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Fringe cracks and plumose structures in layered rocks: stepping senses and their implications for palaeostress interpretation

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Abstract

Many joint surfaces show en échelon arrays of microfractures (fringe cracks, F-joints, twist hackles) along fringe zones in continuity with plumose structures. In layered rocks, joints with two fringe zones showing opposite stepping senses at the top and bottom (type A) are more frequent than those showing a single stepping sense (type P). Consistent with such an arrangement, their curved advancing fronts show continuous, 180°-radial patterns of steps showing a 'spiral-staircase' geometry. In double plumose structures diverging from an initiation point, different combinations of symmetry elements allow us to define four basic stepping types: (type PA) single stepping sense on the full joint surface; (type AA) opposite stepping senses at both fringes; (type PP) opposite stepping senses at both sides of the starting point; (type AP) four alternate quadrants with opposite stepping. Most of these types have been observed in limestone beds of the Mequinenza area (Ebro Basin, Spain) and Glamorgan coast (South Wales). According to our observations, the varied stepping arrangements are independent of changes in orientation within the parent joint, the latter showing more persistent strikes than fringe cracks. All these features suggest that fringe crack arrays in continuity with plumose structures are related to local stress redistribution at the advancing front and, as a general rule, do not record remote stresses. After careful observation and discrimination, only those en échelon cracks consistently stepped and showing no geometric continuity with plume barbs should be included in palaeostress analysis.

Keywords: Fringe cracks; Plumose structure; Palaeostress; Joint propagation

1. Introduction: the question of stepping sense of fringe cracks (twist hackles, F-joints) in the literature

Plumose structures in joint surfaces can be interpreted in the light of Fractography as indicators of direction and sense of fracture propagation, as done since the earliest descriptions (Woodworth, 1896). In layered rocks, plumose structures usually develop a symmetry axis parallel to the layer (*herringbone* type; Syme-Gash, 1971). Sometimes, they are flanked by one or two fringe zones of small en échelon fractures, the latter being commonly designated as *fringe joints, F-joints* (Hodgson, 1961; Syme-Gash, 1971; Ramsay and Huber, 1987), *twist hackles* (Kulander et al., 1979) or *fringe cracks* (Younes and Engelder, 1999). We refer to 'two fringe zones' instead of 'two fringes' because, according to the definition by Woodworth (1896), a fringe is a single region that surrounds the main joint plane. Therefore, where two fringe zones at the top and bottom of a bed are observed, they actually belong to a unique fringe, which may be either completely or partially exposed depending upon outcrop conditions.

En échelon fringe cracks propagate from the parent joint (main joint face) by rotating their orientation (up to an angle of 5–30°) either smoothly or sharply. In smooth or continuous break-up, small planes spring out from the edge of the parent joint and turn gradually. Continuity between plumose structure and F-joints is observed in this case, the latter being a prolongation of the plume ridges or barbs, which increase their relief from delicate striae up to differentiate into distinct fracture surfaces. Where break-up is sharp or discontinuous, mirror and fringe are clearly separated, the boundary being frequently marked by an edge or shoulder (Woodworth, 1896; Hodgson, 1961). Ramsay and Lisle (2000, p. 949) and Younes and Engelder (1999) suggest that the presence of a smooth or sharp boundary on the parent joint depends on whether bedding is marked by a gradual or abrupt change in lithology.

The geometric continuity from plume ridges to en échelon cracks, clearly shown in sketches and descriptions by numerous authors (Woodworth, 1896; Ramsay and Huber, 1987, p. 659; Younes and Engelder, 1999, fig. 1), suggests that one structure evolves into the other as the main joint propagates. The process is essentially the same no matter

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how sharp and pronounced the break-up is. So, the genetic meaning of such en échelon cracks is independent of (a) the amplitude of their relief, (b) the angle of twisting, and (c) their sharp or smooth transition to the parent joint. As soon as the steps can be recognized with the naked eye and a twist angle as small as 1° (the usual resolution of the compass) can be measured, the existence of an en échelon crack array should be accepted.

A classic view of F-joints is represented by Hodgson's (1961) diagram, in which only the upper fringe zone of a joint is shown. Actually, most plume structures in layered rocks have their axes much closer to one of the interfaces and therefore only a very small percentage of them show both fringe zones. This can explain why the vast majority of published sketches show a single fringe-crack array close to the top of the bed (e.g. Kulander et al., 1979; Davis and Reynolds, 1996; Younes and Engelder, 1999).

Very few works, such as that by Bankwitz and Bankwitz (1984), have focussed on the distribution of stepping senses within fringe crack arrays. In layered rocks, owing to the scarcity of joints with double fringe boundaries, comparison of the sense of stepping of en échelon crack arrays at the lower and the upper fringe zones has not received enough attention. The case of single stepping sense is well documented in the literature (e.g. Price and Cosgrove, 1990, fig. 2.13b; Bahat and Rabinovitch, 2000, fig. 1d; Bahat et al., 2001b, fig. 4), and it has been considered to be the unique arrangement by Ramsay and Lisle (2000, p. 949). Nevertheless, cracks with opposite sense of stepping at both sides of a plume can also be found. As an example, Ramsay and Huber (1987, fig. 27.32) show a plumose marking with a number of incipient en échelon cracks, which indicate that faint opposite twisting occurred at both sides of the plume axis during propagation.

On the other hand, examples of fringe cracks showing a radial pattern at the curved advancing joint front are frequent in the literature, either in natural joints or in artificially generated fractures in laboratory tests on glass or other man-made materials (De Freminville, 1914; Bankwitz, 1966; Sommer, 1969; Pollard et al., 1982; Holloway, 1986, all in Bahat, 1991; Suppe, 1985). Almost in every case, if we follow the steps around the propagating front, the stepping sense does not change. In this way, after completing a turn of 180°, two fringe zones at the top and bottom of a bed would show opposite stepping senses for an external observer ('spiral-staircase' geometry). The only exceptions we have found are a plumose structure developed experimentally by Müller (2001, fig. 3a) in a starch–water mixture and a natural example described by Bahat et al. (2003, fig. 12). In this case, radial hackles show opposite steps at both sides of a symmetry plane—'opposite' to each other within the curved advancing front, thus giving rise to a single stepping sense at both fringes for an external observer.

