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The Santopétar flat-ramp-flat normal fault (Huércal-Overa Basin, SE Betic Cordillera)

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Abstract: The geometries of the normal faults developed in the Huércal-Overa Basin are clearly linked with the rheology of the deformed sediments. While the conjugate normal faults that deform thick homogeneous conglomerate and calcarenite beds commonly show planar surfaces with a 50-60º dip, the normal faults that deform multilayered sediments frequently have flat and ramp geometries. We have studied in detail the flat-ramp-flat Santopétar fault. A new evolution model is proposed to explain their development linked to successive phases of faulting accommodated by consecutive flat-ramp-flat faults with opposite senses of movement. A fault-bend fold fits the geometry of a S-dipping ramp during a first phase of 23 m top-to-the NE extension. Later, a top-to-the SW 20 m slip over a contractive flat fault partially reactivates the previous fault surface. However, it is necessary to consider new models that explain the deformation of the Santopetar structure during a single extensional phase.

Keywords: neotectonic, extensional fault-related folds, strain distribution, shallow deformation.

Normal faults generally initiate with dip angles of 50-60°. However, in subhorizontal multilayer successions where the beds show high contrasts in mechanical behavior, the dip of the fault surfaces decreases and becomes parallel to low dipping layers (e.g. Peacock and Sanderson, 1992 and references therein). The Huércal-Overa Basin, located in the Eastern Betic Cordillera (Fig. 1), offers the opportunity to study in detail field examples of small-scale normal faults developed in multilayer sequences with high rheology contrast between the sedimentary beds.

The aim of this contribution is to analyze the geometry of the small-scale flat-ramp-flat Santopétar normal fault in order to determine its evolution, quantify the extension accommodated along the structure and finally discuss the role of the rheology during the normal fault and related roll-over development.

The selected normal faults are located in the Huércal-Overa Basin, mainly filled by Upper Miocene sediments (Fig. 1). The stratigraphical sequence starts with a thick continental red conglomerate formation, which lies unconformably on the basement. These continental deposits are gradually in upwards transition into a sequence where alternate beds of conglomerates, sands, grey silts, and gypsum (Turbidites micacées et gypseuses unit of Briend, 1981; the TSU2b of Guerra-Merchán, 1992; the Santopétar formation of Mora, 1993, and Augier, 2004; and the “turbidites micacees et gyseuses” of Meijninger, 2006). The succession of brittle and ductile levels has determined the fault pattern

