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En échelon sigmoidal vein arrays hosted by faults

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Abstract—The morphology of en échelon sigmoidal veins generally supports an extension fracture origin for host fractures. Nevertheless, a shear fracture origin has been proposed in some cases, mainly on geometric arguments, often without morphological support. This study describes a system of sigmoidal en échelon quartz veins in a deformed greywacke which displays morphological evidence that the veins are hosted by faults. The veins occur in the hinge zone of an upright horizontal antiform and their configuration is consistent with both faulting and vein opening occurring during folding. The formation of close-spaced vertical dextral faults transformed thick massive greywacke beds into a discontinuous multilayer structure of rock bridges between faults. As the length to thickness ratio of the multilayer structure increased, the deformation mechanism changed to one of rotation and bending of rock bridges along sinistral shear displacement zones resulting in sigmoidal openings between rock bridges. Morphological features which indicate that the host fractures are faults include: (1) continuity of host fractures well past the tips of the sigmoidal veins and shear displacement of markers by unopened host fractures, (2) pinnate extension veins emanating from host fractures particularly near terminations and (3) shear quartz fibres on host fractures. Basic kinematic analysis shows that shear displacement (with opposite shear sense to the array) must occur before sigmoidal forms develop as the curvature produces contractional jogs which are incompatible with vein opening. Recognition of these features may assist in determining the role of shear displacement on host fractures of sigmoidal en échelon vein arrays. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

There has been considerable debate over the nature of fractures which host en échelon arrays of veins. Mechanisms which have been proposed include extensional fracturing (e.g. Ramsay 1980, Nicholson & Pollard 1985), shear fracturing (faulting) with the opposite sense of shear to the array (antithetic shear fractures, Beach 1975), shear fracturing with the same sense as that of the array (synthetic shear fractures, Hancock 1972) and a hybrid of extensional and shear fracturing (Hancock 1972). In a review of published examples of vein arrays, Smith (1995) noted that most interpretations of a shear fracture origin of en échelon veins were based on geometric, rather than morphological, evidence. Morphological evidence supporting a shear fracture origin for the host fractures of en échelon veins include: (1) continuation of host fractures outside the vein array with evidence of shear displacement on host fractures and (2) shear fibres in veins (Rickard & Rixon 1983). Although these features indicate shear displacement on a fracture they do not exclude the possibility of its nucleation as an extension fracture, as has been described for faults in granite (Segall & Pollard 1983).

The potential for complex structural histories has been recognised in the distinction between vein arrays which exploit pre-existing planar weaknesses and those which form new fractures (Ramsay 1967, Hancock 1985). Those arrays which exploit pre-existing weaknesses are similar to other structures in anisotropic materials, such as kink bands (e.g. Davies & Pollard 1986). The formation of some pre-existing weaknesses (bedding for example) is unrelated to the deformation producing veining. Conversely, some pre-existing weaknesses may be closely related to the vein opening, not merely fortuitous. Where host fractures are not considered to be pre-existing, the newly formed fractures can strongly influence the future deformation process and could be considered to be 'pre-existing' weaknesses for the deformation mechanisms which follow. For example, some arrays form from the interactions of propagating 'pre-existing' cracks, as observed in numerical models (Olson & Pollard 1991). Similarly, the opening of veins by the rotation and bending of bridges of rock (Nicholson & Ejiofor 1987) could be said to occur on 'pre-existing' fractures. Consequently, any complex structure such as a vein array needs to be carefully interpreted in terms of its assemblage of minor structures and structural processes.

This paper describes a field occurrence of sigmoidal en échelon veins which have clear morphological evidence of the host fractures being faults which formed prior to, but in the same progressive deformation as, the opening of the arrays.

