Trabajos de Geología, Universidad de Oviedo, 29 : 375-380 (2009)

Oviedo (Spain) 1-3 July 2008 International Meeting of Young Researchers in Structural Geology and Tectonics
YORSGET

Geometric reconstruction and trishear model of folding: a case study in the western Principal Cordillera, Central Chile (34°15'S – 34°30'S)

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Abstract: The western Principal Cordillera consists of thick volcanic successions accumulated in an extensional basin and deformed in Early Neogene times during tectonic inversion of the basin. In the study region, key-layers are lacking and, for this reason, geometrical reconstructions are difficult. The main structure is a N-S-oriented syncline bounded by faults. Reconstructions using the fault-propagation fold and trishear models indicate that this structure is controlled by faults, a western (WF, cut-off angle ~40-60°) and an eastern fault (EF, cut-off angle ~20°). WF, the most important one, is interpreted as an inverted normal fault associated with basin inversion, whereas EF is interpreted as a short-cut related to WF. Shortening is 2-3 km (~30%).

Keywords: Andes, Central Chile, Principal Cordillera, Cenozoic, structural analysis.

Structural models and balanced cross-sections in the Southern Central Andes have been mostly constructed in regions where shortening was accommodated in predominantly sedimentary successions, generally in the back arc. Such successions contain easily recognizable layers, which facilitate structural mapping and geometrical reconstructions. Because of the lack of key layers it has been difficult to construct reliable balanced cross-sections and structural models in the monotonous, predominantly volcanic Cenozoic rocks in the fore arc. In this contribution, we present a structural model based on six W-E-oriented cross-sections across a broad syncline with a very tight fault-bounded core, which is located in the western Principal Cordillera in Central Chile. This structure records the last major compressive tectonic event in this region.

Geological and structural setting

The Principal Cordillera in Central Chile and Central-Western Argentina (33°S-35°S) consists of Cenozoic and Mesozoic units, intruded by several Miocene-Pliocene plutonic bodies. The stratified Cenozoic units correspond to the Abanico and the Farellones formations. The Late Eocene to Late Oligocene-Early Miocene Abanico formation consists of a 3000 m thick volcanic and volcano-clastic succession with minor sedimentary intercalations deposited in an extensional basin. The Early-Middle Miocene, 3000 m thick Farellones formation, consists predominantly of volcanic deposits formed during inversion of the basin. Mesozoic sequences correspond to marine and continental sedimentary deposits exposed on the easternmost part of the Principal Cordillera in

