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Inherited controls in Andean structure in a sector of the Malargüe fold-and-thrust belt, Mendoza province, Argentina

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Abstract: The thick-skinned Malargüe fold-and-thrust belt characterizes the Andes in southern Mendoza province, Argentina. This complex structure is the result of the combination of the Andean deformation and inherited fabrics of the substratum. A sector of this fold-and-thrust belt has been mapped in detail to evaluate the controls on the Andean deformation. These controls include the presence of basement pre-existing structures and the rheology of the deformed units, especially the occurrence of a thick gypsum horizon that worked as a boundary layer where the cover is detached, and locally produced important diapirism.

Keywords: fold-and-thrust belts, thick-skinned, rheology, fold interference, Andes.

The Malargüe fold-and-thrust belt has a mainly thick-skinned deformation which is widely exposed in the Main Andes of southern Mendoza province, between 34º S and 36º S. At the latitude of the study area (35º S), a western thick-skinned sector and an eastern thin-skinned sector can be recognized (Kozlowski *et al.*, 1993). The main uplift episode for the belt has been constrained between 15 and 7 Ma (Giambiagi *et al.*, 2005; Silvestro *et al.*, 2005).

The study area (Fig. 1) is located in the western thick-skinned sector of the Malargüe fold-and-thrust belt. This area shows a complex structure generated as a result of the interaction of pre-existing basement structures and the Andean deformation controlled by a thick evaporitic horizon located in a Mesozoic succession characterized by important differences in rheology.

Stratigraphy

The local succession comprises a Mesozoic predominantly sedimentary sequence, and Miocene intrusives and volcanic rocks. Pliocene to Quaternary volcanoes and Quaternary deposits related to fluvial, glacial and mass wasting processes complete the stratigraphic record.

The structural basement crops out to the east of the study area, in the Las Leñas area. It consists of the Permian to Triassic volcanic rocks of the Choiyoi group, emplaced in Late Paleozoic schists and quartzites (Nullo *et al.*, 2005).

Outcrops of the Mesozoic succession begin in the area with the Lower to Middle Jurassic Cuyo group, composed of marine limestones, shales, silicified sandstones, and interfingered volcanics. This unit is

