Journal of Structural Geology, Vol. 12, No. 2, pp. 217 to 226, 1990
Printed in Great Britain

0191-8141/90 $03.00+0.00

Relationships between thrusting and joint systems in the Jaca thrust-top basin, Spanish Pyrenees

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(*Received* 16 *December* 1988; *accepted in revised form* 1 *September* 1989)

Abstract—The Oligo-Miocene rocks of the West Jaca thrust-top basin and adjacent parts of the Ebro basin are cut by up to eight sets of joints and allied mesofractures. The fractures belong to three groups that can be distinguished on the basis of their relative ages and geometry. An older group of joints strikes normal or subnormal to the Pyrenean mountain front and is restricted to subareas (here called front-normal joint domains) coincident with the immediate footwalls of thrusts. Joints striking parallel to a buried lateral ramp characterize a lateral ramp joint domain. Younger joints striking parallel or subparallel to the mountain front occur throughout most of the West Jaca and Ebro basins, and define front-parallel joint domains.

The joint domains appear to reflect the geometry and evolution of thrust sheets. Joints in front-normal domains were formed during stretching of footwalls as a result of their loading by overriding thrust sheets. Stretching above a lateral ramp is thought to be responsible for the development of joints in the lateral ramp domain. Joints in the front-parallel domains of the West Jaca basin are related to stretching in growth folds that were amplifying during salt doming. Front-parallel joints in the Ebro basin are attributed to stretching of a foreland basin sequence above a basement flexure related to thrust loading.

PURPOSE AND SCOPE

THE purpose of this paper is to argue that joints and allied mesofractures cutting Oligo-Miocene molassic rocks in the western part of the Jaca thrust-top basin (N. Spain) can be used to predict whether a locality is in the footwall or hangingwall of a thrust. If joint sets in other thin-skinned contractional settings are also related to such local strains, these ubiquitous fractures are potentially of great value for predicting structural setting.

The southwest Pyrenees, within which the Jaca thrust-top basin is situated, has been the object of numerous recent investigations aimed at improving our understanding of thrust-sheet geometry and kinematics. Indeed, the Pyrenees is one of the regions of the world in which recent ideas about thrust tectonics have been developed (e.g. Deramond *et al.* 1984, Williams & Fischer 1984, Vann *et al.* 1986, ECORS Pyrenees team 1988). The intimate relations between deformation and sedimentation so spectacularly displayed in the molassic rocks of the Jaca and neighbouring Ebro basin have also stimulated many field studies within the last 15 years (e.g. Puigdefabregas 1975, Puigdefabregas *et al.* 1975, Friend *et al.* 1979, 1981, Ori & Friend 1984, Hirst & Nichols 1986, Farrell *et al.* 1987). Despite being exceptionally well developed, the joint system in the sandstones of the Jaca basin has attracted little interest other than passing references to it by Hancock (1985, 1986).

Figure 1 shows the tectonic setting of the Jaca and Ebro basins, the principal map-scale faults and folds within the study area, and two representative cross-sections. According to Solé-Sugranes (1978) and Turner (1988), among others, the latest Eocene to early Miocene sequential development of the principal thrusts and associated fanglomerates involved north to south migration of new thrust planes and east to west propagation of existing ones.

The most significant map-scale structures are the S-directed Leyre-Alaiz, Ruesta, Sanguesa and Tafalla fore-thrusts, the back-thrust beneath the S-facing Pena flexure, the Ruesta fault zone, and the blind Alaiz-Ujue oblique ramp. The Ruesta fault zone, which contains several NNE-striking normal faults downthrowing towards the west, formed as a consequence of hangingwall collapse above a lateral ramp in the linked Ruesta thrust system. Turner (1988) interprets the Pena flexure as the uppermost component in a passive-roof duplex which forms the Pyrenean mountain front west of the emergent fore-thrusts of the Exterior Sierra.

The Pena flexure terminates in the west above the buried Alaiz-Ujue oblique ramp. Although thrusting migrated south with time, activity switched back to the north in the late Oligocene or early Miocene. This led to reactivation of the western end of the Alaiz thrust and, according to Turner (1988), a 45° anticlockwise rotation of the rocks of the Sierra de Alaiz.

The Oligo-Miocene sediments of the West Jaca basin are folded by nearly upright, gently WNW- or ESE-plunging structures. Shortening related to thrusting and folding decreases from more than 35% in the east to about 7% in the west (Fig. 1) (Turner 1988). Many of these folds (e.g. Bailo syncline, Villalangua syncline, Olleta syncline, Pena flexure) are growth folds which started to amplify during sedimentation. Growth folding was most vigorous during accumulation of the late Oligocene–early Miocene Bernues and Uncastillo Formations. The buoyant rise of Triassic evaporites above blind thrusts in some anticline cores enhanced fold amplification.

