74	2.67
La Negra Formation	Andesites	2	2.75	2.48
Punta del Cobre Formation	Andesites	2	2.75	2.48

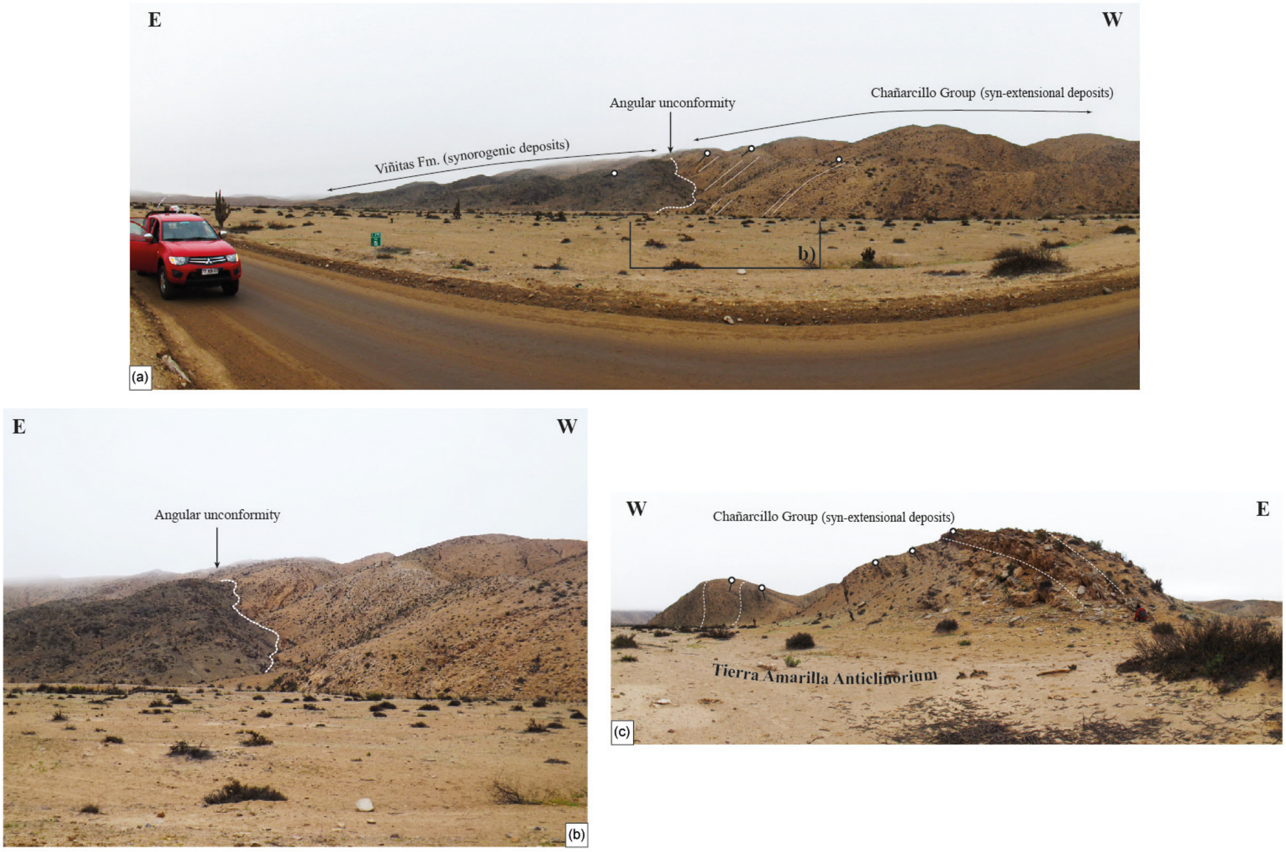

Figure 8. (a) E–W panoramic view of the angular unconformity between the synorogenic deposits of the Viñitas Formation and the Pabellón Formation along the frontal limb of the Tierra Amarilla Anticlinorium (see location in Fig. 3); **(b)** detail of the contact between the synrift deposits of the upper 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).

was better constrained at the western extreme of the northern profile, where the contact between the basement rocks and the synextensional cover is exposed. Another part of the geological modeling was constrained mainly by the geometry of the synextensional and sag facies, field structural measurements (Fig. 3), the geometry of folding observed in surface and by more regional measured gravity (scale: 1 : 500 000; Vivallos et al., 2008).