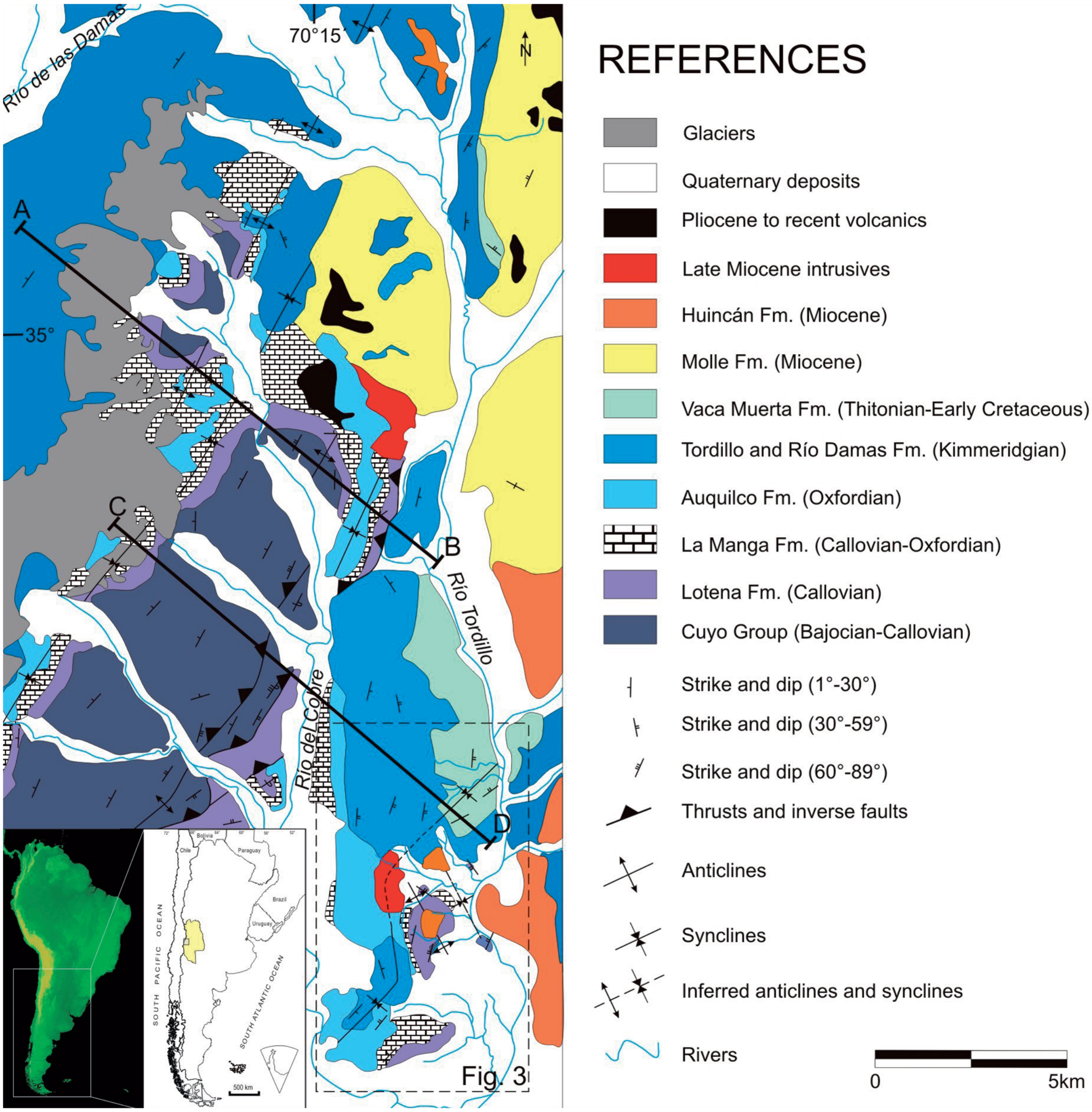

Figure 1. Geological map of the study area. A-B and C-D show the traces of the cross-sections in figure 2 and the box shows location of figure 3.

conformably covered by the Lotena formation, consisting of an upward-fining succession of red sandstones and shales. These units are covered by a fossiliferous succession of limestones, marls and sandstones of the La Manga formation. Ammonites and bivalves recovered from these three units indicate a Bajocian to an Oxfordian age (Gerth, 1931; Davidson and Vicente, 1972). Oxfordian deposits also include the overlying Auquilco formation, a thick evaporitic succession of gypsum and anhydrite. Kimmeridgian Tordillo and Río Damas formations consist of more than 1200 m of continental red sandstones, conglomerates and shales with interfingered ocoitic lavas (i.e. porphyritic basaltic andesites) and andesitic breccias. The contact of the Kimmeridgian units with the underlying rocks is hard to evaluate in the study area because of the ductile flow of the Auquilco gypsum, evidenced by the important thickness variations and the presence of internal deformation in this unit. On a regional scale, the contact is conformable. A few local exceptions have been reported where the contact is a low angle unconformity, which we attribute to a Kimmeridgian extensional episode (Mescua *et al.*, 2008). The record of the Mesozoic succession ends in the area with the Tithonian to Early Cretaceous

Vaca Muerta formation, formed by marine limestones, sandstones and thinly laminated shales bearing an abundant ammonite fauna.

Two partially overlapping episodes of Miocene magmatism have been recognized in the area (Nullo *et al.*, 2002). The Molle eruptive cycle took place between 19 and 13 Ma, and the Huincán eruptive cycle between 17 and 5 Ma.

Lava flows and ignimbrites of Pliocene to pre-glacial Quaternary age are found near the eastern and northern borders of the study area. Finally, Quaternary deposits are related to glacial, fluvial and mass wasting processes.