2. Scope of the work

According to the above described stepping patterns, two distinct geometric types can be defined for joints developed in layered rocks, in which both en échelon arrays of fringe cracks and radial hackles around curved rupture fronts are consistently related to each other (Fig. 1). It is useful to refer to their symmetry elements as a tool for description:

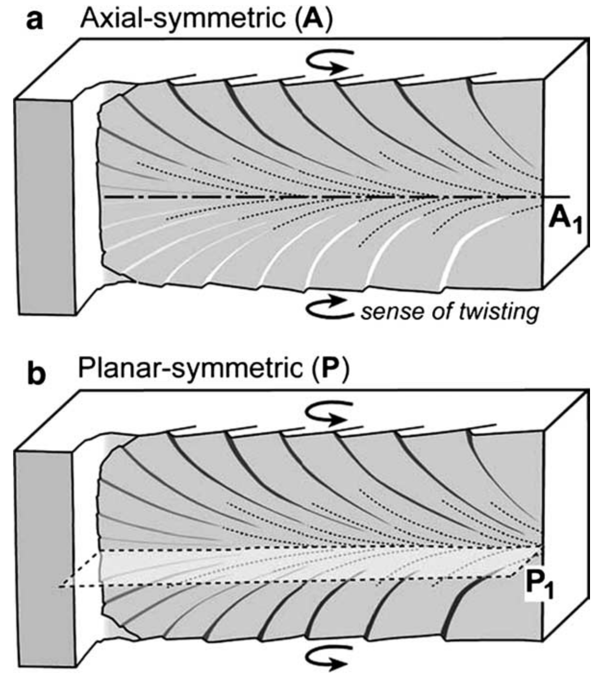

Fig. 1. The two basic models of stepping geometries of fringe cracks. (a) Type A: opposite sense of stepping; (b) Type P: single sense of stepping. A_1: symmetry axis; P_1: symmetry plane.

(a) Axial-symmetric (type A): fringe cracks with opposite stepping senses at the top and bottom fringe zones, which are joined at the propagating front by radial steps showing a continuous 'spiral-staircase' arrangement (Fig. 1a). The plume axis represents a binary symmetry axis (A_1) for the stepping relief of fringes.
(b) Planar-symmetric (type P): fringe cracks with single stepping sense at both fringe zones, which are separated at the curved advancing front by a symmetry plane (P_1) from which steps either converge or diverge (Fig. 1b).

Keeping in mind these two basic geometric models, systematic field surveys were carried out in two regions with widespread joint systems showing good examples of plumose structures: the Ebro Basin, southern Pyrenean front (Spain) and Welsh margin of the Bristol Channel Basin (UK). Our first purpose was to estimate the frequency of single and double stepping senses at fringe crack arrays of natural joints (types A and P). Second, a brief discussion on the mechanical constrains of both geometric patterns is an obvious need, focussed on their eventual relationship with fracture propagation modes, regional stress fields or local stress redistribution. Finally, the mechanical interpretation of en échelon arrays of fringe cracks has decisive implications for palaeostress analysis of joint systems. Usefulness of F-joints as palaeostress indicators will depend on whether they are related or not to remote stresses.

3. Results of field surveys in NE Spain and South Wales

Jointing in Tertiary limestones and sandstones of the Ebro Basin and southern Pyrenees (NE Spain) has been intensively studied in the last 20 years (Hancock and Engelder, 1989; Simón, 1989; Hancock, 1991; Arlegui, 1996; Arlegui and Simón, 2001). A previous file of field photographs and detailed schemes had been compiled in this region (Fig. 2a and b) before the present study was initiated. It contained 25 cases (74%) of joints showing two fringe zones (with twist hackles clearly connected to plumes through smooth fringe boundaries) in which stepping pattern corresponds to type A (Fig. 3a and b). On the other hand, nine cases (26%) can be classified as type P (single stepping sense at the upper and lower fringe zones; Fig. 3d).

Having in mind that, as a general rule, schemes and photographs represent only the most conspicuous examples found during field surveys, one could believe that the former case collection did not constitute a representative sample. We tried to reduce such bias by collecting new cases after systematic inspection of every joint fringe in a number of selected outcrops.

The first specific field survey was carried out at several classic localities for joint research along the Glamorgan coast