In order to define the regional gravity, we observed that the western limit in both profiles was registered near the basement outcrops. Additionally along the northern profile, two magnetotelluric stations have been acquired, and these data have been used to constrain the depth of the Chañarcillo Group and the regional gravity along the profile (see Fig. 9, more details and the magnetotelluric models can be found in the supplementary material). In the case of the southern profile, the regional gravity (Fig. 10a) was selected to obtain the same basement depth in the eastern limit (200 m) that the obtained for the northern profile. In spite of the ambiguity of the regional level in the eastern limits of the southern section, it is important to note that the main geometric characteristics of the modeled basin remain clear, even considered large changes in the regional gravity (see supplementary material for details of a sensitivity analysis).

The complete residual gravity-anomaly values ranged from 4 to −9 mGal (Figs. 9b and 10b) 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. 9b and 10b, the gravity signal over the Chañarcillo Basin shows wedge-shaped anomalies probably caused by the synextensional infill, which were modeled with an average density of 2.48 g cm^{-3} (see Figs. 9b and 10b). On the other hand, the gravity signal also shows that there are steep gradients between the higher and lower gravity-anomaly values, but these are frequently inclined to the west.

The northern profile was extended perpendicular to the NNE-trending central section of the Chañarcillo Basin

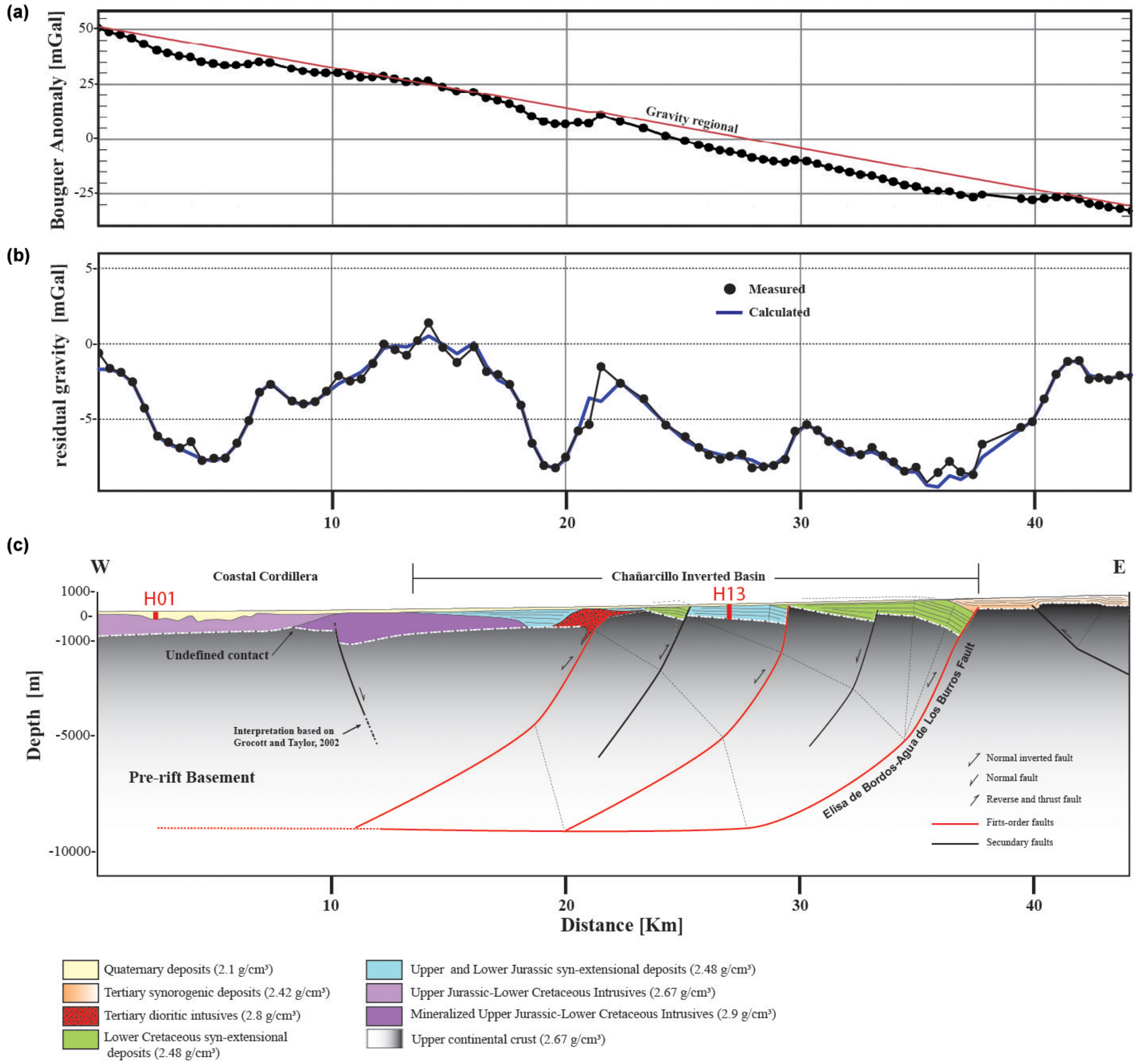

Figure 9. (a) Gravity profile A–A′ (see location in Fig. 3) showing the Bouguer and the regional anomaly; **(b)** gravity profile showing the measured gravity and the calculated gravity; **(c)** balanced cross section and structural interpretation constrained with field and gravity data. H1 and H2 represent two magnetotelluric stations used to constrain the depth of the Chañarcillo Group and the regional gravity along the profile (see details in the Supplement).

(Figs. 3 and 9). This profile shows four gravity lows; the three lows located at the eastern side of the profile are interpreted as three west-tilted 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 mainly incline to the west and 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, and two synthetic buried faults; moreover, other second-order faults and very small half-grabens were identified (Fig. 9c).

According to this interpretation the gravity highs match with the hanging wall faults (Fig. 9c) 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

