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Kinematic analysis of small-scale faults and its application to the study of an extensional depocentre, Neuquén basin, west-central Argentina

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Abstract: In this contribution we present a case study where valuable structural information on the extensional architecture of the Atuel depocentre (Neuquén basin) is obtained from kinematic analysis of small-scale normal faulting. The area was subsequently inverted during the Andean uplift, concealing most of the previous rift episode. We integrated the results of the kinematic analysis of minor faults with data from inferred major normal faults. We found a wide dispersion of the results obtained by the inversion method of fault-slip data, suggesting that the observed fault patterns reflect local deformations instead of responding to the regional stress field.

Keywords: rift basin, Andes, fault-slip data, transtension, oblique rifting, reactivation.

The kinematic study of small-scale faults can be crucial for the recognition of previous tectonic events in areas that have undergone several deformation stages. Major faults related to previous deformation are often reactivated or covered during subsequent tectonics, making difficult their recognition and study. On the other hand, small-scale faults often escape subsequent reactivation and are generally abundant and well exposed (Schlische *et al.*, 1996; Homberg *et al.*, 2002). Moreover, strain or stress inversion methods carried out with slip data from small-scale faults can give important information about the kinematics and/or dynamics of previous tectonic stages (Carey and Brunier, 1974; Angelier, 1984; Marrett and Allmendinger, 1990).

In this contribution we present a case study from which we obtained valuable structural information from small-scale faulting for a previous tectonic event. Our study area is located in the northern sector of the Neuquén basin (Fig. 1A), one of the most important oil and gas bearing basins of southern South America. We focused our research on the Atuel depocentre, which Late Triassic to Early Jurassic sedimentary infill records the first stages of the Neuquén rift basin opening. In Neogene times, the Andean orogeny deformed and uplifted the Atuel depocentre infill, which is now very well exposed in the Malargüe fold and thrust belt (Fig. 1A). We focused our analysis on the kinematic evolution of the sub-basin, integrating the small-scale slip-analysis with timing and orientation of inferred major normal faults.

Methodology

In order to recognize the main normal faults that were active during the Mesozoic rifting, we carried out a detailed mapping of the Cenozoic compressive structures, based on our field observations and subsurface data (Fig. 1B). We integrated our structural analysis with previous sedimentological and stratigraphic studies (Lanés, 2005, 2007), constraining the location, orientation and timing of the main normal faults (Fig. 1C).

We identified in the field more than 300 small-scale normal faults with displacements ranging from a few centimetres to several meters, widely distributed in a number of localities within the study area (Fig. 1C). We measured values of strike, dip, and amount and sense of displacement (from kinematic indicators). We dated the strata

