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Distinguishing lateral folds in thrust-systems; examples from Corbières (SW France) and Betic Cordilleras (SE Spain)

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Abstract—Folds with axes almost parallel to the mean tectonic transport direction are frequent in fold-thrust belts, particularly along the borders of arcuate belts. Such structures have been frequently explained in terms of superimposed tectonic events but, in some cases, they are most realistically understood in terms of lateral folds inherited from lateral footwall ramps and initiated subparallel to the tectonic transport direction. In order to distinguish frontal and lateral folds, we have established criteria based on field examples from two regions where folds occur parallel to the regional transport direction: the Betic Cordilleras (Southern Spain) and the Corbières thrust-front (northeast Pyrenees, France). The main differences between frontal and lateral folds concern the geometry, the evolution of the structures and the modes of strain accommodation in the roof strata enveloping imbricate stacks. Recalling that, above a duplex or even on individual horse, the roof layers are thinned along sections normal to transport, we examine the precise location where the extension is expressed, illustrated by examples from the two regions. This leads us to address some tectonic problems of these orogenic zones, such as the thrust-sequence and development of thrust-related cleavage.

INTRODUCTION

Among thrust-related folds, ramp-flat folds are demonstrated to be widespread in many mountain belts (Dahlstrom 1969, Boyer & Elliott 1982, and many others). The orientation of such folds depends directly on the trend of the footwall ramps above which they develop. Consequently, footwall ramps and the related hangingwall folds are classified according to their orientation to the tectonic transport direction (Fig. 1). Ramps (and related folds) which strike normal, oblique or parallel to the thrust transport direction are termed frontal, oblique or lateral ramps (or folds) respectively (Butler 1982a).

In linear non-transpressional mountain belts, the determination of the tectonic transport is easy because major folds strike normal to the thrust transport and lateral structures (or transfer zones) are easily identi-

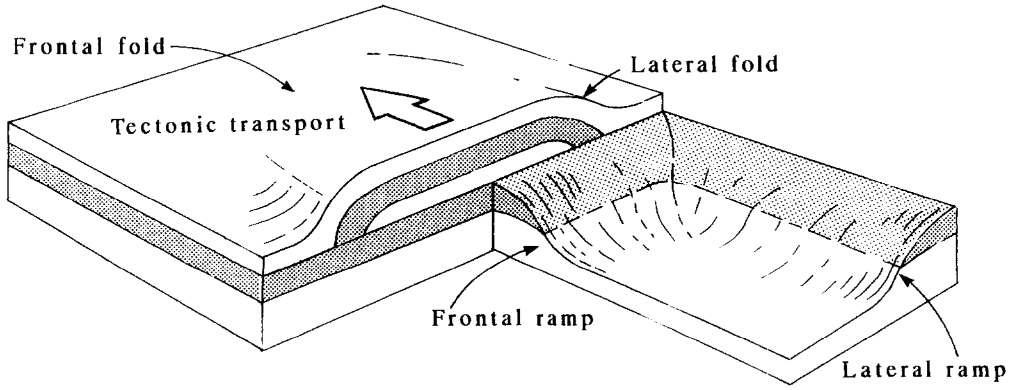

Fig. 1. Block diagram illustrating the geometry of frontal and lateral ramps with resulting hangingwall geometry (modified from Schirmer 1988, and Frizon de Lamotte *et al.* 1991).

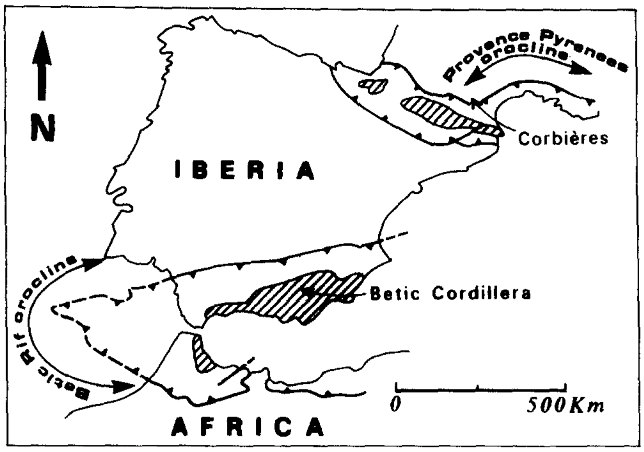

Fig. 2. The Pyrenees-Provence and Betic-Rif oroclines in the general framework of the western Tethyan belts.

fied. The problem is more complex in arcuate mountain belts because fold trend variations can result from at least two main mechanisms (Marshak 1988): (i) the orogenic belt was initiated with its present curved form and built up with a constant transport direction during thrusting, or (ii) it results from the superimposition of a later strain on a previous generation of folds. In the first case, the folds parallel to the lateral branches of the orocline are lateral folds. In the second hypothesis, they constitute either rotated frontal folds or a second generation of frontal folds which overprints the first one at more or less a high angle to the early tectonic transport. Thus, the folds in the lateral branches of an orocline need not be lateral folds.

The purpose of this paper is to discuss some field criteria which, in addition to kinematics analysis, can be useful in distinguishing when the folds are truly lateral as opposed to a frontal overprint. We can rule out rotations of individual folds from frontal to lateral position; such rotations, due to differential movements on thrusts, would be readily detectable by structural indicators, lacking in the studied examples. We will focus on two main aspects: (i) the geometry and evolution of the structures, and (ii) the distribution of strain within the cover strata enveloping the imbricate stacks. These criteria will be tested in examples from two orogenic regions: the Betic Cordilleras (southern Spain) and the Corbières thrust belt (northeast Pyrenees, France) that are both situated within wide oroclines (Fig. 2). The Betic cordilleras are the northern branch of the Betic-Rif orocline, sometimes called the Gibraltar Arc (Durand-Delga 1966). The Corbières thrust belt and the overlying 'Nappe des Corbières orientales' (Barrabé 1922, Ellenberger 1967) form the western branch of an orocline joining the Provence fold-thrust belt and the North-Pyrenean Zone.

DIFFERENCES BETWEEN FRONTAL AND LATERAL FOLDS

Within a thrust system, the geometry of a frontal fold, above a frontal ramp, is directly dependent on the ramp dip (Rich 1934, Suppe 1983). An equivalent relationship between a lateral footwall ramp and the related lateral fold should exist too. However, in this case, the development of the fold requires that the thrust-sheet passes over the frontal ramp (Fig. 1). As the lateral discontinuity is often a steep strike-slip fault, the lateral fold should have a steeper short limb than the adjacent frontal fold (Fig. 3). This criterion is not sufficient because nearly vertical (or even overturned) frontal forelimbs are commonly observed in thrust belts (for example Elliott 1976). Although the limb attitude may be similar between the two types of folds, the causes are quite different. The limb dip of a lateral fold is strictly the geometric result of the dip of the parent lateral ramp. On the other hand, steep frontal forelimbs have been considered to result either from fault-propagation folding (Jamison 1987, Suppe & Medwedeff 1990, Mercier 1992) or from adhesional drag along the thrust plane leading to the blocking of the displacement below fault-bend folds (Berger & Johnson 1982, Coward & Potts 1983). In the following section we will consider only this second case.