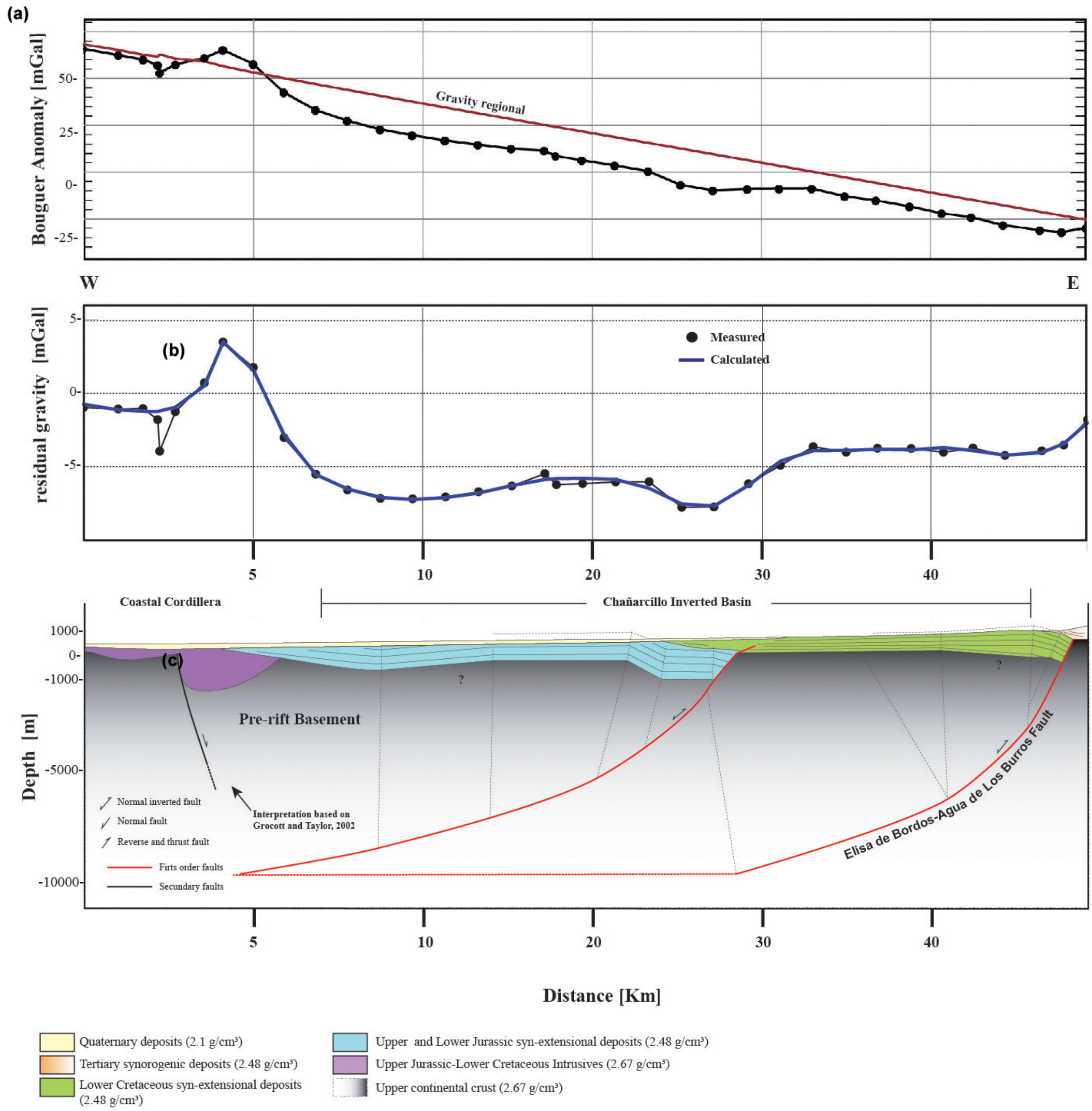

Figure 10. (a) Gravity profile B–B′ (see location in Figs. 2 and 8) showing the Bouguer and the regional anomaly; **(b)** gravity profile showing the measured gravity and the calculated gravity; **(c)** balanced cross section and structural interpretation constrained with field and gravity data.

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. 10b). Both gravity anomalies could indicate a continuity of the west-tilted half-grabens identified in the central section of the basin (Fig. 10c). Similar to the northern profile, the gravity gradients incline to the west, and therefore they were interpreted as west-dipping first-order faults that correspond to the Elisa de Bordos–Agua de Los Burros Fault and another synthetic buried fault (Fig. 10c). Applying the vertical shear constant heave method (Yamada and McClay, 2003), we have determined a basal detachment near 10 km, which could coincide with a major discontinuity into the crust (brittle–ductile transition); however, this must be considered as a hypothetical depth, since by other methods the basal detachment position could be deeper. On the other hand, 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 synextensional infill (Fig. 10). 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. 10c). 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.

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. 10b) 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

Geometry and internal architecture of the Chañarcillo Basin