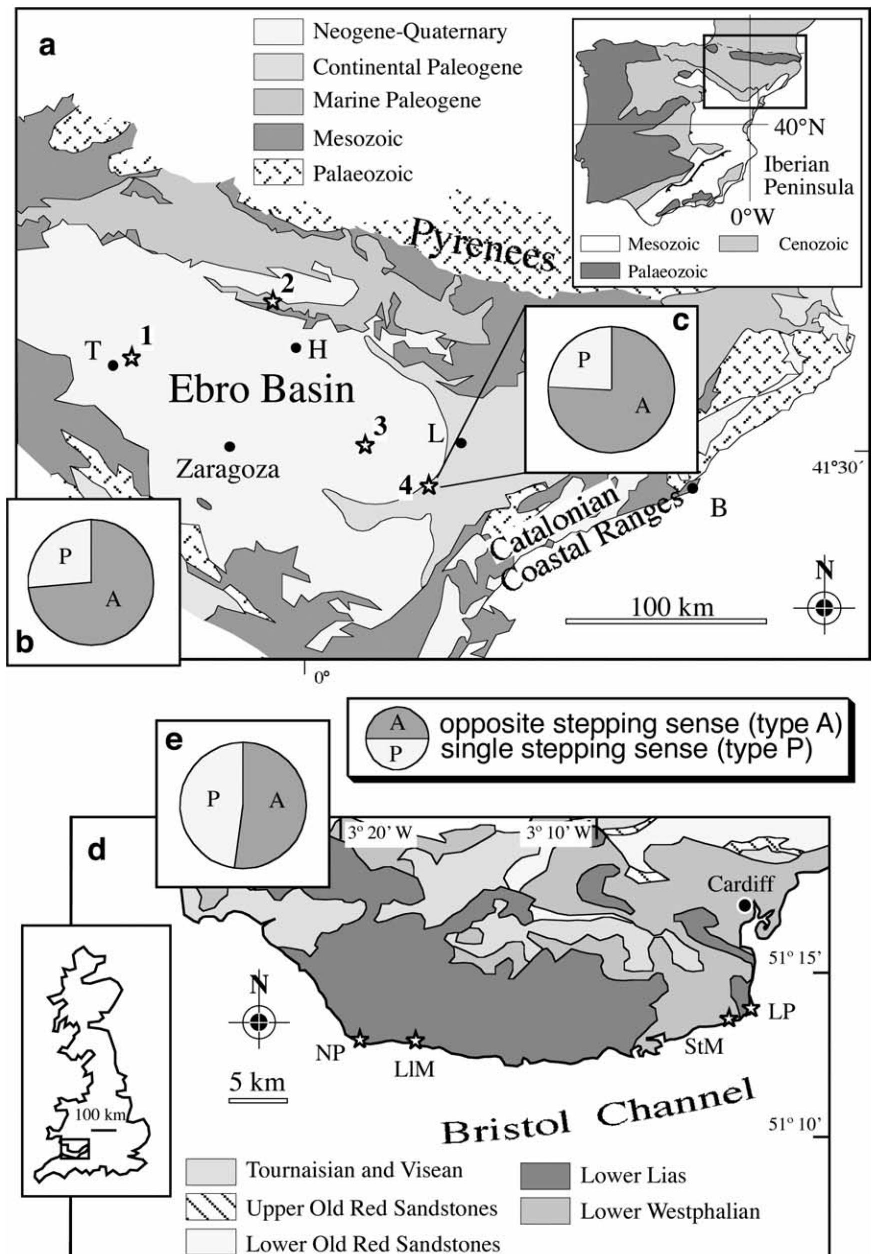

Fig. 2. (a) Location map of the studied areas in NE Spain. 1–4: location of field examples. T: Tudela; H: Huesca; L: Lleida; B: Barcelona. (b) Frequency of the observed types of stepping sense in previous surveys. (c) Frequency of the observed types of stepping sense at Mequinenza. (d) Location map of the studied areas in South Wales. NP: Nash Point; LlM: Llantwit Major; StM: Saint Mary's Well Bay; LP: Lavernock Point. (e) Frequency of the observed types of stepping sense in South Wales.

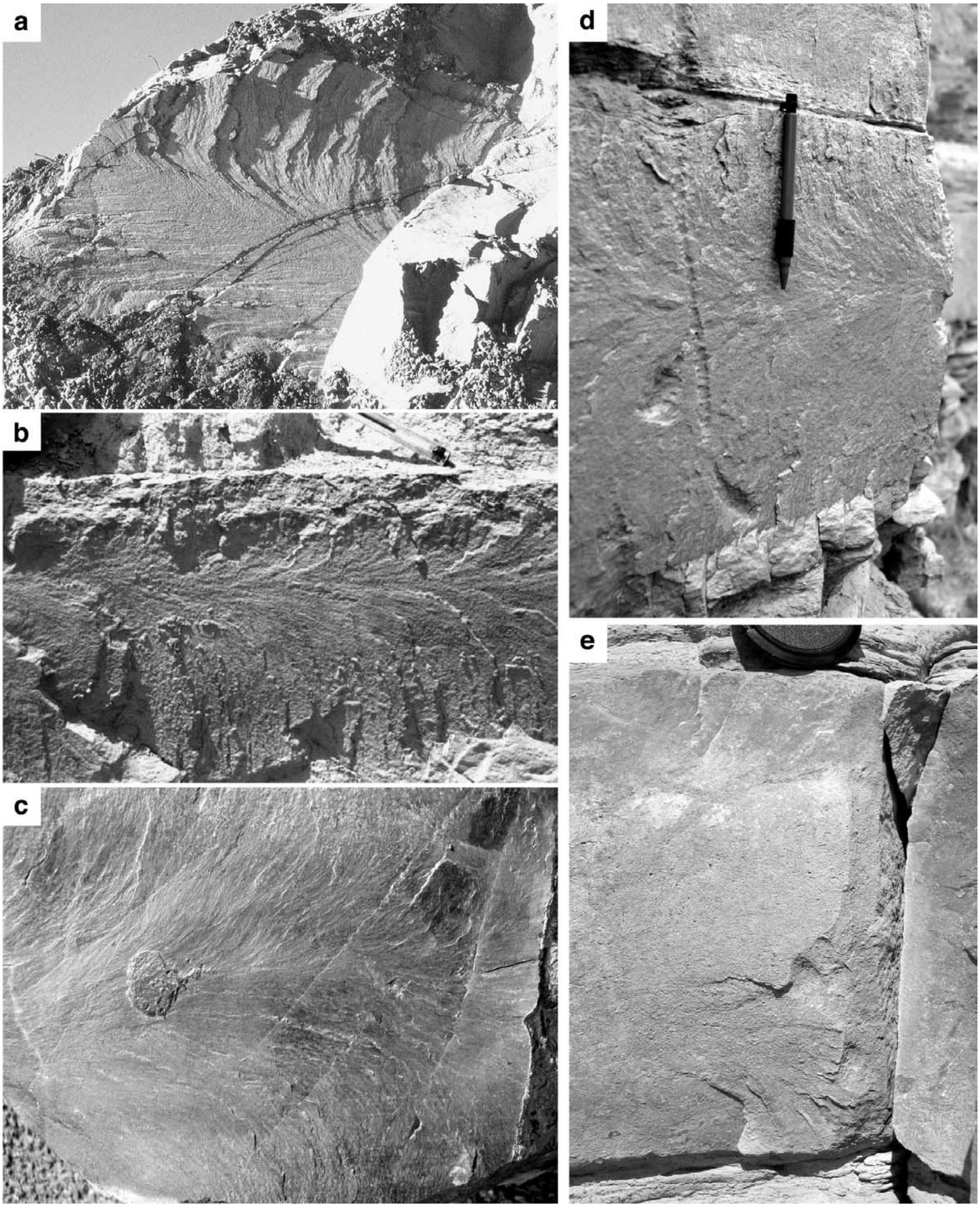

Fig. 3. (a) Plumose structure with opposite stepping senses at the top and bottom fringes (type A). Eocene marls, Arguis (location 2 in Fig. 2a). (b) Same as (a); the transition from one fringe to the other can be observed at the right hand. Upper Oligocene limestones near Mequinenza (location 4 in Fig. 2a). (c) Same as (a). Liassic limestones, Nash Point (location NP in Fig. 2d). d) Same stepping sense in both fringes (type P). Upper Oligocene limestones near Mequinenza (location 4 in Fig. 2a). (e) Same as (d). Liassic limestones, Saint Mary's Well Bay (location StM in Fig. 2d).

(South Wales): Lavernock Point-St. Mary's Well Bay, Llantwit Major and Nash Point (Fig. 2d and e). The concerned rocks are mostly micritic limestones of Early Jurassic age, appearing in nearly horizontal, decimetric-thick layers. The dominant set of systematic joints usually strikes NNW–SSE, although orthogonal joints both with grid-lock and cross-joint architecture (in the sense of Hancock (1985)) also appear (Rawnsley et al., 1992; Rives et al., 1992; Caputo, 1995; Pascal et al., 1997). The joint surfaces exposed along scanlines totalling some 700 m at the base of the cliffs were inspected. The total number of joints with two fringe zones observed in those outcrops was 23; 12 of them correspond to type A (Fig. 3c) and 11 to type P (Fig. 3e).

