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SHORT NOTES

True and apparent geometric variability of en-échelon vein arrays

JOHN V. SMITH

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

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Abstract—The wide range of vein-array angles reported for en-échelon vein arrays can be attributed to both true and apparent geometric effects. A survey of published figures supports a continuum of orientations rather than distinct populations related to different fracture mechanisms. The results of the survey indicate a modal vein-array angle of less than 45° which indicates area increase as described by a displacement vector oriented outward from the array. A stereometric analysis of the effects of exposure-plane orientation on the apparent vein-array angle is developed. Examples of vein arrays, from the Nambucca Slate Belt of eastern Australia, exposed on two differently-oriented surfaces are shown. These examples include non-profile exposures with apparent vein-array angles which are (1) less than, (2) greater than, (3) approximately equal to, and (4) of opposite shear sense to the true vein-array angle.

INTRODUCTION

En-échelon vein arrays exhibit a diversity of morphological and geometric characteristics. An important parameter is the acute angle which veins make with their host array. In studies of natural vein systems this vein-array angle is found to vary considerably. Such diversity has been attributed by some workers to different fracture mechanisms. In this approach, veins at 45° to the array have been attributed to extensional fracturing, veins at 15° have been attributed to synthetic shear fracturing and those in between have been ascribed to a hybrid of those fracture mechanisms (e.g. Hancock 1972, 1973, 1985, Engelder 1987). An alternative approach attributes diversity of orientation to differences in the kinematics of the array, such that veins at 45° to the array are attributed to extensional fracturing in simple shear whereas lower vein-array angles indicate greater components of opening or area increase of the array (e.g. Durney 1981, Ramsay 1982).

Three-dimensional study of vein system morphology by serial sectioning has been performed on isolated samples such as loose cobbles (Nicholson & Ejiofor 1987; Craddock & van der Pluijm 1988, Nicholson 1991). However, field studies are commonly reliant on observations of vein traces on two-dimensional exposures. Most published measurements of vein-array angles on single exposures are supported by evidence that the exposure is oriented at a high angle to the veins (Roering 1968, Hancock 1972, 1973, Rothery 1988).

The purpose of this study is to present a summary of the diverse vein-array angles from published figures, to discuss explanations which have been proposed for such diversity and to present an analysis of the relationship between apparent vein-array angles and the orientation of exposure surfaces. The range of apparent vein-array angles is illustrated by selected field examples.

VEIN-ARRAY ANGLE DIVERSITY

Hancock (1972) measured the orientation of veins in 40 arrays in exposures of greywackes. He observed a range of vein-array angles from 10 to 46° and attributed this variation to the operation of three fracture mechanisms (1) shear fracture, (2) extensional fracture and (3) a hybrid of those two mechanisms. Most of the measurements (Hancock 1972, 1973) were in the form of trace pitches on bedding with the observation that the veins were approximately normal to bedding-parallel exposure. Vein orientation has been used by other authors to support the existence of multiple fracture mechanisms (Shainin 1950, Roering 1968, Beach 1975, Hancock 1985, Engelder 1987, Rickard & Rixon 1983, Rothery 1988, Nicholson 1991). In contrast, other work has proposed that a range of vein-array angles can result from extensional fracturing in zones of shearing accompanied by area change (Durney 1981, Ramsay 1982, Collins & De Paor 1986).

Experimental results such as those of Durney (1985) and Smith & Durney (1992) show that real variations of fracture-array angles ranging from 0 to 45° can be accounted for by variations in kinematic settings ranging from orthogonal divergence to strike-slip, respectively. It is also feasible that higher fracture-array angles could result in convergent kinematic settings, as suggested by Ramsay (1982).

