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Geometry and kinematics of convergent conjugate vein array systems

JOHN V. SMITH

Centre for Coastal Management, Southern Cross University, P.O. Box 157, Lismore, 2480, NSW, Australia

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Abstract—Conjugate arrays of quartz veins in the Neranleigh–Fernvale turbidite beds at Norries Head, eastern Australia occur in configurations in which the trends of the veins, in a principal section, converge towards the acute bisector of the conjugate arrays (a convergent configuration). Such a configuration is common in vein arrays, and has been attributed to initiation of the veins as antithetic shear fractures based on geometric arguments. The morphology of the veins in this study indicates that the veins are hosted by extension fractures which formed by en échelon breakdown of faults.

Previous models of extension fracture arrays emphasise that all fractures lie parallel to the bisector of conjugate arrays and that arrays develop after initiation of extension fractures and concurrent with fracture propagation. Sigmoidal vein shapes have been attributed to concurrent shear strain and fracture propagation.

An alternative model is proposed for the geometry of conjugate arrays formed by en échelon breakdown of faults. The conjugate angle between parent faults is established before the en échelon extension fractures are formed. The fracture–array angle depends on the local displacement of the parent fault, thus, there is no necessity for the fractures in different arrays to be parallel. If the fracture–array angle is greater than half the conjugate angle between parent faults, a convergent configuration of fractures is produced. The kinematics of opening of veins in this study involved bending of rock bridges between fractures producing a gradation from planar to sigmoidal shapes in serial sections, without evidence of concurrent fracture propagation. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Conjugate arrays of en échelon veins partition rock into wedge-shaped blocks. During formation of the arrays some wedge-shaped blocks move towards each other and other blocks move away from each other providing a commonly used kinematic indicator (Collins & De Paor 1986). The three principal strain axes are approximated by the two bisectors of the arrays and the intersection line of the arrays. The bisector lying within blocks which move toward each other is interpreted as the principal shortening direction; the bisector lying within blocks which move away from each other is interpreted as the principal extension direction, and the line of intersection of the arrays is interpreted as the intermediate strain axis. Unevenly developed vein sets can produce bulk strain with principal axes which do not bisect conjugate arrays (Ramsay & Huber 1987), but the array bisectors are a useful approximation in most cases. The orientation of veins with respect to these principal strain and stress axes has been the focus of much research on en échelon vein arrays.

Theoretical and experimental studies have shown that the orientation of extension fractures within en échelon arrays can vary according to the dilation and shear strain of the deforming zone (Durney 1979,1985). Since extension fractures are generally oriented parallel to principal (incremental) strain axes, the conjugate angle between arrays is variable (Ramsay 1982, Ramsay & Huber 1987, p. 629). In this 'Durney–Ramsay' model of en échelon vein formation, sigmoidal vein shapes are caused by fracture propagation concurrent with shear displacement across arrays (Durney & Ramsay 1973). Such a mode of formation is the implicit assumption in studies which interpret the host fracture mechanism based on geometric relations between veins and the stress field inferred from array orientations (Roering 1968, 1988). That approach precludes the formation of extension fractures in a convergent configuration but the approach does not take into account temporal and spatial variations in the stress field as will be done here.

It is problematic that the veins in many natural conjugate array systems are not parallel, but rather, the veins typically converge as their trend is traced towards the wall rock blocks containing the principal shortening strain axis (Fig. 1). Numerous examples of 'convergent conjugate vein array systems' are illustrated in published sources (Table 1) and additional field examples from northeast New South Wales, Australia are described in this paper. Because the veins in convergent conjugate arrays are oblique to the inferred principal compressive stress they have been interpreted as shear fractures (Shainin 1950, Roering 1968, Beach 1975). However, this geometric interpretation has not be corroborated by observations of the morphology of veins.

Some of the difficulties in interpretation of vein kinematics come from attempting to do so based on two-dimensional exposures. In three dimensions, fracture systems (Craddock & Moshoian 1995) and veins (Nicholson & Ejiofor 1987, Craddock & van der Pluijm 1988) can change from continuous into discrete segments. By making a three-dimensional investigation of

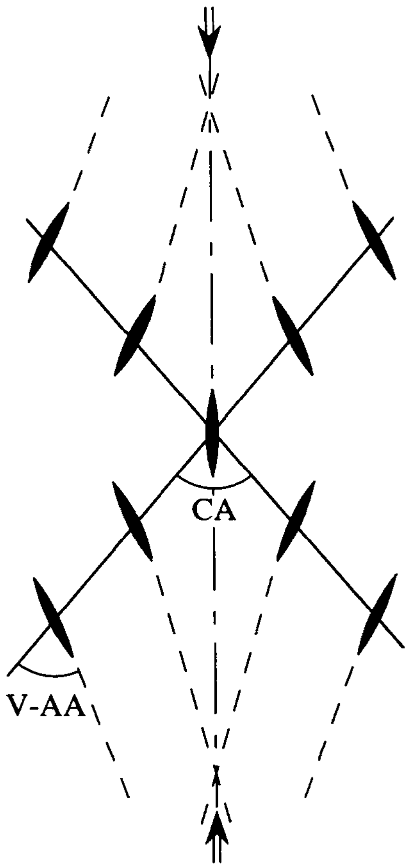

Fig. 1. Illustration of conjugate arrays of veins (black) in which the trends of the veins (short dashes) converge as they are followed towards the wall rock blocks containing the principal shortening strain axis (arrows). In the convergent configuration the vein-array angle (V-AA) is greater than half the conjugate angle (CA).