Description of the structures

The main structures of the study area, both folds and faults, present NNE trends, as observed in figure 1. The western sector comprises a broad anticline with a wavelength of 10 km. The folding is highly disharmonic, with the Tordillo and Río Damas formations forming a single anticline, whereas the Cuyo group and the Lotena, La Manga and Auquilco formations comprise a series of second order, large-scale asymmetric folds with eastern vergence, characterized by anticlines of 3 km wavelength and tight synclines of 1 km wavelength. In the frontal sector of the anticline an important fault zone is observed with NNE thrusts and reverse faults emplacing the rocks of the Cuyo group over the Lotena formation in the southern part of the study area, and the Lotena and La Manga formations overriding the Tordillo formation in the northern part (Fig. 2).

East of the Río del Cobre, folds show a particular form of type 2 interference pattern (Ramsay, 1967), defined as type 2a by Simón (2004). This pattern was generated by refolding of NNE trending folds with a NNW trend (Figs. 1 and 3). On the other hand, a salt stock was developed in this sector where the gypsum of the Auquilco formation has flown, presumably, into the core of an eroded anticline located in the present valley of the Río del Cobre (Figs. 3 and 4). A plutonic body has been intruded in the gypsum after the salt stock was formed.

Discussion

Influence of rheology

The variations in lithology of the Mesozoic units have exerted a major control in Andean deformation in the study area. Contrasting behavior of rocks during compression is reflected in different folding styles.

A lower mechanical layer with low competence is defined by the Cuyo group and the Lotena and La Manga formations, given their predominant thin-bedded limestone and shale composition. These units have been tightly folded in kilometer scale folds (Fig. 2).

An upper mechanical layer with high competence is defined by the Tordillo, Río Damas and Vaca Muerta formations. The lithological composition of this layer consists mostly of sandstones and volcanics, and its deformation produced folds of tens of kilometers of wavelength.

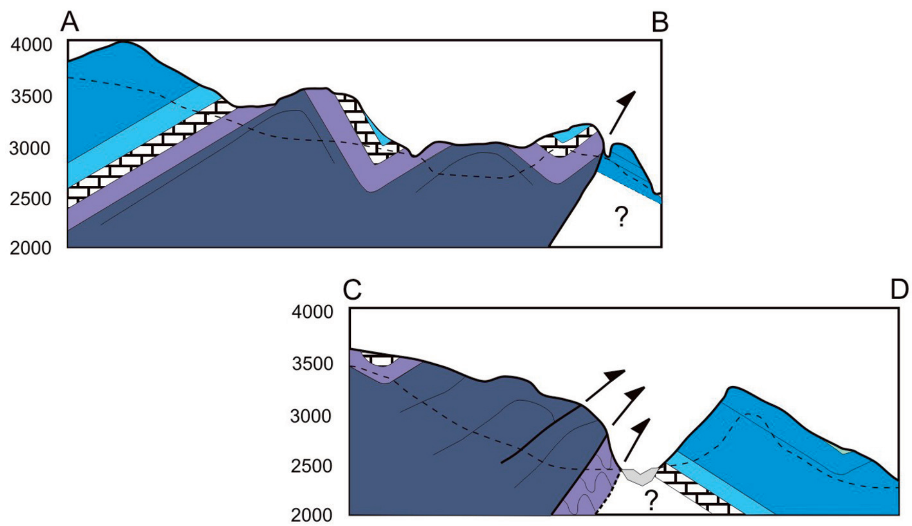

Figure 2. Schematic cross-sections A-B and C-D (see location in figure 1). Unit colors as in figure 1; height in meters, no vertical exaggeration. The discontinuous line shows the approximate exposure level. "Folds" in the Lotena formation in section C-D represent a high strain zone affecting rocks of this unit located between two faults (not actual folds).