Frontal structure evolution

Two alternative effects related to changes in the ease of thrust propagation have been observed.

(i) Forward rotation of beds leading to the overturning of the frontal limb of the ramp anticline (Fig. 4a).

(ii) Backward rotation leading to the development of a back-fold directly above the ramp (Fig. 4b).

In the first case, the overturned forelimb is often associated with subhorizontal forelimb thrusts (Butler 1982a), which develop from the flat beneath the fold. In the second, back-thrust faults extend from the ramp and cross-cut the ramp syncline (Serra 1977, De Feyter & Menichetti 1986). The back-thrusts are a systematically higher angle than the forelimb thrusts. Before discussing the factors that control the development of such structures, we will present two examples.

Example from the Corbières thrust belt: the Lagrasse fold. The Corbières thrust belt which lies below the 'Nappe des Corbières Orientales' (northeast Pyrenees) exposes beautiful examples of steep or overturned frontal forelimbs (Ellenberger 1967). This region is affected by numerous folds and faults involving a mostly Cenozoic sedimentary cover which consists of about 1000 m of fluviatile silts and lacustrine limestones. The major kilometric scale folds which crop out close to the mountain front trend NE–SW, normal to the northwestward tectonic transport (Fig. 5) determined from microfault populations (Cluzel 1977). Among these frontal folds, the Lagrasse fold is asymmetric with a vertical (or even overturned) short limb and a subhorizontal long limb (Fig. 6). The short limb is cross-cut by subhorizontal forelimb thrusts. The difficulties in thrust propagation responsible for the forward rotation of beds and the subsequent development of forelimb thrusts are attested by the existence of an imbricate stack, the 'la Cagalière

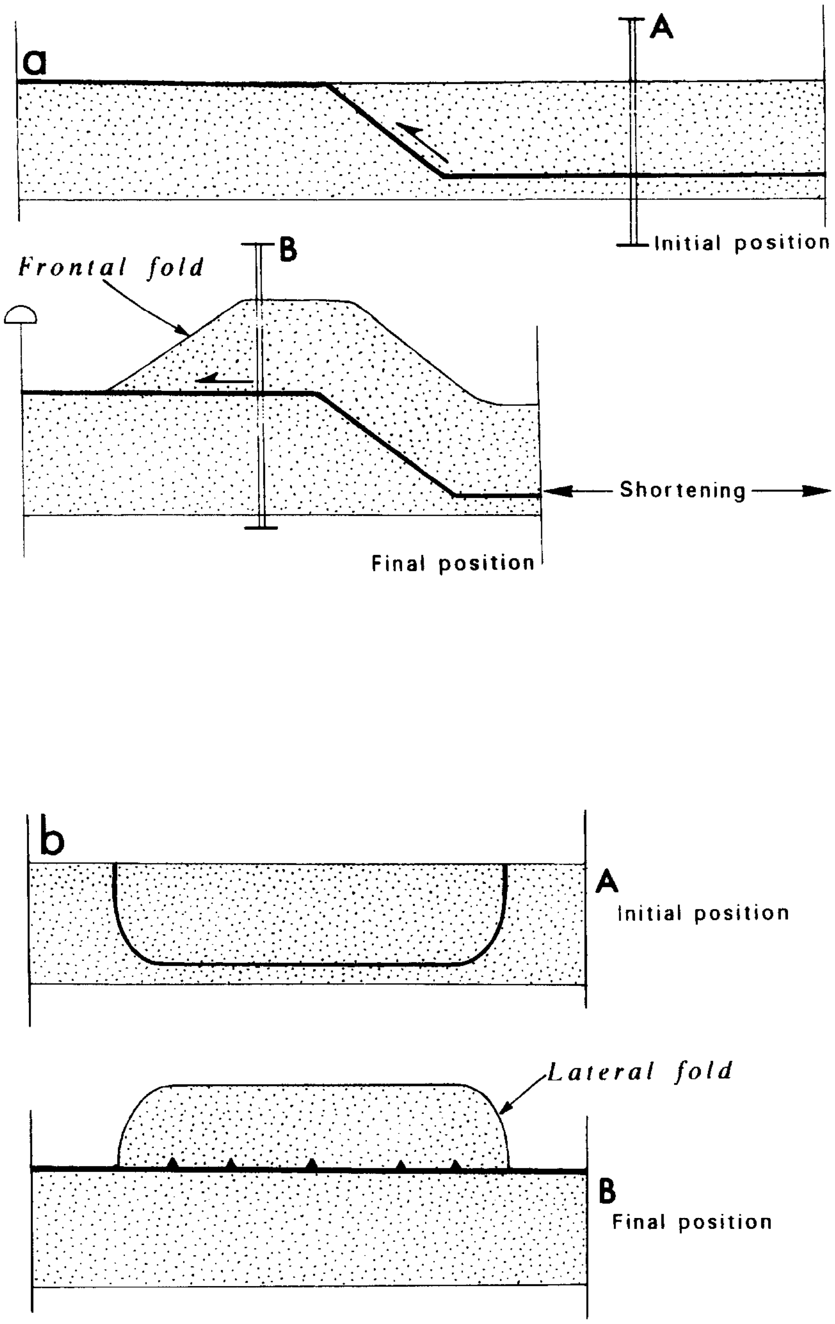

Fig. 3. Schematic sections illustrating the relationships between ramp dips and resulting fold geometry on (a) a section parallel to the thrust transport directions and (b) a section normal to transport direction. On (a) the lines A and B locate the sections presented in (b).

duplex' (Ellenberger 1967), developed in the front of the vertical forelimb during its transport on the upper flat (Fig. 6). Averbuch *et al.* (1992) performed strain analysis on these rocks, based on magnetic fabric measurements. The magnetic fabric (anistropy of the low field Magnetic Susceptibility) reflects the preferred orientation of grains and crystal lattices of all minerals which contribute to the susceptibility. It is described by a symmetric tensor of second-order which can be visualized as an ellipsoid with principal axes Kmax ≥ Kint ≥ Kmin. The study by Averbuch *et al.* (1992) shows that, except within the forelimb part of the structure, internal deformation occurred prior to any fold development as the result of layer parallel shortening. The typical early magnetic fabric consists of a magnetic foliation normal to bedding and parallel to a rough cleavage in which a vertical lineation (cluster of Kmax) develops as progressing towards the frontal footwall ramp (Fig. 6). During the folding, the distortion is localized within the forelimb. The new magnetic fabric is characterized either by a lineation parallel to the fold axis or, in the vicinity of the forelimb thrusts, by a lineation parallel to the vertical plane containing the thrust transport direction (Fig. 6). Other examples of this tectonic style can be found in many places in the Corbières thrust belt: the fronts of the 'Montagne d'Alaric' (Plaziat 1969), of 'the Serre d'Oupia' (Berger 1990) or in its extension towards the Languedoc and Provence; the Saint Chinian Arc (Ellenberger 1967).