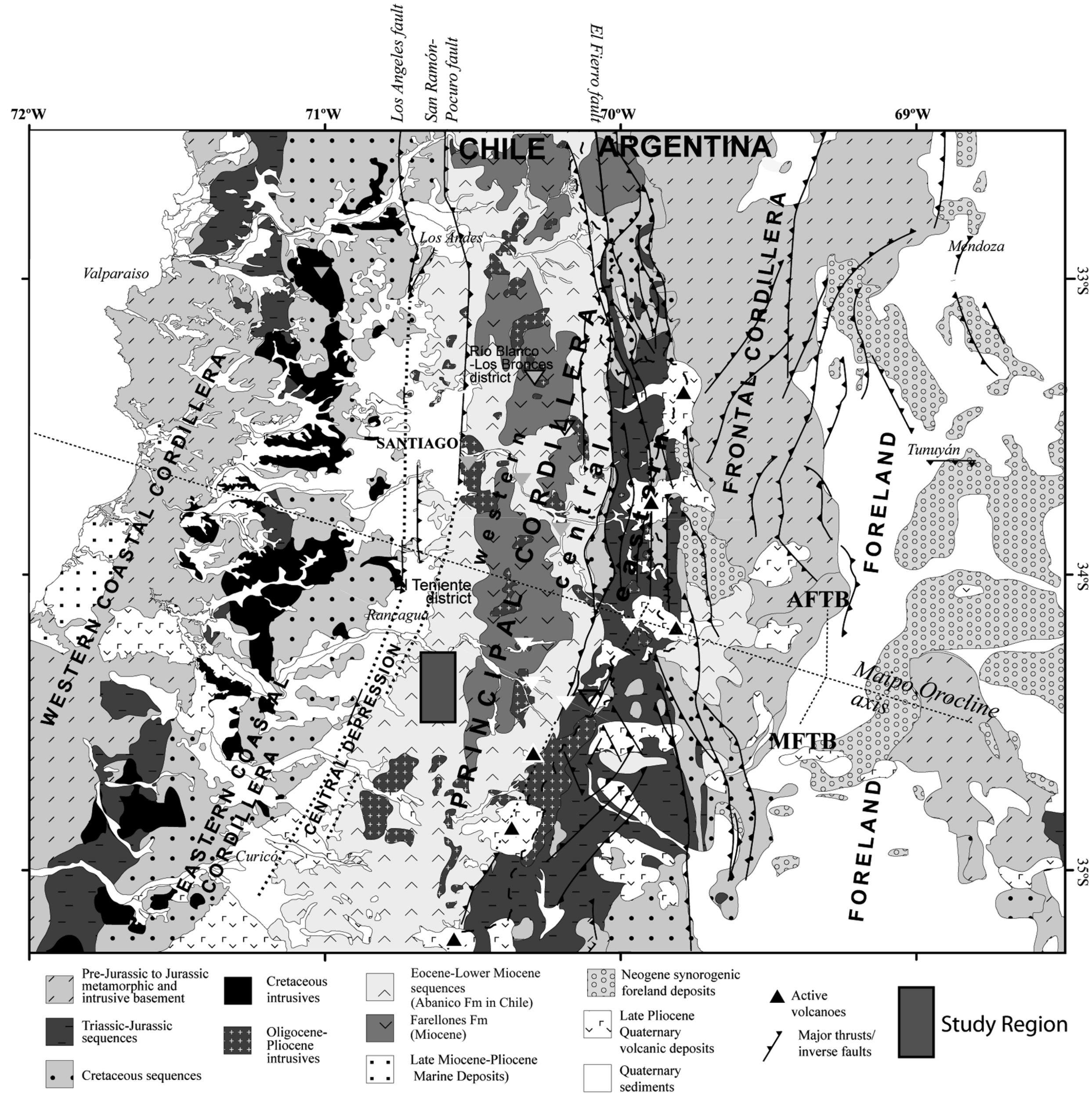

Figure 1. Simplified geological map of Central Chile and Western-Central Argentina. Compiled by Farías *et al.* (2008).

Chile and extending eastwards on the Argentinean flank of the Cordillera (Fig. 1). Deformation of the Cenozoic succession is mainly concentrated in the Abanico formation, while the Farellones formation is generally mildly folded.

Structural features in the study region

The study region, located in the western Principal Cordillera between 34º15'S — 34º30'S, is characterized by an intense contractive deformation affecting the Cenozoic sequence. The structural features observed in the Cenozoic units have been attributed to thick-skinned deformation related to basin inversion during the Miocene (Charrier *et al.*, 2002, 2005; Fock *et al.*, 2006).

The structural array consists of a 2 km-wavelength syncline (Co. Alto de Los Peñascos syncline, figure 2) with a very tight fault-bounded core. Layers on both sides of the faults dip in opposite directions. These layers and the flanks of the syncline suggest the presence of anticline crests “broken” by the movement of two reverse faults: a western (WF)