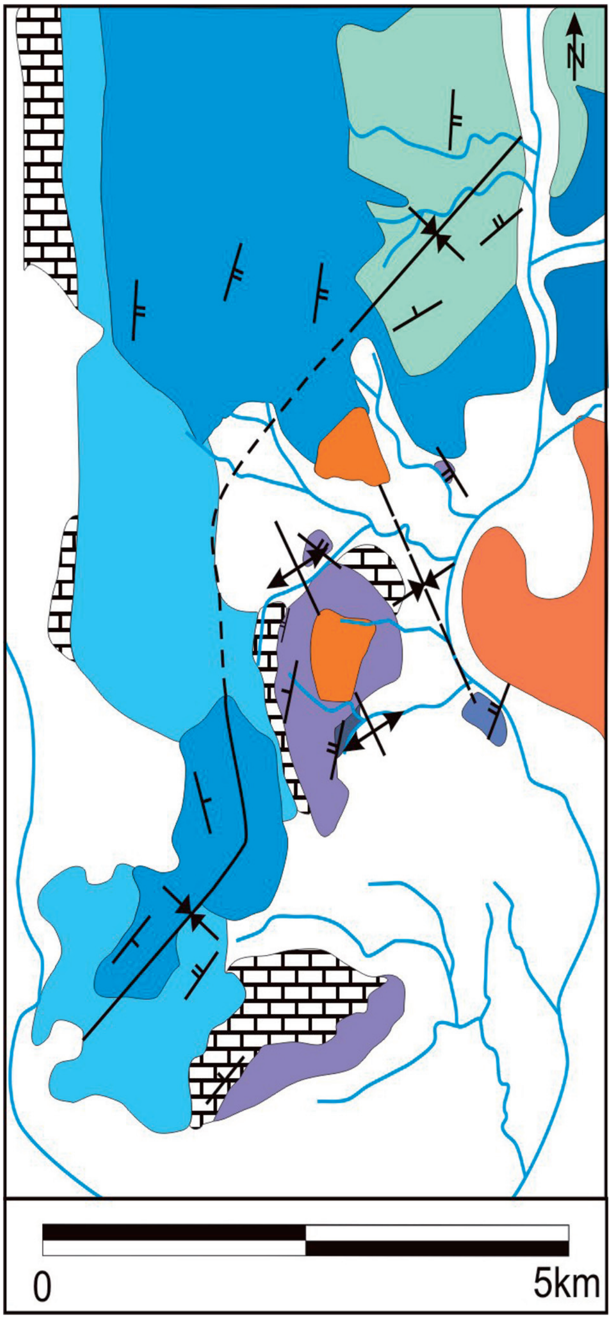

Figure 3. Fold interference pattern type 2a in the southwestern sector of the study area. References as in figure 1. Notice the undulation in the axial trace of the NNE fold caused by the interference of the NNW fold system. The anomalously high thickness of the Auquilco formation corresponds to a salt stock (see figure 4).

These two mechanical layers were decoupled by the gypsum of the Auquilco formation, interbedded between them. Due to its ductile behavior, this unit acted as a detachment and favored the different response given by each mechanical layer by flowing into the empty spaces created by the different folding styles.

Influence of pre-existing structures

The main structures in the area show a consistent NNE trend. This orientation is the dominant trend throughout this sector of the Malargüe fold-and-thrust belt. Its origin (Andean vs. reactivated) is not yet clear; it could be related to the pre-existing fabric in the Paleozoic basement, which varies from N-S to NE as observed in the Cordillera Frontal (Sellés Martínez, 1999), the San Rafael block (Criado Roque and Ibáñez, 1979) and Precordillera (Giambiagi *et al.*, 2008). Alternatively, it could be the result of the local Andean shortening direction or of the rotation of originally N-S Andean structures. Further studies are needed to solve this question.

In the eastern sector of the study area, pre-existing structures and fabrics in the structural basement seem to have played a significant role. We interpret the interference of the NNE structural trend with NNW trending structures as a control inherited from the Permian San Rafael orogeny and the Triassic and Jurassic extensional event, given the orientation of these pre-Cenozoic structures (Japas and Kleiman, 2004; Bechis and Giambiagi, 2009).

Fold interference

The eastern sector of the study area is characterized by a type 2 fold interference pattern (Fig. 3). In type 2 interference, both the hinge lines and the axial planes of the first folding episode are folded in the second episode (Ramsay, 1967, Thiessen and Means, 1980). In our case study, the axial trace of a NNE-trending syncline shows an undulation produced by the superposition of NNW-trending folds. Although the intense glacial and fluvial erosion suffered by the study area prevents the identification of all the fold interference characteristics, the observed pattern can be classified as the type 2a defined by Simón (2004). This is indicated by the conical F_2 folds, with triangular map shapes. According to many authors (e.g. Grujic, 1993; Simón, 2004), when the angle between interfering fold systems is small, the main controlling factor for the generation of type 2 (vs. type 1) interference patterns is an interlimb angle <90° for F_1. In our case study the F_1 interlimb angle ranges between 40° and 70°. Additionally, type 2 interference is favored by a high viscosity contrast between beds (Johns and Mosher, 1996; Simón, 2004), also observed in our study area as stated in a previous section.