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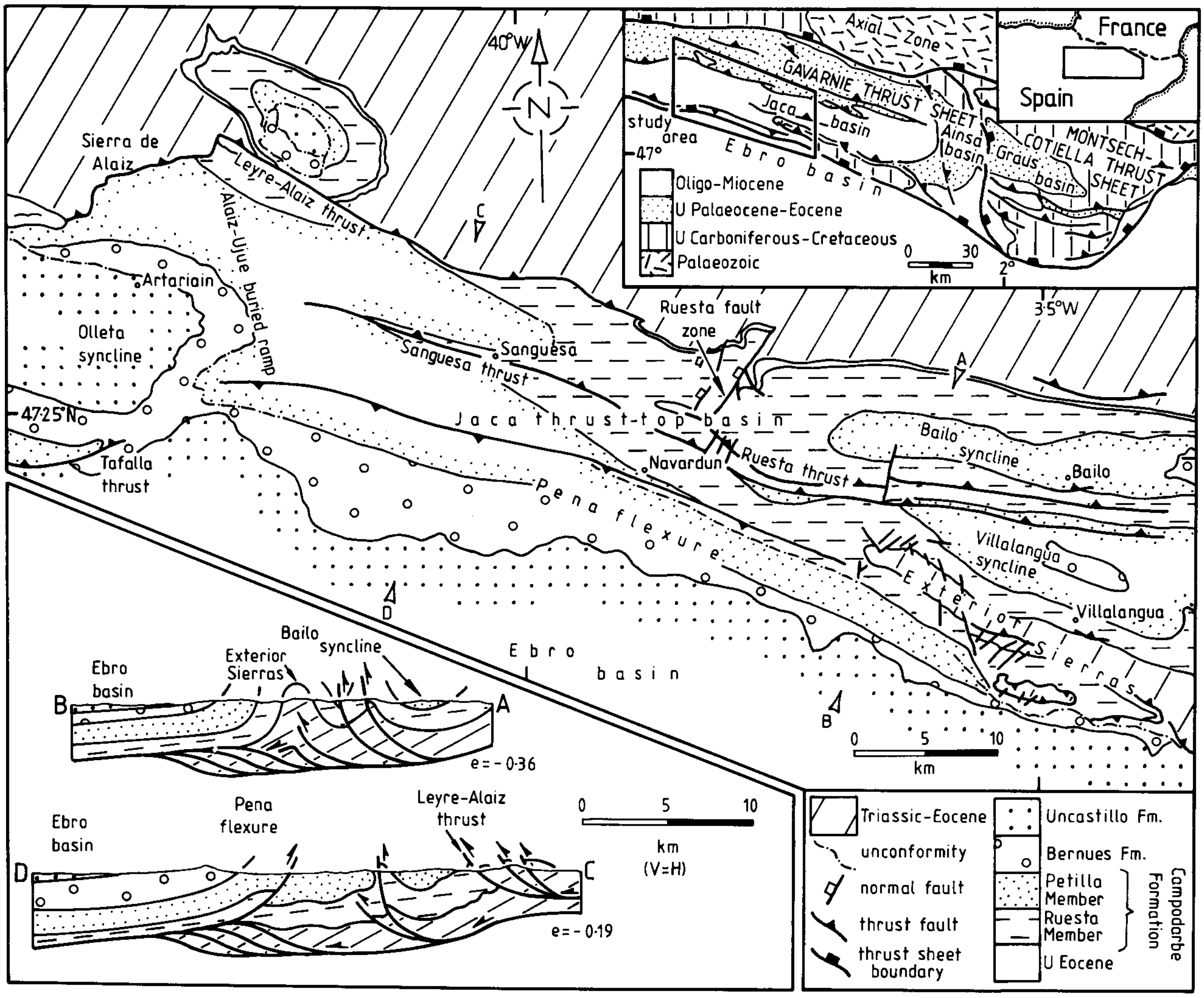


Fig. 1. Geological map of the West Jaca basin and adjacent parts of the Ebro basin. After Puigdefabregas (1975), Castiella *et al.* (1978) and Turner (1988). Inset of the tectonic setting of the study area modified from Seguret (1972), Choukroune & Seguret (1973) and Deramond *et al.* (1984). Sections are along lines A–B and C–D of main map. e is unit extension (negative extension indicates net contraction). Sections from Turner (1988).

METHODOLOGY

The methodological principles used in this study are those described by Hancock (1985, 1986). Mesofracture types, orientations, dimensions, spacings, architectures, morphologies and relative age relationships were recorded at 129 localities (stations) throughout the study area. Stations were sited so that all structural settings and stratigraphic horizons were sampled. At each station the dip of the beds is uniform and there are no significant variations in the fracture pattern throughout the sampled rock mass. The average size of stations is about 10,000 m^2.

Between four and 15 orientations of bedding planes and systematic mesofractures in each set were measured at each station. Arithmetic mean orientations were then calculated for each of these sets and plotted as great circles on equal-area, lower-hemisphere diagrams. These 'stereoplots' were then used to determine for each station the symmetry of the fracture system with respect to either the geometry of the fold containing the fractures, or the trend of the nearest part of the Pyrenean mountain front. The presence or absence of non-systematic fractures of superficial origin was noted, but their orientations were not plotted.

More than 85% of sampled mesofractures within the study-area are joints in the sense of being barren cracks on which, at the scale of observation possible in the field, there is no evidence of shear offset. The remainder of mesofractures are either thin (<10 mm) calcite veins or mesofaults across which displacements rarely exceed 1 m. Veins are most abundant in the Ruesta fault zone and mesofaults are commonest in the southern limb of the Villalangua syncline.

The order in which joints propagated was determined from abutting relationships, knowing that a younger joint abuts an older one. Only where there are mesofaults or veins was it possible to establish their relative ages on the basis of offsetting or cross-cutting relationships.

Assessing whether a joint set comprises extension, hybrid-shear or Coulomb-shear fractures was carried out using criteria suggested by Hancock (1985). In the West Jaca basin, the most workable criteria proved to be: (1) symmetry with respect to fold geometry; (2) conjugate angle (2θ); (3) symmetry with respect to nearby kinematic indicators, such as mesofaults or dilatational veins; and (4) joint-system architecture. The orientations of extension axes were inferred knowing that they are normal to single sets of extension joints and veins, and parallel to obtuse bisectors between conjugate hybrid-shear or Coulomb-shear joints (Fig. 2). Figure 2, which illustrates geometrical relationships between single or paired conjugate sets and bedding at imaginary stations, can also be used to interpret the stereoplots given in Figs. 3–6.

Most joints at the majority of stations were, without difficulty, assigned to well-ordered sets of subparallel surfaces. At a minority of stations, however, assignment to sets was more difficult because the joints are members of a coaxial angular continuum of orientations enclosing a maximum 2θ angle of 45°. Such joints can be interpreted as belonging to joint spectra (Hancock 1986), comprising roughly coeval extension and hybrid-shear fractures.

MESOFRACTURE SYSTEM GEOMETRY AND SYMMETRY

Figures 3–6, illustrating average systematic mesofracture and bedding plane attitudes at the 129 stations, show that the majority of fractures are either perpendicular to bedding or they subtend high angles with it. In addition, the figures demonstrate that sets are roughly symmetrical about layer dip and fold plunge within most parts of the West Jaca basin (Fig. 7).