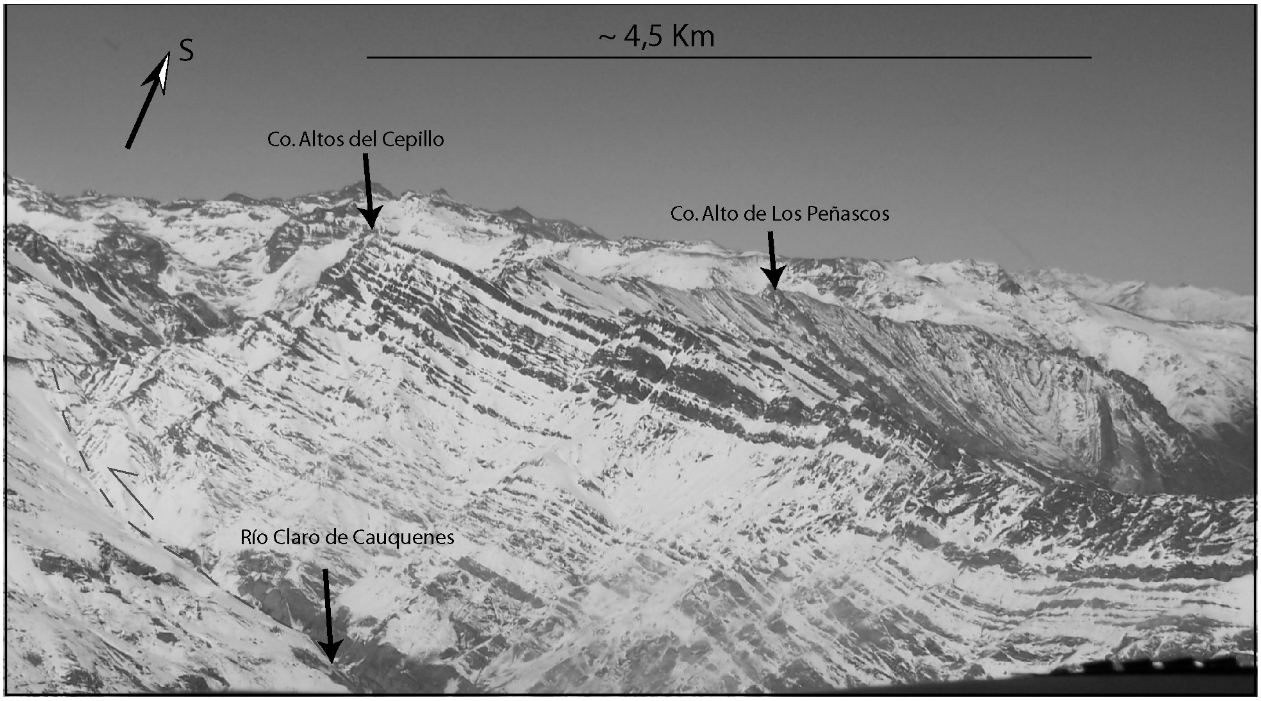

Figure 2. Features of the study region.

and an eastern (EF) fault. The width of the syncline decreases northward and disappears in the northern part of the study region. Here, because of the lower altitude it is possible to observe deeper portions of the studied structure, which consist only of an anticline that corresponds to the northward prolongation of the western "broken" anticline crest located west of the syncline.

Geometric reconstruction

We first considered the prolongation in depth of the surface structural data by the kink-band method (Fig. 3). The geometry obtained suggests that deformation occurred through fault-propagation folding. Therefore, and assuming that the faults that bound the Alto de los Peñascos syncline to the west (WF) and east (EF) are located along the crests of "broken" anticlines, the fault-propagation folding should have occurred with considerable displacement, transporting the anticlines along axial-plane faults in a similar way to the anticlinal breakthrough deformation mechanism (Suppe and Medwedeff, 1990) (Fig. 3).

Considering the dip of the layers on both sides of the western broken anticline, we obtained first the axial plane angle (γ in figure 3) of the anticline using the kink-method. This angle was considered to obtain the cut-off angle of the associated fault (θ in figure 3), following the graphs for fault propagation folding given by Suppe and Medwedeff (1990). In a similar way, we obtained the cut-off angle for the fault controlling the eastern broken anticline. Field observations and the results of the geometrical reconstruction indicate an eastward vergency for the faults (WF and EF) controlling the two broken anticlines. The dip of WF (θ' in figure 3) determined with the geometrical reconstruction is close to 60°W, whereas the dip of EF is close to 20°W.

