Pergamon

Journal of Structural Geology, Vol. 18, No. 8, pp. 1107 to 1109, 1996

0191-8141/96 $15.00+0.00

PII: S0191-8141(96)00027-2

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

DOMINIQUE FRIZON DE LAMOTTE and JEAN-CLAUDE GUÉZOU

Université de Cergy-Pontoise, Département des Sciences de la Terre, CNRS URA 1369-groupe de Cergy, Le Campus, F91 011 Cergy-Pontoise Cedex, France

(*Received* 14 *February* 1996; *accepted in revised form* 20 *March* 1996)

INTRODUCTION

The discussion by A. Crespo-Blanc, J. M. Martínez-Martínez and J.-M. Azanón concerns only the Betics examples discussed in our paper (Frizon de Lamotte *et al.* 1995). The principal objective of this paper was not to discuss the geodynamic evolution of the Betics, which is complex and controversial, but to detail some typical field structures. However we welcome the opportunity to present further our data and to discuss the extensional model put forward by Crespo-Blanc *et al.*

We divide our reply into sections addressing the main topics of the comment.

ATTITUDE OF BEDDING RELATIVE TO A THRUST FAULT IN A FAULT RELATED FOLD

Owing to some inconsistencies in Crespo-Blanc and others' comment of fault related structures, the discussion will turn first on simple case studies. As defined by Dahlstrom (1970), either in a simple step fold–thrust structure or in a piggy back sequence, the thrusts cut up-section in the transport direction and emplace older rocks onto younger rocks. Conversely, a normal fault cutting down horizontal layers emplaces younger rocks against older rocks. However according to the polyphase tectonic history of the Betics, the faults that we describe cut through earlier nappe structures and correspond fundamentally to out-of-sequence thrusts. Such thrusts cut up section and down section in the transport direction and can emplace younger rocks on older, as well as the reverse (Morley 1988). In such a context the basic geometric rules established for an original 'layer cake' geometry are not appropriate, and a fault which "provokes omission in the direction of transport" may be a thrust fault. It is worth noting that even in a simple step fold, the development of forelimb thrusts (Butler 1982) can lead to the geometry observed in our fig. 8. The real question is to know if, at the scale considered, the whole system is thickened by addition or thinned by subtraction. Based on this criterion, we maintain that the structures discussed by Crespo-Blanc *et al.* (Frizon de Lamotte *et al.* 1995, figs. 8 and 9) as well as structures previously published (Guézou & Frizon de Lamotte 1988, Frizon de Lamotte *et al.* 1989) are thrust structures.

MINOR FAULTS IN A THRUST SYSTEM

Crespo-Blanc *et al.* suggest that the antithetic normal faults that cross cut in the hangingwall of our fig. 9 imbricate structure (Frizon de Lamotte *et al.* 1995) are inconsistent with a "westward shear zone". It is known that in thrust belts a complex pattern of microfaults more or less synchronously with slip along the master fault develops as discussed, among others, by Casas and Sabat (1987) and Wojtal (1986). In particular, close associations of subcoeval low angle reverse and normal synthetic faults but also high angle antithetic reverse and normal faults are described. They are significant of accommodation in the thrust wedge.

SHEAR CRITERIA IN THE BETICS AND NEOGENE KINEMATICS OF THE BETIC-RIF OROCLINE

In 1987 at an early stage of our work in the Betic Cordilleras, the purpose was to use shear criteria to define the Neogene tectonic transport direction in the northern flank of the Betic-Rif orocline. Frizon de Lamotte (1985, 1987) gave evidence showing that the Rif suffered a westward translation during the Neogene times, but the situation in the Betics was quite confused. On the one hand the debate turned around an ancient question (Durand-Delga 1966) concerning the north or south origin of the nappe complexes forming the internal zone of the chain (i.e. Betics s.s.). On the other hand, some authors noted the E–W stretching lineation in the Sierra Nevada and Sierra de Los Filabres and claimed, using quartz fabrics, that the ductile thrust transport (the only one considered) was eastward (Gonzales-Lodeiro *et al.* 1984, Martínez-Martínez 1984, Orozco 1986)

In the Sierra Alhamilla, the state of things was more confused. In two adjoining areas situated in the centre of this relatively small Sierra, Platt *et al.* (1983) and Platt and Behrmann (1986) described a N–S to N30 lineation and a top-to-the-north sense of shear but Weijermars (1980, 1985) noted a N60 to N120 lineation.