A survey of the orientation of veins in published figures of en-échelon vein arrays has been made. Tangents to the outer margin at each vein tip were taken to represent the orientation of initiation of the fracture (Nicholson & Pollard 1985). The angle between this tangent and the centre line of each array is the vein-array angle (β) of the vein. Figure 1 shows the vein-array angle of 777 en-échelon veins with a 5° class interval (sources are in Table 1). The graph shows a wide range of vein-array angles between 0 and 90° with a peak value between 35 and 40°. The continuum of angles shown on the graph (Fig. 1) does not support a relationship between vein orientation and discrete fracture mechanisms, rather, it supports the concept of continuous variability dependent on the kinematics of the array. The mode of vein-array angles between 35 and 40° corresponds to an array-displacement vector oriented between 20 and 10° (respectively) outward from the array. Most of the vein-array angles exceeding 60° come from a study by Roering (1968) of veins in quartzites of the Witwatersrand Basin. He suggested that the high angles could be a result of rotation of the veins from their initial orientations by continued shearing on the array.

The role of apparent variations in the geometry of structures seen in two-dimensional exposures is well known and is one of the cornerstones of structural analysis. In the published examples of en-échelon vein arrays reviewed, it was implicit that the view of the arrays shown was that of, or close to, the profile plane of the array. However, explicit justification of this in terms of the three-dimensional orientation of the exposure, veins, array or vein-array intersection is rare in field studies.

Table 1. Sources of vein-array angle data

Source	Fig. No.	No. of measurements
Hills 1963	IV-17b, VII-14	17
Ramsay 1967	3.26, 3.28	19
Roering 1968	3–11	199
Ramsay & Graham 1970	10	25
Weiss 1972	162–167	74
Dennis 1972	13, 19	10
Hancock 1972	1 to 4	37
Hancock 1973	VI, V	34
Beach 1974	3	10
Beach 1975	2, 5, 6, 10–13	95
Beach 1977	5(a) & (b)	23
Knipe & White 1979	1	6
Ramsay 1980	2b	12
Hanmer 1982	2	7
Hancock *et al.* 1983	3.21(b)&(d)	17
Larter & Allison 1983	13	9
Ramsay & Huber 1983	2.13(A)&(B), 3.22(A)&(B)	51
Rickard & Rixon 1983	1, 2(a)	96
Powell 1983	48	11
Chere *et al.* 1985	8	8
Granier 1985	8	4
Collins & DePaor 1986	3	13

APPARENT GEOMETRIC RELATIONS

The true angle between two planes is only measured on a surface perpendicular to both planes. Consequently, for vein-array systems, the vein-array angle observed on an exposure surface is dependent on the orientation of both these structures with respect to the surface. Thus, demonstrating that the exposure surface perpendicular to veins (e.g. Roering 1968, Hancock 1972, 1973, Rothery 1988) does not necessarily indicate a true profile of vein arrays. The profile plane is perpendicular to both veins and arrays, that is, perpendicular to the intersection of veins and their arrays. Non-profile exposures will have apparent vein-array angles which, in the absence of strict three-dimensional analysis, may account for some of the diversity of angles recorded in Fig. 1. Nevertheless, it is probable that the modal orientation class reflects true geometric relations as most authors imply some attempt to observe the profile of the vein-array systems.

Not only does a non-profile exposure surface show an apparent vein-array angle but, as has been shown for faults (Wheeler 1987), a false apparent sense of shear can be observed in some exposure orientations. The geometric relationships controlling apparent vein-array angles and apparent sense of shear will be further considered by stereographic analysis.

Figure 2 shows a stereograph of a hypothetical vein

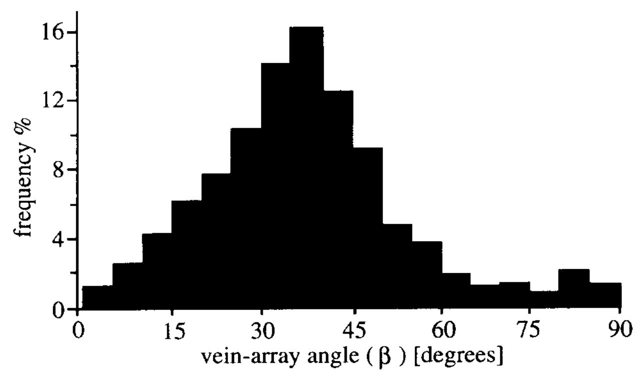

Fig. 1. Percentage frequency distribution of vein-array angles of en-échelon veins in arrays from published sources (5° class intervals, n = 777, sources in Table 1).