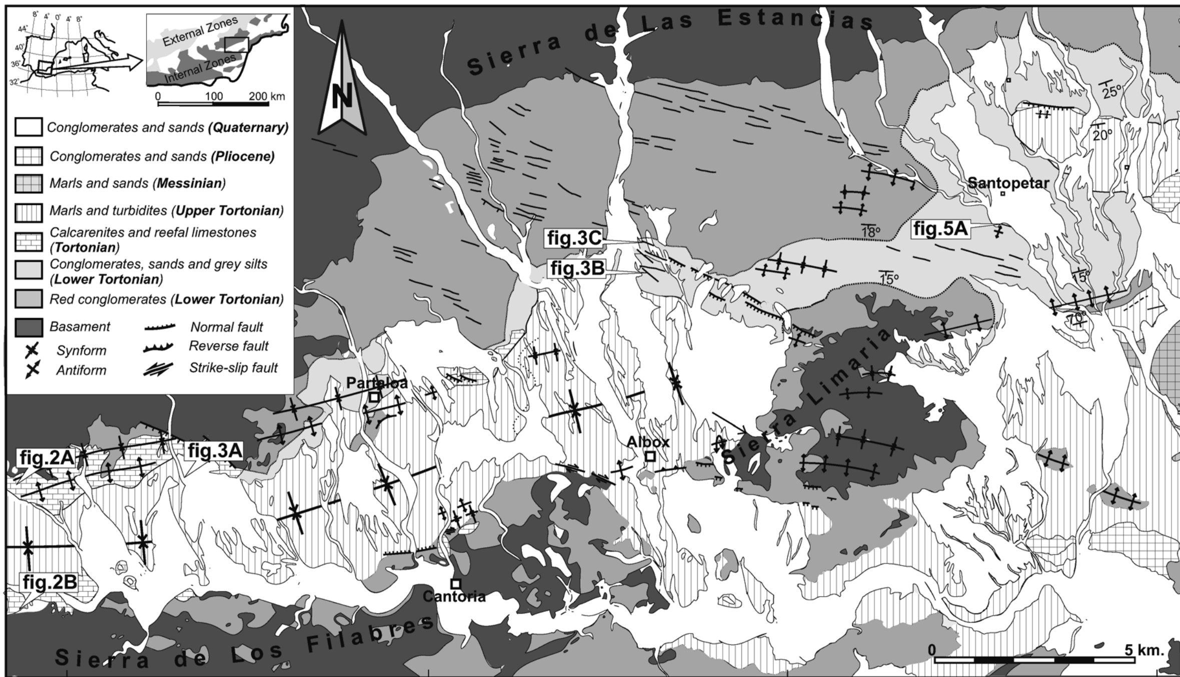

Figure 1. Geological map of the northwestern Huércal-Overa Basin where the location of the main faults and folds is indicated. The position of the outcrops of figures 2, 3 and 5 is indicated.

and the most spectacular flat-ramp-flat examples are located in this unit. At the top, there is an angular unconformity and Late Tortonian bioclastic reefal limestones are gradually in transition to yellow marls toward the center of the basin. Messinian marls crop out only in the easternmost part of the basin. During the Plio-Quaternary, detrital sediments, belonging to the alluvial fan and to the river deposits, were unconformably placed over the Miocene rocks.

The normal faults that deform the Huércal-Overa Basin

The Upper Miocene sediments that infill the Huércal-Overa Basin are quite deformed by several fault sets (Fig. 1). The most prolific group is formed by WNW-ESE to NW-SE normal faults that show a widespread distribution in the basin (Mora, 1993; Augier, 2004; Meijninger, 2006; Pedrera *et al.*, 2010) and in the whole Betic Cordillera (e.g. Sanz de Galdeano, 1983; Galindo-Zaldívar *et al.*, 1993), showing evidence of activity in different periods. The faults observed in the study area comprise different geometries that are clearly linked with the rheology of the deformed sediments.

Planar normal faults

The normal faults that deform the Early Tortonian continental red conglomerate formation and the thick

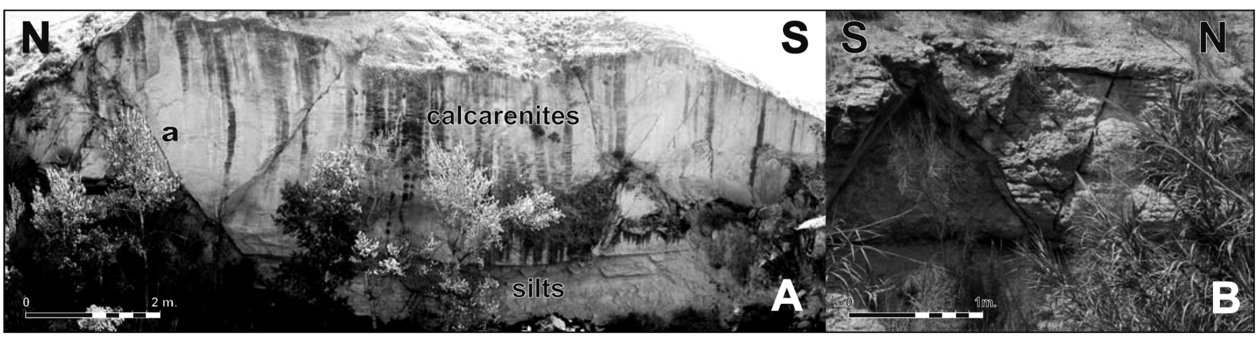

Figure 2. Field examples of planar normal faults. a) Conjugated N120-125ºE oriented and 50º dipping normal fault that deforms a homogeneous thick layer of Tortonian calcarenites. Note the decrease in the dip of the fault a when it approaches the lower silts layers, b) example of NW-SE conjugated normal faults with 60º dihedral angle that deform Tortonian calcarenites. Position indicated in figure 1.

beds of Late Tortonian bioclastic reefal limestones commonly have planar surfaces. These faults have small normal slip, between few centimetres and few meters (Fig. 2). The presence of conjugated faults with dihedral angle of 50º to 60º is very common (Fig. 2).

The kinematic analysis of these faults (Pedrera *et al.*, 2007, 2010) generally shows a dip-slip component that is related with a NE-SW extension, sometimes in transition to a radial extension. However, some fault surfaces show other striae, sometimes superposed, that reveal a local NW-SE shortening.

