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Initiation of convergent extension fracture vein arrays by displacement of discontinuous fault segments

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Abstract—The formation of extension fracture-hosted veins that converge toward the bisector of conjugate arrays is problematical. The orientation of the extension fractures suggests that they formed within zones of re-oriented stress axes, established prior to fracturing. However, the commonly observed acute conjugate angle indicates that brittle dilatancy was already occurring during the initiation of the zones. Previous work has shown evidence of convergent extension fracture vein arrays formed by en échelon breakdown of faults passing from arenitic to pelitic units in turbidites. The present work shows evidence of convergent extension fracture vein arrays in limestone formed by localised re-orientation of stress due to slip on discontinuous fault segments causing en échelon fracture. The calcite veins studied occur in the Siluro-Devonian Jack Formation exposed in the Jack Hills Gorge, 200 km west of Townsville, in the Broken River province of north Queensland, Australia. The vein array systems display a range of acute conjugate angles from 60° to 30°. The veins of conjugate arrays are arranged mainly in convergent configurations (including cross-parallel or Type 1), but bisector-parallel (Type 2) configurations also occur. The shear strain recorded by markers crossing convergent arrays and the morphology of veins was found to be inconsistent with the possibility that convergence resulted from rotation of veins from an initial bisector-parallel configuration. © 1997 Elsevier Science Ltd.

INTRODUCTION

The use of vein arrays as a tool in structural analysis requires understanding of the attributes of geometry from which clear inferences of kinematics can be made (Collins and De Paor, 1986; Craddock and Van der Pluijm, 1988). Roering (1968) and Beach (1975) suggested two distinct types of conjugate vein systems based on the orientation of veins relative to the bisector of conjugate arrays. Smith (1996b) suggested that these types occur within a continuum of configurations from bisector-parallel (Type 2 of Beach, 1975) to convergent configurations, including the special case where veins of one array are parallel to the conjugate array called a cross-parallel configuration (Type 1 of Beach, 1975). Detailed structural analyses of vein arrays have emphasised bisector-parallel systems of veins initiating as extension fractures, but have not considered how convergent configurations might develop (Ramsay and Huber, 1987). However, the occurrence of convergent configurations is common, and some workers have used the orientation of the bisector of single arrays and their veins as a surrogate for principal compressive stress direction (Mitchell and Forsythe, 1988).

Both Roering (1968) and Beach (1975) considered that parallelism between an array and the veins of its conjugate array was an indication of a shear fracture origin of veins. This interpretation of fracture mechanism based on geometry has not been supported by morphological evidence that would be expected of shear fracture-hosted veins (Smith, 1996a). Beach (1975) suggested that convergent vein arrays occurred by fracturing within zones of pre-existing ductile strain. However, such a model is inconsistent with the interpretation of the acute conjugate angle of arrays as an indication of initiation as dilatant brittle failure zones (Ramsay, 1982). This is the essential problem of initiation of convergent extension fracture arrays: the acute conjugate angle of arrays indicates initiation by brittle rupture, but the orientation of fractures suggests that zones of re-oriented stress were established before extension fractures were formed.

It is possible that in some cases, a convergent configuration is produced by the rotation of veins from an initial bisector-parallel configuration, but where extension fractures can be shown to have initiated in a convergent configuration, a new model is required. Smith (1996b) proposed a model by which vein arrays initiated in a convergent configuration by en échelon break-down of parent faults in turbidites. That model was related to specific field evidence and was not a general model that could be related to all initially convergent vein arrays.

In this paper, examples of convergent vein arrays hosted by limestone are examined. Studies of calcite veining in limestone have been especially prominent in the development of understanding of vein arrays due to the brittle behaviour of the rock and the effectiveness of pressure-solution in promoting vein filling (e.g. Shainin, 1950; Hancock, 1973; Rothery, 1988). Conjugate vein arrays in limestone units of the Jack Formation, north Queensland, Australia, include examples of both bisector-parallel and convergent configurations. The range of vein array configurations will be described and an example of a convergent vein array will be investigated in detail. The possibility of rotation of veins from bisector-parallelism to convergence is assessed, and a model to explain convergent extension fracture initiation is proposed.

VEIN ARRAYS

The Jack Formation is a carbonate-rich unit at the top of the clastic-dominated Graveyard Creek Group of the Broken River Province that forms part of the northern section of the Palaeozoic Tasman Fold Belt (Arnold and Fawckner, 1980; Fielding *et al.*, 1993; Lang, 1993). Stylolites are well developed throughout the limestones, are predominantly bedding-parallel and approximately parallel to the hinge surface of major folds, and have been inferred to have formed by the folding deformation (Fielding *et al.*, 1993).