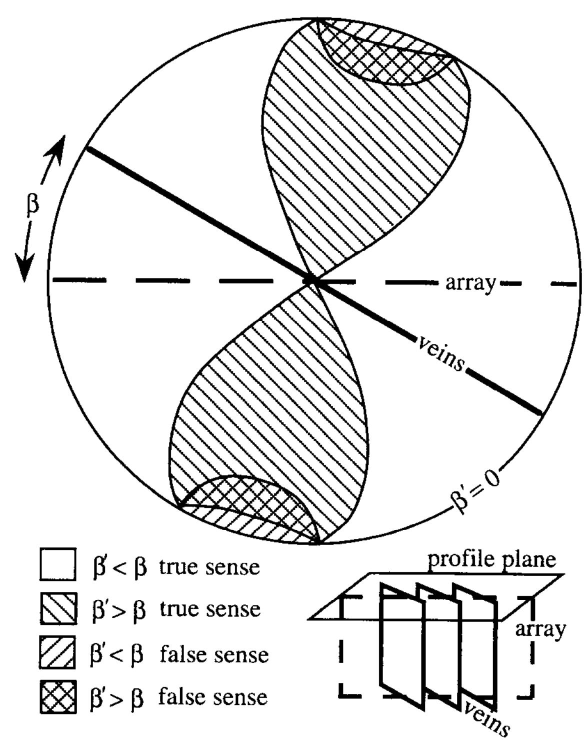

Fig. 2. Stereograph of apparent vein-array angle (β') depending on the pole of the exposure plane. Block diagram shows the orientation of the profile plane (primitive circle on stereograph). Fields for poles of non-profile exposure surfaces are hatched on the stereograph.