The second field survey was done in Oligocene limestones near Mequinenza (Zaragoza province, eastern Ebro Basin, Spain), along 400 m of the N–S-trending road cut north of the village (location 4 in Fig. 2a). In this area, nearly horizontal layers of decimetric-scale thickness show systematic joints mostly striking NNE–SSW to NE–SW. A total of 40 cases of joints with two fringe zones were classified as type A and 13 as type P (Fig. 2c).

In summary, the stepping pattern usually presented in the literature as the most common (type P) is, in our experience, a minority (about 32% of the total observed joints with two fringe zones), whereas type A is clearly a majority in the studied areas ($\approx$68%).

Beyond our simplistic first approach, Bankwitz and Bankwitz (1984, fig. 2) identified three types (A, B, C) of fringe crack stepping according to their symmetry, after the observation of many complete plumose structures in joints affecting Ordovician slates in Thuringia. The application of Bankwitz and Bankwitz (1984) types to the case of layered rocks (which involves an additional element of symmetry normal to the plume axis through the initiation point) leads us to derive four geometric models of fringe crack stepping from our initial types A and P (Fig. 4). If we add a second symmetry axis A_2, we obtain types AA (type A of Bankwitz and Bankwitz (1984); a complete, self-connecting 360° spiral-staircase stepping pattern, similar to the famed 'impossible stair' by Escher (1995); see Fig. 4a) and PA (type B of Bankwitz and Bankwitz (1984); divergent stepping at one side of the starting point, which continues into convergent stepping at the other side; Fig. 4b). If a new plane of symmetry P_2 is drawn we obtain types AP (type B of Bankwitz and Bankwitz (1984); two symmetric 180° spiral-staircase arrangements; Fig. 4c) and PP (type C of Bankwitz and Bankwitz (1984); two P-type en échelon arrangements equally divergent from P_2; Fig. 4d). That is, the single type B applied by Bankwitz and Bankwitz (1984) to circular fractures (commonly found in quasi-isotropic rocks; Bahat et al., 2001b), splits into two distinct patterns, PA and AP, once we consider the case of layered rocks, where the anisotropic constraints imposed by the bedding determine the 'rectangular' shape of joints. Type PA is the only one that involves a single stepping sense all over the joint. Type AA has opposite stepping senses at the top and the bottom fringe zones, but constant sense within each fringe. Type PP involves opposite stepping senses at both sides of the fracture origin, but equal at the top and the bottom fringe zones within each side. Finally, type AP shows four alternate quadrants with opposite stepping.

The Mequinenza area has supplied eight examples of plumose structures showing the stepping pattern associated with the different portions of a complete plumose structure, i.e. both fringe zones, point of fracture initiation and two opposite plume markings. This allows us to classify them in the light of the types explained above. Most of them show no change in stepping sense within a given fringe zone. Three conspicuous examples belong to type AA (Fig. 5a and b). Two cases correspond to type PA, and two others show a symmetry plane P_2 at one fringe zone indicating either type AP or PP. Finally, a singular joint has been found in which changes in stepping sense within an individual fringe zone are not related with the symmetry plane P_2 (Fig. 5c). This complex pattern suggests that A and P symmetry types can be mixed in some way in real joints.

Finally, we should refer to fractures in which minor en échelon cracks with constant stepping sense are randomly distributed on the parent joint. They are neither related to plumose structures nor constrained to differentiated fringes. Therefore, their kinematic and mechanical interpretation should be different from that of the various types of fringe cracks above described, and so their implications in palaeostress interpretation, as will be discussed in Section 5.

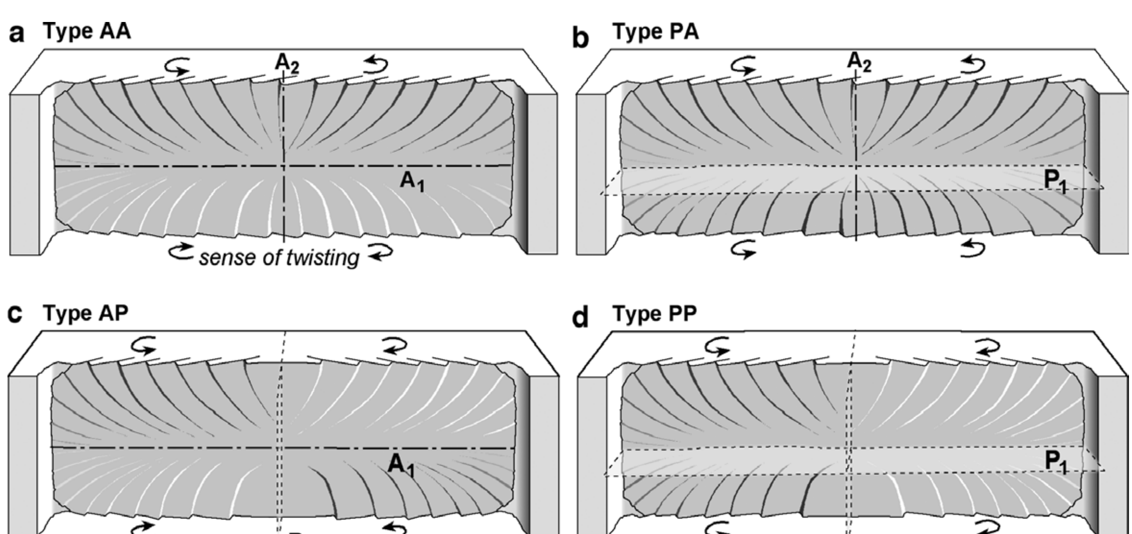

Fig. 4. The four models of fringe crack stepping for joints surfaces showing double plumose structures. (a) Axial/axial symmetry; (b) planar/axial symmetry; (c) axial/planar symmetry; (d) planar/planar symmetry. A_1, A_2: axes of symmetry; P_1, P_2: planes of symmetry.