GEOLOGICAL SETTING

The field site is located on Arrawarra Headland (Fig. 1a & b) within the Coffs Harbour Block of the Late Palaeozoic New England Fold Belt. The 'Arrawarra

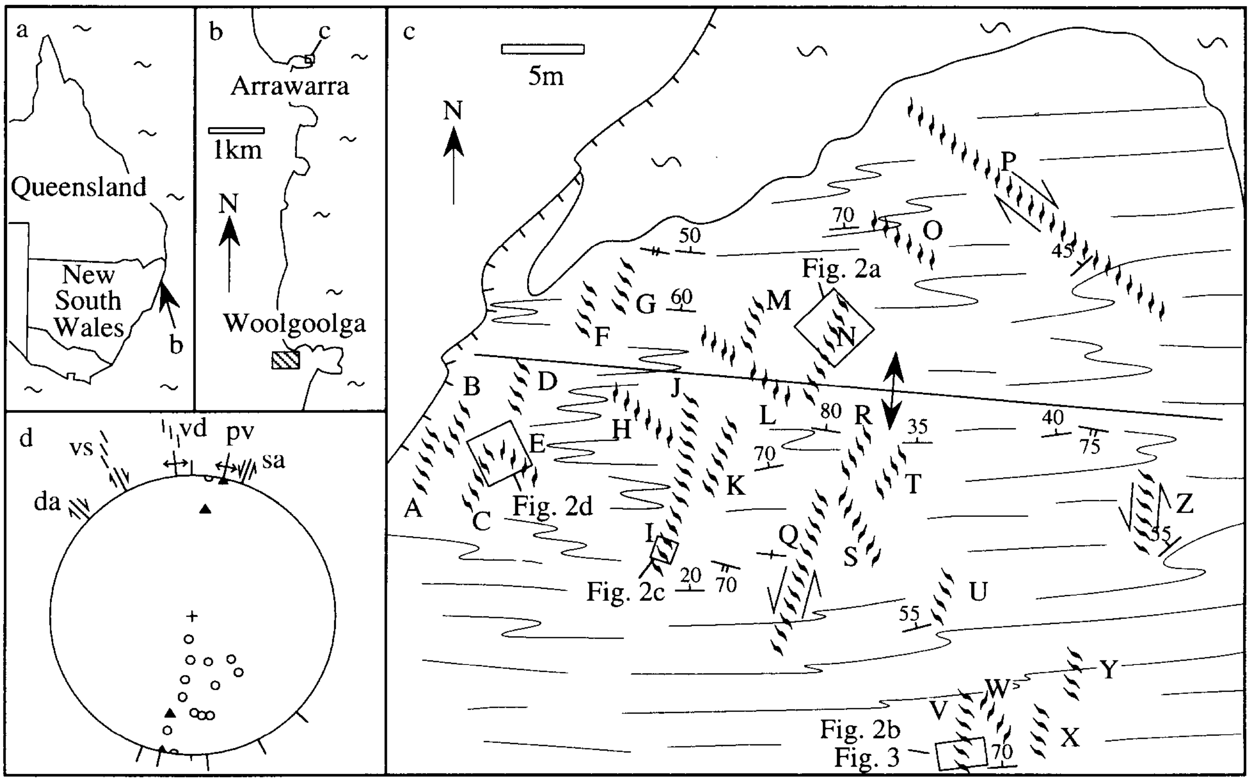

Fig. 1. (a, b) Location maps for Arrawarra Headland. (c) Map showing distribution of vein arrays on Arrawarra Headland, strikes of arrays A–Z given in Table 1. Veins are shown schematically only. (d) Equal angle stereograph of the orientation of bedding (circles) and cleavage (triangles) and the strike of sinistral arrays (sa), veins in sinistral arrays (vs), pinnate veins (pv), dextral arrays (da) and veins in dextral arrays (vd). Note: veins in sinistral arrays occupy dextral faults.

petrofacies' is the uppermost of four main units within the Coramba Beds. The rocks at Arrawarra are lithic greywackes believed to be derived from a volcanic arc (Korsch 1981a). The rocks formed as a succession of turbidite fans incorporated into an accretionary wedge. Deformation of the Coffs Harbour Block has produced three recognisable generations of structures (Korsch 1981b, Fergusson 1982). First, intense mesoscopic folding and foliation developed during regional deformation. The foliation transects the folds by 6–15° in the western part of the block (Fergusson 1982) indicating non-coaxial contractional deformation. Open mesoscale kinks and flexures followed by regional-scale bending of the trend of bedding and fold hinges are interpreted as the second and third generations of structures.