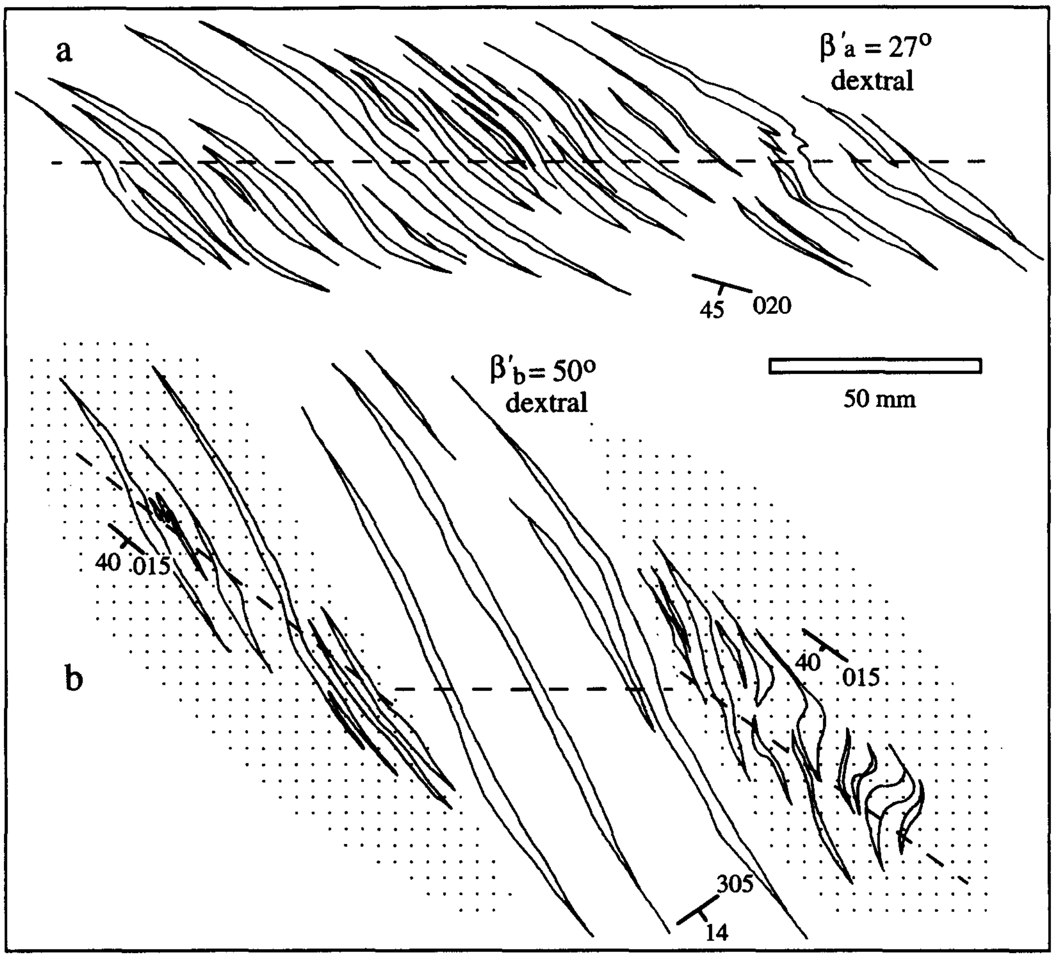

Fig. 3. Two differently oriented exposures (a & b) of the same en-échelon vein array (array 1). Views are perpendicular to the exposure surfaces (except for stippled area) and the orientation of exposure surfaces are shown by dip symbols.

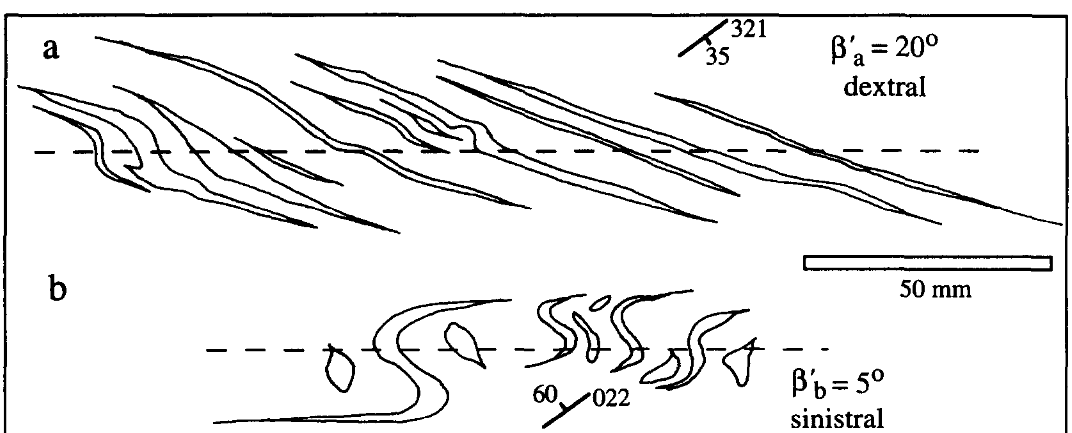

Fig. 4. Two differently oriented exposures (a & b) of the same en-échelon vein array (array 2). Views are perpendicular to the exposure surfaces and the orientation of exposure surfaces are shown by dip symbols.

array with a vein-array angle of 30° and a vertical line of intersection. The true vein-array angle (β) would be seen in an exposure plane with a vertical pole. Fields defining the apparent vein-array angles (β') observed on any exposure plane are shown on Fig. 2. The apparent vein-array angle (β') is the difference between the pitches of the veins and the array, in the exposure plane, which can be found by right spherical trigonometrical relations when the veins and array are vertical:

$$\beta' = |\cot^{-1}(\cos\theta/\tan\alpha) - \cot^{-1}(\cos\theta/\tan\nu)|, \quad (1)$$

where θ is the dip of the exposure surface, α is the acute angle between the strike of the exposure and the strike of the array and ν is the acute angle between the strike of

