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Brevia

SHORT NOTES

Distinguishing lateral folds in thrust systems: examples from Corbières (SW France) and Betic Cordillera (SE Spain): Discussion

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INTRODUCTION

In their paper on lateral folds in thrust systems belonging to arcuate mountain belts, Frizon de Lamotte & Guézou (1995) discuss field criteria and kinematic analysis useful in distinguishing whether the folds in the lateral branch of an orocline are truly lateral or, rather, a frontal overprint. The authors illustrate their discussion with examples from two orogenic regions, the Betic Cordillera (southeastern Spain) and the Corbières thrust belt (northeastern Pyrenees, France). We focus the present discussion on the Betic Cordillera in order to show that the structural evolution these authors propose—a tectonic imbrication resulting in nappe stack culminations—is in contradiction with (a) field data and (b) most of the bibliography on this subject. Therefore, although the Betic Cordillera offers one of the best examples of extensional processes in Mediterranean back-arc basins (Horvath & Berkhemer 1982), for both onshore (García-Dueñas *et al.* 1992) and offshore studies (Comas *et al.* 1994), it should not be used to illustrate classical thrust structures and distinguish folds related with thrust systems.

Our discussion is divided into two sections: (1) the presentation of field data in the eastern Betics and a critical discussion of the thrust model proposed by Frizon de Lamotte & Guézou (1995); and (2) a brief description of an alternative model of the geological evolution of the Betics based on the field data presented in this Brevia and recent studies that we consider to be highly relevant. These publications are not cited by Frizon de Lamotte & Guézou (1995) and do not fit with their model, which is essentially supported by other studies of their own (Guézou & Frizon de Lamotte 1988, Frizon de Lamotte *et al.* 1989, 1991).

SOME FIELD DATA AND DISCUSSION OF THE THRUST MODEL FOR THE BETICS

Kinematic vectors in the eastern Betics: are they associated with thrust or extensional faults?

According to Frizon de Lamotte & Guézou (1995, pp. 235–236), "the internal zones of the Betic Cordillera are made of a pile of Alpine nappe complexes. ... The rocks ... are affected by a major foliation ... developed at an early stage of the structural evolution. The foliation is subsequently folded, sheared and imbricated into interlocking structures ... this late thrusting event ... occurs at all scales, producing duplex zones of a few centimeter thickness, to large thrust sheets many kilometers thick". These structures would have developed "during an east to west tectonic transport" (op. cit., p. 236), active from lower Miocene to Present (Guézou & Frizon de Lamotte 1988, Frizon de Lamotte *et al.* 1989, 1991).

The kinematic vectors presented by Frizon de Lamotte & Guézou (1995, fig. 7), which are meant to illustrate the thrust direction, are only partially correct with respect to their sense and orientation, and are generally erroneous with respect to their tectonic significance. In reality, they represent a mixture of ductile and brittle structures of different ages. In Sierra de los Filabres, the vectors situated around the boundary between what these authors call the Veleta and Tahal units show a westward transport direction, but are related with a ductile extensional shear zone, approximately 16–17 m.y. old and coeval with a reduction in the crustal overburden (González-Casado *et al.* 1995). The kinematic vectors situated in the Sierra Alhamilla region are not correctly documented by Frizon de Lamotte & Guézou (1995). Platt *et al.* (1983) and Platt & Behrmann (1986) described in the Nevado-Filabride complex a NNE–SSW stretching lineation, ductile and penetrative, along which a northward motion was attributed to a fold-nappe emplacement (Fig. 1). Moreover, along the boundary between the Nevado-Filabride and Alpujarride complexes, both in Sierra Alhamilla and in Sierra de los Filabres, a second family of kinematic vectors are oblique with respect to the thrust culmination proposed by Frizon de Lamotte & Guézou (1995). They are SW and WSW directed (hanging-wall movement) in Sierra de los Filabres and Sierra Alhamilla, respectively (García-Dueñas & Martínez-Martínez 1988) (Fig. 1). These vectors are located along a brittle detachment that is the sole fault zone of an extensional system affecting the Alpujarride complex (García-Dueñas *et al.* 1986, García-Dueñas & Martínez-Martínez 1988, Galindo-Zaldívar *et al.* 1989). This fault system, the Filabres extensional system of García-Dueñas *et al.* (1992), is upper Langhian and Serravallian in age. As seen in fig. 7 of Frizon de Lamotte & Guézou (1995), in the Sierra de los Filabres region, the Alpujarride complex lies successively upon the Bédar-Macael, Tahal and Veleta units from east to west. That is, we are clearly looking at a foot-wall ramp of this westward extensional brittle detachment along which omissions are noted in the direction of transport (Gibbs 1984).