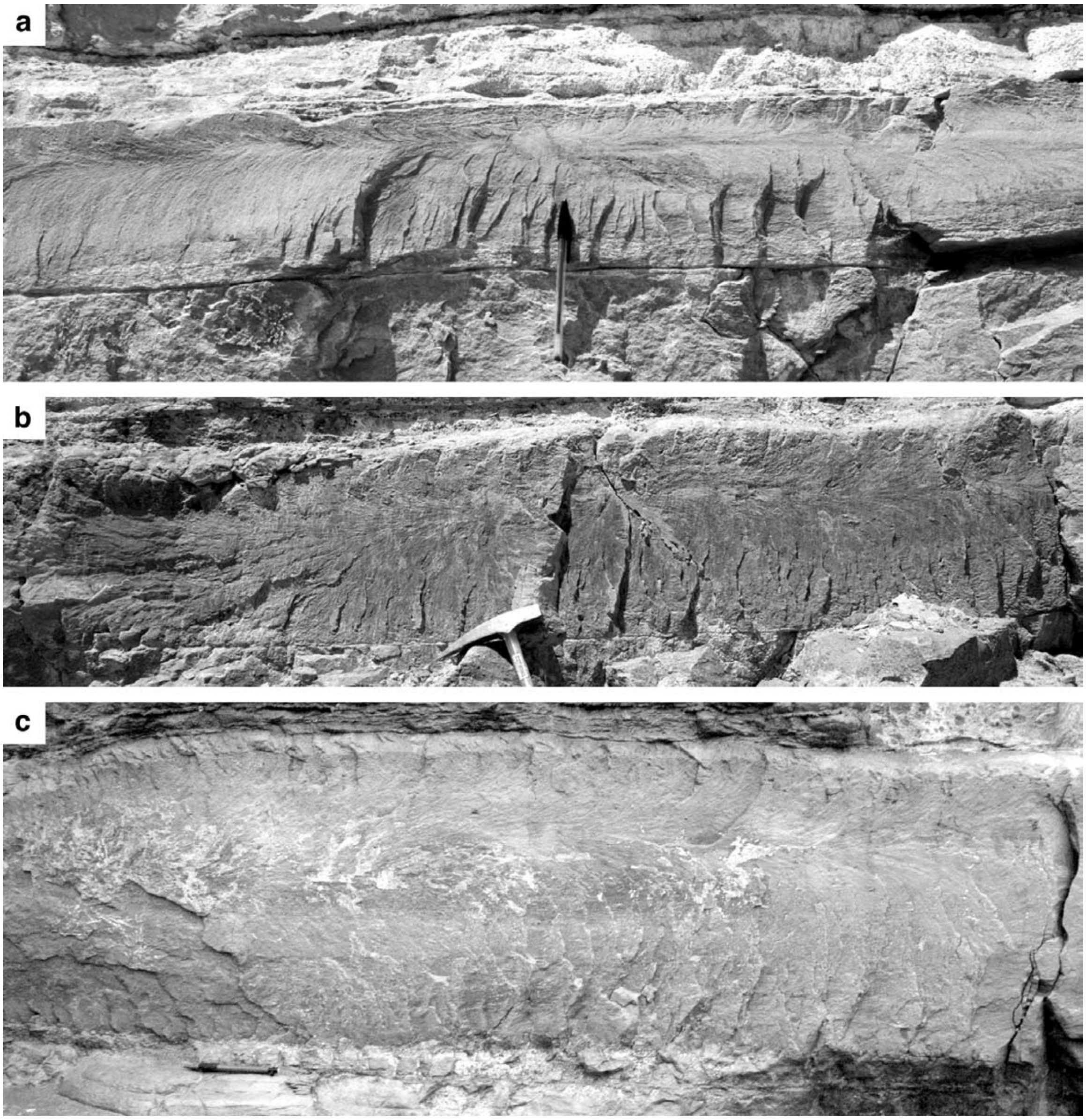

Fig. 5. (a) Complete, 360° spiral-staircase arrangement of fringe cracks (type AA). The point of fracture initiation is located near the centre of the picture. (b) Same as (a); at the leftmost part of the photograph the transition from one fringe to the other can be observed. (c) Joint surface showing change in stepping sense within the lower fringe of a single plume. The lower fringe cracks in the right part show a clockwise twisting, while in the leftmost part, immediately over the pencil, they are twisted counter-clockwise. The upper fringe displays a constant counter-clockwise array of en échelon cracks. The fracture initiation point is outside the frame, to the left. All examples are from the Upper Oligocene limestones of the Mequinenza area, Ebro Basin (location 4 in Fig. 2a).

4. Mechanical approach: remote stress or local fracture-tip stress?

It is currently admitted that local obliquity of the principal stress axes with respect to a joint surface at the propagation edge results in a combination of two of the basic fracture modes defined by Irwin (1960): mode I (tensile or opening), mode II (sliding) and mode III (tearing). Such a combination involves out-of-plane propagation that either can be accomplished with a single surface or requires that the joint breaks into segments (Pollard et al., 1982; Younes and Engelder, 1999). These have been referred to as 'permissible' and 'non-permissible' rotations, respectively, by Ryan and Sammis (1978) and Bahat (1991):

- A 'permissible' rotation occurs about an axis parallel to the rupture front (orthogonal to the propagation direction) under mixed modes I+II. The joint surface remains continuous though it undergoes a change in orientation, 'tilt', either smooth (hooking) or sharp (kinking).
- A 'non-permissible' rotation occurs about an axis parallel to the propagation direction under mixed modes I+III. Since a continuous adjustment of the joint front is not possible, the instability results in break up of the joint surface and

segmentation into twisted partial fronts that give rise to en échelon cracks (twist hackles).

Experimental approaches seem to confirm this mechanical interpretation. Sommer (1969, in Bahat, 1991, fig. 2.8) fractured a round glass rod perpendicular to its axis by applying fluid pressure. He observed that a small torsion superimposed to traction resulted in a complete crown of radial stepping cracks analogue to curved fringes of joint propagating fronts, consistent with mixed modes I+III. Simple experiments using silicone putty were also carried out by Pocoví et al. (1991), comparing pure traction loading with traction+torsion loading. Some examples of plumose structures were found in the first case, but F-joints could only be reproduced by applying traction+torsion (mode I+mode III).

If we consider an initial mode I propagation of the parent joint, orthogonal to the least principal stress axis σ_3, then we should conjecture about the origin of the stress rotation responsible for the mode III component and so for twisting of fringe cracks. Two main groups of hypotheses have been proposed with this respect, which relate their genesis to either changes of propagation conditions at the fracture tip or rotation of remote stress axes, respectively.

According to a number of researchers, en échelon fringe cracks can form as a consequence of local changes in stress distribution, strain energy release rate or propagation velocity, often linked to proximity of free surfaces such as bedding planes (Kulander et al., 1979; Pollard et al., 1982; Barquins and Petit, 1992; Rives, 1992; Lawn, 1993; Sharon et al., 1995; Bahat et al., 2001a; Müller, 2001). Ramsay and Lisle (2000, pp. 948–955) propose a kinematical model in which twist hackles develop under the control of shear deformation parallel to bedding and oblique to the joint surface (e.g. induced by flexural slip).