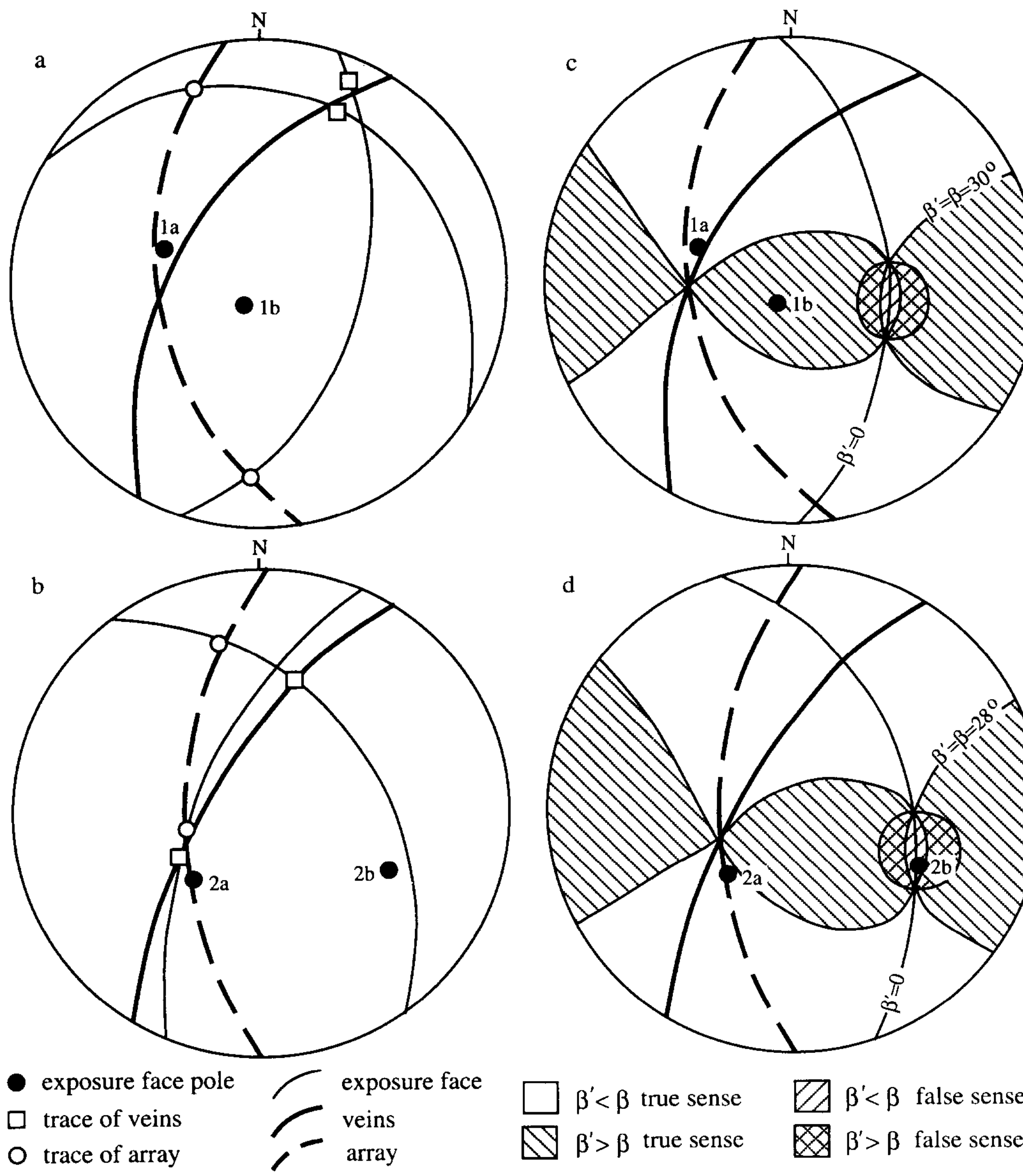

Fig. 5. (a & b) Stereographs of the orientations of the exposure surfaces, traces of veins and arrays and orientation of veins and arrays for array 1 and 2, respectively. (c & d) Stereographs of the apparent vein-array angle fields for poles to exposure surfaces for array 1 and 2, respectively.

the exposure and the strike of the veins (clockwise positive for α and ν).