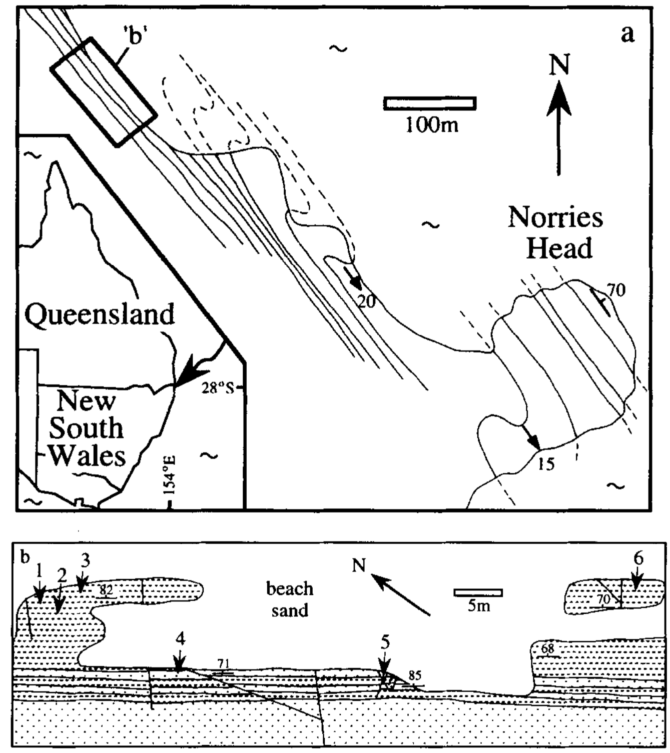

Fig. 3. (a) Tightly folded Palaeozoic turbidites of the Neranleigh–Fernvale beds of the New England Fold Belt exposed at Norries Head, New South Wales, Australia. (b) Locations of conjugate vein array systems described in this paper (inset Fig. 3). Host rocks comprise sandstone beds greater than 1 m thick (shaded) and intercalated sandstone beds less than 1 m thick and laminated graded beds (dashed). Strike and dip of bedding indicated.

vein geometry this paper aims to describe a kinematic process by which veins can initiate as extension fractures and yet have a convergent configuration.

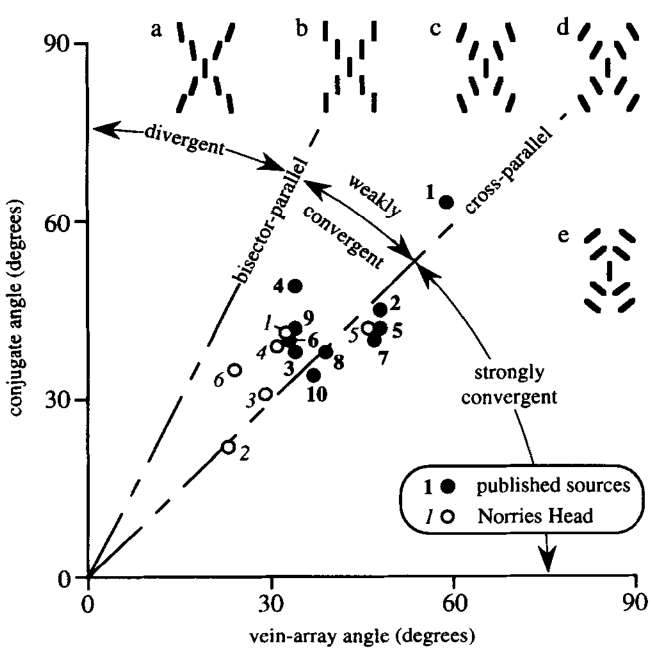

Fig. 2. Examples of conjugate-angle versus vein-array angle for conjugate vein array systems from published sources (Table 1) and field studies described in this paper.

ORIENTATION OF VEINS IN CONJUGATE ARRAYS

A study of quartz veins in quartzites of the Witwatersrand Basin (Roering 1968) and a study of calcite veins in limestones of the Swiss Alps and quartz veins in sandstones from various locations in England (Beach 1975) led to the recognition of two geometric types of conjugate vein systems. In Type 1 systems the veins of one array are parallel to the trend of the conjugate array, whereas, in Type 2 systems all veins parallel a bisector of the conjugate arrays. Yet these two types are only specific cases within a geometric continuum.