The internal structure of many Mesozoic 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; Iaffa et al., 2011; Mescua and Giambiagi, 2012). However, in other regions of northern Chile, the structural geometry of the former Cretaceous extensional back-arc basins has been inferred from indirect evidence such as the distribution of marine deposits, huge volumes of tholeiitic and calc-alkaline magmatic rocks, or by synextensional structures, which are generally obscured by superimposed compressive deformation (Mpodozis and Allmendinger, 1993; Arévalo 2005b; Charrier et al., 2007; Mourgues, 2007; Amilibia et al., 2008; Martínez et al., 2013).

The structural systems in the eastern present-day Coastal Cordillera in northern Chile (27–29° S) (Fig. 11) have long been known and are associated with the Cenozoic contractional and contractional/strike slip 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 (Fig. 11) 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 exerted 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; Fig. 11) that exposed the marine and synrift 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" related to fault reactivation (McClay and Buchanan, 1992; Keller and McClay, 1995; Bonini, 1998; Yamada and McClay, 2003). Furthermore, the gravity profiles obtained in this study have allowed us to interpret 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 extensional system (Fig. 11).

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 a previous extensional architecture, which is associated with the lower Cretaceous extension of the continental margin. Previous studies (Martínez et al., 2011, 2013) also have indicated that the Elisa de Bordos–Agua de Los Burros Fault corresponds to an inverted east-vergent fault, which marks the eastern edge of the basin. Even the Tierra Amarilla Anticlinorium is geometrically associated with this structure, indicating that it has been shorted. However, although there is good structural evidence of tectonic inversion in this structure, it is mainly associated with the first-