Apparent vein-array angles can be lower or higher than the true angles and can exceed 90° such that the observed acute angle is actually the obtuse angle between veins and their array. Exposure planes with poles in this field give arrays which have the opposite sense of shear to the true sense of shear of the arrays.

FIELD EXAMPLES

Selected en-échelon vein arrays from the Nambucca Slate Belt will be used to demonstrate the range of apparent geometrical effects described above.

The Nambucca Slate Belt is a Permian rift basin within the Paleozoic New England Fold Belt of eastern Australia (Leitch 1977). The basin was deformed during the Late Permian with up to five deformational phases being recognised across the belt. Middle Head is situated in the southeastern part of the belt where deformation is less intense although the area of most intense deformation is located only 15 km to the north. At Middle Head, the dominant (D_1) foliation strikes northeast. Veining has exploited the foliation, opening as en-échelon vein array indicating NE–SW shortening. The dextral system is dominant but a conjugate sinistral system was also observed.

Figure 3(a) shows a vein array (array 1) as observed in a near-profile exposure (exposure 1a) and Fig. 3(b) shows the same array exposed on a differently oriented plane (exposure 1b). Exposure 1b shows a greater vein-array angle than exposure 1a. Figure 4(a) shows a vein array (array 2) as observed in a near-profile exposure (exposure 2a) and Fig. 4(b) shows the same array exposed on a differently oriented plane (exposure 2b). Not only is the apparent vein-array angle significantly less in exposure 2b, but the sense of shear of the array is the opposite of the true sense.

The three-dimensional configuration of the structures was constructed from the traces of the veins and arrays on each of the exposure surfaces. The trace of the array is taken as the line which best fits the centre points of the major veins in the array. The trace of the veins is taken as the average orientation of the vein tips. The apparent vein array angle (β') is the angle measured between the vein tip traces and the array trace. In most cases the traces plotted sufficiently far apart on the stereograph to allow a great circle to be drawn, except for the traces of vein tips of array 1 (Fig. 3) which plotted close together on the stereograph (Fig. 5a) making a construction of the orientation of the veins unreliable. In that case, dip and strike of the veins measured on the outcrop was used to supplement the orientation data. Figures 5(c) and (d) show stereographs of the fields of exposure-surface poles and their apparent vein-array angles, as described in Fig. 2. The poles to exposure surface 1a & b and 2a & b are shown in Fig. 5(c) and (d). In array 1, the near-profile plane (exposure 1a) approximates but underestimates the true vein-array angle whereas exposure 1b overestimates the vein array angle. In array 2, the near-profile plane (exposure 2a) has an apparent vein-array angle less than the true vein-array angle, whereas exposure 2b lies within the small field containing poles to planes which show low apparent vein-array angles with a false sense of shear.

DISCUSSION AND CONCLUSIONS

The diversity of measured vein-array angles is dependent on both true and apparent geometric variations. True variation relates to the kinematics of the array which includes both the infinitesimal kinematics related to fracturing, and the finite kinematics which can result in the rotation of veins away from their initial orientations. Apparent variation relates to the orientation of the exposure surface to orientations of both the veins and the arrays. Non-profile exposure surfaces can exhibit vein-array angles which are less than, greater than, or fortuitously equal to the true vein-array angle. Extremely oblique non-profile exposures can even exhibit a false sense of shear.

Where possible, field studies of en-échelon vein systems should utilise differently oriented exposures to determine the true angular relations between veins and their host arrays. An exposure surface perpendicular to the veins is not necessarily a profile plane, the surface must be perpendicular to the intersection line of veins and their array. In the field, the line of intersection between arrays and veins may be approximated by the hinge line of the curvature of sigmoidal veins.

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