Outcrops of some curious frontal thrust-related folds

Two examples presented by Frizon de Lamotte & Guézou (1995, figs. 8 and 9) are meant to illustrate frontal thrust-related folds. Nevertheless, to present these outcrops as "a typical thrust style of the Betic zone" (op. cit., p. 238) is very misleading for the following reasons.

(1) The 'thrust plane' drawn in their fig. 8 shows characteristics of both extensional and thrust faults. With respect to the regional foliation, the fault plane in the foot-wall provokes omission in the direction of transport. The 'thrust plane' is, therefore, a low-angle normal fault ramp. In contrast, with respect to the hanging-wall, the tilting of the 'regional foliation' is coherent with a thrust (Boyer & Elliott 1982). Moreover, the orientation of the regional foliation as presented by Frizon de Lamotte & Guézou (1995) in fig. 8 is inexact, as it is generally E-ward dipping (Fig. 1).

(2) The 'typical frontal fold' of fig. 9 shows 40° east-dipping normal faults cut by a westward thrust. (According to the outcrop sketch, these normal faults do not intersect the thrust plane, as affirmed by Frizon de Lamotte & Guézou 1995, p. 237.) The conjugate Riedel faults, R1 and R2, which would result from secondary fault development in a westward shear zone, should both be west-dipping (e.g. Ramsay & Huber 1987, p. 530). No stress state can reasonably be evoked to explain such an association of faults.

Geometry of Sierra Alhamilla: stack culmination with lateral westward thrust-related folds or extensional core folded during a late Miocene N–S compression?

In order to discuss strain accommodation above blind imbricates, Frizon de Lamotte & Guézou (1995) use an example from the Sierra Alhamilla region. The geometry