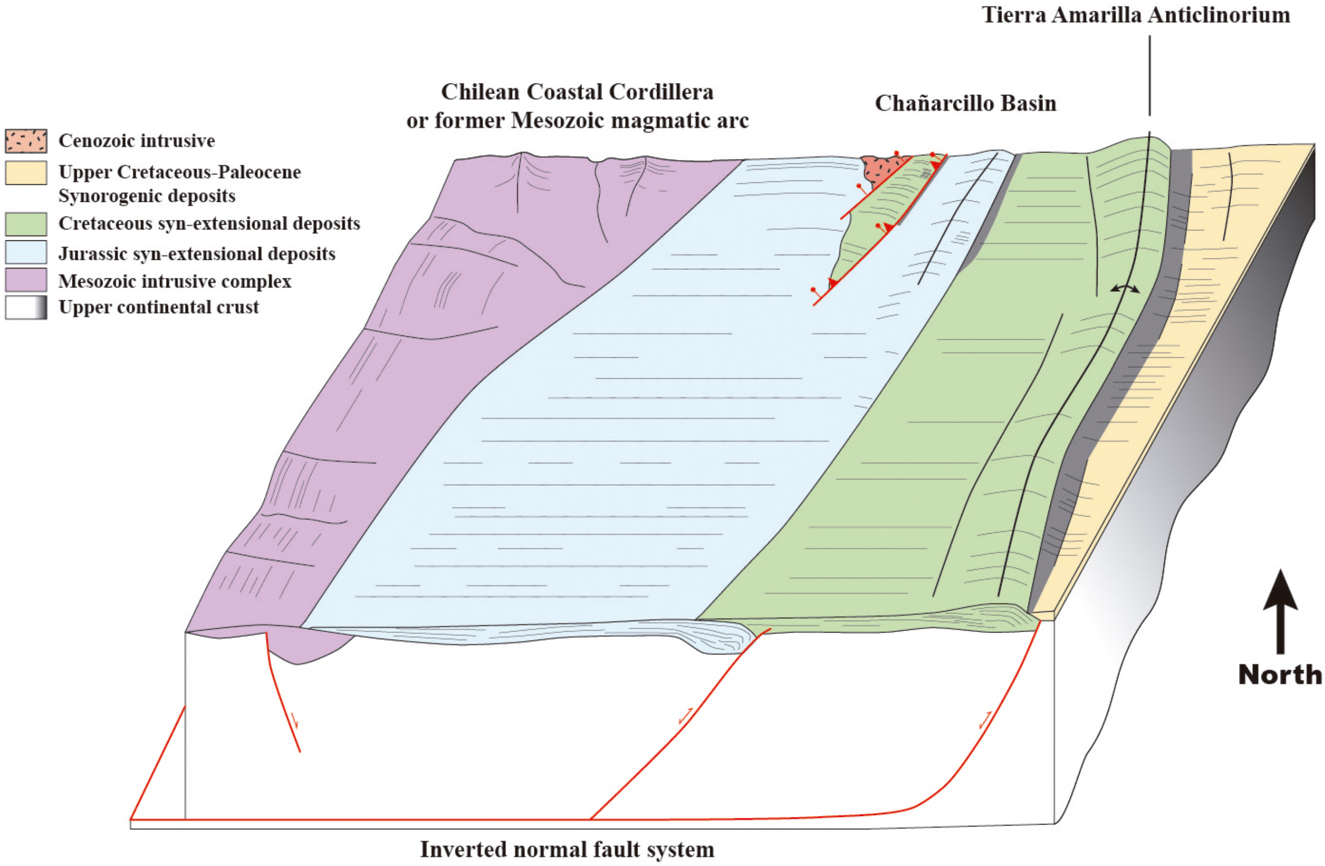

Figure 11. Illustration of the schematic 3-D current architecture of the central section of the Chañarcillo Basin, based on the results obtained.

order folding style, because other minor structural elements, such as kinematic indicators, have not been identified along the fault plane. Also it is possible that some other former faults extended into the basin, the structures of which were interpreted by gravity modeling. These may also have absorbed compressional deformation considering the positive relief linked to the present-day position of the Mesozoic synrift 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 and using the balanced cross-section methods applied to inverted basins (Coward, 1996). Although these faults have high angles, it is possible that these had a moderate angle (45–35°) before the inversion process, and then they were rotated to a higher angle during their reactivation. This last interpretation also was previously determined by Martínez et al. (2013) from the kinematic restorations. This interpretation also has been determined in other inverted basins located to the south and east of the study region, such as the Mercedario rift (Cristallini and Ramos, 2000), Salta Rift (Grier et al., 1991), Lautaro Basin (Martínez et al., 2012) among others. The geometry of the Tierra Amarilla Anticlinorium is best reproduced by an east-vergent reactivated listric fault (Figs. 6 and 8).

On the other hand, notorious gravity lows were not found to the east of the Elisa de Bordos Fault–Agua de los Burros Fault; therefore, it is not as easy to interpret this as Tertiary extensional basins, as 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. 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 Peña 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 synrift 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).

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 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.

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.

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