On the other hand, a direct relationship of fringe cracks with remote stress axes oblique to the main joint has also been postulated. From this general hypothesis, various distinct mechanical interpretations have been proposed. Fringe crack arrays can be seen as semi-brittle shear zones that renders the main joint a hybrid fracture (Bergerat et al., 1991; Dunne and Hancock, 1994). Alternatively, fringe cracks can result from ‘non-permissible’ rotation of the parent joint as a result of either rotation of remote stress axes (Kulander et al., 1979; Pollard et al., 1982; Pollard, 1987; Engelder, 1999; Younes and Engelder, 1999) or incompatibility between remote stress and changing local stress (Belayneh, 2004) during propagation. According to Younes and Engelder (1999), this process is a consequence of temporal rather than spatial change in orientation of stress axes, though simultaneous mode I+II and mode I+III combinations can develop in different parts of the rupture front: “After propagating at some distance, the parent joint may encounter a stress field with principal components that are neither parallel nor perpendicular to its plane. Depending on its orientation relative to the remote stress, the parent joint may break down at its tip line to form the en échelon cracks of a twist hackle […] or it may tilt or deviate from its path to form either a hook or a kink…” (Younes and Engelder, 1999, p. 221).

5. The use of fringe cracks in palaeostress interpretation: discussion

Assuming the hypothesis of their relationship with remote stress, fringe cracks have been used as palaeostress indicators (e.g. Bahat, 1986, 1991; Bergerat et al., 1991; Younes and Engelder, 1999; Belayneh, 2004). Obviously, this would not be possible if local stress changes at the propagating front were the ultimate cause. It is easy to realise that the stepping sense of fringe cracks is a question of first importance for discriminating both possibilities.

Mechanical interpretations of fringe cracks compatible with remote stress (Riedel fractures, rotation of external stress axes) involve secondary cracks that are consistently oriented either clockwise or counter-clockwise with respect to the parent joint. Thus, a constant stepping sense should develop all over the joint surface. In our study areas within the Ebro Basin (Arlegui and Simón, 1993, 2001), this pattern is characteristic of those fractures in which oblique secondary cracks are randomly distributed, neither related with plumose structures nor constrained within separate fringes. These fractures were interpreted as hybrid shear fractures (in the sense of Hancock (1985)) or transitional tensile fractures (in the sense of Engelder (1999)). In all cases, shear senses inferred from stepping on different fracture sets are consistent with nearly N–S-trending σ_1 stress trajectories (Fig. 6). In the case of the Appalachian plateau, Younes and Engelder (1999) illustrate how en échelon fringe cracks can also be consistently twisted either clockwise or counter-clockwise with respect to their parent joints. This fact, together with the abrupt edge that often separates fringes from parent joints, allows Younes and Engelder (1999) to adopt the hypothesis of a temporal change in orientation of remote stresses instead of spatial stress variation.

The case of fringe cracks in continuity with plumose structures is completely different. Our field data indicate that, within this category, the majority of joints with two fringe zones show opposite stepping senses. In some cases, opposite steps have been found even in different sectors within the same fringe zone. Obviously, this is incompatible with the hypothesis of remote-stress-driven twist hackles and prevents their use as palaeostress indicators. On the contrary, such heterogeneous stepping patterns should be explained in terms of local stress redistribution within the rock body, new mechanical models being probably necessary for that purpose. The special symmetry of the 360° spiral-staircase arrangement (type AA; Figs. 4a and 5a and b) poses special mechanical problems. According to results of fracture experiments by Sommer (1969, in Bahat, 1991, fig. 2.8) and Pocoví et al. (1991), both discussed in the former section, it strongly suggests mode III propagation produced by some torsion component. This torsion component might arise, for instance, near the tip of a propagating fracture with a nearly

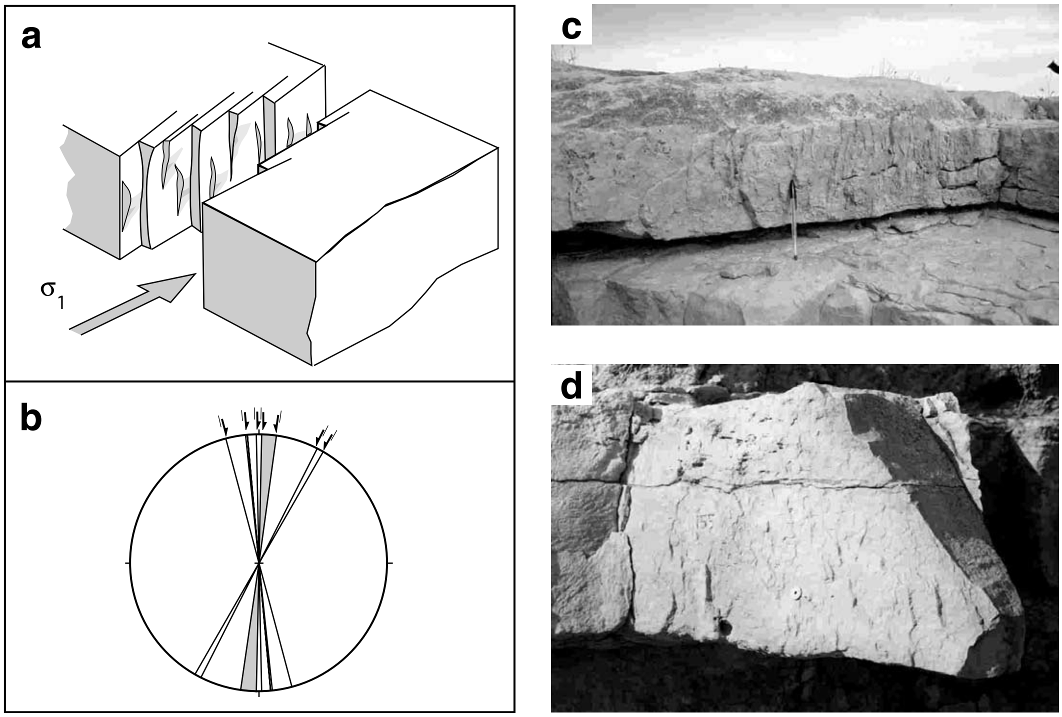

Fig. 6. (a) Scheme of hybrid shear joints with dynamical analysis. The randomly distributed steps along the surface are interpreted as Riedel fractures. Accordingly, σ_1 stress axis bisects the angle between conjugate pairs. (b) Example of distribution of left- and right-lateral Riedel steps in a sample of N–S striking joints (Miocene limestones near Peñalba; location 3 in Fig. 2a). (c) Example of joint with left-lateral shear Riedel steps (same site as (b)). (d) Example of joint with right-lateral shear Riedel steps, Miocene limestones, Barranco de Tudela (location 1 in Fig. 2a).

imperceptible vertical movement, or due to differences in curvature of gentle bending folds transverse to joint surfaces.