Betic example from the Sierra Alhamilla (*eastern Betics*). The internal zones of the Betic Cordillera are

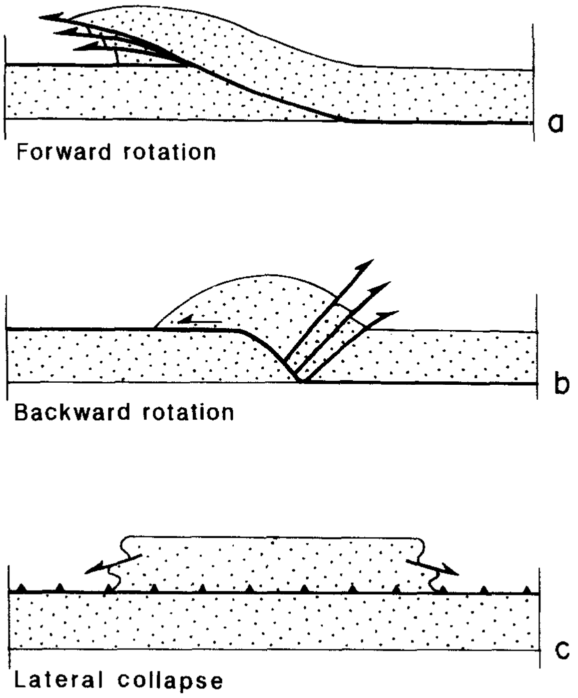

Fig. 4. Evolution of thrust related folds. (a) & (b) are sections parallel to the tectonic transport direction. (c) Is a section normal to the tectonic transport. (a) Forward rotation and development of low-angle forelimb faults: (b) backward rotation and development of back-thrusts; and (c) development of drag folds linked to gravitational collapse.

made of a pile of Alpine nappe-complexes (Platt *et al.* 1983, Bakker *et al.* 1989, De Jong 1991, Lonergan 1993). Our example is from the lowermost complex (called Nevado-Filabride) and, more precisely, from the Veleta unit which consists of slaty rocks and crops out in the core of wide culminations (Fig. 7). The rocks forming the Veleta unit are affected by a major foliation parallel to bedding developed at an early stage of the structural evolution. The foliation is subsequently folded, sheared and imbricated into interlocking structures (Guézou & Frizon de Lamotte 1988, Frizon de Lamotte *et al.* 1989). We will focus precisely on this late thrusting event that occurs at all scales, from minor imbricates producing duplex zones of a few centimeters thickness, to large thrust sheets many kilometers thick. The imbrications developed in a general piggy-back sequence under a thick tectonic cover composed of the previously emplaced nappes: the so-called Alpujarride and Malaguide nappe-complexes. The studied structure is presented in Fig. 8. The hangingwall rocks situated above the ramp are affected by kink folds with backward vergence. The subsequent development of back-faults along the axial planes of the kink-folds leads to a late upward ejection and to the development of a kind of pop-up structure with a typical asymmetry, where the back fold is steeper than the frontal fold.

Discussion. The development of forelimb thrusts and back thrusts associated with a ramp-related fold both reveal difficulties in thrust propagation in the main tectonic transport direction. However the examples observed in the field suggest that these two kinds of structures are mutually exclusive. The reason for this exclusiveness is not known. Lithology or cover thickness may have some control. Backward rotation has been suggested to occur in homogeneous sequences where strain cannot be accommodated by bedding-parallel slip (Serra 1977, Morse 1977, De Feyter & Menichetti 1986). In the internal zone of the Betic Cordillera, the ubiquitous bedding-parallel foliation acted as a décollement surface. Layer-parallel slip could be accommodated even if there is little lithological contrasts within the homogeneous slaty sequence. The thickness of the cover (imbricates are developed as blind structures below a thick tectonic cover) could inhibit forward movement. We believe that this is a possible explanation for the frequency of back-structures in this orogenic domain. Alternatively, in the Corbières thrust belt, high contrasts of lithology within a thin sedimentary sequence (alternation of sandstones, silts, limestones and marls) may favour forward rotation of anticlines.

Evolution of lateral structures

The lateral terminations of imbricate zones are marked by lateral folds. As these folds develop only above the upper flat of the thrust, they are characterized by subhorizontal roof limbs (Fig. 3b). The dips of the short limbs are controlled by the geometry of the lateral footwall discontinuities bordering the thrust sheet and eventually, by the number of superimposed imbricates issued from the same lateral ramp. In the latter case, the stacking can induce an oversteepening of hangingwall beds and even the development of hangingwall drop faults cross-cutting the culmination roof without affecting the floor-thrust of the imbricate stack (Butler 1982a). Even in the case of an individual imbricate, the generally steep dip of lateral footwall ramps necessitates a subvertical dip of the short limb. In contrast to frontal structures, this steepening is not driven by accommodation of along-transport displacement. On the other hand, once a thrust sheet has passed the frontal ramp, it is not laterally retained any more and may spread in the direction normal to tectonic transport. This mechanism can trigger gravitational instability inducing the collapse of the vertical bedding or primary foliation producing drag folds and chevron folds with horizontal axial planes which often provide nucleation sites for later low-angle normal faults (Fig. 4c).

Example from the Sierra de Los Filabres (Betic Cordillera). The Sierra de Los Filabres (eastern Betics) exposes roughly E–W trending folds with vertical limbs showing apparent vergence either northwards or southwards. This geometry has been interpreted to result from successive tectonic events with opposite vergence (Kampshuur 1975, Vissers 1981). West-vergent structures and displacement criteria at the same scale, led us to interpret these as lateral structures developed during an east to west tectonic transport (Fig. 7) (Guézou & Frizon de Lamotte 1988, Frizon de Lamotte *et al.* 1989, 1991).