The geometric continuum of conjugate vein array systems can be defined in terms of the relationship of the angle between conjugate vein arrays (conjugate angle, CA in Fig. 1) and the orientation of veins relative to their host arrays (vein-array angle, V-AA in Fig. 1). The range of geometric configurations (Fig. 2) can be sub-divided in a way analogous to Ramsay (1962)'s classification of fold forms into convergent and divergent types based on the trends of dip isogons from the outer to the inner part of a folded layer. A convergent conjugate vein array system is one in which the trends of veins converge when followed into the blocks of rock which contain the inferred principal shortening strain axis (Figs. 2c–e). In contrast, in divergent conjugate vein array systems the trends of the veins diverge when followed into the blocks of rock

Table 1. Sources of conjugate vein array data. Average angles in degrees, number of measurements in parentheses

Fig. 2 No.	Source	Fig. No.	Conjugate angle	Vein-array angle	Mineralogy
1	Roering 1968	3	63 (3)	59 (54)	quartz in quartzite
2	Roering 1968	4	45 (2)	48 (30)	quartz in quartzite
3	Roering 1968	10	38 (1)	34 (9)	quartz in quartzite
4	Ramsay & Graham 1970	10	49 (1)	34 (13)	calcite in limestone
5	Weiss 1972	167	42 (1)	48 (8)	quartz in greywacke
6	Hancock 1973	Plate V	40 (1)	33 (11)	calcite in limestone
7	Beach 1975	13	40 (3)	47 (19)	quartz in sandstone
8	Beach 1975 (Ramsay & Huber 1987)	2A26.15	38 (2)	39 (27)	calcite in limestone
9	Rickard & Rixon 1983	1	41 (5)	34 (75)	quartz in sandstone
10	Collins & De Paor 1986	3	34 (1)	37 (13)	quartz in sandstone

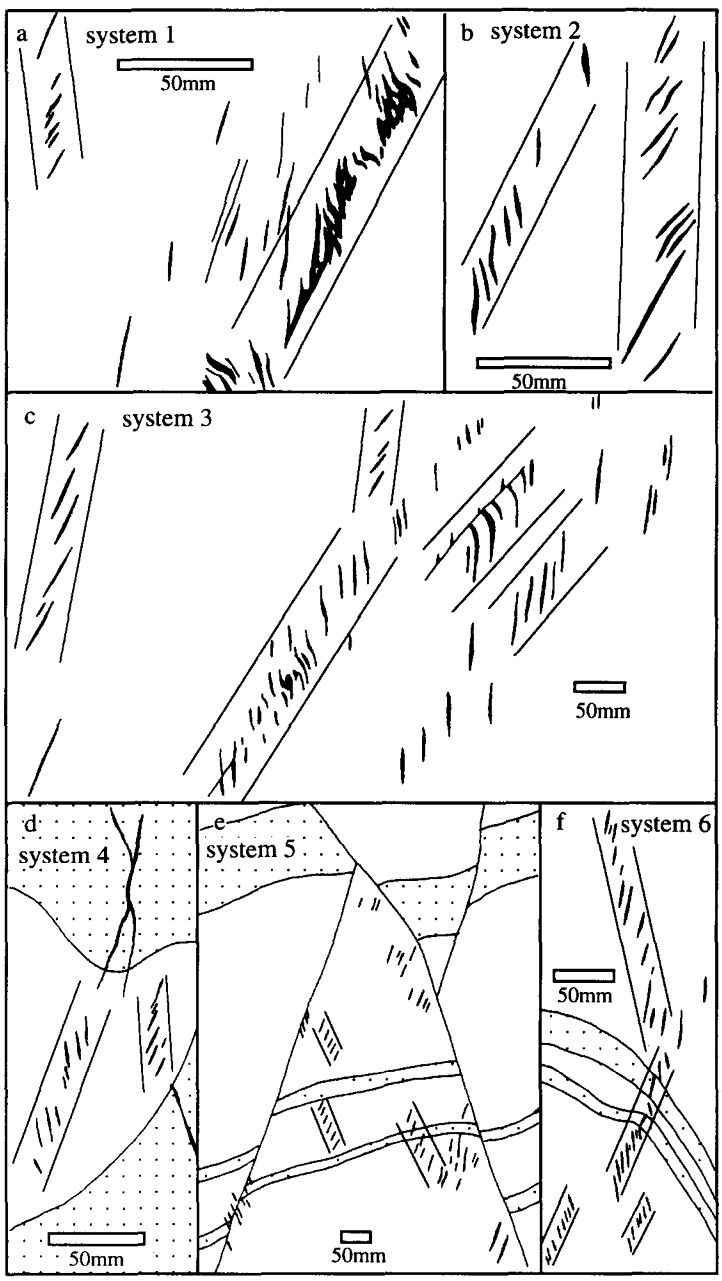

Fig. 4. Detail of conjugate vein array systems exposed on steeply dipping rock faces (locations 1 to 6 in Fig. 3b). Veins (black) are hosted by fine laminated beds (blank) and sandstone (stippled). (a) Vein system 1: a sigmoidal pinnate sinistral array, smaller dextral array and some poorly organised veins. (b) Vein system 2: equivalent dextral and sinistral arrays. (c) Vein system 3: three sinistral arrays with planar, sigmoidal and pinnate morphologies and two dextral arrays with planar morphology. (d) Vein system 4: dextral and sinistral arrays in laminite and single fractures in sandstone. (e) Vein system 5: conjugate fault system with pinnate fractures and vein arrays within the intersection zone of the two faults. (f) Vein system 6: dextral and sinistral arrays in laminite and single fractures in sandstone.