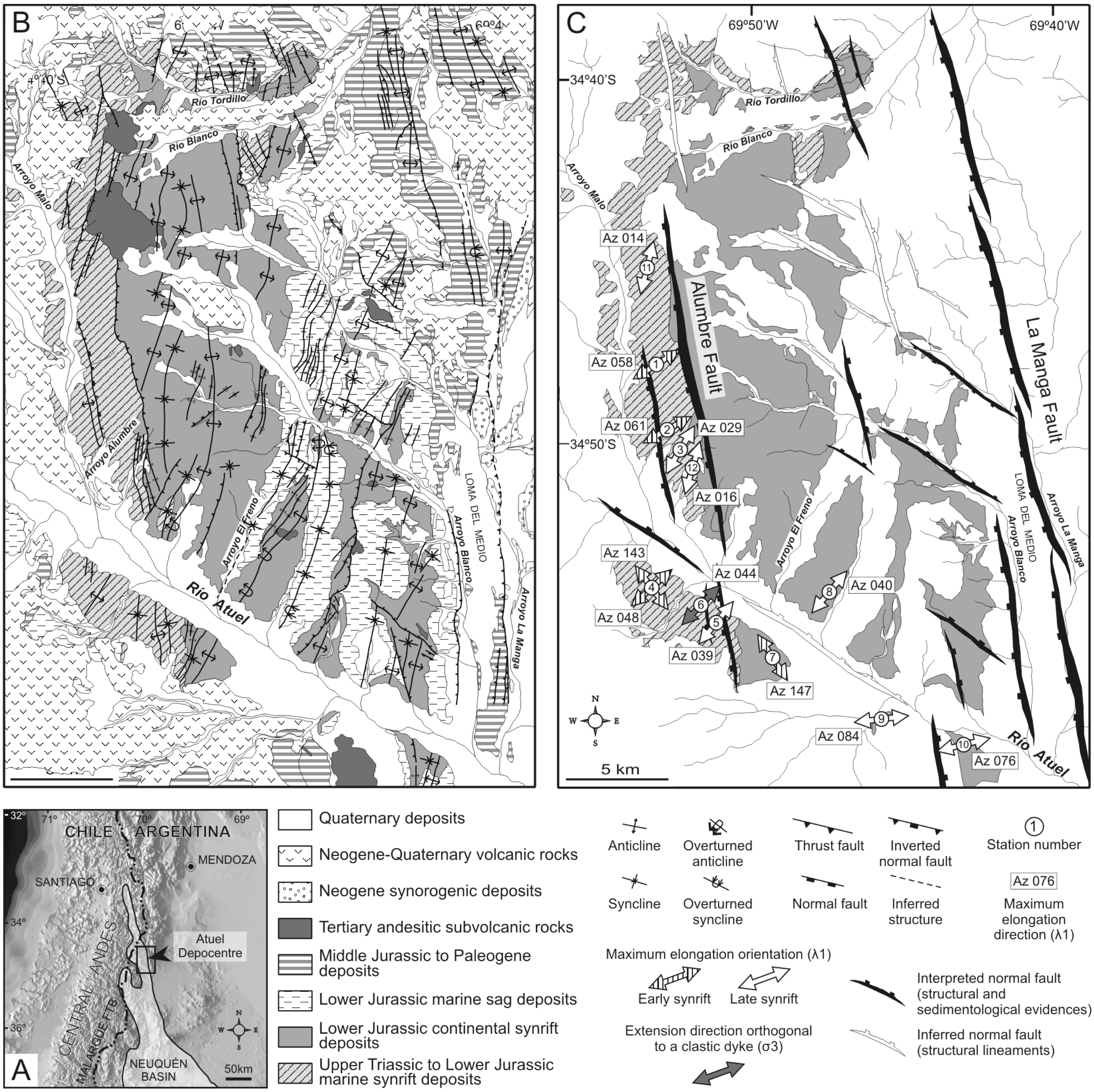

Figure 1. A) Location map (FTB: fold and thrust belt), B) geologic map of the study area, modified from Giambiagi *et al.* (2008), C) extensional architecture of the Atuel depocentre during the Late Triassic to Early Jurassic rifting, modified from Giambiagi *et al.* (2005). Stations where the small-scale faults with kinematics indicators were observed are shown together with a double arrow indicating the major axe (λ1) of the obtained strain ellipsoid in each case (in all cases λ3 is nearly vertical).

where the normal faulting was observed following the biostratigraphic scheme of Riccardi *et al.* (1991). After restoring the data to their original position (pre-Andean folding) we processed the fault-slip data using the R.W. Allmendinger's FaultKinWin program in order to obtain the orientation of the main axes of the strain ellipsoid (λ1, λ2 and λ3) for each location. We used the method based on Bingham distribution statistics (Marrett and Allmendinger, 1990), comparing the obtained values and evaluating possible regional, local and temporal changes. Finally, we integrated the results of small-scale fault-slip analysis with timing and orientation of the previously identified major normal faults.

Results

The extensional structure of the Atuel depocentre is characterized by the presence of the NNW-trending La Manga and Alumbre major faults, evidenced by the distribution of the synrift deposits in outcrops and from subsurface data (Fig. 1C, Giambiagi *et al.*, 2005, 2008). These faults limited two major half-grabens, controlling the main subsidence of the basin and the distribution of sedimentary environments during the synrift phase (Fig. 1C). Inside the half-grabens, we interpreted a bimodal distribution of normal faults with NNW and WNW trends (Fig. 1C).