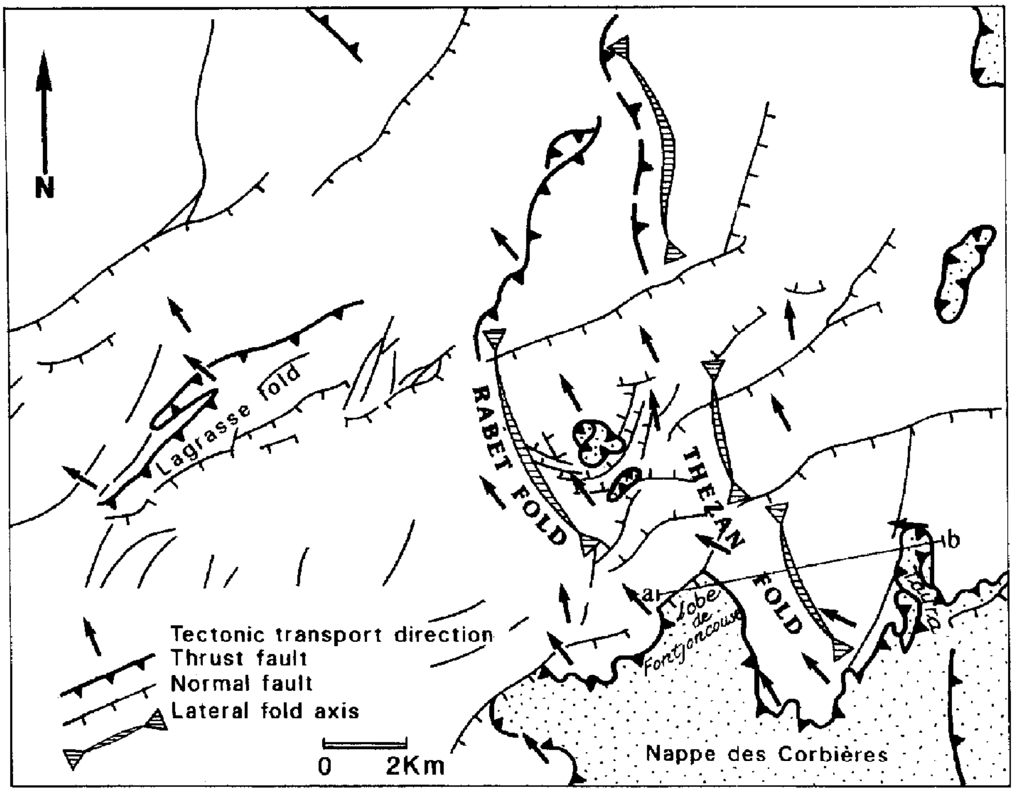

Fig. 5. Schematic map of the Corbières area from Ellenberger *et al.* (1987). The kinematic data are from Cluzel (1977). Folds referred in the text are labelled. The section line a–b refers to the Fig.12 cross-section.

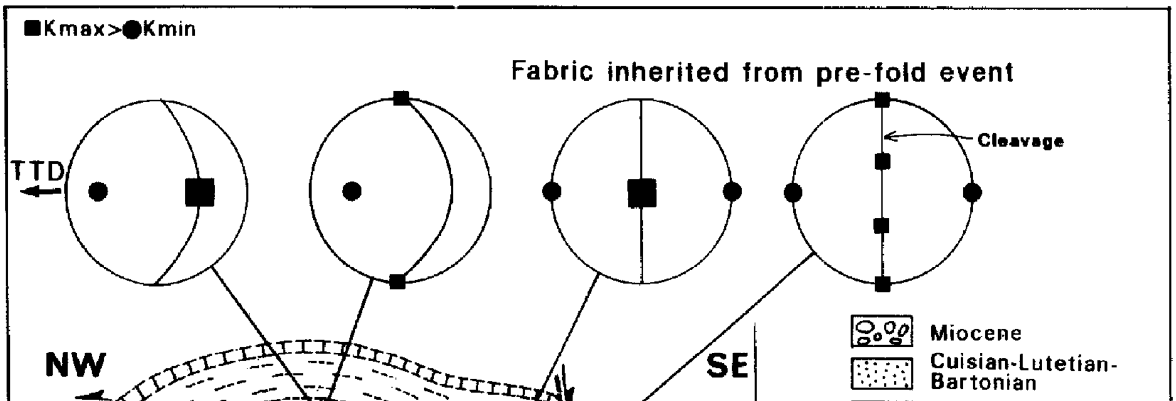

Fig. 6. A cross-section through the Lagrasse fold (after Averbuch *et al.* 1992) showing the development of the La Cagalière duplex in the front of the fold and the geometry of magnetic anisotropy axes (Kmax and Kmin) in the fold.

In the Tahal unit (Fig. 7), made of an association of greywackes and schists, two typical outcrops of respectively lateral and frontal structures are exposed within 100 m of each other. On an east–west section parallel to tectonic transport, the gently W-dipping forelimb of a ramp anticline lies on a horizontal roof flat (Fig. 9). It is cross-cut by high-angle antithetic normal faults intersecting the thrust plane. The footwall ramp and dorsal limb of fault-bend anticline are unexposed. The gentle dip of the forelimb is a common style in this region and is

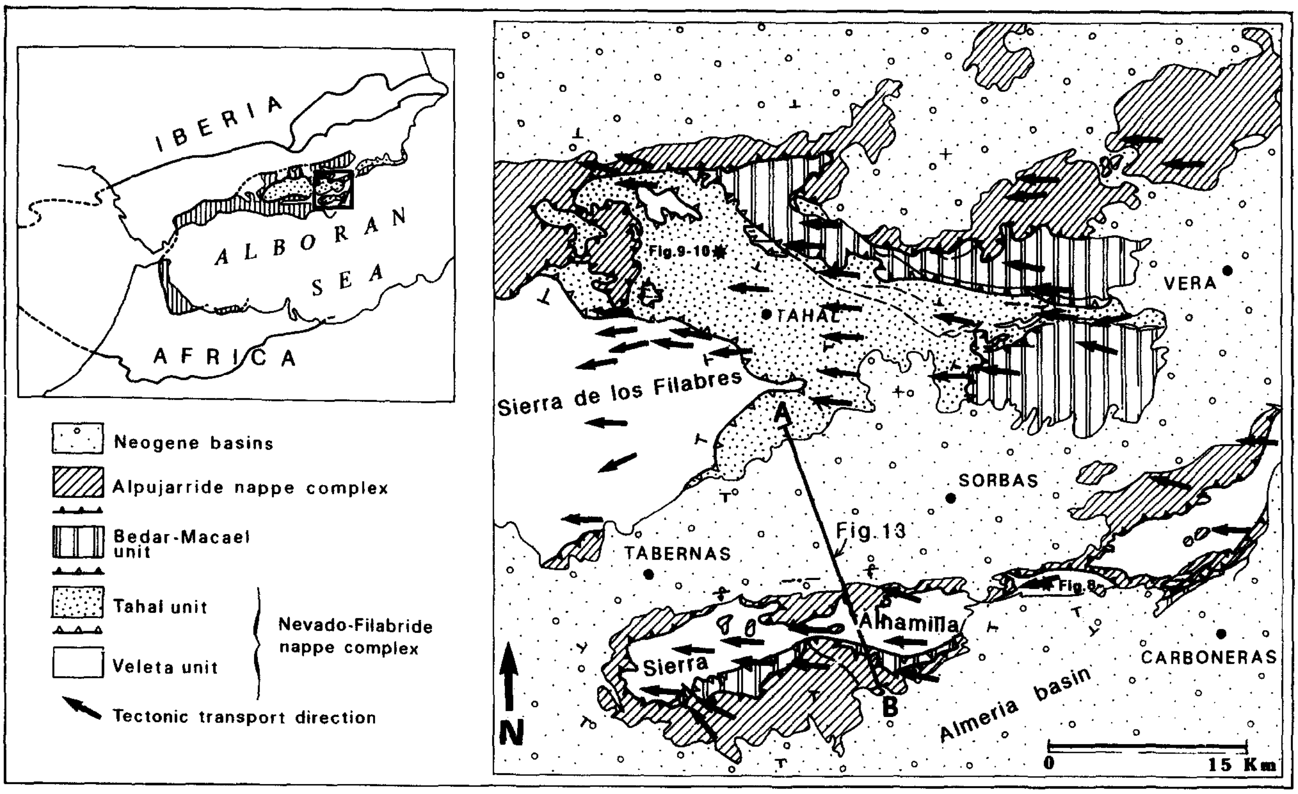

Fig. 7. Schematic structural map of the Eastern Betic Zone (Sierra de Los Filabres and Sierra Alhamilla) and its location within the tectonic framework of the Betic-Rif orocline. The section line A–B refers to the Fig. 13 cross-sections. Figures 8, 9 and 10 are located in the map. The kinematic data refer to the post- foliation events (from Frizon de Lamotte *et al.* 1989).