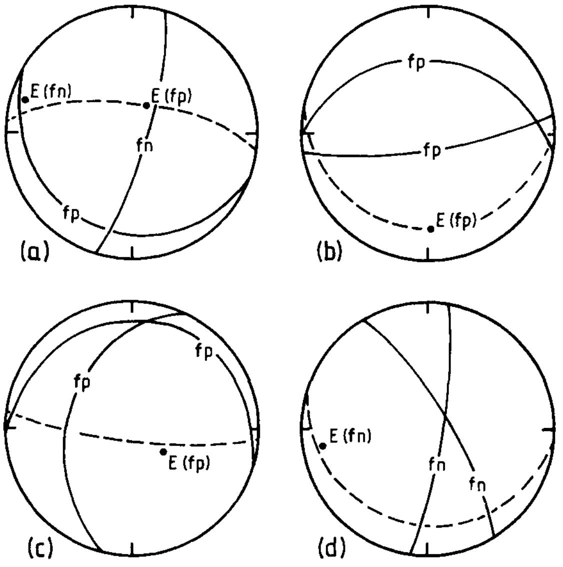


Fig. 2. Equal-area, lower-hemisphere projections ('stereoplots') illustrating relationships between characteristic front-normal (fn) and front-parallel (fp) mesofracture sets and the extension axis orientations (E) inferred from them. (a) Single sets of older front-normal and younger front-parallel mesofractures of the types shown, for example, in the steep limbs of the folds depicted in Figs. 7(a) & (d). (b) Conjugate front-parallel mesofractures at high angles to layering (e.g. gentle limb in Fig. 7b). (c) Conjugate front-parallel mesofractures roughly enclosing an acute angle about a fold axis (e.g. steep limb in Fig. 7c). (d) Conjugate front-normal mesofractures enclosing an acute bisector that is roughly normal to a fold axis (e.g. gentle limb in Fig. 7e). In all parts of the figure, bedding is represented by pecked lines and mesofractures by continuous lines.

The total number of mesofracture sets recognized in the West Jaca basin is eight. They belong to two single sets (parallel or perpendicular to fold axes) and three pairs of conjugate sets, each pair symmetrical about fold axes. In the Jaca basin, single sets and conjugate pairs of sets can be divided into two broad symmetry groups according to whether they (Figs. 7a,b & d) or the acute bisector between them (Figs. 7c & e), are parallel or normal to the Pyrenean mountain front; the term mountain front being used in the sense of Vann *et al.* (1986). The five sets of mesofractures in the former group are here called *front-parallel mesofractures,* while those in the latter group are referred to as *front-normal mesofractures* (Figs. 7 and 8). With only a few exceptions, the traces on bedding planes of front-normal mesofractures are normal or subnormal to bedding strike or the Pyrenean mountain front. Likewise, the traces of front-parallel mesofractures are parallel or subparallel to bedding strike or the mountain front.

The commonest mesofractures in the West Jaca basin belong to the single front-parallel set (e.g. Figs. 9a–c). This set is augmented or replaced in some layers by conjugate fractures (e.g. Fig. 9b). More rarely, a joint spectrum comprising an angular continuum of fractures enclosing an acute bisector perpendicular to a layer replaces the single front-parallel set (e.g. Fig. 9c—for a full description of this locality see Hancock 1986). Fractures in the single front-normal set are also abundant at some stations (e.g. Fig. 9a), and they too are locally replaced by conjugate sets (e.g. Fig. 9b).

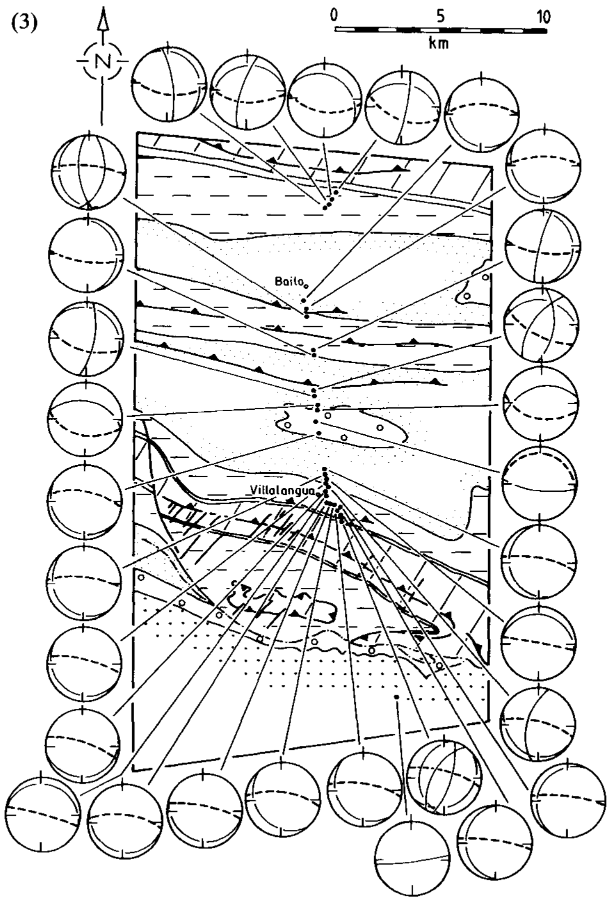
Front-parallel and front-normal mesofracture sets can also be recognized within the flat-lying rocks of the Ebro basin (Figs. 3–6 and 8). The number of sets is, however, smaller, there being a single vertical set of front-normal mesofractures and three sets of front-parallel mesofractures. One set in the latter group is generally vertical or subvertical. The other two sets are steeply inclined but strike parallel to the vertical set and occur only in the Uncastillo Formation south-southeast of Artarian (Fig. 6).

Although many mesofractures in the West Jaca basin are symmetrical with respect to the geometry of the fold containing them, some are asymmetric, fracture planes or the acute bisector between conjugate sets being up to 20° from the perpendicular to layering (Figs. 3–6). Likewise, some front-parallel single sets in the Ebro basin are subvertical, generally being inclined steeply south (e.g. Fig. 9d). Conjugate sets in the Ebro basin are mainly symmetrical about a vertical bisector (e.g. Fig. 9e).