The vertical propagation of WF diminishes northward and increases southward. To the north, along the prolongation of this fault, a well developed (not "broken") anticline is exposed. Here, the tip-line of the fault, determined by means of the kink-band reconstruction, is located at about 0-1 km beneath sea level (Fig. 3). To the south, because of the increase of deformation, the WF is exposed at the present day topographic surface. The resulting shortening is difficult to quantify because of the lack of key-horizons and because of the unknown total thickness involved in deformation or, alternatively, because of the unknown initial length of the deformed section. However, a minimum shortening of ~2 km next to Cerro Alto de Los Peñascos could be determined, which corresponds to ~20-30% of the initial length.

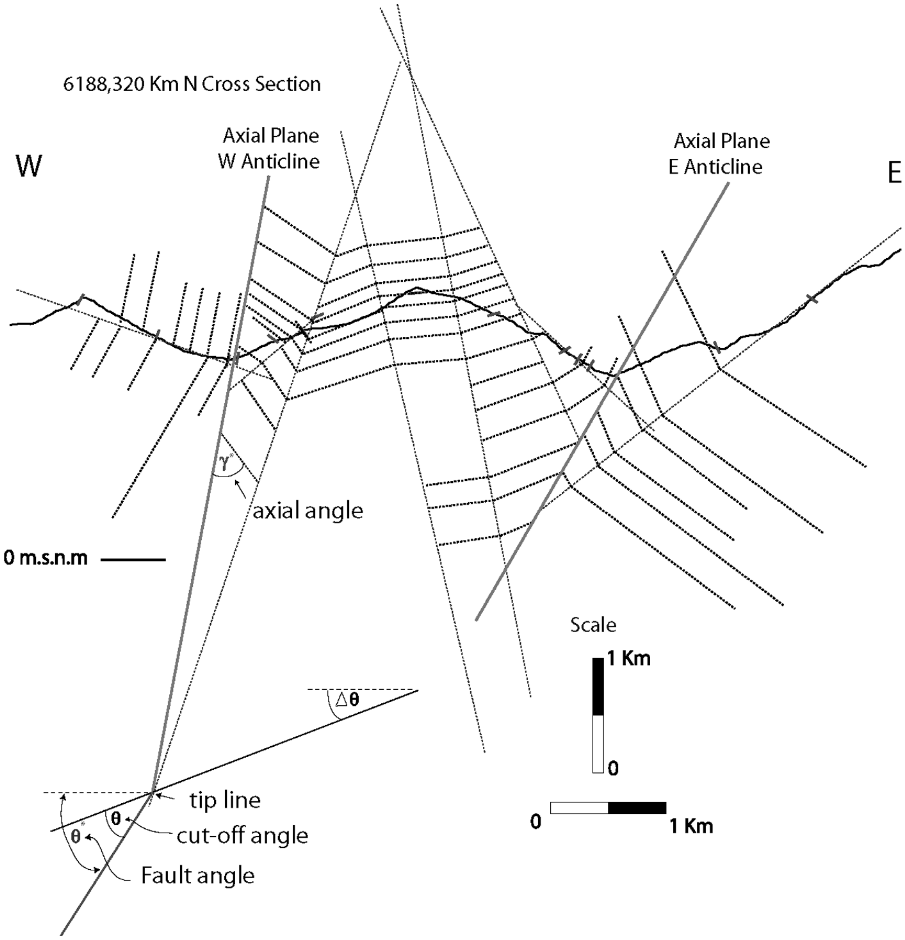

Figure 3. Geometric reconstruction of structure by kink-method and scheme of the fault angles calculated by the fault-propagation folding mechanism (θ′).

Trishear model

On the basis of the information obtained in the field and with the geometrical reconstruction (θ' angles of the faults), we constructed a trishear model (see Erslev, 1991; Hardy and Ford, 1997; Zehnder and Allmendinger, 2000) with the TRISHEAR 4.5.4 Program (Allmendinger, 1997-2003). In this model, we varied the propagation, the slip and the trishear angle in order to obtain the best-fit parameters explaining the deformation caused by the WF. In doing this, we considered some trishear program restrictions to generate the best approximation of the resulting deformation as, for example, we can not produce deformation by moving the two faults at the same time; therefore we first produced deformation along WF and then superimposed the deformation along EF. On the other hand, the method does not allow the faults to break through the axial planes of the anticlines; for this reason we could not reproduce the final geometry observed in the field (particularly the subvertical dips meausured in the axial plane zones).