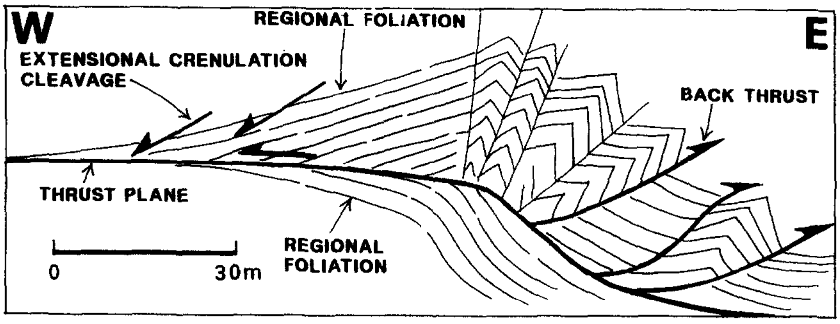

Fig. 8. Typical thrust style of the Betic Zone at the Sierra Cabrera–Sierra Alhamilla junction (drawing from photographs). The outcrop is located by a star on Fig. 7.

consistent with the proposed role for backthrusting as a displacement transfer agent from the main floor thrust (Fig. 4b).

One hundred meters to the north, in the same Tahal unit, a north–south section exposes the same foliation with a vertical attitude. This attitude is due to a steep lateral ramp. The foliation is affected by buckling folds with horizontal axial planes that are truncated by low-angle normal faults (Fig. 10). This geometry is evidence for a component of down-dip shortening which we interpret as a consequence of gravity instabilities related to uplift of the culmination. Numerous identical structures showing both north or south vergence are exposed in this region. Moreover, at a regional scale, the vertical limbs forming the north and south flanks of the major culminations (Fig. 7) exhibit the same tectonic style with large buckle folds cross-cut by low-angle normal faults. These structures are unstable and frequently collapse in the adjacent Neogene basins.

We have shown above that the association of two opposite lateral footwall ramps bounding a thrust sheet produces two unrooted folds with apparent opposite vergence (Fig. 4c). It is interesting to note that, as in frontal anticlines, the resulting structure is frequently asymmetric. For instance, in the eastern Betics, the northern lateral limb of the regional culminations is steeper than the southern one (see below) whereas the opposite is observed in central Betics across the Sierra Nevada culmination (Frizon de Lamotte *et al.* 1991). Consequently, no clear relationship for the bulk kinematics of thrusting can be inferred. The control by inheritance from different initial ramp dips and the

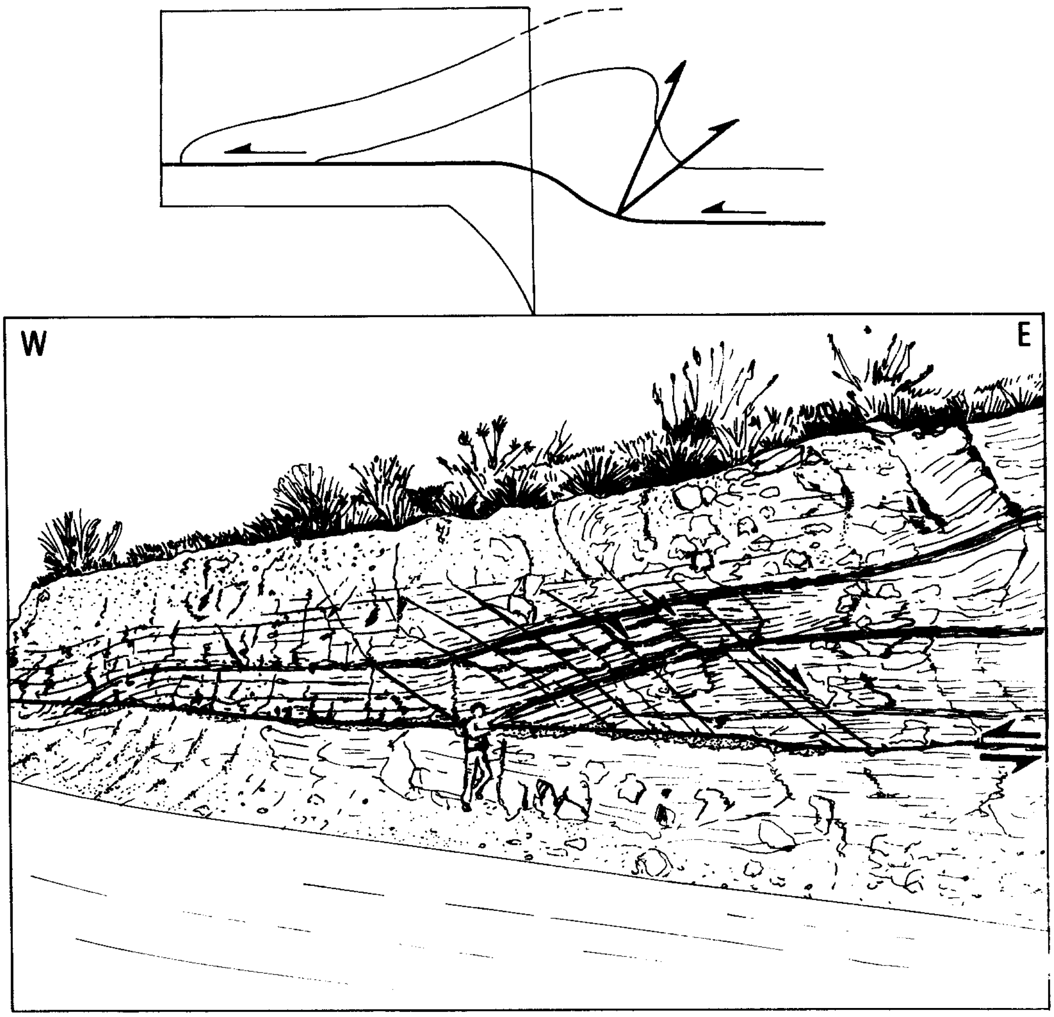

Fig. 9. An example of typical frontal fold in the Tahal unit (drawn from a photograph and interpretative sketch above). The outcrop is located by a single star on Fig. 7.

possible onset of later tectonic event, such as the extensional structures reported by Platt & Vissers (1989) and Garcia-Dueñas *et al.* (1992), are possible explanations.

KINEMATIC ACCOMMODATION ABOVE BLIND IMBRICATES

The problem of strain accommodation in the cover of blind imbricates is drastically different when considering frontal or lateral structures.

The question for frontal structures is how the shortening occurring by blind thrusting of the buried thrust sheets is transferred to the roof layers. This issue has been addressed by many authors and three main modes of deformation have been proposed.