Our study showed that the azimuthal scatter of the kinematic vectors linked to the S2–L2 ductile event was bracketed in a N240 to N300 sector. The shear criteria associated with the stretching lineation related to the S2 foliation were consistent with a top-to-the-west sense of shear (Frizon de Lamotte *et al.* 1989). These data have been reported in Frizon de Lamotte *et al.* (1995, fig. 7) (the post foliation event referred to in the caption is an uncorrected error). The kinematic directions related to the younger semi-brittle event under discussion are more divergent south-westward or north-westward (fig. 7 in Frizon de Lamotte *et al.* 1989) and partly related to the well known extensional crenulation cleavage (Platt & Vissers 1980).

Since then, work in the Sierra de Los Filabres (De Jong 1991), in the Subbetic zone (Allerton *et al.* 1993, Lonergan *et al.* 1994, Platt *et al.* 1995), in the Prebetic zone (Guézou *et al.* 1991) as well as in the external Rif (Morley 1992), confirm the large scale extent of the westward translation of Betic-Rif. At this scale, the transport is more southwestward in the Rif and more northwestward in the Betics (Frizon de Lamotte *et al.* 1991, Vissers *et al.* 1995).

Another question is to know if this translation is linked to nappe stacking, unroofing of an early nappe stack, crustal collapse or a combination of such processes. The answer depends on the areas considered. At the periphery of the Arc (external zones), stacking of cover thrust sheets was still active during Upper Miocene. Crustal collapse is perhaps responsible for the sagging of the Alboran sea as a consequence of the detachment of a dense lithospheric root (Platt & Vissers 1989, Vissers *et al.* 1995) or, in our mind more likely, as back-arc extension due to trench retreat (Frizon de Lamotte 1985, Frizon de Lamotte *et al.* 1990, Morley 1993, Royden 1993, Lonergan & White 1995) according to the models developed elsewhere in the Mediterranean regions (see review in Jolivet *et al.* 1994). However as discussed below, such a process is inadequate to explain the evolution of onshore Betics where extensional structures result from frontal (i.e. to the west) and lateral (i.e. to the north and the south) unroofing of culminations.

WHY THE SIERRAS OF THE BETICS ARE NOT METAMORPHIC CORE COMPLEXES

Crespo-Blanc *et al.* describe the Betics Sierras as "extensional cores" made of "extensional units" folded during a late Miocene N–S compression. We are not familiar with these structural terms, but their brief description of the Alpine metamorphism suggest that they use "extensional cores" as a synonym of "metamorphic core complex". However this point remains obscure because they also write about "rifting episodes" and we do not know how rifting is involved in this context.

A metamorphic core complex is characterised by metamorphic rocks showing a pervasive ductile deformation developed during extension. The top of these metamorphic rocks is underlined by a flat lying detachment flooring a non metamorphic upper plate in which brittle extensional structures are developed (Coney & Harms 1984, Lister & Davis 1989). The geometry of the Betics Sierras (Sierra Nevada; Sierra de Los Filabres; Sierra Alhamilla, etc.) is very different because the highly metamorphosed rocks belong to the Upper Units of the Nevado-Filabrides complex (Mulhacen or Bedar-Macael Unit) or to a Lower unit at the sole of the Alpujarrides complex. They are flanked at their footwall as well as their hangingwall by less metamorphosed rocks forming the Veleta Unit and the Higher Alpujarrides and Malaguides nappes respectively. De Jong (1993) shows, in an area situated between the eastern Sierra Nevada and the Sierra de Los Filabres, that "pressures and temperatures (in the Veleta complex) were lower than those of the Mulhacen Complex (i.e. the Upper Nevado-Filabrides)". He adds that "the movement of the Mulhacen Complex over the relatively cold Veleta complex explains cooling of the former during its decompression". The same geometric pattern and probably the same P–T evolution are expressed in the Sierra Alhamilla (fig. 13 in Frizon de Lamotte *et al.* 1995).

That is the reason why Platt *et al.* (1983) first imagined that the Lower Alpujarrides unit (i.e. Castro Slice) had been emplaced on the less metamorphic Veleta schist by a major recumbent N-vergent fold (see also Vissers *et al.* 1995). For our part and according to geochronological data (Priem *et al.* 1966) we admit that part of the metamorphic assemblages are inherited from pre-Mesozoic events (Frizon de Lamotte *et al.* 1991).

