Analysis and structural restoration of the Abanico Formation, Principal Cordillera of central Chile, between 33°40' – 34°20'S (Maipo and Cachapoal river valleys)

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1. Introduction

In the Principal Cordillera of central Chile there are few quantitative structural analyses that continuously and completely cross over the western Principal Cordillera and, simultaneously, displays values of tectonic shortening with models of the geometry of structures toward deeper levels. The knowledge of the percentage of tectonic shortening and the geometry of the surface structures would help to understand the deformation that gave rise to the uplift and current configuration of the Principal Cordillera, and also, to establish hypotheses about the internal architecture of the Abanico extensional basin (Charrier et al., 2002). There are a large number of structural sections and the evaluation of the structures that compose them, by remote sensing methods and by the contribution of new data for specific zones, allow their integration into continuous sections that completely cover the area of the western Principal Cordillera in the study region.

In this publication, we present the preliminary results obtained for two structural models of 50 km long cross sections that encompass the Principal Cordillera and extend from the eastern edge of the Central Depression to the El Diablo fault system, which separates the Cenozoic sequences from the Mesozoic in this region. The first model is based on 3 sections oriented at 95° azimuth, within an east-west strip between 33°47' and 33°53'S, and the second model based on 3 sections oriented at 105° azimuth within the strip between 34°12' y 34°26'S.

The orientation of the principal structures and the parameters that define them were obtained from the generated structural models, from the calculation of the minimum crustal shortening value and from the combination of these data with the location of seismic hypocenters within the study area. Finally, high-angle deep structures were identified, which would constitute master faults that delimit the compartments of the Abanico basin for depth levels up to 2500 m.

2. Tectonic and geological settings

In the study region, the Principal Cordillera has been categorized as a double-vergent orogen (Fock et al., 2006; Armijo et al., 2010; Farias et al., 2010), displaying faults and folds with predominant vergence to the west on the western edge of the Principal Cordillera and an eastern vergence to the east of the El Diablo fault system, where a fold-thrust belt develops.

The Cenozoic deposits, which constitute most of the stratified sequences of the western Principal Cordillera, would have accumulated from the Upper Eocene in an intra-arc extensional basin (Abanico basin) that would have inverted tectonically in the Miocene (Godoy et al., 1999; Charrier et al., 2002; Fock et al., 2006; Farías et al., 2010).

As a generalization, for the Principal Cordillera in Chile, the stratified units are arranged in N-S orientation strips arranged on both sides of the El Diablo fault system, recognized between 29° and 37° S (Fock et al., 2006). The western fringe, studied area of this work, is mainly composed of powerful continental volcanic successions of Cenozoic age, belonging to the Abanico and Farellones formations. The eastern one, on the other hand, is made up of Mesozoic sedimentary units deposited on the northwestern edge of the Neuquén back arc basin, accumulated during two transgression-regression cycles.

At the studied region, the Principal Cordillera between 33°30' and 34°15'S, the deformation on the Cenozoic successions and, in particular, the Abanico Formation, is characterized by presenting large structures with subparallel orientations and with variable strike tending N-S direction. The extension of these structures varies from >10 km, considered first order, to local structures with kilometric to hectometric latitudinal extension. At the latitude of the Maipo river valley, the preferential strike orientation of the structures is N-S, grading slightly towards NNW-SSE or NNE-SSW with important variations in deformation style and vergence. At the latitude of the Cachapoal river valley, the structures are preferentially oriented with a strike of N10°-15°E, presenting, as in the Maipo river sector, significant variations in deformation style and vergence.

3. Methodology

The sections were constructed based on the characterization of the superficial geology, attained from data obtained in field campaigns, by remote sensing analysis and by compilation of structural sections elaborated by other authors. The extrapolation towards subsurface levels was achieved by balancing the sections maintaining constant line length. The precepts used for the construction of both sections are based on the work of Woodward et al. (1989, and references cited in the text) and Allmendinger.

The structural modeling was accomplished using the software Andino3D (Cristallini et al., 2022). The procedure is summarized in the construction of a first model of kink-type geometry that was then fitted to geometric models of kink band migration for folds related to faults (detail of these models on Woodward et al., 1989). It was also modeled with the Trishear equations (Allmendinger, 1998) in order to characterize the faults involved in the generation of more complex structures, although the final geometry was drawn in kink bands to keep the section line length constant.

In order to determine floors of the same age, the following was carried out: (i) a characterization of the deformation geometry based on data acquired *in situ,* remote sensing analysis and bibliographic compilation, and (ii) construction of a database with geochronological ages (U-Pb, K-Ar, Ar-Ar) collected from other works and sampled within the study area.

Using a single regional level and regional dip for the Principal Cordillera is ambiguous if the purpose is making a balanced cross section. This is due the fact that both, the foreland and the hinterland, are tilted towards the orogen, without knowing how much of this dip is related to: (i) flexure due to lithostatic load (of the Principal Cordillera), (ii) structures linked to the development of the Abanico basin western edge, or (iii) with the development of the Aconcagua fold-thrust belt, at the eastern side of the El Diablo fault system.