(i) Displacement acting on the buried thrust is transferred forward some distance further into the foreland (Morley 1986a,b, Vann *et al.* 1986) or directly into the frontal adjacent syncline (out-of-syncline thrusting).

(ii) Shortening occurs by movement on antithetic roof thrusts (Jones 1982, Banks & Warburton 1986, Morley 1986a,b, Vann *et al.* 1986).

(iii) Shortening occurs by internal deformation (layer-parallel shortening) restricted to the cover strata which can be realized by buckling, minor thrust faults or distortion (Morley 1986a,b, Geiser 1988, Dunne & Ferril 1988).

These three aspects of the accommodation problem in frontal structures have been discussed in detail and illustrated by many regional examples (Vann *et al.* 1986), so will not be repeated here. However it is worth noting that difficulties still exist in partitioning the layer-parallel shortening developed before and after the imbricate thrusting (i.e. the passage over the ramp).

The cover requires another mode of strain accommodation when lateral folds develop. From a geometric point of view, this folding tends to increase the length of the roof layers relative to their initial length (Butler 1982b). The cover thus needs to undergo layer-parallel extension as a result of lateral fold emplacement. Obviously, the intensity of this transport-normal extension depends on the relative altitude of the culmination and the spacing between the lateral limbs. This is probably the critical parameter, and lateral accommodation of the cover is significant if the distance between the lateral walls does not greatly exceed the altitude of the culmination, as in the following examples. It is worth noting that the development of hangingwall drop fault at an

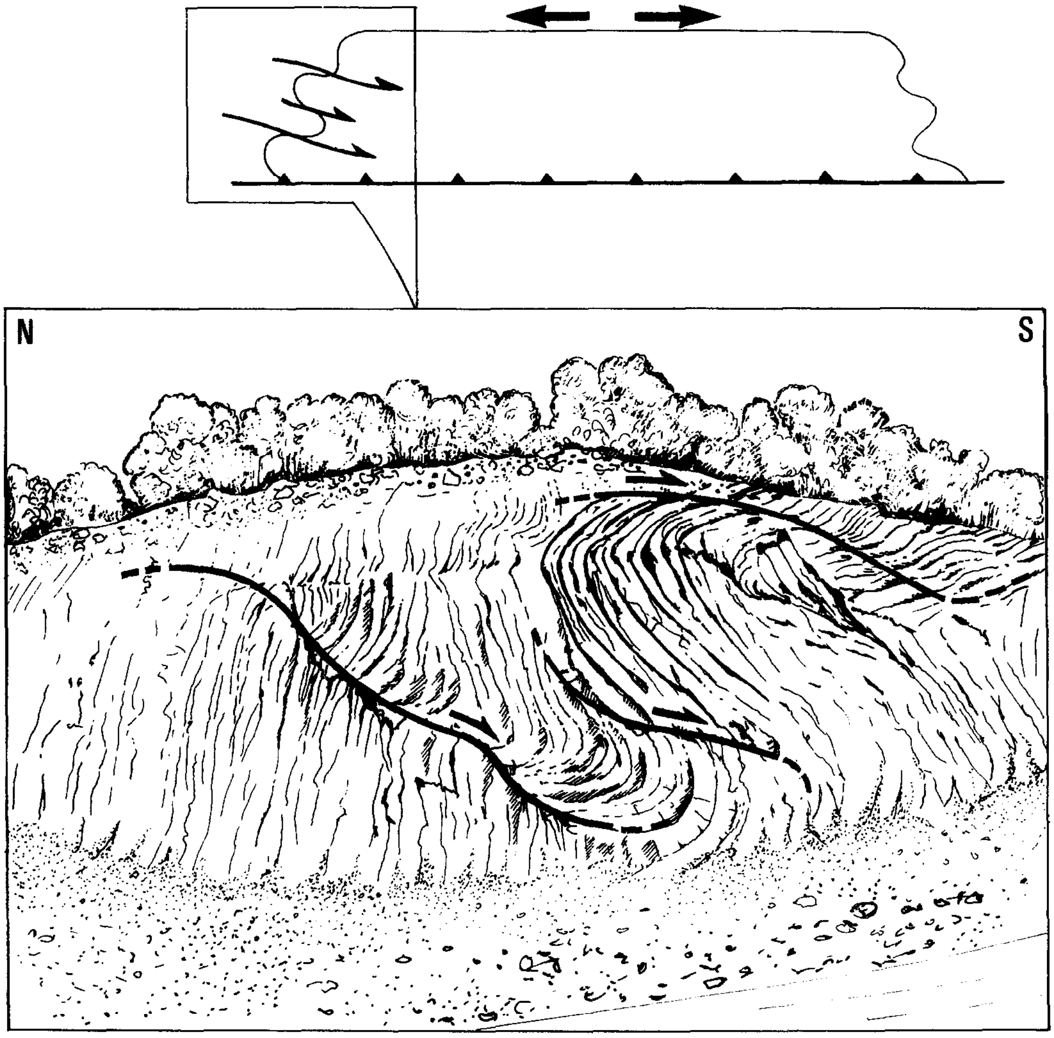

Fig. 10. An example of typical lateral fold in the Tahal unit (drawn from a photograph and interpretative sketch above). The outcrop is located by a single star on Fig. 7.

extremity of the thrust sheet also minimizes the required extension of the roof strata.

Three possible extension geometries can be considered (Fig. 11).

(i) The extension is equally distributed through the culmination (Fig. 11a).

(ii) The extension is restricted to the lateral walls as proposed by Butler (1982b), (Fig. 11b).

(iii) The extension is restricted to the culmination roof (Fig. 11c).

Field examples displaying both the lateral walls and the roof of the same culmination are scarce, because erosion tends to remove the elevated parts of the culminations. However, both the regions studied here provide examples. In all cases, our data agree with the third model: the required thinning occurs exclusively along the horizontal roof of the culminations, whereas the lateral fold limbs exhibit down-dip-parallel shortening or are cut out by major hangingwall drop faults.

Example from the front of the 'Nappe des Corbières Orientales'

In the Corbières thrust-belt, two regional folds, called 'Thezan flexure' and 'Rabet flexure' (Ellenberger 1967) trend approximately NNW–SSE. They are situated beneath the 'Nappe des Corbières Orientales' (Fig. 5) at about 10 km southeast of the Lagrasse fold analysed above. Cluzel (1977) and Viallard (1987) showed that the 'Nappe des Corbières Orientales' have been emplaced towards the northnorthwest. As the basal thrust flooring the nappe is folded, we infer that the development of the NNW–SSE folds is subsequent to the nappe emplacement, and probably subcoeval with the formation of the Corbières thrust belt (Averbuch *et al.* 1993). As displacements in the Corbières thrust belt are NW–NNW directed (Fig. 5), we infer the NNW–SSE folds are oblique sublateral folds probably inherited from synsedimentary extensional Mesozoic structures. These two folds form the western boundary of a major lateral culmination (Fig. 12). Its eastern boundary is buried below the Narbonne–Sigean basin.