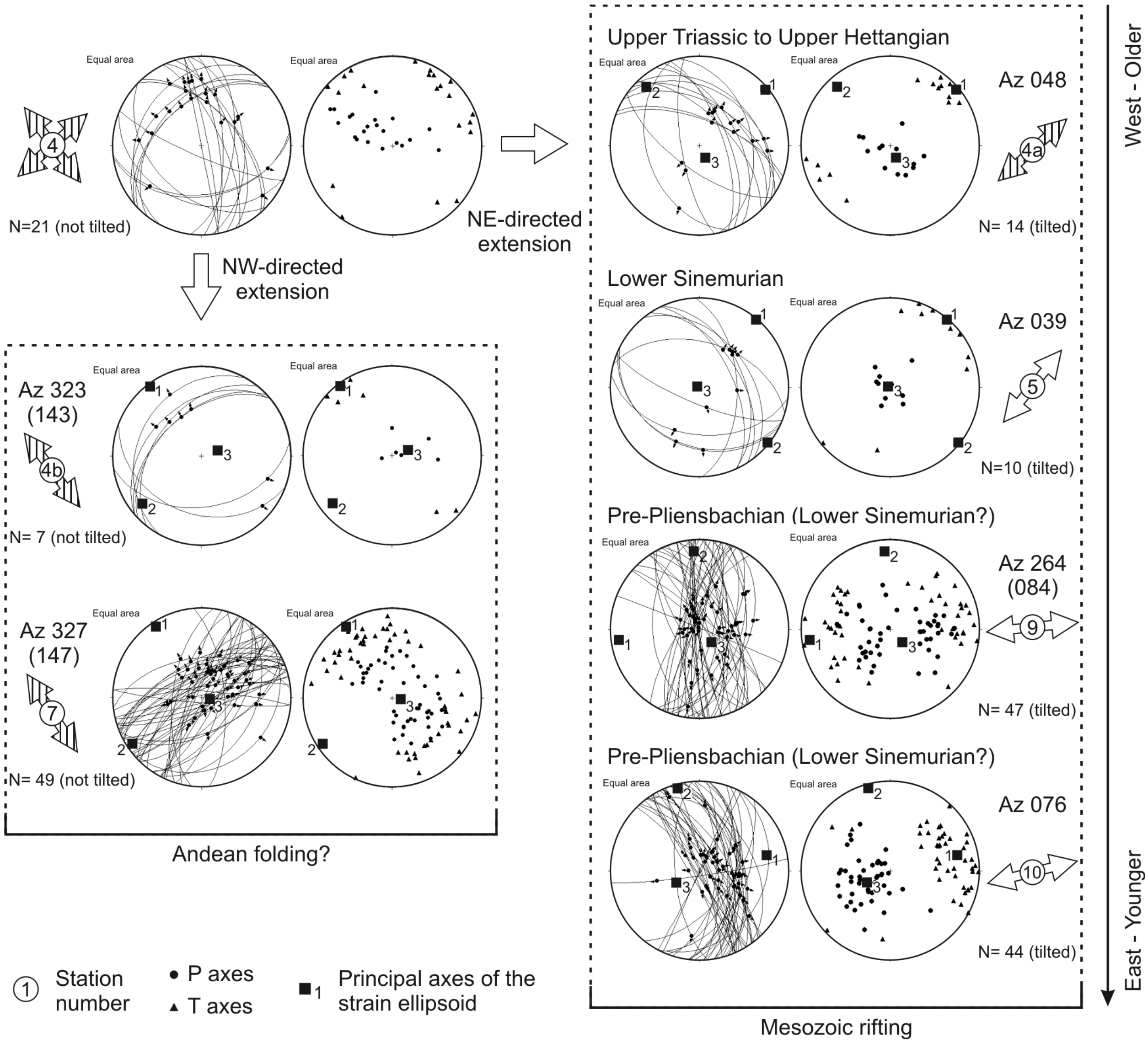

Figure 2. Kinematic data from small-scale faults observed in the southern sector of the Atuel depocentre. Note the bimodal orientation of the T-axes in station 4, with two groups aligned in the NE-SW and NW-SE directions, respectively. As is explained in the text, the NW-SE extension direction was interpreted as related to NE normal faulting during Andean folding.