At Arrawarra Headland, bedding and mesoscopic first generation structures are readily observed but mesoscopic evidence of later folding is not seen. Beds of massive greywacke up to about 3 m thick separated by thin pelitic beds strike mainly east–west. Tight angular folds in the pelitic beds are parasitic to sub-horizontal folds of the greywacke beds. The foliation consists of a rough penetrative cleavage and pressure-solution seams and is axial planar to the folding. The east–west structural trend is common to most of the southern part of the Coffs Harbour Block; however, farther north and on offshore islands, structures trend toward NNE (Korsch 1993) indicating Arrawarra is near the hinge of the regional-scale bending. Faults on a range of scales displace bedding and foliation.

VEINING

Vein systems are exposed sporadically on coastal exposures of the Coffs Harbour Block including Arrawarra Headland. The exposure described in this paper is the most intensely veined exposure and comprises conjugate sets of en échelon vein arrays (Fig. 1c).

The veins have a sigmoidal shape (Fig. 2a & b) and resemble other en échelon vein arrays which have been interpreted as originating as extension fractures. Unlike other vein arrays, however, these examples show evidence that the host fractures are dextral faults, namely: (1) the fractures continue beyond the tips of the sigmoidal veins and displace bedding along the fracture (Fig. 3a); (2) pinnate extension veins occur on the host fractures, particularly at terminations (Fig. 2a & b and Fig. 3b); and (3) quartz shear fibres fill some of these fractures (Figs. 2e and 3c). The nucleation of the faults is not clear, they may have originated as shear fractures or as extensional fractures (joints) which later underwent shear displacement as has been observed in granite (Davies & Pollard 1986).

As the number of faults increased, the narrow bridges of rock between faults became susceptible to bending and rotation. This bending was concentrated along zones of sinistral shear displacement and the opening of the fractures between rock bridges produced the sigmoidal central part of the veins. The rotation of rock bridges can be seen by the deflection of bedding (Fig. 2c). The rock fabric within the rock bridges is of a similar intensity to