The horizontal roof of the culmination is preserved in the 'lobe de Taura' (Charrière 1980) to the east of the west-Taura hangingwall drop fault (Fig. 12). A cleavage is developed in the Vitrollian formation (Cluzel 1977). Generally, in this region the angular relationships between cleavage and bedding remained unchanged whatever their position in the structure (Fig. 6). In contrast, in the Thezan and Rabet folds the attitude of cleavage

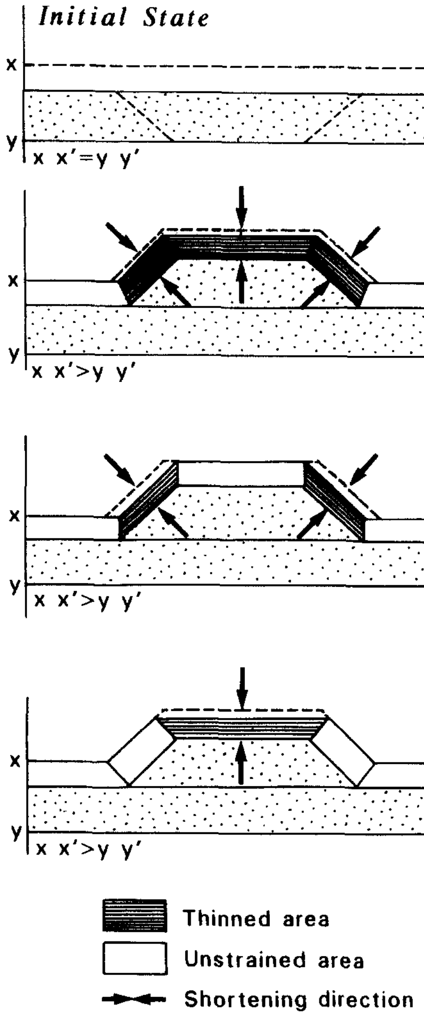

Fig. 11. The problem of balance for cover and blind lateral hanging-wall ramps: (a) extension distributed throughout uplifted cover; (b) extension restricted to the lateral fold limbs; and (c) extension restricted to the culmination roof.

with respect to bedding varies with structural position in the culmination. In the lateral culmination walls, it strikes N–S normal to bedding. Under the 'lobe de Taura' on the contrary, the cleavage is subhorizontal and parallel to the bedding. In the Thanetian limestones situated between the Vitrollian levels and the nappe itself, no cleavage is observed. However, the normal faults under the 'lobe de Taura' (Cluzel 1977, Averbuch *et al.* 1993) and interbed drag folds with bedding-normal axial planes along the lateral folds are consistent with the attitude of the cleavage in the underlying Vitrollian fluviatile silts, because they result from an identical shortening direction (Fig. 12).

Magnetic fabric measurements performed by Averbuch *et al.* (1993) allow us to complete the deformation pattern. Under the 'Lobe de Taura' the typical fabric consists of a well defined magnetic foliation that is parallel to bedding and cleavage. A NE–SW magnetic lineation (cluster of Kmax) is expressed in this foliation (Fig. 12). The lineation is normal to the last episode of thrusting (Cluzel 1977) and parallel to the extension direction derived from microfaults. Some sites exhibit a more complex magnetic fabric showing either no clear lineation or an evolution towards a prolate fabric about the horizontal lineation defined above (see Averbuch *et al.* 1993 for more details).

Along the Thezan and Rabet lateral folds, the magnetic fabric shows a conspicuous pattern characterized, at all sites, by a magnetic lineation parallel to the fold axes. When it is defined, the magnetic foliation is normal to bedding (i.e. parallel to the cleavage) (Fig. 12). The cleavage attitude along the lateral folds can be interpreted as the result of a pre-fold layer parallel shortening. On the other hand, the obliquity between the local direction of prefold shortening given by tilted conjugate reverse faults (Fig. 12) and the regional direction (Fig. 5) suggests an important deflection of the shortening direction in the vicinity of the future lateral fold. This result agrees with the experiments performed by Apotria *et al.* (1992) and with the kinematic data collected by Genna (1989). The parallelism between the magnetic lineation and the direction of the fold axes leads us to consider (Averbuch *et al.* 1993) that the tilting of the early strain markers during lateral folding is accompanied by shearing parallel to the lateral walls of the thrust-sheet, as already noted by Coward & Potts (1983).

All data are consistent with a normal to bedding flattening of the roof, and a pre-folding layer parallel shortening of the culmination walls. For a piggy-back sequence of thrusting, the cleavage appears to have developed after the emplacement of the 'Nappe des Corbières Orientales', during building of the lateral culmination. The cleavage, the normal faults, the magnetic foliation and the magnetic lineation can be interpreted as the direct result of the uplift of the underlying culmination. They express the required thinning above a lateral culmination. A basic geometric analysis leads us to infer a longitudinal roof thinning of about 20%.

Application in the Sierra Alhamilla (Betics)

The study of the Corbières lateral folds provides an analogy for similar structures in the Betic Cordillera. For example, the Sierra Alhamilla culmination, to the south of Sierra de Los Filabres (Fig. 7) consists of a pile of Alpine nappes which presently forms a wide anticline trending E–W. This culmination results from deeper thrusts that were active before and during the development of the adjacent Neogene basins (Guezou *et al.* 1991). As the tectonic transport was westward during this thrust event (Frizon de Lamotte *et al.* 1989, De Jong 1991), the two large 'folds' which flank the Sierra (Fig. 13) represent lateral structures. The northern flank is a subvertical fault that accommodates the differential uplift between the Sierra and the adjacent Tabernas basin. The southern flank exhibits a gentle dip toward the Almeria basin (Fig. 13).

The higher nappe (Upper Alpujarride nappes) consists of thick carbonate rocks (dolomite). On the southern part of the culmination these are cut by a set of low angle faults (Platt *et al.* 1983). The geometry of these listric faults (Fig. 13) is consistent with the existence of a décollement surface at the base of the carbonate layers belonging to the Upper Alpujarride nappe, and suggests