A single exercise may help to understand how twist hackles in continuity with plumose structures cannot be a consequence of temporal change in orientation of remote stress axes. As stated by various authors (e.g. Kulander et al., 1979), the faint ridges of plumose structures parallel the propagation direction of the growing main joint, so successive propagation fronts can be drawn by tracing concentric arches perpendicular to the ridges, effectively mimicking arrest lines or ribs. The loci of such tracings represent the lines of isochronous rupture. In the case of gradual twist hackles (Fig. 7), it is easy to realize that en échelon fractures at the top and bottom fringe zones, as well as the parent joint, developed simultaneously as they are linked by isochrons. Therefore, any difference between such fringe cracks at the top and bottom of the layer can never be interpreted in terms of temporal variation of stress. On the contrary, the gradual twist hackles and their stepping sense must be related with spatial changes in stress trajectories at the scale of the propagating front.

A further approach to the problem should be made by comparing attitudes of parent joints and F-joints. Bahat (1986, 1991) and Belayneh (2004) described cases in Beer Sheva (Israel) and the southern coast of the Bristol Channel (Great Britain), respectively, where strike variation of fringe cracks is lower than that of parent joints. This suggests quite uniform σ_3 axis orientation close to fracture tips during incremental propagation, independently on the orientation of the already formed joint surface. In such a situation: (i) a direct relationship between F-joints and remote stress, as stated by the authors, can be seen as a reliable hypothesis; (ii) opposite stepping senses in fringe crack arrays could be envisaged as a consequence of variations in strike of the parent joint relative to the individual fringe cracks (Fig. 8a), so that the geometric types here defined would be meaningless.

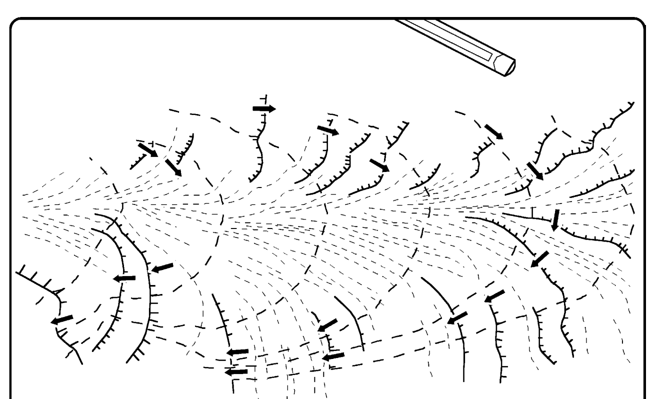

Fig. 7. Traces of successive propagation fronts (lines of isochronous rupture on the joint surface shown in Fig. 3b, drawn as concentric arches (dotted thick lines) perpendicular to the plume ridges (dotted thin lines). Arrows indicate the sense of ascending stepping.

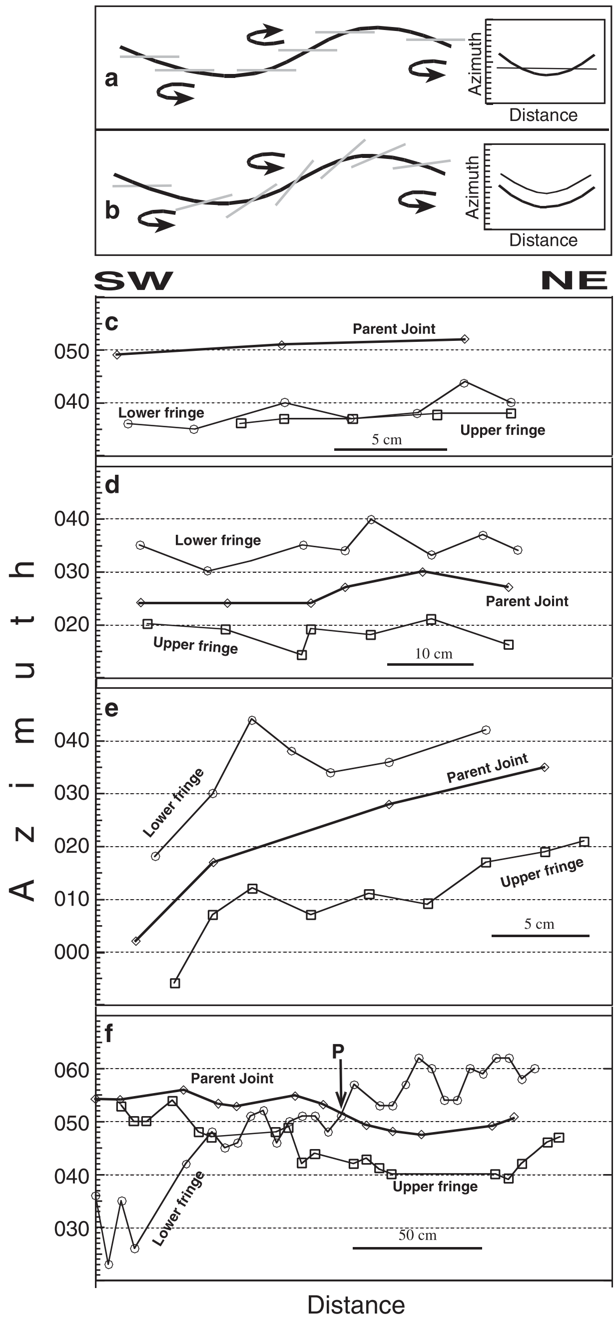

Fig. 8. (a) Sketch showing ideal relationships (not found in our field examples) between hypothetical persistent fringe cracks and variable parent joints resulting in opposite stepping senses. (b) Idem for a stepping arrangement independent of changes in orientation of the parent joint. (c) and (d) Azimuth vs. distance plots of two joints surveyed in the Mequinenza outcrop (Ebro Basin), with rather constant strike both in the parent joint and the individual en échelon cracks of each fringe zone. (e) Idem showing a parent joint whose variation in strike is accompanied by a similar variation of fringe cracks. (f) Idem for the NE–SW striking joint shown in Fig. 5c; point P indicates the change from anti-clockwise twisting to clockwise twisting caused by variation in strike of F-joints.