ORDER AND TIMING OF MESOFRACTURE DEVELOPMENT

Abundant abutting relationships between joints, and rare offsets across mesofaults, indicate that front-normal systematic mesofractures are older than front-parallel systematic mesofractures in the West Jaca and Ebro basins (Figs. 3–6 and 9a & b). Both groups are accomp-

(3)



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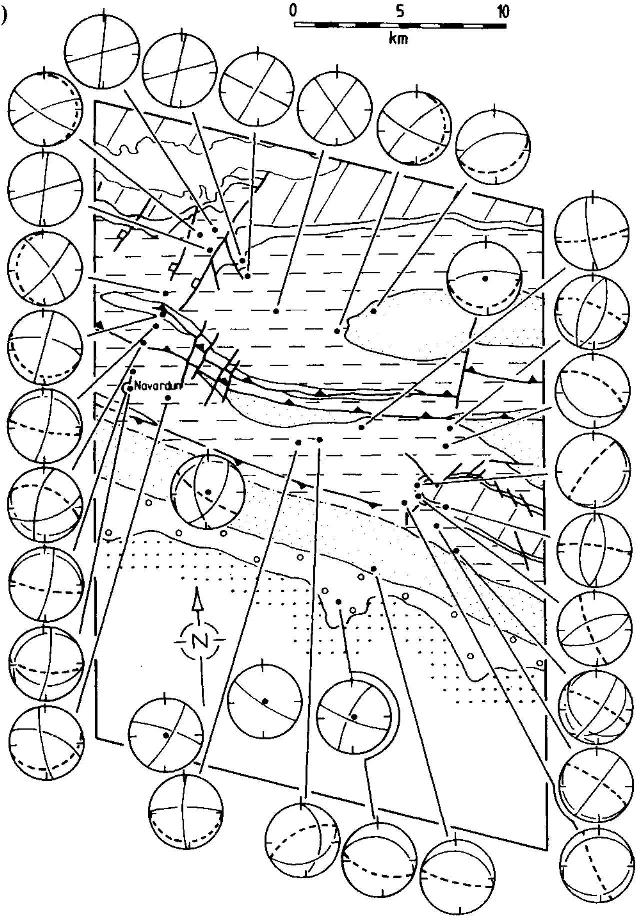
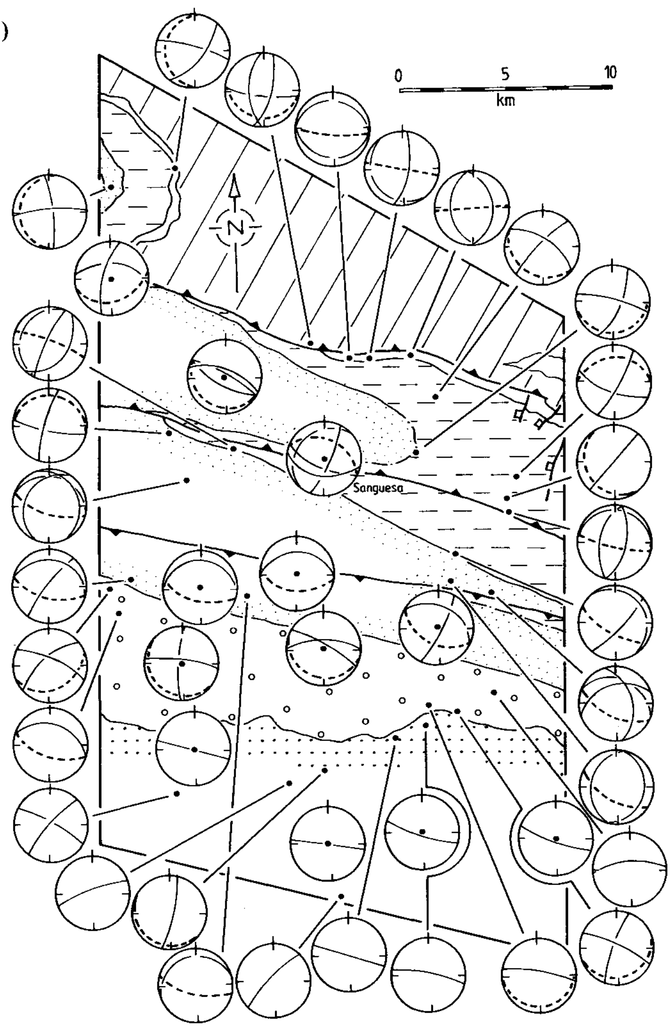


Fig. 3. Stereoplots for 30 stations showing the mean orientations of mesofracture sets in the eastern part of the study-area. Bedding is represented by pecked lines and mesofractures by continuous lines. A great circle representing the orientation of a younger mesofracture set is shown broken where it crosses that of an older mesofracture set. Great circles that cross each other without interruption depict conjugate sets. Where bedding is not shown the rocks are horizontal. Lithological ornament and structural symbols are as in Fig. 1.

Fig. 4. Stereoplots of mean mesofracture and bedding plane orientations at 33 stations in the east-central part of the study-area. Symbols and conventions as in Fig. 3.

(5)



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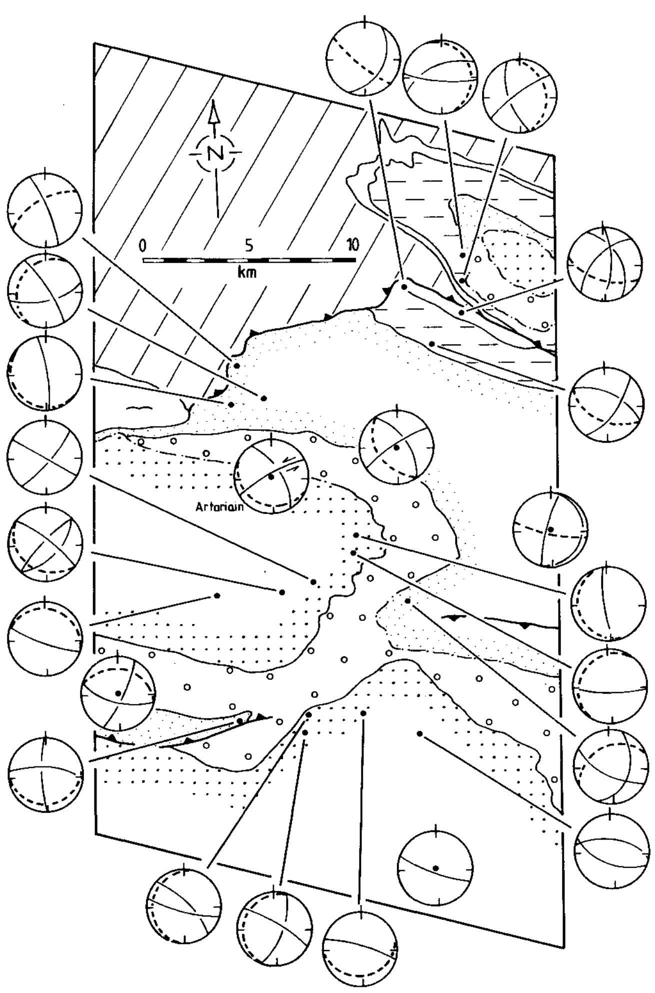

Fig. 5. Stereoplots of mean mesofracture and bedding plane orientations at 42 stations in the west-central part of the study-area. Symbols and conventions as in Fig. 3.