CONCLUSION

We agree with the existence of extensional structures developed during the late Tortonian to early Messinian growth of the culminations which led to the inversion of the Serravalo-Messinian basins. A general overview of the unroofing and collapse of these units has been considered in Frizon de Lamotte (1989) and Frizon de Lamotte *et al.* (1994). The single section (Frizon de Lamotte *et al.* 1995, fig. 13) shows that the basins flanking the Sierra Alhamilla are involved in the collapse not only at Turillas but within the emergent imbricate South of La Mina. Along the southern margin of the Huercal Overa basin, NE of Lijar, Alpujarrides sheets collapsed on top of the Tortono-Messinian sediments and, last but not least, Malaguides fragments occur on the top of the Tortonian (?) sediments in the Alpujarra corridor!

Our model which connects the top-to-the-west, top-to-the-north and top-to-the-south extensional structures with a sub coeval out-of-sequence westward stacking reconciles this set of structures with the Neogene Geodynamics of the Alboran region. This seems to us more likely than the alternation of extension and compression advocated by Crespo-Blanc *et al.*

REFERENCES

Allerton, S. L. L., Platt, J. P, Platzman, E. & McClelland, E. 1993. Paleomagnetic rotations in the eastern Betic Cordillera, southern Spain. *Earth Planet. Sci. Lett.* **119**, 225–241.

Butler, R. W. H. 1982. The terminology of structures in thrust belts. *J. Struct. Geol.* **4**, 239–245.

Casas, J. M. & Sabat, F. 1987. An example of three-dimensional analysis of thrust-related tectonites *J. Struct. Geol.* **9**, 647–657.

Coney, P. J. & Harms, T. A. 1984. Cordilleran metamorphic core complexes; Cenozoic extensional relics of Mesozoic compression. *Geology* **12**, 550–554.

Dahlstrom, C. D. A. 1970. Structural geology in the eastern margin of the Canadian Rocky Mountains. *Bull. Can. Petrol. Geol.* **18**, 332–406.

De Jong, K. 1991. Tectono-metamorphic studies and radiometric dating in the Betic Cordilleras (SE Spain)—with implications for the dynamics of extension and compression in the western Mediterranean area. Unpublished Ph.D. thesis, Vrije Universiteit, Amsterdam.

De Jong, K. 1993. The tectono-metamorphic evolution of the Veleta Complex and the development of the contact with the Mulhacen Complex (Betic Zone SE Spain). *Geologie Mijnb.* **71**, 227–237.

Durand-Delga, M. 1966. Titres et travaux scientifiques. Imp Priester Paris.

Frizon de Lamotte, D. 1985. La structure du Rif Oriental (Maroc): role des fluides et importances de la tectonique longitudinale. *Thèse d'Etat (Université Paris VI) et Mémoires des Sciences de la Terre* No. 85-03.

Frizon de Lamotte, D. 1987. La structure du Rif externe (Maroc) mise au point sur le rôle des décrochements, des chevauchements et des glissements gravitaires. *J. African Earth Sci.* **6/7**, 755–766.

Frizon de Lamotte, D., Guézou, J.-C. & Albertini, M. A. 1989. Deformation related to westward translation in the core of the Betic zone. Implications on the tectonic interpretation of the Betic orogen (Spain). *Geodin. Acta* **3/4**, 267–281.

Frizon de Lamotte, D., Guézou, J.-C., Andrieux, J., Albertini, M.-A., Coulon, M. & Poisson, A. 1990. Comment on "Negogene extensional collapse in the Western Mediterranean (Betic-Rif Alpine orogenic belt): implications for the genesis of the Gibraltar Arc and magmatic activity". *Geology* **11**, 381.

Frizon de Lamotte, D., Andrieux, J. & Guézou, J.-C. (1991). Cinématique des chévauchements Néogènes dans l'arc Bético-Rifain: Discussion sur les modèles géodynamiques. *Bull. Soc. geol. Fr.* **162**, 611–626.

Frizon de Lamotte, D., Guézou, J. C. & Mercier, E. 1994. Contrôle tectonique de la sédimentation détritique aux pieds de structures frontales et latérales. Application à la chaine bético-rifaine (Espagne-Maroc). *Géologie Alpine, série spéciale 'colloques et excursions'* **No. 4**, 46–47.

Frizon de Lamotte, D., Guézou, J. C. & Averbuch, O. 1995. Distinguishing lateral folds in thrust systems; examples from Corbières (SW France) and Betic Cordillera (SE Spain). *J. Struct. Geol.* **17**, 233–244.

Gonzales-Lodeiro, F., Orozco, M., Campos, J. & Garcia-Duenas, V. 1984. Cizallas ductiles y estructuras asociadas en los mantos Mulhacén y Veleta: primeros resultados sobre Sierra Nevada y Sierra de los Filabres. In: *El Borde Mediterraneo-Espanol: Evolucion del Orogeno Betico y Geodinamica de las depresiones neogenas, Granada*, 5–8.