Flat and ramp normal faults

Studied examples of flat and ramp normal faults are developed in multilayered sedimentary sequences. Close to the fault ramps, the sedimentary layers are folded forming roll-overs, both in hanging wall (Fig. 3a) and also affecting locally the footwall (Fig. 3b). Soft silt layers concentrate the deformation constituting detachment levels parallel to bedding (Fig. 3c).

The Santopétar Fault is a remarkable example of roll-over associated to a flat-ramp-flat normal fault (Figs. 1 and 4). Briend (1981) was the first to describe the structure as an example of "extensional syn-sedimentary deformation" related to non-fully lithified sediments deformed by the load of overlying sediments. Jabaloy *et al.* (1993) and Mora (1993) re-interpreted the structure as a result of the deformation of both the footwall and the hanging wall along a major normal fault system composed by a flat and several high dipping ramps cutting through the beds. Late, Augier (2004) performed a kinematic analysis of their secondary normal faults pointing out a NNE-SSW extension direction and again described a "major slip zone" with a flat-ramp-flat geometry which is constituted by 2 to 20 cm thick brittle fault gauge. Most recently, Meijninger (2006) recognized several hiatuses in the hanging wall that again support a syn-sedimentary development. Nevertheless, there is not a satisfactory explanation of the structure that justify the observed fault kinematics and the presence of associated folds in the hanging wall and the footwall.

The Santopétar structure

The Santopétar cross-section is the best exposed outcrop of flat-ramp-flat normal fault parallel to the extension direction with related folds. In the hanging wall, a N110-120º trending gentle antiform is developed showing an interlimb angle of ~160º, an axial surface dipping ~85º to the north, and 7 m of minimum vertical throw. In the footwall, there is a gentle synfom, approximately symmetrical to the hanging wall antiform. The folds show a mixed flexural slip/flexural flow behavior. While flexural slip accommodates the deformation along discrete surfaces parallel to the beds, flexural flow produced

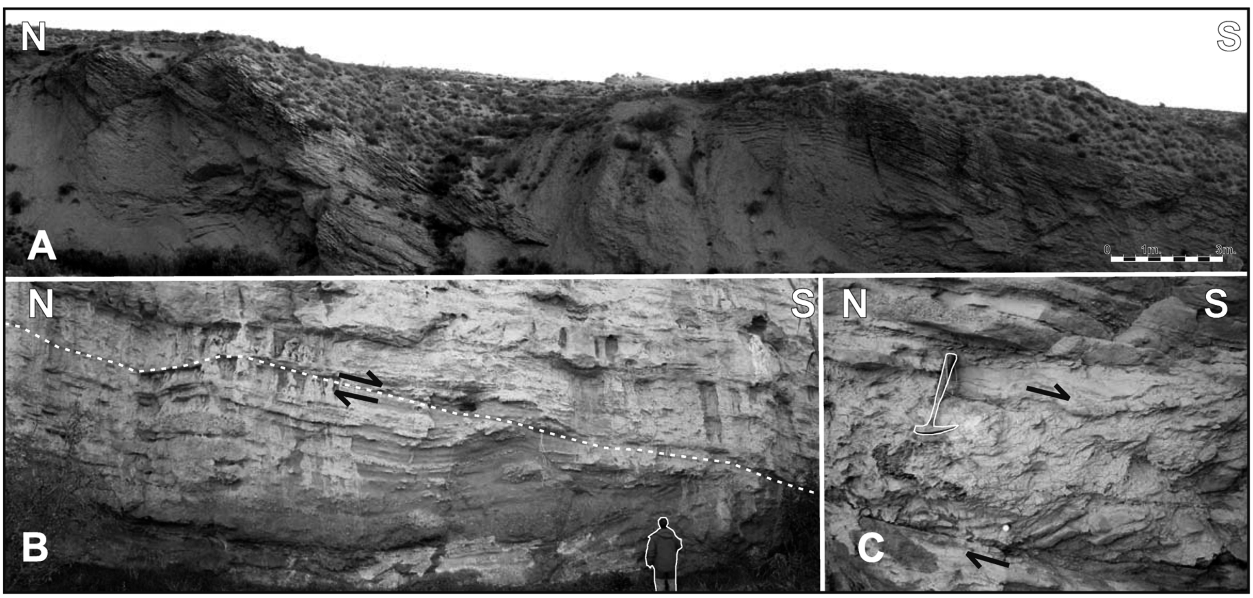

Figure 3. Field examples of normal faults with flat-ramp geometries. a) Example of a WNW-ESE normal fault that deforms multilayer calcarenites with associated roll-over in the hanging-wall, b) detachment parallel to the beds with an associated roll-over in the footwall developed in the succession of conglomerates, sands and grey silts layers, c) detail of fault rock from a detachment nucleated parallel to a bed of silts. Position indicated in figure 1.