During the Andean deformation, some of these faults were reactivated as inverse or accommodation faults, while in other cases they had a passive role evidenced by the bending of compressive structures.

We found a wide range of orientations for the small-scale normal faults, ranging from WNW to NE (Figs. 2 and 3). In all cases the intermediate and major axes of the strain ellipsoid (λ2 and λ1) show a nearly horizontal position after the strain inversion, indicating an extensional tectonic regime. WNW- to NNE-trending faults show a dispersion of the maximum elongation directions (λ1) from NNE to ENE directions, with a NE mean value of Az 055º (Figs. 2 and 3). On the other hand, in two localities we measured NE-oriented normal faults that indicate a NW-directed extension (Fig. 2). As these stations are located near the hinge of two major NE-trending Andean anticlines (Fig. 1), we interpret these structures as faults possibly related to bending of strata during Cenozoic compressional folding.

The obliquity between the main NNW rift trend, marked by the orientation of the La Manga and Alumbre major normal faults, and the calculated mean elongation direction (Az 055º) suggests that the Atuel depocentre acted as an oblique rift. The orientation of the principal faults is similar to the orientation of Permian-Triassic shear zones (Japas and Kleiman, 2004), indicating that they could have formed as the result of normal or oblique-normal slip reactivation of previous discrete structures. These reactivated structures localized great part of the strain during the rifting stage. We estimated a regional extension oriented in a NNE direction, with possible refraction of the elongation to a NE direction inside the rifted area respect to the regional motion (Teyssier *et al.*, 1995).