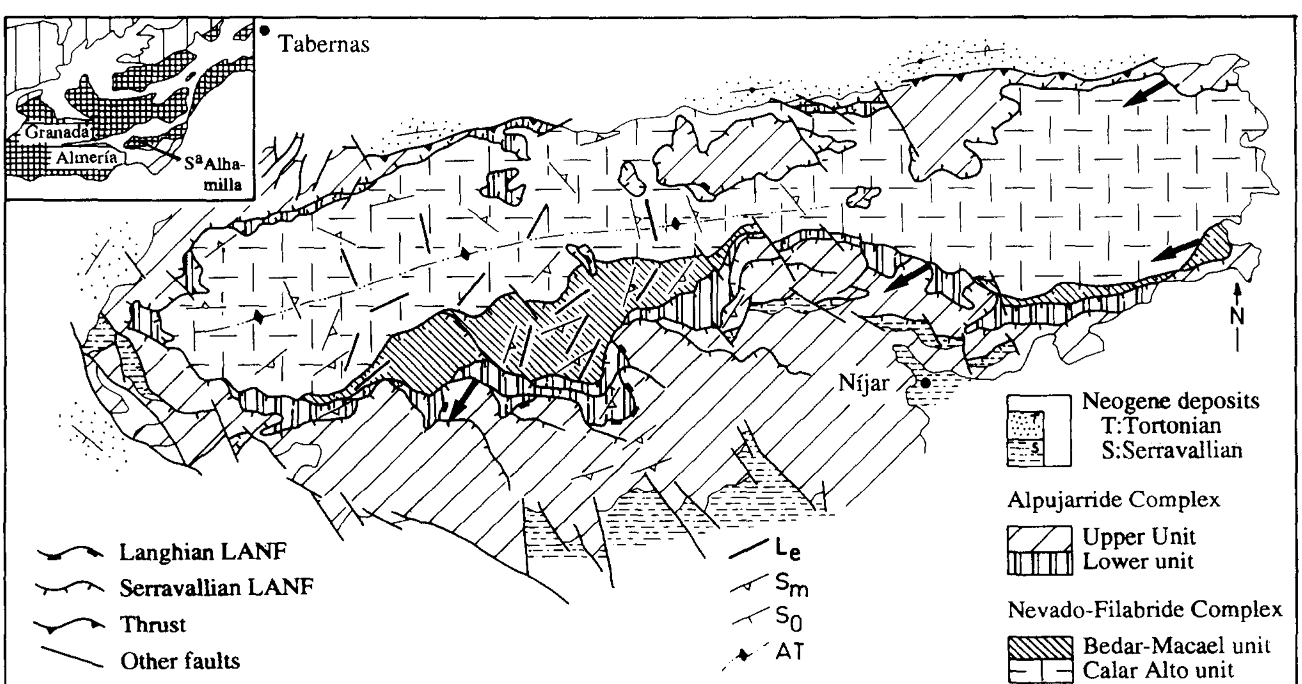

Fig. 1. Geological sketch of Sierra Alhamilla region, according to Martínez-Martínez (1995), slightly modified. Main foliation (S_m), stretching lineation (L_e) and axial trace of Sierra Alhamilla anticlinorium (AT) according to Platt *et al.* (1983). Kinematic indicators along brittle faults according to García-Dueñas *et al.* (1992). LANF: Low angle-normal fault. Arrows: hanging-wall movement along LANF belonging to the Filabres extensional system. S_0: Bedding.

presented in their fig. 13 (op. cit.), a N–S cross-section subperpendicular to the transport direction, leads the authors to deduce that "this culmination results from deeper thrusts", active from lower Miocene to Present (Guézou & Frizon de Lamotte 1988, Frizon de Lamotte *et al.* 1989, 1991), and that "the two large folds which flank the Sierra ... represent lateral structures" (Frizon de Lamotte & Guézou 1995, p. 241). These conclusions, however, do not agree with the field data described below.

(1) The kinematic vectors presented in our Fig. 1 and discussed in a previous section are not systematically parallel to the alleged 'thrust culmination'.

(2) A stack culmination must be accompanied by frontal folds (Boyer & Elliott 1982). Yet the hypothetical N–S directed frontal folds associated with this 'Sierra Alhamilla thrust culmination' have not been observed. Nor have frontal folds been associated with the huge 'Sierra Nevada thrust culmination'. In fact, the only major post-metamorphic N–S trending compressive structure that developed during the same age interval as the proposed thrusts (lower Miocene to Present) is the one described 350 km further to the west, in the Gibraltar thrust front, which was active from Aquitanian to Burdigalian (Balanyá & García-Dueñas 1988).

(3) In order to explain how the lowest unit of the Nevado-Filabride could be situated above the roof of Sierra Alhamilla culmination—where the different horses of a thrusted sequence were accumulated (Boyer & Elliott 1982)—Frizon de Lamotte & Guézou (1995) suggest that "two coeval phenomena are combined: denudation along the roof and imbrication along the southern lateral wall of the culmination" (op. cit., p. 242). If this were true, these 'lateral walls' would show evidence of the thrusting of part of the Nevado-Filabride complex (the so-called Tahal unit and most of the Bédar-Macael unit, their fig. 7) and the whole Alpujarride complex onto the Neogene sediments towards the north or the south. This is not the case (cf. compare their fig. 7 with our Fig. 1).

We believe, instead, that the Sierra Alhamilla represents an extensional core folded during a late Miocene N–S compression, for the following reasons.

(1) The Sierra Alhamilla anticline can be followed westward in the Contraviesa area to just south of Granada. Similarly, the Sierra de los Filabres–Sierra Nevada anticline, in which the eroded core outcrops the lowermost unit of the Nevado-Filabride complex (fig. 7 of Frizon de Lamotte & Guézou 1995) can be traced over more than 120 km (Junta de Andalucía 1985, García-Dueñas *et al.* 1992). These anticlines are separated by E–W aligned basins, in which very slightly folded Messinian sediments seal synclines marked by Tortonian sediments (Ott d'Estevou & Montenat 1990, Briend *et al.* 1990, fig. 13 of Frizon de Lamotte & Guézou 1995). Most of the authors working in the Betics have shown that these large-scale folds formed during the Tortonian–Messinian transition (Platt *et al.* 1983, Weijermars *et al.* 1985, Comas *et al.* 1992, Rodríguez-Fernández & Martín-Penela 1993).