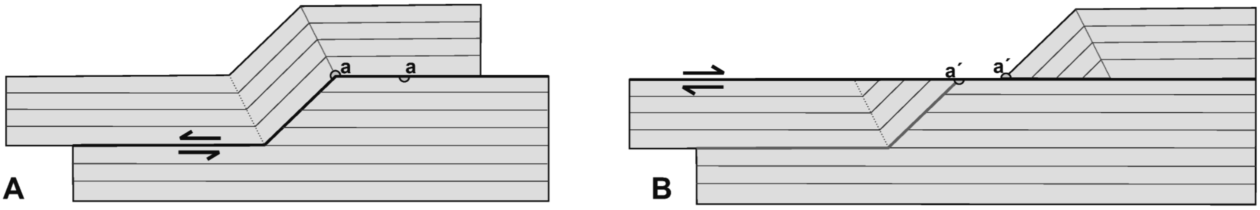

Figure 4. Sketch showing the proposed evolutionary folding model, in the hanging wall and the footwall, associated with faults with flat-ramp-flat geometry.

parallel shear by distributed layer-parallel flow. Therefore, it has been retro-deformed considering shear parallel to the beds. Both folds are separated by a top-to-the southwest flat fault zone developed over a highly micaceous silt layer. Both folds are deformed by ENE-WSW secondary normal faults that accommodate SW-directed extension.

Evolution models and cross-section restoration

The Santopétar structure is interpreted to be developed during faulting along a flat-ramp-flat fault surface. Deformation history may start with generation of a high-dipping normal fault developed in one of the brittle conglomerate levels. When this precursory fault progressed up to the highly micaceous levels, the extension was transferred parallel to the easily deformable bed, developing the flat-ramp geometry.

We propose a possible model to explain the Santopétar faulting and their associated folds linked to successive faulting phases (Figs. 4a and 4b). During a first phase of top-to-the SW movement, an extensional flat-ramp-flat fault developed favoring the formation of a fault-bend fold over a S-dipping ramp. Later, a top-to-the NE flat fault partially reactivates the previous flat segment displacing the preceding bend fold. Nevertheless, this solution is not exclusive and we are working in a model to explain the Santopetar structure during a single extensional phase linked to a top-to-the NE ramp-flat-ramp normal fault.

Figure 5 shows a general restoration of hanging wall and footwall taking into account the proposed evolution model. As much as possible, the bed-length, bed thickness and cross-sectional area have been conserved. Stages 1 and 2 show the restoration of 20 m slip (point A as deformation marker) along a major top-to-the SW flat fault surface that cuts and displaces the antiform-synform pair. Stages 2 and 3 reconstruct the development of the antiform-synform linked to fault-bending associated with 23 m of top-to-the NE extensional flat-ramp-flat fault activity.

Discussion and conclusions

Flat-ramp-flat faults underwent a complex deformation process that can neither be always straightforward recognized by only studying the final geometry of the related folds, nor the final fault rocks. We propose a new model to explain the extensional flat-ramp-flat Santopétar fault and their associated folds as the result of successive phases of faulting accommodated by consecutive flat-ramp-flat normal faults. A fault-bend fold fits the geometry of a S-dipping ramp during a first phase of 23 m top-to-the NE extension latter cut by a top-to-the SW 20 m slip over a flat fault that partially reactivates the previous fault surface.

It is difficult to elucidate if the last top-to-the SW stage is linked to compression or extension only studying the Santopétar outcrop. However, compressive and extensional deformations interact in the Huércal-Overa Basin since Tortonian (Pedrera *et al.*, 2010). In addition, the location of the studied outcrop is near to a band of compressive WNW-ESE oriented open folds that deform the metamorphic rocks of Sierra Limaria and the Lower Tortonian sediments located in the central sector of the basin (Fig. 1). However, we want to remark that this solution is not exclusive, although it is geometrically correct. Therefore, in the future it is necessary to consider new models that explain the deformation of the Santopetar structure during a single extensional phase.