which contain the inferred principal shortening strain axis (Fig. 2a). Field examples of divergent arrays have not been described, and this type will not be discussed further.

Figure 2(d) shows that Type 1 systems, termed here 'cross-parallel systems', are a special case of convergent conjugate vein array systems. The cross-parallel configuration is taken as the boundary between weakly convergent and strongly convergent sub-types. Type 2 systems, termed here 'bisector-parallel systems', are also a special case representing the boundary between convergent and divergent types (Fig. 2b).

A survey of natural conjugate vein arrays illustrated in published sources (Table 1, Fig. 2, black circles) and field examples described in following sections (Fig. 2, open circles) shows that convergent configurations are common and that there is no special affinity with the precise condition of Type 1 or Type 2 conjugate arrays. The common occurrence of convergent conjugate vein array systems is significant because geometric evidence has figured prominently in arguments about the fracture mechanisms of filled fractures.

Both Roering (1968) and Beach (1975) concluded that in bisector-parallel (Type 2) systems, veins initiated as extension fractures, whereas veins in cross-parallel (Type 1) systems initiated as shear fractures (faults) because of their obliquity to the inferred principal compressive stress. The sense of shear of the shear fracture would be opposite to the host array, so such veins were interpreted as antithetic shear fractures. Hancock (1973) also argued for a role for shear fracture in the formation of en échelon veins. He proposed that veins could initiate as extension fractures, synthetic shear (Riedel) fractures or combinations of the two.

FIELD EXAMPLES

Conjugate arrays of en échelon quartz veins occur near Norries Head (Fig. 3a) within the Early Carboniferous Neranleigh–Fernvale beds of the Late Palaeozoic New England Fold Belt (Fergusson *et al.* 1993), northeast New South Wales, Australia. The beds are turbidites comprising sandstone beds (quartzite) locally up to 8 m thick intercalated with laminated graded beds (laminite). The beds have been folded and metamorphosed to low grade during accretion of the subduction complex. Both deformed (ptygmatically folded) and undeformed veins are found in the rocks indicating fracturing during progressive deformation. Many of the undeformed veins occur as en échelon arrays within laminite, and it is these vein systems which are studied in this work.

Six prominent conjugate vein array systems have been studied in detail (Figs. 3b & 4). The three-dimensional orientation of the arrays and veins indicates that the profile plane of the arrays is variable but generally near horizontal. Exposure of the vein systems is mainly on non-profile exposure surfaces which are illustrated in Fig. 4. The three-dimensional arrangement of the structures is shown stereographically in Fig. 5.

The vein array systems are numbered 1 to 6 from north to south. Vein system 1 (Fig. 4a) is dominated by a sigmoidal and pinnate sinistral array accompanied by a smaller dextral array. Vein system 2 (Fig. 4b) comprises equivalent dextral and sinistral arrays. Vein system 3 (Fig. 4c) comprises three sinistral arrays with planar, sigmoidal and pinnate morphologies and two dextral arrays with planar morphology. Vein system 4 (Fig. 4d) consists of a dextral and sinistral array, but where the host rock is sand beds, single veins occur. Vein system 5 (Fig. 4e) consists of a conjugate fault system with veins within the intersection zone of the two faults and as pinnate fractures on the faults. Vein system 6 (Fig. 4f) consists of dextral and sinistral arrays and, as observed in vein system 4, where the veins cross sand beds, single veins parallel to the array have formed rather than an en échelon array.

In each case the conjugate vein systems are convergent and approximate the cross-parallel configuration. Although the non-profile orientation of the surfaces exposing the vein systems distorts the conjugate angle