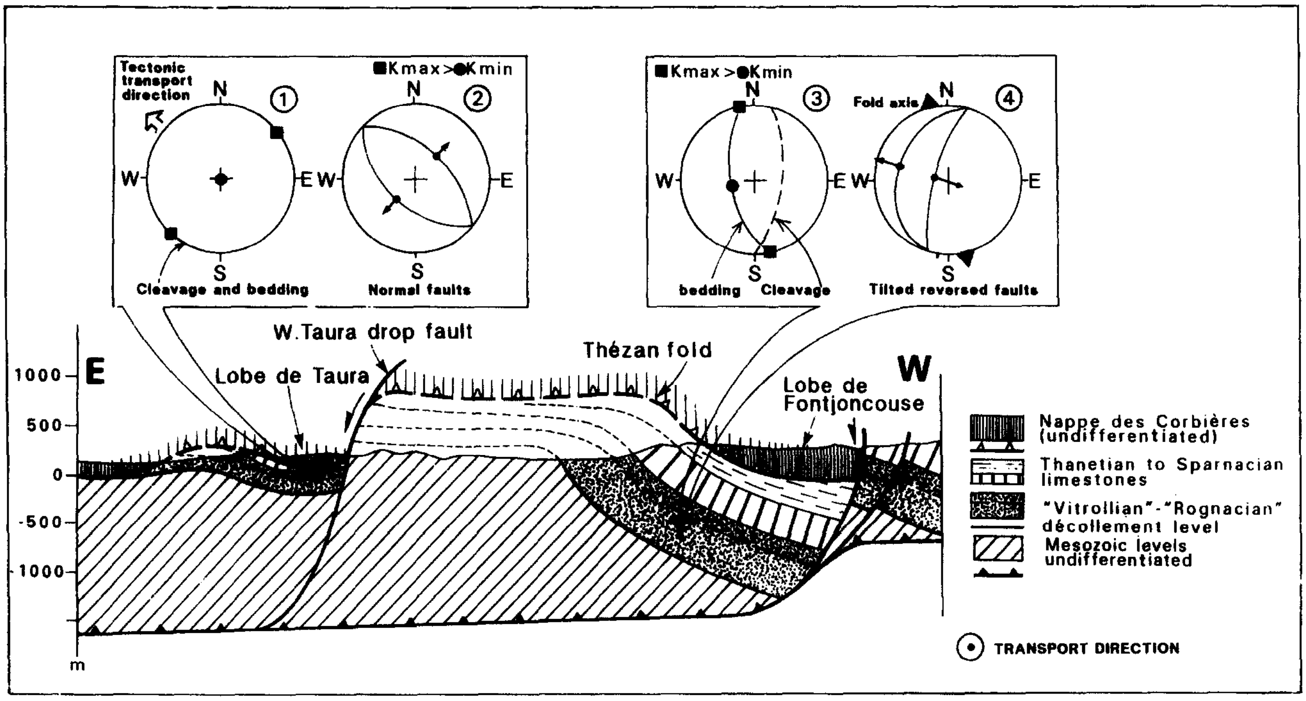

Fig. 12. A general E–W cross-section in the Corbières thrust-belt from the 'Lobe de Taura' to the 'Lobe de Fontjoncouse' showing the folding of the 'nappe des Corbières' above the Théan flexure that we interpret as a lateral fold. The two inserts show schematic representation of microfaults and magnetic measurements (Averbuch *et al.* 1993) as observed along the roof and the lateral wall of the culmination. The section is labelled on Fig. 5.

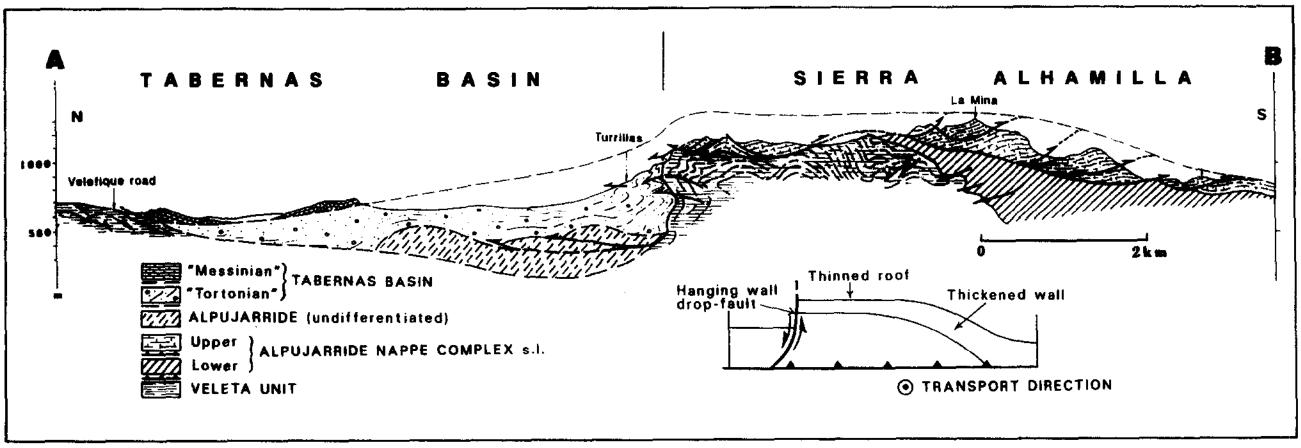

Fig. 13. A general N–S section through the Sierra Alhamilla culmination and the Tabernas–Sorbas basin (Betics). The depth to the thrust flat is unknown, so that its position is indicated only on the schematic diagram. This section also illustrates the general asymmetry of the culminations in the eastern Betics where northern limbs are steeper than southern ones. The section is labelled on Fig. 7 (line A–B).

that two coeval phenomena are combined: denudation along the roof and imbrication along the southern lateral wall of the culmination. As in the Corbières, the resulting geometry of the culmination cover is characterized by a thinned roof and relatively thickened walls. Platt *et al.* (1983) noted that the south-directed structures were not easily reconciled with their assumption of an essentially northward tectonic transport. Our interpretation, which links these apparent south-directed thrusts with the uplift of the culminations during a westward tectonic transport, reconciles this important set of extensional structures with the regional tectonic framework.

DISCUSSION AND CONCLUSION

During the development of a thrust system, several generations of folds with various orientations may form. Such a complex pattern of folding contrasts with the simplicity of the displacement paths generally characterized by a unique or dominant tectonic transport direction. Thus, in order to document the kinematic evolution of a thrust belt, it is imperative to recognize frontal folds which develop normal to the transport direction from lateral or oblique folds which are controlled by inherited fractures, and have no kinematic significance to the regional transport direction. Our field examples from Corbières and Betic Cordillera show that such elements of discrimination can be inferred from a precise analysis of the geometry and the evolution of individual folds or association of folds. When lateral folds are recognized, our work confirms that the analysis of lateral folds and related structures constitute an efficient tool to define the thrust sequence (Boyer & Elliott 1982, Schirmer 1988).

Concerning the analysis of accommodation processes and strain distribution above imbricate stacks, it appears that the response is very different in sections normal and in sections parallel to the tectonic transport. In sections parallel to the transport, a layer-parallel shortening in the roof beds is observed. In sections normal to the transport, a stretching of the roof beds leads to layer parallel extension. The geometric model proposed by Butler (1982b) assumes that this extension is restricted to the borders of the lateral culminations. It is clear that the strains arise from those parts of the thrust sheets which overlie ramps. However, our field examples show that the thinning occurred exclusively along the horizontal roofs of the lateral culminations. This needs a transfer from the ramps, probably by bed-parallel shear.

The recognition that lateral extension accompanies the development of lateral folds is an important consideration in the construction of balanced cross-sections, because this extension is not accounted for by structures expressed in the plane of the balanced section (Butler 1982b). The intensity of the extension is a function of two factors (Fig. 9): the relative altitude of the culmination and the spacing between the lateral culmination walls. The spacing is obviously the critical parameter and the problem of lateral accommodation really exists only if the distance between the lateral walls does not greatly exceed the altitude of the culmination, as in the examples given above.

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