Fig. 6. Stereoplots of mean mesofracture and bedding plane orientations at 24 stations in the western part of the study-area. Symbols and conventions as in Fig. 3.

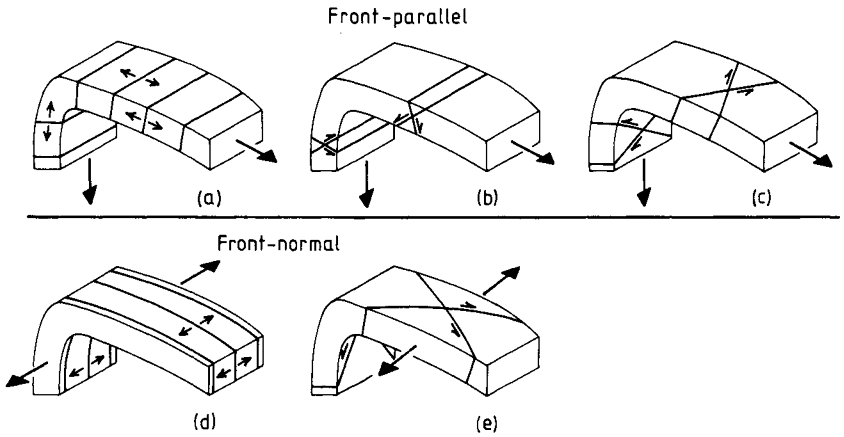

Fig. 7. Relationships between mesofracture sets and folds in the West Jaca basin. (a) Single set of front-parallel extension fractures. (b) Conjugate sets of front-parallel fractures at high angles to layering. (c) Conjugate sets of front-parallel fractures enclosing an acute angle about the fold axis. (d) Single set of front-normal extension fractures. (e) Conjugate sets of front-normal fractures enclosing an acute angle about a bisector normal to a fold axis. Bulk extension axes inferred from the fractures are shown. The diagram is schematic and it should be noted that fractures at many stations are not as perfectly symmetrical as those illustrated.

anied by small younger non-systematic joints. In the Ruesta fault zone the oldest joints strike parallel to, or enclose an acute bisector about, faults in the zone (Figs. 4 and 5).

In the absence of an unconformable cover of younger sediments there is uncertainty about the absolute ages of front-normal and front-parallel mesofractures. Because the majority of fractures are joints not displaying signs of reactivation it is probable that most of them propagated after Oligo-Miocene folding had started. The most commonly reactivated joints in the Jaca basin belong to the front-parallel group in the southern limb of the Villalangua syncline (Fig. 9f). The reactivation of fractures in this group is, however, to be anticipated because many of them occur in beds rotated through at least 90° and they strike parallel to fold axes. Older front-normal fractures are less likely to have been reactivated, although some veins normal to a fold hinge and cutting a layer of sandstone within the moderately N-dipping limb of the ramp anticline, 13 km east-southeast of Sanguesa, were reactivated as small mesofaults displaying no consistent sense of offset (Fig. 9g).

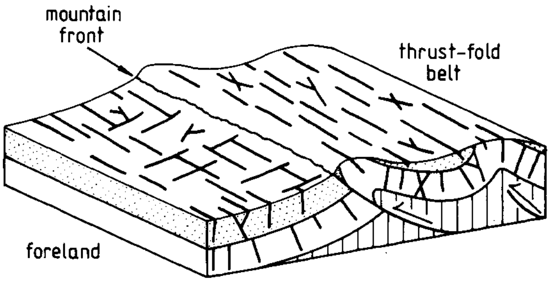

Fig. 8. Cartoon illustrating typical joint-system architectures characteristic of front-normal and front-parallel joint domains in both the thrust-fold belt of the West Jaca basin and the undeformed rocks of the Ebro basin foreland.

FRACTURE CLASSES AND INFERRED BULK EXTENSION DIRECTIONS

In this section, the genetic classes (i.e. extension, hybrid-shear, Coulomb-shear) of mesofracture sets are discussed and directions of bulk extension are inferred from them. The most abundant of the rare kinematic indicators are thin (<10 mm) calcite veins, most of which are non-fibrous but possess matching walls indicating that their formation involved pure dilatation. Parallel to these non-fibrous veins, which belong mainly to single sets (Figs. 7a & d), there are a few fibrous calcite veins containing growth fibres orientated normal to vein margins, which also indicate that extension was perpendicular to fracture walls.

With the exception of front-parallel or front-normal fractures that were reactivated in shear (Figs. 9f & g), the majority of mesofaults are parallel to the system of conjugate front-parallel fractures at high angles to layering (Fig. 7b). Some of these faults are also calcite veins containing growth fibres indicative of dip-slip. The sense of slip on such mesofaults, which occur most commonly in the nearly vertical southern limb of the Villalangua syncline, is extensional when sedimentary layering is taken as defining the datum plane. Other mesofaults have layer-parallel slip vectors, displacements being either dextral or sinistral when bedding planes are viewed in plan (Figs. 7c & e and 9b).