In addition, after the extensional phase, the paleo-relief could be variable in different depocenters of the basin, generating different local regional elevations. For this work, local reference levels were used for each zone so that the balancing procedure was carried out by blocks that were joined later. The error value calculated after stretching the layers was determined individually for each block and then for the complete cross sections, so that it does not exceed 10%.

4. Results

The preliminary results obtained are summarized in Figure 1, where the final model and sub superficial interpretation of structures are shown. The structures were fitted in models of fault propagation folds and fault bend folds, generating structures as asymmetric folds, monoclines, translated and/or rotated blocks by fault movements, imbricate fan systems, duplex systems and inversion structures.

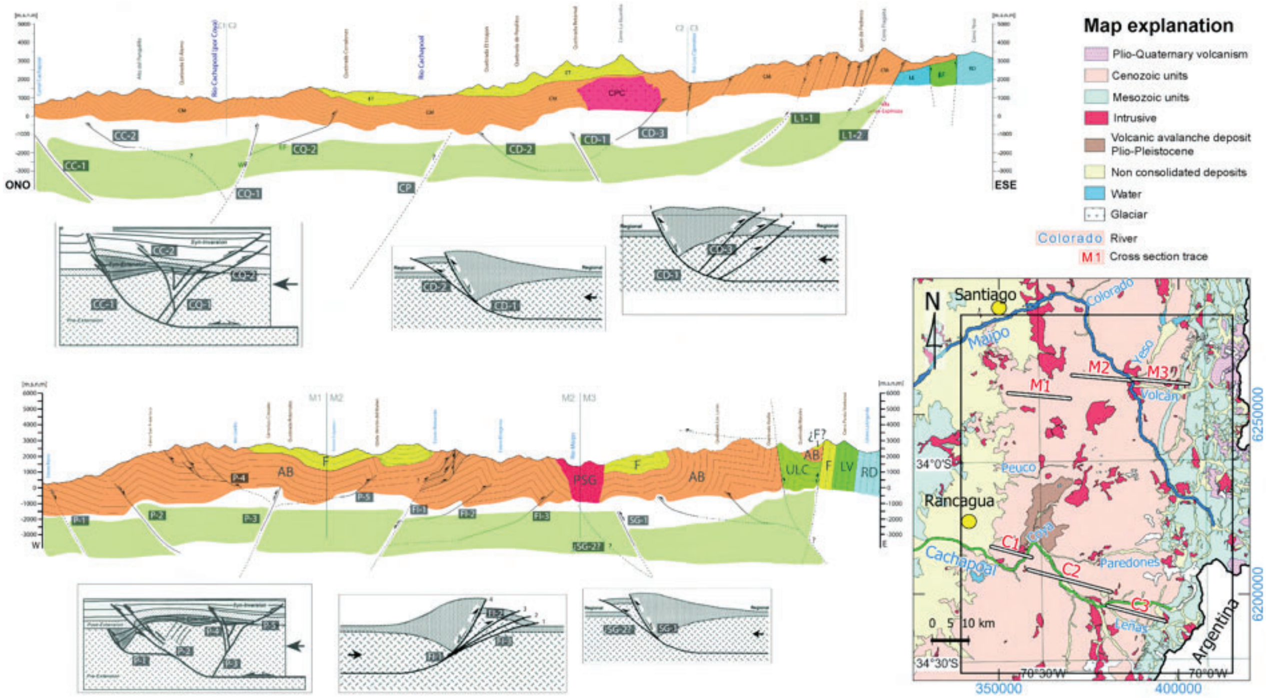

Figura 1: Preliminary results of the superficial structural modeling. Upper profile from the Cachapoal river valley and lower profile from the Maipo river Valley. The boxes below the profiles are schematics of analog modeling structural systems obtained from experiments in McClay (1995) and there are placed for comparison with the geometry obtained in this work. Symbology for profiles: (i) Cenozoic units, F: Farellones Fm., ET: El Teniente Volcanic Complex; AB: Abanico Fm., CM: Coya Machalí Fm.; (ii) Mesozoic units, ULC: Las Coloradas Unit; LV: Lo Valdés Fm.; BF: Baños del Flaco Fm.; RD: Rio Damas Fm.; LE: Leñas-Espinoza Fm.; (iii) Intrusive units, PSG: San Gabriel Pluton; CPC: Cortaderal Plutonic Complex. For this work, the Farellones with CV El Teniente, Abanico with Coya-Machalí and Lo Valdés with Baños del Flaco formations were considered as lithostratigraphic equivalents.