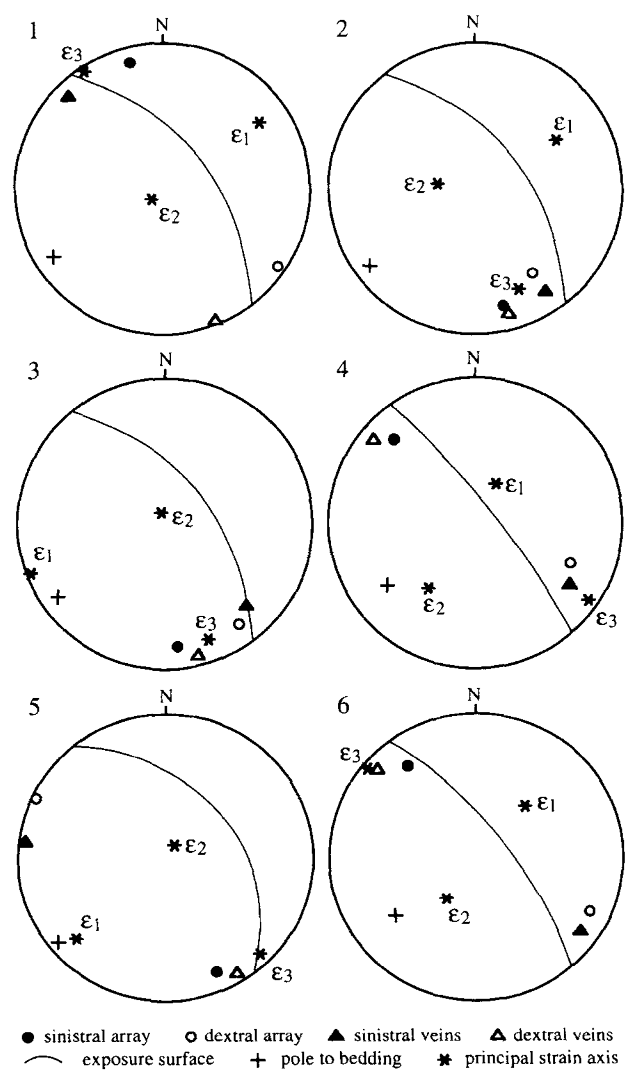

Fig. 5. Stereographic representation of the three-dimensional configuration of veins and arrays (locations 1 to 6 in Fig. 4). In each case the poles to veins (triangles) lie close to the poles of arrays (circles) of opposite sense to those hosting the veins. The non-profile exposure surfaces illustrated in Fig. 4 are shown as great circles.

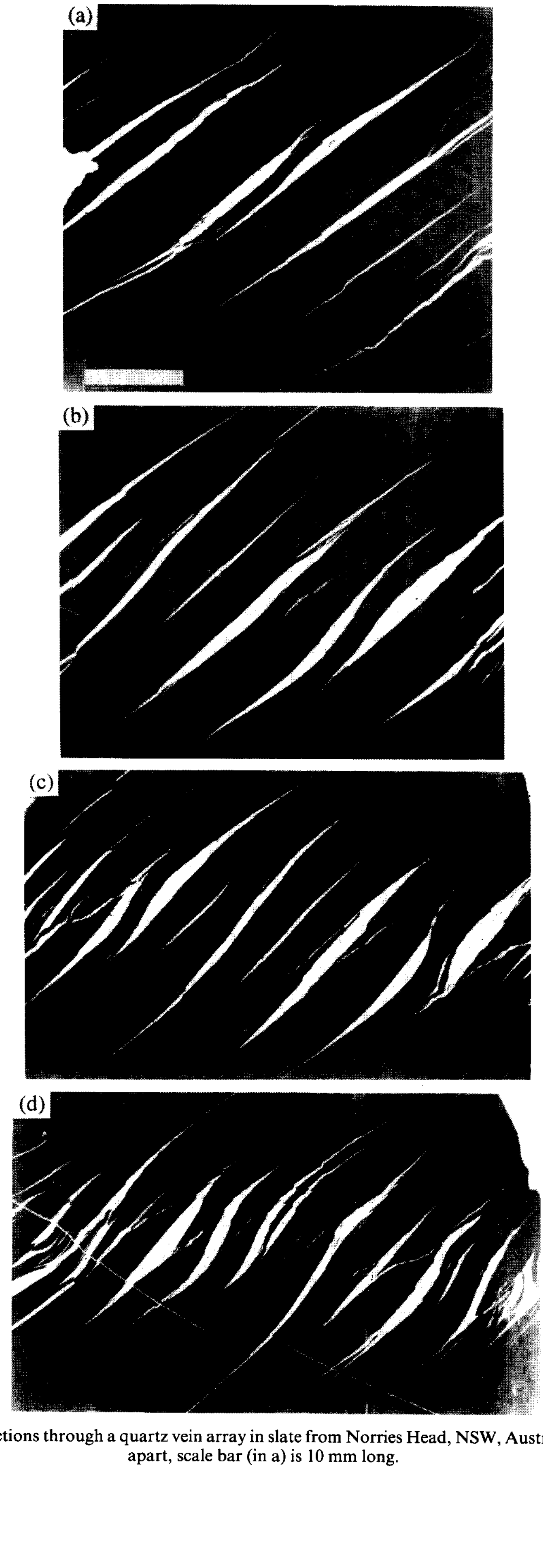

Fig. 6. (a–d) Serial thin sections through a quartz vein array in slate from Norries Head, NSW, Australia. Sections are 12 mm apart, scale bar (in a) is 10 mm long.

and vein-array angle, because the exposure plane is normal to the plane containing the principal shortening and intermediate strain axes, the overall symmetry of the conjugate arrays is seen (Smith 1995).