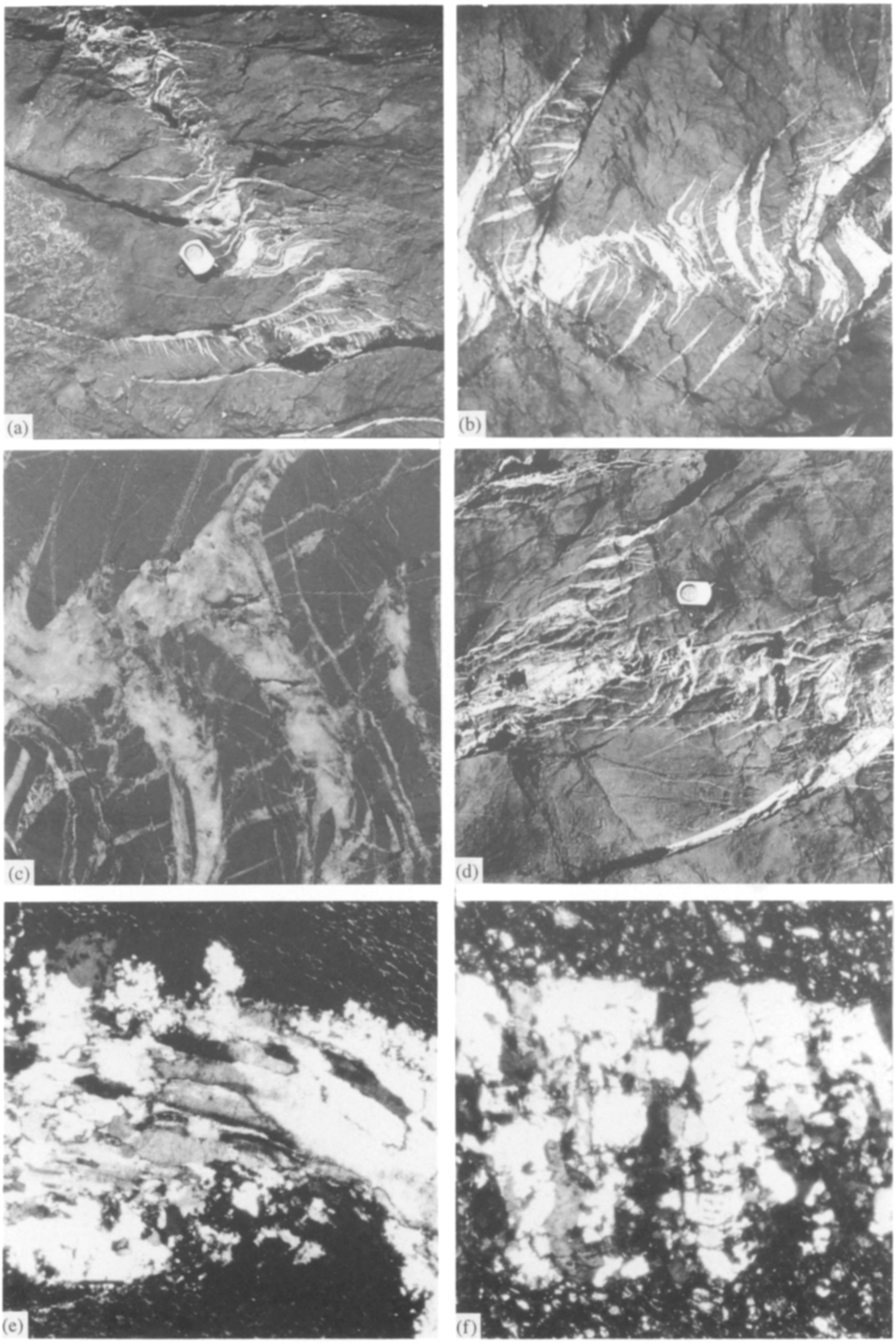

Fig. 2. (a) Oblique photograph of a vertical vein array exposed on a horizontal rock platform (compass is 5 cm across). (b) Detail of a vein array (field of view 25 cm across). (c) Detail of veins from a polished slab (field of view 9 cm across). Bedding runs from top left to bottom right but has been rotated through 90° in the central rock bridge. (d) Detail of conjugate vein arrays (compass is 5 cm across). (e) Photomicrograph of quartz shear fibres (field of view 2 mm across). (f) Crack-seal extension vein (field of view 2 mm across).