After a comparative analysis of the models obtained by trishear modelling and the observed deformation, we consider that the best fit for WF was obtained with the model designed with a cut-off angle of 60º, a trishear angle of 30º, a slip of 150 pixels (1.5 km) and a P/S of 1. The deformation caused by EF on the previously obtained models was modelled with trishear angles of 30º, 45º and 60º, and with slips between 100 and 250 pixels (in intervals of 50 pixels), for a P/S of 0.5 and 1. Superimposing the deformation caused by EF, we ascertained that the geometry that best fitted the field observations corresponds to the model performed with: a trishear angle of 60º, a slip of 200 pixels (2 km) and a P/S of 0.5. Finally, we compared the geometries resulting from the geometric and the trishear reconstructions (Fig. 4). By doing this, we observed (considering the restrictions of the TRISHEAR program) that the field data match well with the trishear model and the dip of the axial planes determined with the geometric reconstruction (subvertical measured dips) fits very well with the location of the axial zones of the anticlines resulting from the trishear model. The total shortening of the deformed trishear section is 30% (~3 km), which is coherent

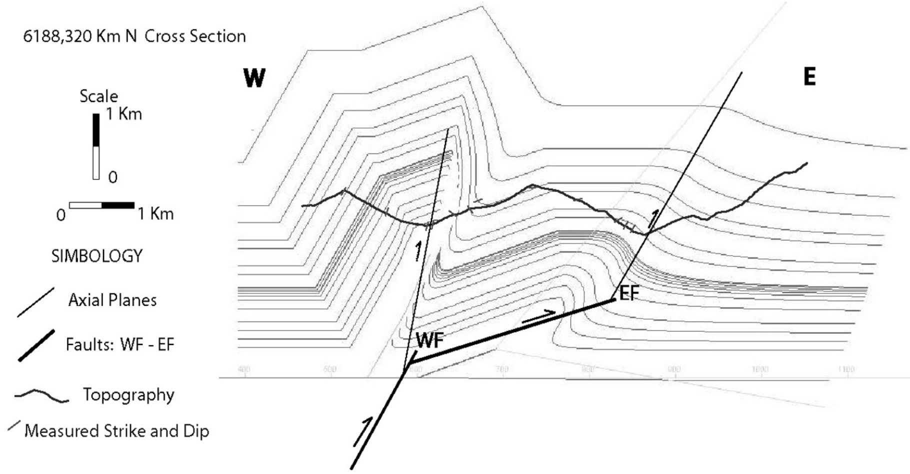

Figure 4. Trishear model result and geometric reconstruction (WF and EF).

with the shortening obtained with the geometric reconstruction.

Discussion and conclusions

The results of the geometric reconstruction and the trishear modelling suggest that folding in the study region would have been controlled, at least, by two E-vergent faults (a western, WF, and an eastern, EF). The most important one, the WF, has a high dip angle close to 60ºW. Deformation of the Cenozoic deposits in the western Principal Cordillera has been interpreted as having been caused by inversion of pre-existent normal faults that participated in the development of a Late Eocene to Oligocene extensional (Abanico) basin (Charrier *et al.*, 2002, 2005; Fock *et al.*, 2006; Farías, 2007). According to this and based on the high dip angle of WF, which is mechanically compatible with dips expected for inverted normal faults, we propose that WF would correspond to an inverted fault of the Abanico Basin. Based on the resulting geometric model, we interpret the EF (with a dip angle near 20ºW) as a neo-formed short-cut, which would have facilitated the shortening accommodation. The estimated shortening using these models is about 30% (2-3 km for the study region). Considering that the upper levels of the Farellones formation remain regionally undeformed, such shortening would have been accommodated during the basin inversion stage in Late Oligocene to Early Miocene times. Absolute age deter-