Each of the en échelon vein arrays observed in the Norries Head area occurred in the finely laminated facies of the turbidite sequence. Where vein arrays in laminites extend into sandstone beds, a single planar fault hosting thin veins replaces the vein array. This relationship was particularly clear in vein system 5 (Fig. 3b, location 5) where conjugate faults displace sandstone beds. Faults intersect in a band of laminite where the faults have pinnate veins and en échelon arrays have formed (Fig. 4e).

The near parallelism of veins and conjugate arrays is shown by the proximity of the poles of arrays to the poles of the veins in the conjugate arrays (Fig. 5). The shortening (ε_1), intermediate (ε_2) and extensional (ε_3) principal strain axes were derived from the bisectors of the arrays. Although the plunge of the principal shortening direction varies, its trend is NE–SW, approximately perpendicular to the strike of bedding and the hinge surface of the dominant folds, suggesting that the veins are related to common stress and strain fields.

The detailed morphology of vein arrays was investigated by preparing serial thin sections through an array (Fig. 6). This investigation confirms that the veins are not distorted by later deformation. A shear fracture origin for the veins can be eliminated on basis of a lack of evidence of shear displacement of bedding across vein tips as would be expected in veins hosted by shear fractures (e.g. Smith in press). The serial sections (Fig. 6) show a gradual change in morphology from planar to sigmoidal. In profile, the veins lack rotational symmetry but the bridges of rock between veins are rotationally symmetrical and maintain constant orthogonal thickness.

DISCUSSION

The foregoing description of the geometry of conjugate vein arrays from published sources and the field study demonstrates that the convergent configuration is common and cannot be ignored in practical and theoretical considerations of the formation of vein arrays. In particular, a new model is required to explain how extension fractures can form in conjugate arrays which have a convergent configuration.

Kinematics of fracture initiation

The non-parallelism of extension fractures within a convergent configuration of arrays indicates that the principal strain axes causing fractures are not parallel throughout the rock and are therefore locally influenced. This was alluded to by Beach (1975) when he not only made a geometric distinction between Type 1 (cross-parallel) and Type 2 (bisector-parallel) arrays but also suggested a mechanistic distinction between the formation of the two types. He proposed that the initiation of bisector-parallel fractures pre-dates the arrays (in the way described above) but, cross-parallel fractures form subsequent to the initiation of the shear zone represented by the array. In his model it was the ductile strain in the array zone which determined the orientation of the fractures (antithetic shear fractures in his model). Control of fracture orientation by ductile shear strain cannot be a general explanation of convergent conjugate vein arrays because many examples (such as those at Norries Head) have very low strain, yet it may be one case of a more general model in which the kinematics of the array zone exerts local influence over the orientation of fractures.

The geometry of the extension fractures in convergent conjugate arrays indicates that the modifications of stresses in arrays possess mirror symmetry across the bisector of the conjugate arrays. Such modifications are compatible with, and controlled by, the bulk strain accommodated by the system. Any model for the origin of convergent conjugate systems must perturb the stresses in such a symmetric manner. A pair of conjugate faults could, if the parent faults broke down into en échelon fractures, lead to the formation of extension fractures in convergent conjugate geometry. The fracture–array angle is dependent on the specific conditions of breakdown, particularly the kinematics of the parent faults (Pollard & Segall 1987), and is not directly related to the conjugate angle of the parent faults. The configuration of veins within the conjugate arrays therefore depends on the combination of these two angles. A strongly convergent configuration will occur when the fracture–array angle is greater than the conjugate angle. A cross-parallel configuration will occur when the fracture–array angle is equal to the conjugate angle. A weakly convergent configuration will occur when the fracture–array angle is less than the conjugate angle but greater than half the conjugate angle. Within this continuum of geometric relations no special significance resides in the cross-parallel configuration other than the coincidental equivalence of the fracture–array angle of arrays and the conjugate angle between arrays.

In the proposed model, initiation of extension fractures post-dates the establishment of array orientations by the parent faults. This contrasts with the 'Durney–Ramsay' model of the formation of bisector-parallel vein arrays (Ramsay 1982) in which the initiation of fractures slightly pre-dates the formation of arrays.

Analogue modelling

In order to illustrate the proposed model of extension fractures forming in a convergent configuration by en échelon breakdown of parent faults, an analogue model will be presented. The experiment was based on breakdown of simple fault movement to en échelon fractures as has been modelled by deforming a layer of clay overlying rigid boards (Riedel 1929, Smith & Durney 1992). In those experiments, two rigid boards were used to replicate movement of a single fault or deformation zone. To model the formation of conjugate fracture arrays, four boards were required to replicate simultaneous movement on two differently oriented faults. The boards comprised two acute triangles and two obtuse triangles. The tips of the acute triangles were cut so that the boards could move towards each other. Apart from this modification, the experimental conditions were the same as those reported by Smith & Durney (1992).