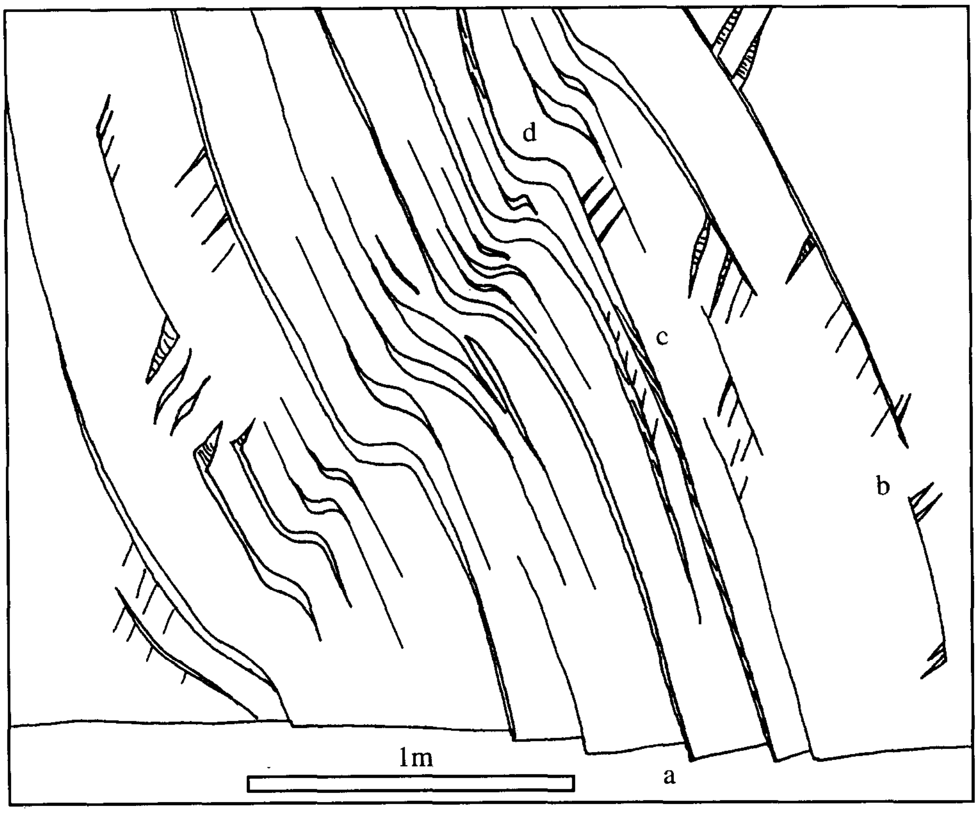

Fig. 3. Line drawing of a vein array showing (a) vein host fractures displacing a bedding interface between lithic sandstone (hosting the array) and a pelitic bed (base of Fig.), (b) pinnate veins on host fractures, (c) shear fibres in host fractures and (d) sigmoidal segment of vein formed by rotation of rock bridges within the array. Note: dextral displacement (a) must have preceded sigmoidal curvature (d) as the curvature is a contractional jog on the fault.

that outside the arrays indicating that the arrays were not localised by ductile strain within a shear zone. Veins on host fractures contain shear fabrics which have been bent (Fig. 2e) by the formation of the sigmoidal arrays. Pinnate veins have extension fabrics (Fig. 2f) and sigmoidal veins have both shear and extension fabrics. The sigmoidal curvature of the veins produced contractional jogs along the dextral faults. Thus dextral slip could not have occurred during or after sigmoidal vein opening. As deformation proceeded, and movement on dextral faults ceased, dextral arrays of extension fractures formed (Fig. 2d).

The close temporal association of the structures is shown by four strain axis indicators: (1) fold hinge and axial cleavage (Fig. 4a); (2) pinnate extension fractures on dextral faults (Fig. 4a); (3) the bisector of dextral faults and sinistral vein arrays (Fig. 4b); and (4) the bisector of sinistral and dextral vein arrays (Fig. 4b). The fold axial plane, veins and vein arrays are vertical indicating a horizontal shortening strain and allowing analysis of orientations in terms of horizontal bearings. These four indicators show an approximate north–south shortening direction (Fig. 4c) supporting their formation within a progressive deformation. These indicators represent a sequence of development of the structural assemblage and their analysis allows changes in strain axes with time to be recognised. The orientation of these indicators, based on data in Fig. 1 and Table 1, indicates that shortening by folding and cleavage development was parallel to that forming the dextral faults and pinnate fractures. The third and fourth strain axis indicators described above differ from the earlier ones by 17° and 26° anticlockwise, respectively (Fig. 4c).

CONCLUSIONS

The model proposed for the veins at Arrawarra involves openings created by the bending of pre-existing faults. The faults initiated prior to, but during the same progressive deformation as, the opening of the veins. The progression of the principal shortening strain axis, from N through 26° toward the NW, as indicated by the four main strain axis indicators, suggests that the progressive deformation was non-coaxial. The anticlockwise progression of strain axes indicates that the contractional deformation had dextral non-coaxiality, during which early-initiated structures such as the fold hinge and pinnate extension fractures were rotated in a clockwise sense. Such a dextral, non-coaxial contraction is also consistent with the dominance of dextral faults in the early brittle phase of the deformation.