Veins in single sets are interpreted as extension fractures because there is dilation normal to them as indicated by matching crack walls or the orientation of mineral fibres. Front-normal and front-parallel joints in single sets are also interpreted as extension fractures because they: (1) are orientated normal or parallel to fold axes, respectively; (2) are parallel to dilational veins; (3) display in thin-section matching walls indicative of pure dilation. In addition, where both sets occur together their traces define either T- or +-shapes, joint-

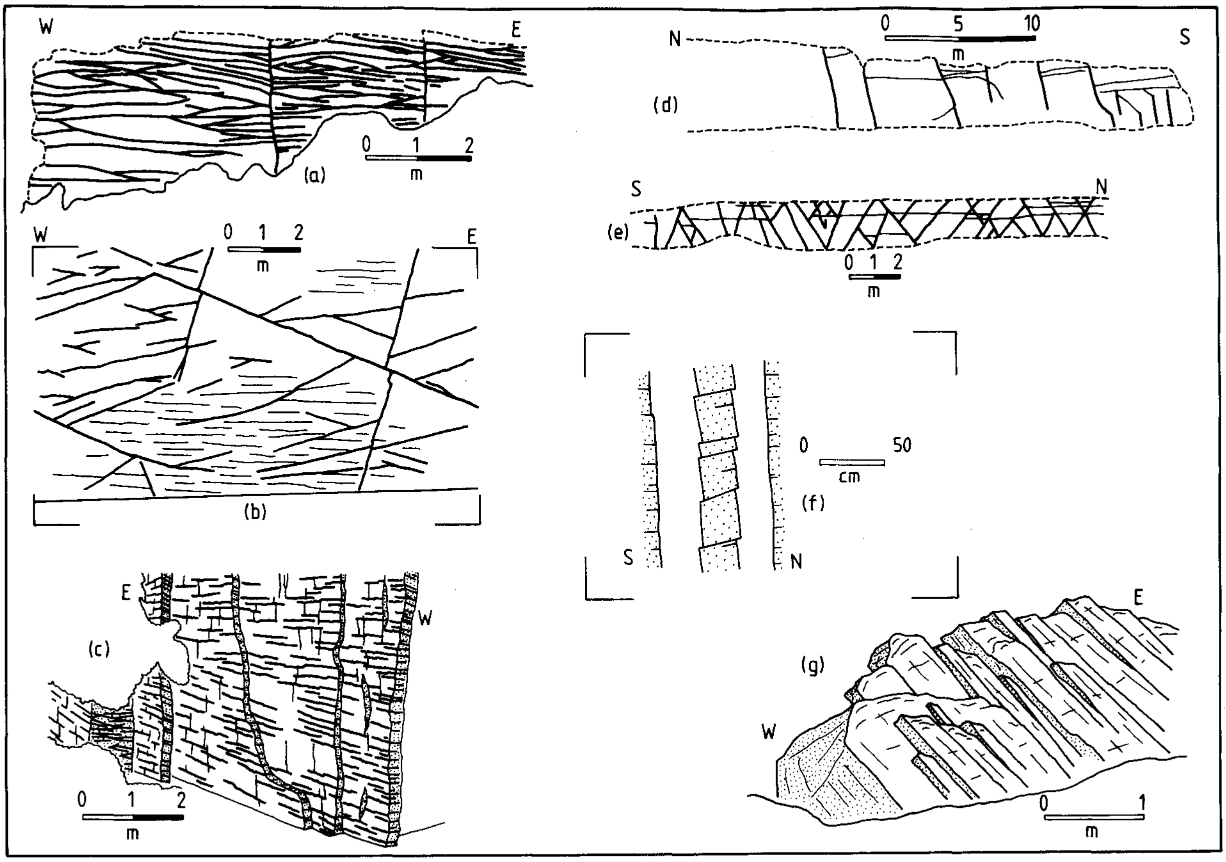

Fig. 9. Sketches from photographs illustrating field relationships between mesofracture sets at seven stations. (a) Traces of front-normal (vertical) and front-parallel (horizontal) single sets exposed on the upper surface of a bed of vertical sandstone. Note that many front-parallel traces abut front-normal traces. 3 km SSE of Bailo. (b) Traces of front-normal (steep) and front-parallel (horizontal and gentle) mesofractures exposed on the lower surface of a nearly vertical bed of sandstone. Note the offset of the front-normal fractures by a mesofault belonging to one set in the conjugate system of front-parallel fractures (see Fig. 7c). About 1 km ENE of Villalangua. (c) Nearly vertical beds of sandstone cut by closely spaced front-parallel joints. The lower thin beds (right) contain a single set of extension fractures while the thicker upper bed (far left) is cut by a joint spectrum, first described by Hancock (1986). 1 km NE of Villalangua. (d) A single set of extension joints inclined steeply south and cutting a horizontal bed of sandstone in the Ebro basin. Monte Aragon, near Huesca. (e) Conjugate steeply inclined front-parallel joints cutting a horizontal bed of sandstone in the Ebro basin. Ujué, 13 km SE of Artariain. (f) Profile view of reactivated front-parallel extension joints cutting vertical sandstones in the southern limb of the Villalangua syncline. 0.5 km E of Villalangua. (g) Front-normal extensional veins reactivated in shear, displacing inclined bedding planes within the fore-limb of a ramp anticline. 13 km ESE of Sanguesa.

system architecture characteristic of orthogonal extension joint sets according to Hancock (1985). A few front-normal joints north of Bailo and in the Ruesta fault zone (Fig. 1) bear plumose (hackle) marks, which are generally interpreted as occurring on extension fractures (Hancock 1985).

Joints in the three pairs of conjugate sets are interpreted as being either hybrid-shear or Coulomb-shear fractures depending on whether the 2θ angle they enclose is in the range 10–50° or is about 60°, respectively. The principal reasons for thinking that joints in these systems are hybrid-shear or Coulomb-shear fractures is that they: (1) are obliquely but symmetrically arranged about layering and fold axes; (2) are parallel to rare mesofaults; and (3) define V-, X- and Y-shaped architectural styles (Figs. 9b & e). Joint spectra in which the 2θ angle is less than 45° are interpreted as consisting of extension and hybrid-shear fractures.

From either the single set or the two pairs of conjugate sets of front-parallel mesofractures in the West Jaca basin it is possible to infer that the direction of bulk extension during their formation was either parallel to, or roughly parallel to, layering and normal to fold axes and the mountain front (Figs. 7a–c). During the development of the three front-normal sets, bulk extension was parallel to, or roughly parallel to, fold axes (Figs. 7d & e). In the Ruesta fault zone, bulk extension was nearly horizontal and normal to the NNE–SSW strike of faults in the zone. The important conclusion that the three sets of front-normal mesofractures are kinematically compatible with each other and formed before the five sets of front-parallel mesofractures (also kinematically compatible with each other) requires explanation.