Our observations in a number of randomly selected joints in the Mequinenza area allow us to interpret that this is not the case:

(a) The varied symmetries of stepping arrangements of fringe cracks seem to be completely independent of changes in orientation of parent joints (Fig. 8b). In some cases, strike of both the parent joint and the individual en échelon cracks within each fringe zone is rather constant (Fig. 8c and d). Other parent joints show a variation in strike that is accompanied by a similar variation of fringe cracks (Fig. 8e). In every case, fringe cracks are consistently oriented either clockwise or counter-clockwise with respect to the parent joint, irrespective of them being type A or type P. Anomalous changes in stepping sense, such as that shown by the lower fringe zone in Fig. 5c (anti-clockwise twisting SW of the intersection point P and clockwise twisting NE of it; Fig. 8f), are caused by variation in strike of F-joints whereas the strike of the parent joint remains constant.
(b) The overall distribution of strikes of F-joints clearly shows a higher dispersion than that of parent joints (Fig. 9a). No case of parent joint showing significantly larger strike variation than its F-joints has been observed.
(c) Strike distribution of type-A joints is very similar to that of type P, as well as to that of joints with an only or no fringe zone (Fig. 9b).
(d) The distribution of angles between parent joints and fringe cracks is remarkably similar for types A and P (Fig. 10).

6. Conclusions

According to the cases compiled from the literature and to our own observations, single stepping sense of en échelon cracks is characteristic of hybrid or transitional-tensile fractures, where steps do not maintain any special geometric relationship with the edge of a parent joint. On the contrary, most true fringe cracks in continuity with barbs of plumes show opposite stepping senses in the upper and lower fringe zones. When the curved advancing front of such joints is observed, opposite steps at both fringe zones are connected by a continuous, 180°-radial pattern of steps showing a 'spiral-staircase' arrangement (type A). A minority of joints with two fringe zones show another pattern characterised by steps either converging or diverging from a plane of symmetry at the propagating front, giving rise to a single stepping sense at both joint fringe zones (type P). Where the full joint surface is observed, the sense of stepping along each fringe zone is usually constant (types AA and PA). Nevertheless, in a few cases, stepping sense within a single fringe zone does change either between both sides of the initiation point (symmetry plane orthogonal to the plume axis, types AP and PP) or within the same side.

This non-systematic en échelon arrangement of fringe cracks cannot be due to rotation of remote stress axes during propagation; it is only compatible with local stress redistribution at the advancing front. The case of 360° spiral-staircase arrangement (type AA) is especially significant in this respect, since it strongly suggests mode III propagation produced by a torsion component affecting the overall rock body surrounding the joint. Probably, propagation modes I, II and III interact in most joints in a complex way that is independent of remote

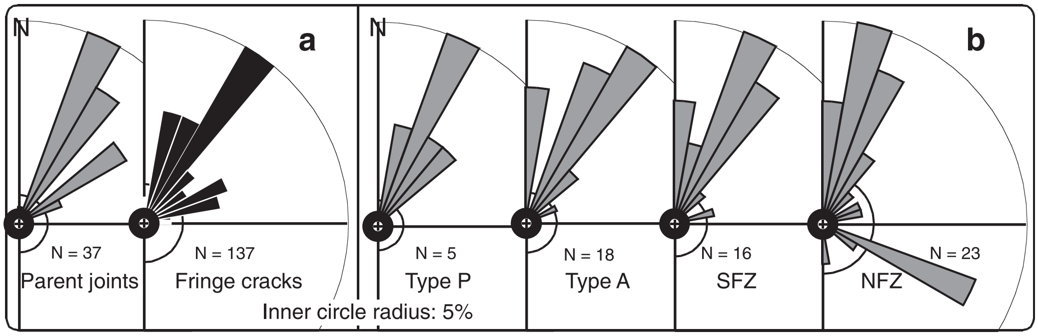

Fig. 9. Strike distributions of joints surveyed in two limestone beds in the Mequinenza outcrop (Ebro Basin). (a) Comparison between parent joints and fringe cracks measured in seven randomly selected joint surfaces; strike of each parent joint was measured in several points in order to express its variability. (b) Comparison between parent joints with two fringe zones (type-P and type-A), parent joints with a single fringe zone (SFZ), and joints with no fringe zone (NFZ).

stress setting and is controlled by subtle stress changes at fracture tips and layer surfaces. We hope that, in the near future, further mechanical modelling will contribute to understand the varied combinations of fracture propagation shown here within the framework of stress fields and rheological behaviour of rock layers.

The mechanical analysis by Pollard et al. (1982), used as the main theoretical basis for the regional study by Younes and Engelder (1999), can explain the development of remote-stress-driven twist hackles; nevertheless, this useful model does not suggest that every fringe crack array must develop in such a way. In fringe zones clearly separated from the parent joint by an edge that represents a line of isochronous rupture, propagation of twist hackles beyond that line may be controlled by a new remote driving stress. On the contrary, our observations on fringe crack arrays in continuity with plumose structures suggest that, in most cases, twisting should be attributed to local stress changes. Therefore, such fringe cracks should be considered unfit for recording palaeostresses. This is incontrovertible in the case of fringe cracks with double-stepping sense. But also the abundant asymmetric plumose structures connected with a single fringe zone, as well as the minority double-fringed joints with single-sense stepping, are dubious as palaeostress indicators. As a general rule, en échelon cracks associated with joints should be included in palaeostress analysis only after careful observation and discrimination, preferably selecting only those randomly distributed on the joint surface showing no relationship with plumose structures.

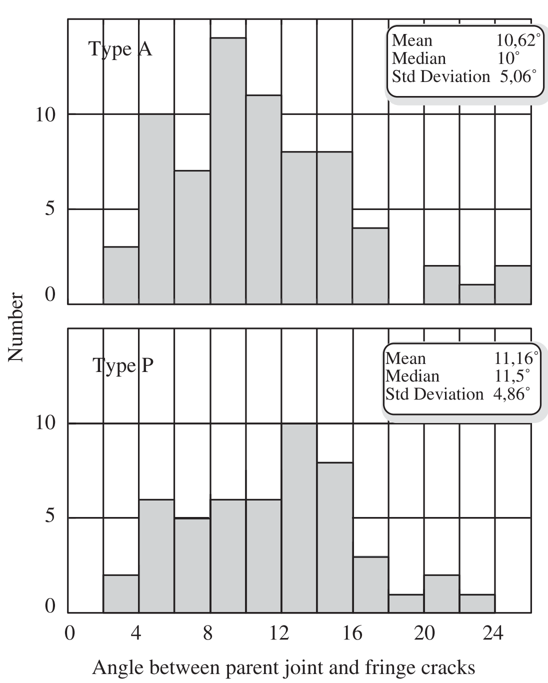

Fig. 10. Distributions of angles between parent joints and fringe cracks in type-A and type-P joint surfaces in Mequinenza.

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