The kind of fault related fold was determined, for each case, based on a series of criteria: **(i)** geometric relationships of the axial surface and fold limbs that correctly fit the parameters of well proved geometric-kinematic models, **(ii)** greater inclination and lesser length of the frontal limb in fault propagation folds, **(iii)** length and inclination of the back limb, **(iv)** growth structures reported in or close to the profile trace, **(v)** larger regional structures located in the proximity of the profile trace, and **(vi)** comparison with seismicity data collected and summarized in previous works (Armijo et al., 2010; Farias et al., 2010). For each criterion described, if we make an isolated analysis, there are exceptions or variants to the generalization, so that the evaluation was carried out considering simultaneously all these criteria for each structure and not based on just one.

The interpretations assumed the development of an intra-arc basin, which deposits would have accumulated from the upper Eocene and would have been tectonically inverted in the lower Miocene, a situation that is justified based on abundant sedimentological, structural, geochemical, geochronological and geophysical evidence (Godoy et al., 1999; Charrier et al., 2002, and references cited in those texts). Also, this basin has an architecture developed on a crust with structures inherited from previous tectonic phases.

5. Discussion

Crustal shortening and structural style.

The total crustal minimum shortening calculated for latitude ~33.50°S (Maipo river valley) is 19.5 km, while for latitude ~34.10°S (Cachapoal river valley) it is 17.1 km.

Regarding the distribution of shortening, various observations can be made:

(i) The minimum shortening value is heterogeneously distributed and is concentrated around (not by) high angle structures. The structures that cause the greatest shortening are reverse faults with an average cutting angle of 30°-35°.

(ii) The segments located between the high deformed zones are characterized by developing homoclinal geometries with dips with values between 5° and 10°, and that usually constitute limbs of monoclines, synclines with interlimb angles greater than 160° or the back limbs of anticlines.

(iii) The high-angle structures located at the basin edges (Abanico basin) cause greater folding in the hanging wall block compared with the high-angle structures located in central zones, which has a role as nucleus zones at which root complex systems of faults with dips <35°, capable of generating, locally, high values of shortening.

(iv) After the restoration, two sets of compressive phase faults were identified: (a) faults rotated between 5° to 10°, that nucleates toward high-angle structures and developed essentially at greater deps >1 km and (b) faults rotated <5° located at superficial levels (<1 km) and nucleating into high-angle structures or in structures defined in (a).

Surface architecture of the Abanico basin

The modelling of structures has allowed the elaboration of a proposal of the orientation and depth of the faults that generate the outcropping folds. The geometric arrangement was compared with structural configurations for positive tectonic inversion systems obtained by analogic modelling, generating a model of the surface architecture of the basin. The proposal made here is superficial and is valid only for maximum depths between 2000 m and 2500 m.

Accuracy and limitations of the model

This model allows visualizing the geometry of the deformation at surface levels no greater than about 2500 m. Its validity does not affect that of regional architecture models that shape the Andean Orogen (e.g. Armijo et al., 2010; Farias et al., 2010) and is oriented, rather, to contribute with new data to the characterization of the superficial structural style, both qualitatively and quantitatively.

There is always the possibility that structures that do not fit into theoretical models may form in areas below the surface. Furthermore, the theories of fold formation related to faults based on parallel slip between layers correspond to a geometric and kinematic description, without foundation in the mechanical behavior of the rock (Woodward et al., 1989), therefore, heterogeneities between different layers, such as the alternation of lithological types, wedging or mechanical anisotropies can locally cause notoriously different results in the predictions of these models. Anyway, the model presented here has the purpose of identifying the principal structures that controlled the basin development and a minimum value of shortening, so, more precisely models require work at major scales and even different structural modelling approaches as they can consider secondary order structures as fold accommodation faults.

6. Conclusions

The high value of minimal shortening concentrated around the master structure of the eastern edge of the Abanico basin, higher than those recorded on the western edge, makes visible its first-order importance in the inversion phase. This, together with the identification of deeper depocenters in the eastern sector of the Principal Cordillera, compared to its western sector (Fock et al., 2006), reveals that the regional fault system that separates the Cenozoic from the Mesozoic sequences at the Principal Cordillera is a first-order structure, at least during the entire development phase of the Abanico basin (Upper Eocene – Lower Miocene).

Based on the projection toward the subsurface of the emerged faults and the blind faults that generated the folds of the deformed system of the Abanico Basin, structural configurations geometrically similar to those obtained by analogous modeling experiments were identified. Principally the structures identified are: simple listric fault systems and double-listric ramp composed fault systems, with the development of collapse grabens, hanging wall shortcut fault structures and footwall bypass faults, these structures are compared with those presented in the works of McClay (1995).

Based on the preliminary results of this work, it is proposed that the surface architecture of the Abanico basin, for ~33°50'S and ~34°15'S, is dominated by a symmetrical extension system, with the development of a raised block in the central segment, shorter in length at the Maipo sector compared to the Cachapoal.

Keywords: Abanico basin, balanced cross section, crustal shortening, tectonic inversion

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