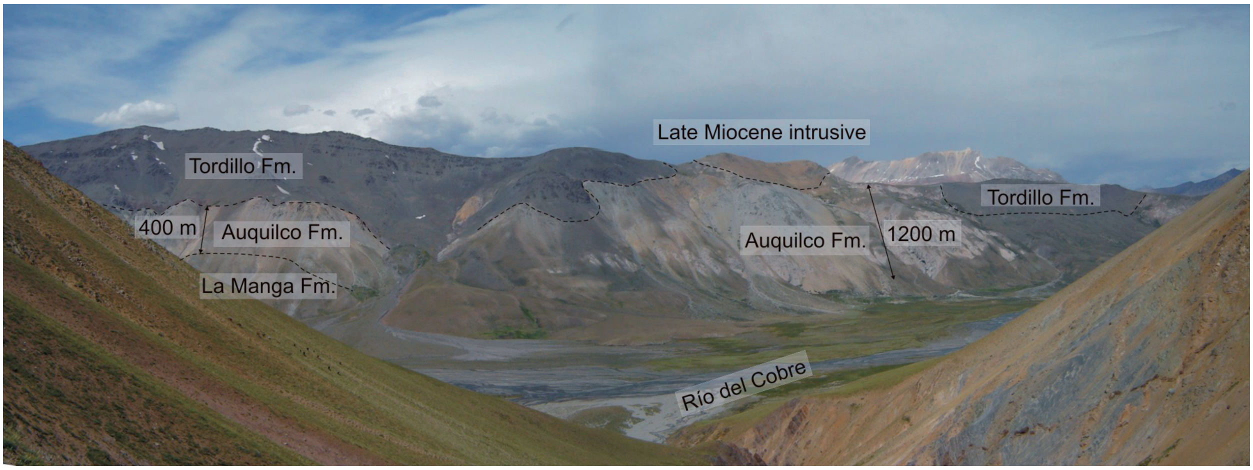

Figure 4. Salt stock in the eastern margin of Río del Cobre. View to the east.

We propose that the second generation of folding is the result of the transport of F_1 folds over a basement structure and consequent buttressing against the rigid block, based on its orientation (f_2 = 348º, 23º) which coincides with the NNW trend of Permian and Mesozoic structures, and the existence of a Mesozoic basement high (e.g. "dorsal del Río Tordillo" of Davidson and Vicente, 1972) and of present basement thrust sheets immediately to the east of the study area. This would explain why the fold interference is only found locally and is absent in the western sector of the study area.

Salt tectonics

The existence of a thick horizon of gypsum within the Mesozoic succession, the Auquilco formation, has been recognized as a major control in Andean deformation throughout the orogen, acting as a detachment level for thrusts (Kozlowski *et al.*, 1993). Locally, diapiric structures have also been described (Cegarra y Ramos, 1996; Cristallini, 1996). In the study area, this horizon has acted as a detachment between the two contrasting fold styles below and above it; and in the eastern sector it has also formed a salt stock intruding the overlying rocks (Figs. 3 and 4). The original thickness of the Auquilco formation in the area is estimated at 400 m; whereas in the salt stock, where the base of this unit is covered, up to 1200 m of gypsum have been observed.

Concluding remarks

The complex structure of the study area shows the influence of the previous geological history in the Andean orogeny. This influence is not only given by reactivation of inherited structures but also as a result of the variations in the lithological characteristics of the Mesozoic units which were deformed during the formation of the Andes. These variations have resulted in different behaviors when the rocks underwent deformation, given their different rheological characteristics. Moreover, the existence of a thick horizon of gypsum within the Mesozoic succession has acted as a detachment layer and locally produced salt tectonics processes.

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