The classical failure criterion (Anderson, 1942) predicts in a very reliable way that the new formed conjugated shallow normal faults generate 50-60º dipping surfaces, produced by a vertical maximum stress. The studied flat-ramp-flat normal faults were developed in relatively shallow position and show unexpected low dips. In the shallowest crustal levels, σ_1 should be vertical because the topographic surface cannot support shear stresses. However, it is not well established the extension at depth of this setting. The high rheology contrast between sedimentary layers

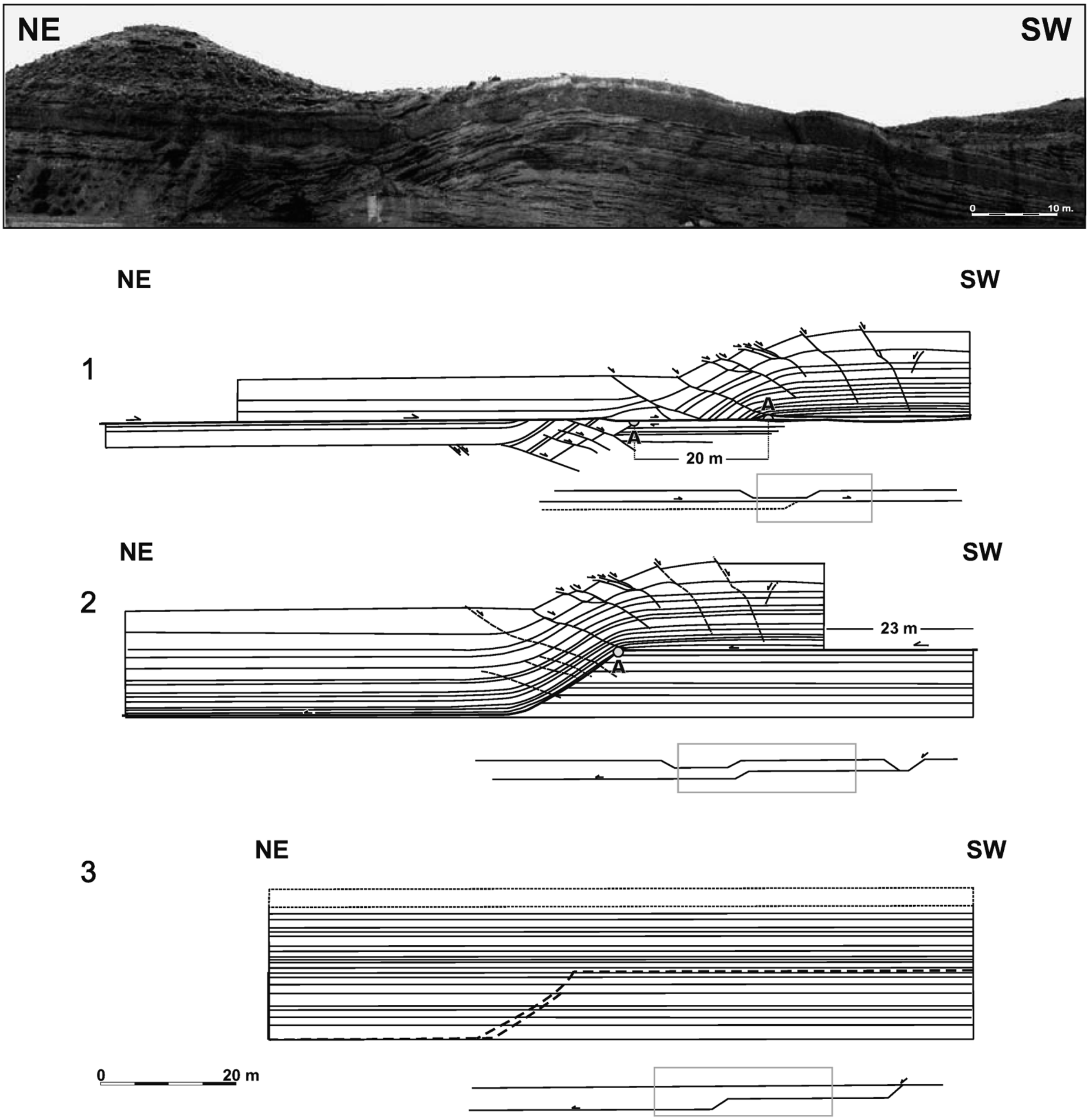

Figure 5. Santopétar flat-ramp-flat extensional fault and possible restoration. Position of the outcrop is indicated in figure 1.

allows the development of low-angle normal faults parallel to the beds and evidences the presence of inclined σ_1 in shallow crust. In addition, the secondary faults related to the deformation over these main detachments also need to be formed under an inclined σ_1. Taking into account these rheological effects in multilayers that determine local perturbations, the paleostress analysis could lead equivocal interpretation for the regional setting.

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