MESOFRACTURE DOMAINS: THEIR ORIGINS AND SIGNIFICANCE

Two principal mesofracture (joint for brevity) domains can be recognized. The first type, here called a *front-parallel joint domain* is an area containing only front-parallel systematic mesofractures. The second type, called a *front-normal joint domain* contains both front-normal and front-parallel mesofractures (Fig. 10).

Much of the study-region is a front-parallel joint domain but it contains several front-normal joint domains. Each elongate (<3 km wide) front-normal joint domain is everywhere coincident with the proximal part of the footwall to an emergent thrust trace (Fig. 10). The remaining parts of footwalls form the hangingwalls of adjacent thrust sheets, and correspond to front-parallel joint domains.

The Ruesta fault zone coincides with a roughly equilateral joint domain within which the strikes of extension fracture sets, or the acute bisectors of conjugate sets, are parallel to the trends of faults in the zone. The strikes of some of these faults depart by up to about 10° from the normals to nearby fold axial traces. Because: (1) the shape of the domain is not elongate parallel to thrust traces; (2) veins are abnormally abundant in the Ruesta fault zone; and (3) joints in the zone are symmetrical about the faults it contains, we consider that the zone defines a special type of domain—here called a *lateral ramp joint domain.*

Bulk extension directions for each of the three joint domains are as follows (see Fig. 10):

(1) mainly WNW–ESE, but ranging from E–W to ENE–WSW, within the front-normal domain;

(2) mainly NNE–SSW, but ranging from N–S to NNW–SSE, within the front-parallel domain; and

(3) WNW–ESE in the Ruesta lateral ramp domain.

Figure 11 is a set of three cartoons illustrating how such extension directions could be generated during contraction within and adjacent to the West Jaca thrust-top basin. To appreciate how front-parallel extension in the immediate footwall of a thrust could arise, consider the thrust geometries shown in the map on Fig. 11(a). There is a displacement gradient which increases from zero at each lateral tip to a maximum in the central part of the thrust. Such a displacement gradient also implies a loading gradient in the footwall of the thrust sheet. Strain related to this loading could be accommodated by strike-parallel elongation and expressed by the development of front-normal mesofractures. This model also implies that front-normal mesofractures were propagated before collapse and detachment of the footwall containing them. Support for this idea comes from relationships exposed in the hinge zone of the ramp anticline 13 km ESE of Sanguesa, where front-normal fractures predate radial tension veins formed during folding.

Once detachment had occurred there was also localized front-parallel stretching within hangingwalls. As shown in the strike section (Fig. 11b), this is likely to be most effective above lateral ramps. In the Ruesta fault zone, stretching was largely accommodated by the formation of NNE-striking hangingwall-collapse faults, but a minor proportion of the strain was achieved by the development of extension and hybrid-shear fractures in a sub-area that defines the lateral ramp joint domain.

An explanation is required as to why the buried Alaiz-Ujue ramp, a structure subparallel to the local thrust transport direction (Fig. 1), is not accompanied by a lateral ramp joint domain. A reason for this might be that the rocks above the present ramp were cut by pre-existing front-parallel sets that propagated before reactivation of the Sierra de Alaiz thrust and the 45° anticlockwise rotation of the Artariain block. These events were responsible for developing the ramp according to Turner (1988). During SSE-directed thrust transport over the ramp, pre-existing mesofractures were reactivated in shear, resulting in small sinistral displacements on some of them.

Two mechanisms that probably augment each other are thought to be responsible for the widespread front-parallel fractures that accommodate N–S extension

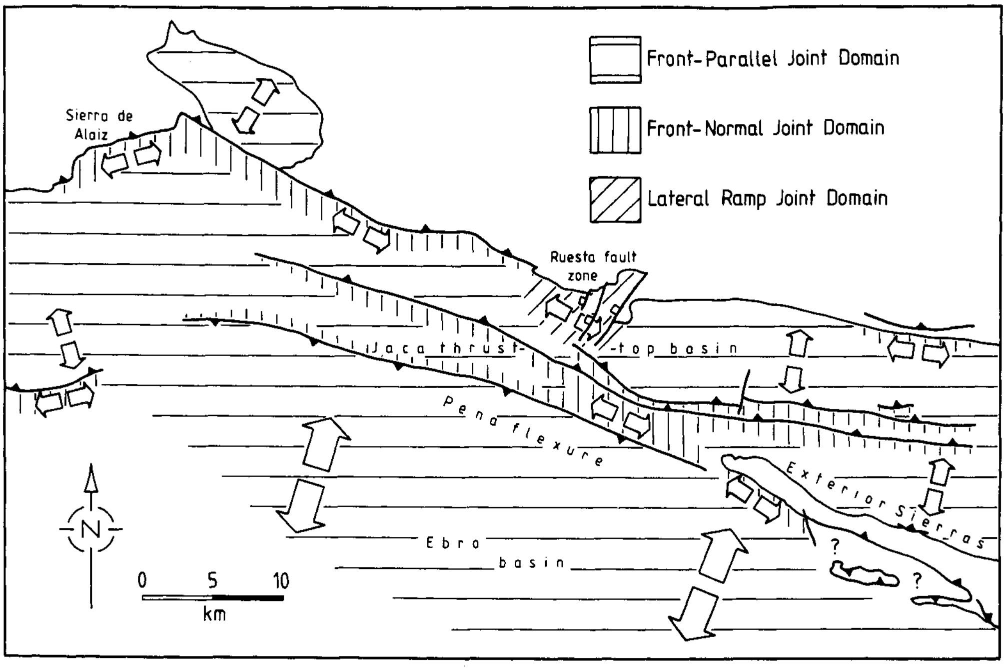

Fig. 10. Joint domains, inferred bulk extension directions (open arrows) and their relationships to thrust geometry in the West Jaca and Ebro basins, N. Spain. Structural ornament as in Fig. 1.