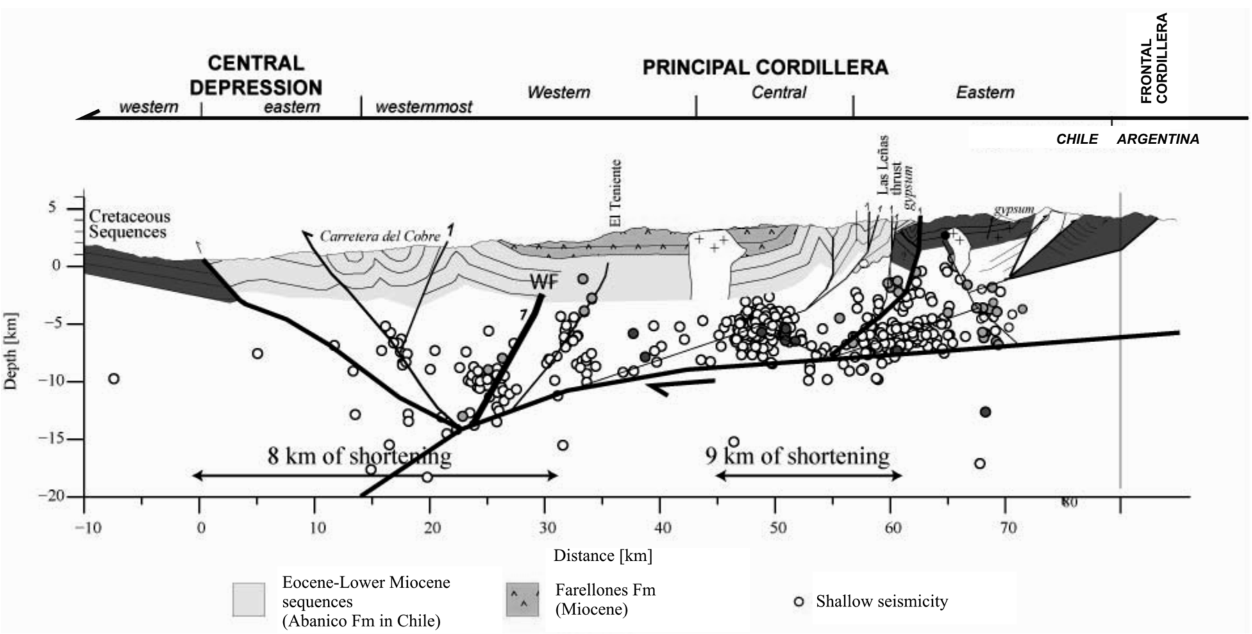

Figure 5. Structural cross section at 34ºS. Modified after Farías *et al.* (2008).

minations would be necessary to establish the exact age of deformation in this region.

In the northern part of the study region, the WF is replaced along strike by a broad anticline. Considering the regional extent of these structures, it can be assumed that the WF corresponds to a segment along a major tectonic feature along the western flank of the Principal Cordillera. Indeed, 30 km north of the study region on the prolongation of this structure, another (or the same) fault marks the western boundary of the Farellones formation (WF in figure 5). According to Farías (2007), this E-vergent fault has a deep origin rooted in a crustal-scale ramp-flat décollement located at a depth of near 15-20 km beneath the western side of the Principal Cordillera connecting the subduction zone with the tectonic front of the Andes in Argentine territory (Fig. 5). In this structural context, the WF would correspond to a pass-by thrust developed where the décollement passes from the ramp to the flat segment.

Finally, we wish to point out that the combined use of geometrical reconstructions and numerical models to analyse the deformation in fore arc volcanic deposits lacking key horizons represents a satisfactory approach to the kinematic interpretation of major structures.

Acknowledgements

This work was supported by FONDECYT Project N°1030965, and ANILLO Project ACT N° 18 (CONICYT's Bicentennial Program in Science and Technology).

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