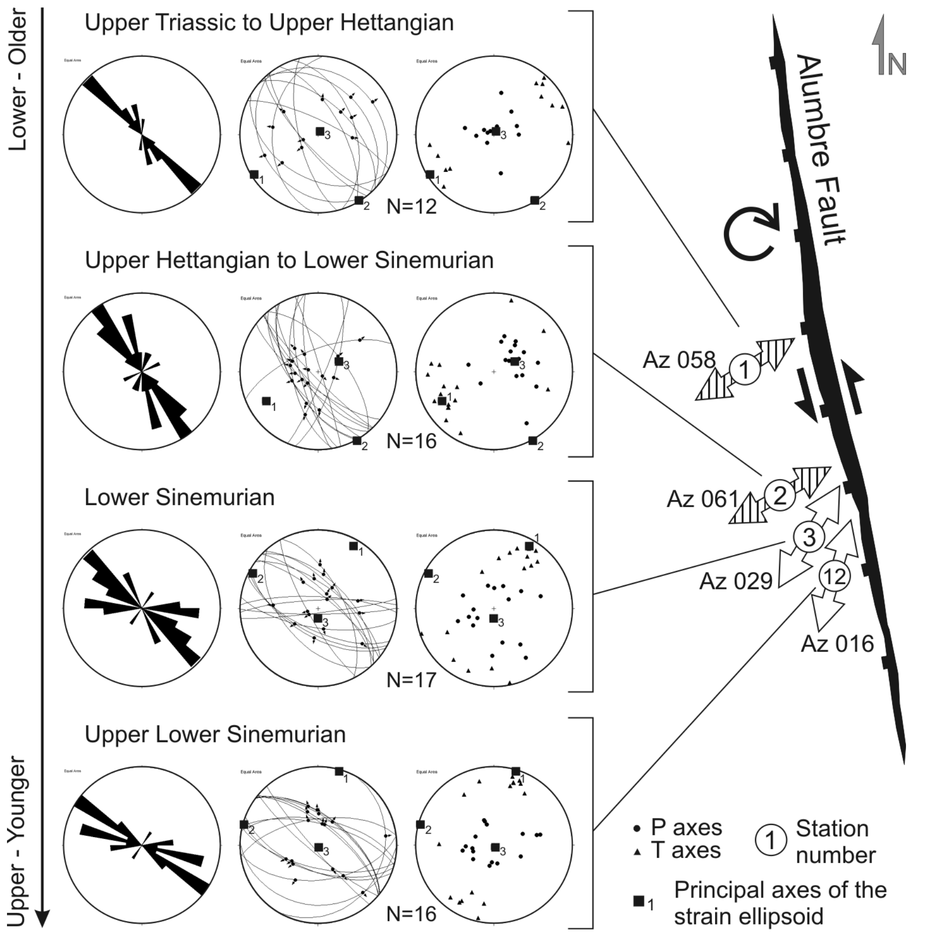

Figure 3. Kinematic data from small-scale faults observed in the western sector, in the hanging-wall of the Alumbre fault.

Close to the Alumbre fault we observed a variation of the elongation direction (λ1) from ENE to NNE, from older to younger deposits, respectively (Fig. 3). We evaluated a possible change in the regional extension direction form ENE to NNE during the opening of the depocentre, but we discarded it because in the eastern sector we calculated an ENE elongation direction affecting the late synrift deposits (Figs. 1C and 2). An angular unconformity present between stations 2 and 3 near the Alumbre fault suggests that the extension direction had a NNE to NE orientation, and that local clockwise rotation could have occurred in the hanging-wall of the fault. This constitutes an independent evidence for our proposal of an oblique left-lateral movement for the Alumbre fault, as a reactivated discrete structure under NNE to NE extension.

On the other hand, we observed a spatial variation from NE extension directions in the western sector of the Atuel depocentre, to ENE directions in the south-eastern sector (Fig. 2). One possible explanation for this variation is to infer a local perturbation of the stress field near the La Manga major fault. Other possibility is to attribute these changes to strain variations related to the oblique stretching of the rift basin. Normal faulting sub-parallel to the rift is likely to occur near its borders, and faults sub-orthogonal to the regional extension direction are generally more common towards the centre of the extended area, as was observed in analogue models of oblique rifting (McClay and White, 1995). If this is the case the La Manga fault probably had a predominantly normal slip, at least during the late synrift, in contrast with the oblique slip inferred for the Alumbre fault.

Discussion

Major faults are formed by finite or accumulative strain, and they can be the result of reactivation of previous anisotropies or can undergo a progressive syntectonic rotation along their activity history. They usually control the location of rift basins and their main depocentres, being one of the main factors that affect the distribution of depositional environments. On the other hand, small-scale normal faults could be considered as representing instantaneous strain. As was previously noted (Homberg *et al.*, 2002) and as we showed here, they can be very useful in areas that underwent subsequent deformation episodes, where major faults have been reactivated or obscured by newly formed structures.

An important matter of discussion is the question whether to consider fault slip data in terms of kinematic (strain) or dynamic (stress) terms (Marrett and Allmendinger, 1990; Twiss and Unruh, 1998). Are the small-scale normal faults of our case study (the Atuel depocentre) reflecting accommodation of strain in the hanging-wall of major faults or are they reflecting local perturbations of the stress field? We postulate that it is difficult to infer the regional stress field from our data because they show a wide dispersion of the results obtained by the inversion method. The heterogeneity of our results seems to favour the hypothesis that the fault patterns are reflecting local deformations instead of responding to the regional stress field, in agreement with the proposal presented by Gapais *et al.* (2000).

Conclusions

In this contribution we presented an integrated multi-scale faulting analysis for the study of an extensional basin, the Atuel depocentre of the Neuquén basin. This sub-basin has a main NNW orientation controlled by two major normal faults, La Manga and Alumbre. We interpreted them as reactivated discrete structures with normal and oblique normal-sinistral movement, respectively. We carried out a detailed kinematic analysis of the small-scale faulting data, obtaining NNE to ENE elongation directions for the synrift stage. The obliquity between the main rift trend and the calculated elongation directions from the fault-slip analysis suggests that the Atuel depocentre acted as an oblique rift. We conclude that slip-data obtained from small faults inside the studied oblique rift are best interpreted in terms of strain than stress.

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