(2) The geometric distribution of the Nevado-Filabride and Alpujarride units in the Sierra Alhamilla region illustrates the extensional character of the WSW-trending faults that bound the units (Fig. 1). The post-Tortonian folds facilitate a direct view of a cross-section of this brittle fault system, the Filabres extensional system of García-Dueñas *et al.* (1992) (see previous section), in the almost vertical southern flank of Sierra Alhamilla. This would then represent an ENE–WSW cross-section subparallel to the 'thrust' direction proposed by Frizon de Lamotte & Guézou (1995). This system, composed of listric fault fans of low-angle normal faults, divides the Alpujarride complex into extensional units and coalesces in a floor fault that represents the current Alpujarride/Nevado-Filabride complex boundary. An out-of-sequence fault (between the Bédar-Macael and Calar Alto units) penetrated below this boundary, which is tilted. In summary, the orientation of the regional foliation with respect to the faults (Fig. 1) indicates that they constitute a foot- and hanging-wall extensional ramp, with omissions along the transport direction (Gibbs 1984). The Serravallian sediments were deposited synkinematically with these faults, which are sealed by lower Tortonian sediments (Fig. 1, Martínez-Martínez 1995). Thus, in Sierra Alhamilla, the faults belonging to this extensional system were active during the Serravallian.

Geological evolution of the Betic Cordillera: an alternative model

The data from Sierra Alhamilla presented in this Discussion illustrate only one of the extensional systems associated with the Miocene rifting of the Alboran Domain (García-Dueñas *et al.* 1986, 1988, 1992, Platt & Vissers 1989), its oldest synrift deposits being of latest Oligocene and Early Miocene age (Jurado & Comas 1992, Durand-Delga *et al.* 1993). Other rifting episodes with different extensional directions have been observed onshore by various authors. At present, the main units of the Alboran Domain are extensional units, bounded by brittle shear zones in the central Betics (Galindo-Zaldívar *et al.* 1989, Alonso-Chaves *et al.* 1993, Azañón *et al.* 1993, 1994, Crespo-Blanc *et al.* 1993, 1994, Crespo-Blanc 1995), and with both ductile and brittle boundaries in the western Betics (García-Dueñas & Balanyá 1991, Balanyá *et al.*, 1993). The extensional denudation processes resulted in the opening of the Alboran Sea (Comas *et al.* 1992, 1994). At the same time, outward propagation of the collisional front of the Gibraltar arc coincided with the development of thin-skinned tectonics in its outer part (Balanyá & García-Dueñas 1988). Finally, the extensional systems were folded into large open E–W trending folds and faulted. The main folds were formed during the Tortonian–Messinian transition (Weijermars *et al.* 1985) and are ubiquitous in the Betics (García-Dueñas *et al.* 1992).

The pre-Miocene evolution of the Alboran crustal Domain includes a complex succession of contractional and extensional events (Balanyá *et al.*, submitted). The Alpine metamorphism evolves from a high pressure episode (Bakker *et al.* 1989, Goffé *et al.* 1989) to a nearly isothermal pressure decrease in both the Nevado-Filabride and the Alpujarride complexes (Tubía & Gil-Ibarguchi 1991, Azañón *et al.* 1992, 1994, Balanyá *et al.* 1993, Soto & Azañón 1994). The high pressure mineral assemblages of the Alpujarride units are believed to have formed during a former crustal stacking, followed by ductile regional flattening (Balanyá *et al.* 1993). Yet still before the Miocene, an extensional event followed by north-vergent folding of the thinned metamorphic sequences resulted in the drastic modification of the previously thinned Alpujarride stack (Balanyá *et al.* 1987, Simancas & Campos 1993). It is this pre-Miocene stack which is affected by the extensional denudation processes associated with the Miocene rifting of the Alboran Domain.

The model of the geological evolution of the Alboran Domain described very briefly here contradicts the Miocene to Present westward thrusting proposed by Frizon de Lamotte & Guézou (1995). In consequence, we believe that the example of the Betics as used by these authors is clearly inappropriate for illustrating the development of a thrust system, for proposing geometrical criteria in order to differentiate lateral and frontal thrust-related folds, or for analysing accommodation processes above imbricate stacks. We feel certain that in the near future the Betics will become an important reference, instead, for extensional processes in orogenic belts.

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