Guézou, J. C. & Frizon de Lamotte, D. 1988. Mise en évidence et interprétation de cisaillements à vergence ouest au coeur du Bétique interne (Espagne méridionale). *C. r. Acad. Sci., Paris* **307, II**, 1021–1026.

Guézou, J. C., Frizon de Lamotte, D., Coulon, M. & Morel, J. L. 1991. Structure and kinematics of the Prebetic nappe complex (southern Spain): definition of a 'Betic Floor Thrust' and implications in the Betic-Rif orocline. *Annales Tectonicae* **V**, 32–48.

Jolivet, L., Daniel, J. M., Truffert, C. & Goffé, B. 1994. Exhumation of deep crustal metamorphic rocks and crustal extension in back-arc regions. *Lithos* **33**, 3–30.

Lister, G. S. & Davis, G. A. 1989. The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region U.S.A. *J. Struct. Geol.* **11**, 65–94.

Lonergan, L., Platt, J. P. & Gallagher, L. 1994. The internal–external zone boundary in the eastern Betic Cordillera SE Spain. *J. Struct. Geol.* **16**, 175–188.

Lonergan, L. & White, N. 1995. Rotations and roll-back in the Western Mediterranean. *EUG 8 Strasbourg, Terra Abstract* **7**, 169.

Martínez-Martínez, 1984. Evolucion tectonometamorfica del complejo Nevado-Filabride en el sector de union entre Sierra Nevada y Sierra de los Filabres (Cordilleras beticas, Espana). Unpublished Ph.D. Thesis, Universidad de Granada.

Morley, C. K. 1988. Out-of-sequence thrusts. *Tectonics* **7**, 539–561.

Morley, C. K. 1992. Tectonic and sedimentary evidence for synchronous and out-of-sequence thrusting Larache-Acilah area, Western Moroccan Rif. *J. geol. Soc. Lond.* **149**, 39–49.

Morley, C. K. 1993. Discussion of origins of hinterland basins in the Rif-Betic Cordillera and Carpathians. *Tectonophysics* **226**, 359–376.

Orozco, M. 1986. Fabrica de cuarzo y cabalgamientos hacia el ENE en Sierra Nevada y Sierra de los Filabres (Cordilleras Beticas). *Geogaceta* **1**, 40–41.

Platt, J., Allerton, S., Kirker, A. & Platzman, E. 1995. Origin of the western Subbetic arc (South Spain): palaeomagnetic and structural evidence. *J. Struct. Geol.* **17**, 765–775.

Platt, J. P. & Behrmann, J. H. 1986. Structures and fabrics in a crustal-scale shear zone Betic Cordilleras, SE Spain. *J. Struct. Geol.* **8**, 15–33.

Platt, J. P., van den Eeckhout, B., Janzen, E., Kohnert, G., Simon, O. J. & Weijermars R. 1983. The structure and tectonic evolution of the Aguilon fold–nappe, Sierra Alhamilla Betic Cordilleras, SE Spain. *J. Struct. Geol.* **5**, 519–538.

Platt, J. P. & Vissers, R. L. M. 1980. Extensional structures in anisotropic rocks. *J. Struct. Geol.* **2**, 397–410.

Platt, J. P. & Vissers, R. L. M. 1989. Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar arc. *Geology* **17**, 540–543.

Priem, H. N. A., Boelrijk, N. A. I. M., Hebeda, E. H. & Verschure, R. H. 1966. Isotopic age determinations on tourmaline granite-gneisses and a metagranite in the eastern Betic Cordilleras (southeastern Sierra de los Filabres). SE Spain. *Geologie Mijnb.* **45**, 184–187.

Royden, L. H. 1993. Evolution of retreating subduction boundaries formed during continental collision. *Tectonics* **12**, 629–638.

Vissers, R. L. M., Platt, J. P. & Van der Wal, D. 1995. Late orogenic extension of the Betic Cordillera and the Alboran Domain: A lithospheric view. *Tectonics* **14**, 786–803.

Weijermars, R. 1980. Geologie van de sierra Alhamilla, Band 1. Unpublished M.Sc. Thesis, Vrije Universiteit, Amsterdam.

Weijermars, R. 1985. Directional variations of fold axis in progressive deformation, an example from a Betic fold nappe in Southern Spain. *Geologie Mijnb.* **64**, 271–280.

Wojtal, S. W. 1986. Deformation within foreland thrust sheets by population of minor faults. *J. Struct. Geol.* **8**, 341–360.