Displacement parallel to the interfaces of the boards was induced, resulting in a fracture–array angle of 45°, as seen in previous clay modelling work (Riedel 1929, Smith & Durney 1992). The conjugate angle of the boards can be determined arbitrarily and, in order to experimentally reproduce a cross-parallel configuration of fractures, an angle of 45° was used. As the model illustrated in Fig. 7 shows, the fractures formed in each array are parallel to the conjugate array. In this experiment the fracture–array angle and the conjugate angle are independent and the cross-parallel configuration of en échelon fractures occurs because these two angles happen to be equivalent.

Figure 8 illustrates two ways that faults may break down into en échelon arrays as they pass from one material to another. The material which undergoes en échelon breakdown can be considered to be less competent, and the displacements of the more competent blocks have determined the overall displacement of the en échelon array. This process has been described as kinematic control on fracturing (Mandl 1988 p. 135, Smith & Durney 1992, Smith 1993) to emphasise the way the displacements have induced a local stress field in the less competent material. The model in Fig. 8(b) is analogous to the field examples at Norries Head where the competent material represents sandstone beds and the incompetent material represents laminite beds. The single continuous faults with veining seen in sandstone beds breakdown into en échelon arrays as they pass into, or through, the laminated facies of the rock package.

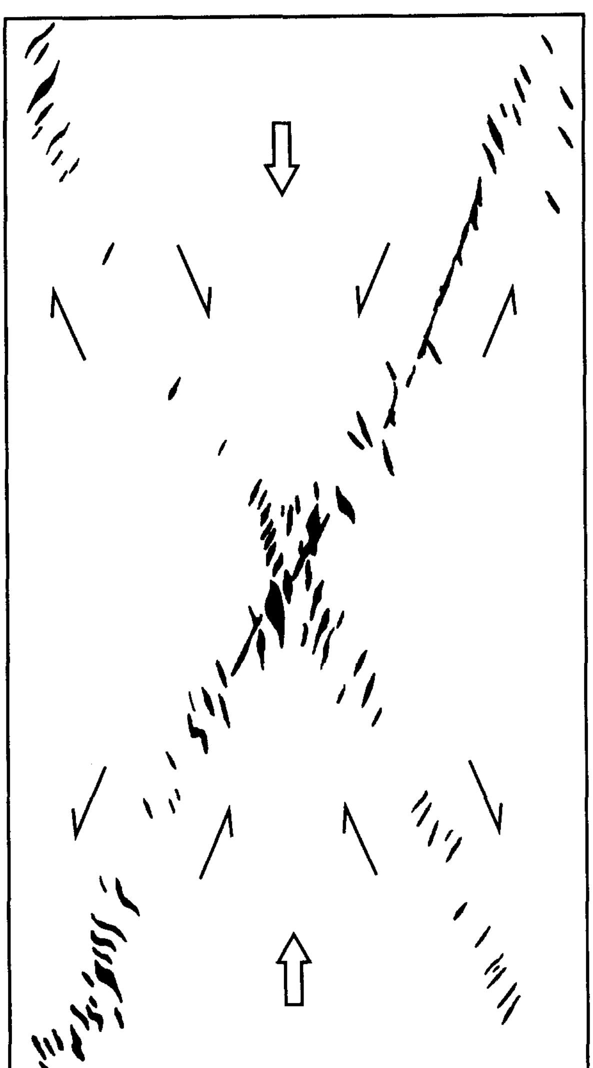

Fig. 7. Experimental model of cross-parallel fractures in a conjugate array. The veins (black) have formed in clay overlying four rigid boards which have moved according to the arrows shown.

Kinematics of vein opening

The 'Durney–Ramsay' model of en échelon vein development emphasises the role of concurrent fracture propagation and shear displacement on arrays in producing sigmoidal veins. This process produces an increase in the size of veins as they change from straight to sigmoidal (Durney & Ramsay 1973). This process can be contrasted with the bridge-bending model for sigmoidal veins (Nicholson & Ejiofor 1987) in which the bridges of rock defined by overlapping en échelon fractures buckle, usually maintaining constant orthogonal thickness.

The three-dimensional morphology of veins, as indicated by serial thin sections (Fig. 6) indicates that the sigmoidal shape of the veins is primarily due to the rotation of bridges of rock between veins in the manner described by Nicholson & Ejiofor (1987). Evidence for

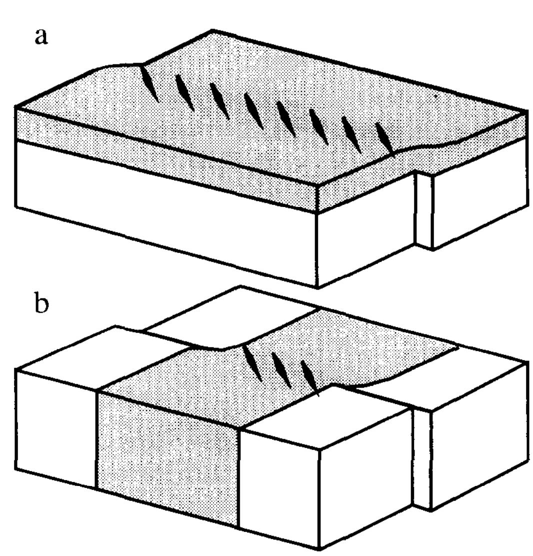

Fig. 8. (a) En échelon break-down due to displacement parallel to the layering of competent (blank) and incompetent (shaded) material and (b) en échelon break-down due to displacement perpendicular to the material layering.