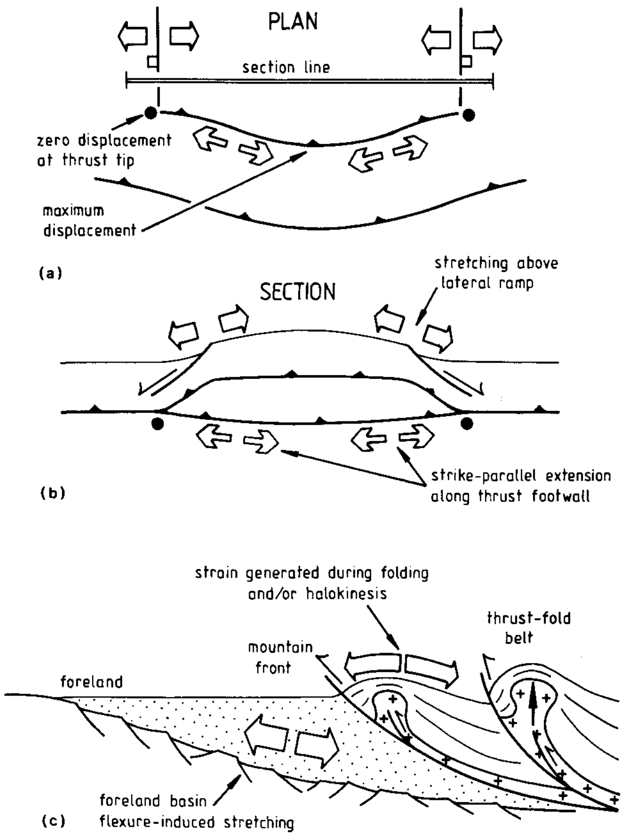

Fig. 11. Cartoons illustrating mechanisms for generating the extensional strains responsible for jointing in the West Jaca and Ebro basins. (a) Schematic plan view of thrust traces and extension directions in a footwall. (b) Cross-section showing front-parallel extension above lateral ramps. (c) Schematic N–S profile showing front-normal extension related to stretching in amplifying folds (partly driven by salt doming) and the flexing of a foreland basin basement during thrust loading. For details see the text.

within the West Jaca thrust-top basin, a tectonic unit that was experiencing N–S regional contraction. Firstly, normal to fold axes and parallel to layering there was stretching above neutral surfaces within developing folds. Such stretching was reinforced where salt doming during the buoyant rise of Triassic evaporites above the tips of blind thrusts in anticlinal cores caused additional fold amplification (Fig. 10c). Because folding and filling of the thrust-top basin were synchronous processes, stretching of layers in growth fold limbs was greater lower in the succession. Hancock (1985) proposed that this enhanced growth-fold-related stretching on the limbs of the Villalangua syncline was responsible for forming the very closely spaced front-parallel extension joints that it contains (e.g. Figs. 9a & c).

Most mesofractures in the front-parallel joint domain of the West Jaca basin were propagated after or during the closing stages of fold amplification. This inference is largely based on the observation that only a few joints have been reactivated. Reactivation in shear of former extensional strike-joints would be common had the fractures developed early during folding. The high degree of symmetry of the joints with respect to the folds containing them does, however, suggest that they reflect small strains imposed during the closing stages of folding.

Although the widespread and well-developed front-parallel mesofractures in the West Jaca basin can be accounted for by invoking geometrically necessary strains generated during folding, this mechanism is inadequate to explain the occurrence of pervasive front-parallel joints in the gently tilted or horizontal sediments of the Ebro basin. Front-normal, N–S stretching of this otherwise largely undeformed foreland basin sequence could be related to one or both of two mechanisms. (1) Above the passive-roof duplex underlying the Pena flexure the northwards-overriding wedge of Ebro basin rocks (Fig. 1) was elongated during flexing. (2) Extensional stresses were transmitted up into the foreland basin sequence from the underlying 'basement' which was being flexed as a consequence of thrust loading (Fig. 11c). Because front-parallel extension joints occur up to 25 km south of the Pyrenean mountain front and within horizontal rocks, we prefer this second explanation. It is also capable of explaining why some of the front-parallel extension joints are not vertical but dip steeply south (Figs. 3–6 and 9d). The plunge of the direction of stretching at the depth where joints were being initiated and propagated would be parallel to the top surface of the flexed 'basement', although beds at that depth would not be precisely parallel to the basement–cover interface as a result of basin filling being syntectonic.

If the relationship between type of joint domain and structural setting that exists in the West Jaca and Ebro basins occurs in other thin-skinned thrust terrains it follows that information about the joint pattern in a sub-area permits prediction of the location of that sub-area with respect to the footwall or hangingwall of a thrust or lateral ramp. Such predictions could be of commercial significance during exploration for and production of hydrocarbons in a poorly exposed terrain.

CONCLUSIONS

(1) The distribution of joint domains in the West Jaca and Ebro basins reflects thrust system geometry and evolution. Three types of domain are recognized. Front-normal joint domains contain older joints striking normal or subnormal to the Pyrenean mountain front and younger joints striking parallel to the front. These domains are coincident with the immediate footwalls of thrusts. A lateral ramp joint domain contains joints striking subparallel to the trend of a buried lateral ramp. Front-parallel joint domains, containing mesofractures striking parallel or subparallel to the front, underly the remainder of the West Jaca basin and adjacent parts of the Ebro basin. Front-parallel joints are superimposeed on older mesofractures in the front-normal and lateral ramp joint domains.

(2) Mesofractures in front-normal joint domains are related to extension that acted parallel to the mountain front as a result of the thrust loading of footwalls. Stretching above a lateral ramp was responsible for the formation of mesofractures in the lateral ramp joint domain. Mesofractures in the front-parallel joint

domains of the West Jaca basin were generated by stretching during growth-fold amplification, that was partly driven by salt doming. Front-parallel joints in the Ebro basin are probably related to the stretching of a succession above a foreland basin basement that was flexed during thrust loading.

(3) The recognition of a joint domain in the West Jaca and Ebro basins permits the structural setting of a subarea with respect to an emergent thrust to be predicted.

Acknowledgements—We thank M. P. Coward and G. D. Williams for their encouraging comments on several aspects of this work. E. J. M. Willemse and A. McCaig provided incisive and detailed reviews. J. P. Turner is grateful for the support provided by a Scholarship from Shell International Petroleum Company Limited. P. L. Hancock's fieldwork was funded by The Royal Society, Shell and the University of Bristol.

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