The vein system at Arrawarra Headland demonstrates that it is possible for en échelon sigmoidal veins to be hosted by faults as indicated by: (1) continuity of fractures beyond the tips of the sigmoidal veins and

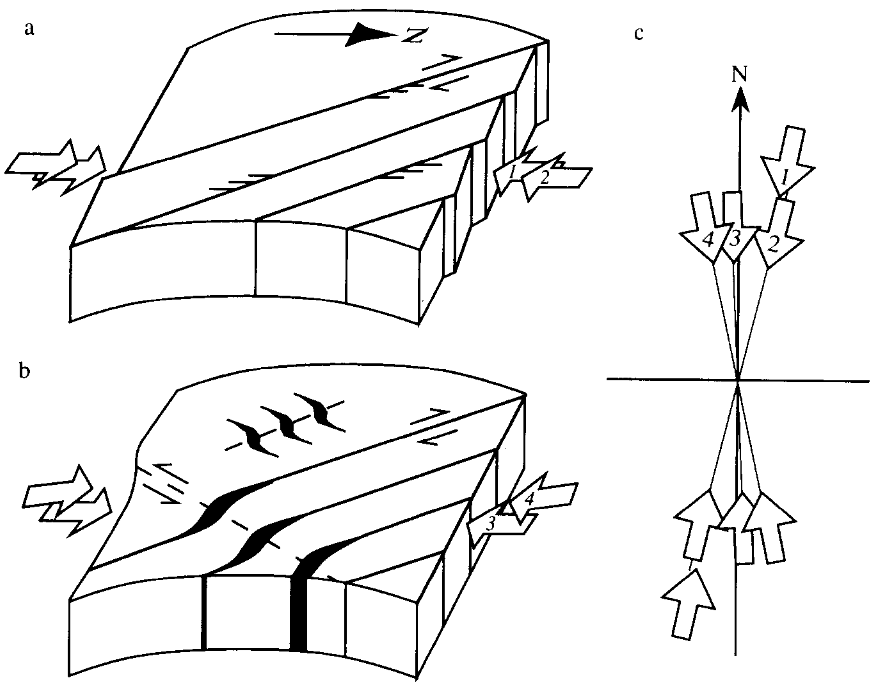

Fig. 4. Schematic representation of the sequence of events forming the vein systems. (a) Horizontal contraction causing folding and dextral faults with pinnate extension fractures. (b) Bending of rock bridges between host fractures to form sinistral sigmoidal vein arrays. Contraction also causes conjugate dextral arrays of extension fractures. (c) Orientation of shortening direction indicators: (1) normal to fold hinge line, (2) pinnate extension fractures on dextral faults, (3) bisector of dextral faults and sinistral vein arrays and (4) bisector of sinistral and dextral vein arrays.

their displacement of bedding; (2) pinnate extension fractures on the shear fractures, particularly at terminations; and (3) quartz shear fibres within these fractures. Such features have not been described in previous published studies of en échelon veins which suggests that in the absence of such evidence, fractures hosting en échelon veins are most likely to have formed as extension fractures.

Table 1. Strike orientations of (a) sinistral arrays (sa), tips of veins in sinistral arrays (vs), vein-array angles (vs-sa), pinnate veins (pv) and pinnate vein-array angles (pv-vs); (b) dextral arrays (da), tips of veins in dextral arrays (vd), vein-array angles (vd-da). Note: the veins in sinistral arrays occupy dextral faults. Array locations shown in Fig. 1(c)

(a)	sa	vs	vs-sa	pv	pv-vs
A	006	324	42	012	48
B	032	344	38	022	38
C	021	324	57	367	43
D	019	338	41	016	38
F	006	320	46	354	34
G	024	332	52	012	40
I	023	339	44	019	40
J	037	342	55	002	20
K	027	332	55	007	35
M	024	330	54	006	36
N	032	340	52	015	35
Q	029	333	56	024	52
R	025	335	50	012	37
T	040	342	58	028	46
U	025	336	49	022	46
V	017	334	43	022	48
X	358	329	29	359	30
Y	008	323	45	011	48
Z	017	337	40	012	35
av.	021	333	48	013	39
SD	11	7	8	9	8

(b)	da	vd	vd-da
E	290	323	33
H	308	347	39
L	322	009	47
O	331	019	48
P	321	333	12
S	306	359	53
W	320	359	39
av.	314	353	39
SD	14	20	14

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