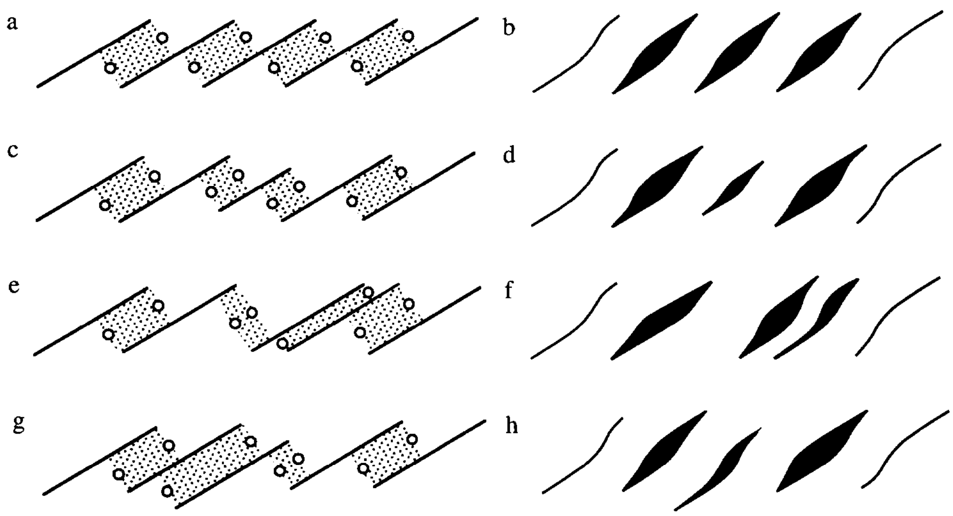

Fig. 9. Schematic diagrams of arrays of fractures (lines) defining bridges (stippled with end points marked by circles) which rotate to produce veins (black). (a) An ideal fracture array and (b) an ideal vein array. (c & d) Non-ideal fracture and vein arrays with the centre fracture/vein smaller than others. (e & f) Non-ideal fracture and vein arrays with the centre fracture/vein spaced differently to others. (g & h) Non-ideal fracture and vein arrays with the centre fracture/vein positioned differently to others with respect to the centre line of the array.

this is two-fold. First, vein shapes grade from straight to sigmoidal without commensurate increase in vein size, which would be required for the model of concurrent fracture propagation and shear strain. Second, rock bridges maintain constant orthogonal thickness and have rotational symmetry, whereas individual veins lack rotational symmetry.

This geometry indicates that the two margins of each vein deformed independently of each other and that the shape of the veins is dependent on the geometry of the rock bridges on either side of the vein. In an ideal vein array, that is one with evenly sized, spaced and positioned fractures (Figs. 9a & b), both veins and rock bridges can have rotational symmetry in profile. However, natural vein arrays typically have non-ideal geometries in which vein size (Figs. 9c & d), vein spacing (Figs. 9e & f) and vein position relative to the array centre line (Figs. 9g & h) all vary. These variations produce different amounts of fracture overlap and hence, different rock bridge aspect ratios. In the bridge-bending model these variations lead to the diversity of vein shapes observed in Fig. 6.

CONCLUSIONS

A field example of conjugate arrays of filled extension fractures which converge towards the shortening strain axis of the arrays requires a reassessment of the conceptual models for the formation of conjugate vein arrays. The assumption that extension fractures must all be parallel to the bisector of the arrays is not valid. The model proposed here is that the arrays form by localised break down of parent faults into en échelon extension fractures. Because the angle of fractures relative to their host array often approximates the angle between the conjugate parent faults, the conjugate en échelon arrays have a configuration in which the veins of each array are approximately parallel to the trend of a conjugate array.

This model involving stress and strain localisation does not negate the existence of a regional stress field. Indeed a consistent stress and strain field was found in the field study. Rather, the model acknowledges the localised temporal and spatial variations that can occur within such a stress field and the influence these perturbations can have on the geometry of minor structures such as en échelon vein arrays.

The three-dimensional morphology of veins in the field study indicates their formation by bridge-bending after the fractures had propagated. The sigmoidal veins so formed, and the intervening rock bridges, have distinctive morphologies which can be distinguished from those formed by the process of vein rotation concurrent with fracture propagation which occurs in the 'Durney–Ramsay' model of en échelon vein array kinematics.

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