Calcite vein arrays are abundant in the limestones of the Jack Formation. Sections along the centre of the Broken River channel in the lower limestone unit and along the northwestern wall of the Jack Hills Gorge for the upper limestone unit were chosen for detailed study. Twenty-three conjugate vein array systems were recognised along these exposures. Outcrop surfaces are generally irregular, allowing measurement of the three-dimensional orientations of veins and arrays, as required for geometric analysis (Smith, 1995). The geometry of the vein systems was determined from both the three-dimensional measurements and inspection of exposed surfaces.

The conjugate angle and the vein-array angle are the main determinants of the geometry of each vein system as a whole. By graphing conjugate angle against vein-array angle, specific geometric configurations of veins and arrays can be defined (Fig. 1). Four of the vein systems have a bisector-parallel configuration, whereas the remaining 19 vein systems are convergent and approximate the cross-parallel configuration. Morphological features indicating a shear fracture origin (Smith, 1996a) are absent, and an extension fracture origin for the veins is accepted.

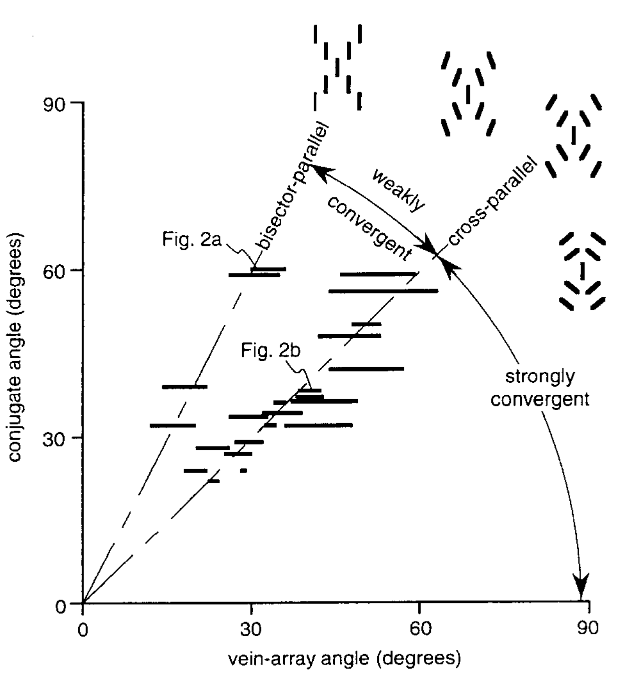

Fig. 1. Graphical representation of the configurations of the conjugate vein arrays, exposed in the Jack Hills Gorge, north Queensland, in terms of their conjugate angle and vein-array angle. Configurations range from bisector-parallel to strongly convergent. Bars link the average vein-array angle determined from each array of a conjugate pair.

DISCUSSION

The conjugate vein arrays studied have systematic variations in orientation and geometry, which will be reported elsewhere. The configurations of vein array systems in terms of conjugate angle and vein-array angle (Fig. 1) indicate two populations of vein system types, bisector-parallel (e.g. Fig. 2a) and convergent (Fig. 2b). Veining in the two systems appears similar, although diffuse micro-veining is associated with the bisector-parallel arrays.

In convergent vein systems, the amount of pressure-solution, as indicated by the amplitude of stylolites, is greater in the bridges between veins than in the surrounding limestone. This indicates that some of the shear displacement of the arrays was accommodated as ductile strain by the mechanism of pressure-solution. Stylolites parallel to bedding also acted as markers recording the shear displacement along arrays. In order to determine whether it is possible that rotation of the veins by ductile strain could cause a change from a bisector-parallel to a cross-parallel configuration, the vein system shown in Fig. 2(b) will be investigated.

Ductile strain can be accumulated synchronously with fracture propagation producing a sigmoidal vein shape (Durney and Ramsay, 1973). Alternatively, sigmoidal veins are formed by bending of the wall rock bridges between veins (Nicholson and Ejiofor, 1987). The rotation of the central part of the vein is often associated with development or intensification of cleavage (Rickard and Rixon, 1983). It is possible that continuing ductile shear strain can cause the rotation of the entire vein, including its tips, thus modifying a bisector-parallel configuration into a convergent configuration. The veins in the convergent system (Fig. 2b) are not strongly sigmoidal, but the possibility of rotation of the veins during the accumulation of the ductile strain must be assessed. The geometric parameters of the vein system (Fig. 2b) approximate the cross-parallel configuration: conjugate angle of 39° and average vein-array angle of 40°.

If the vein system had initiated in a bisector-parallel configuration the vein-array angle would have been half the conjugate angle, that is, 19.5°. Therefore, a rotation of 20.5° would be required to produce the observed final configuration. The deflection of stylolites will be used as a

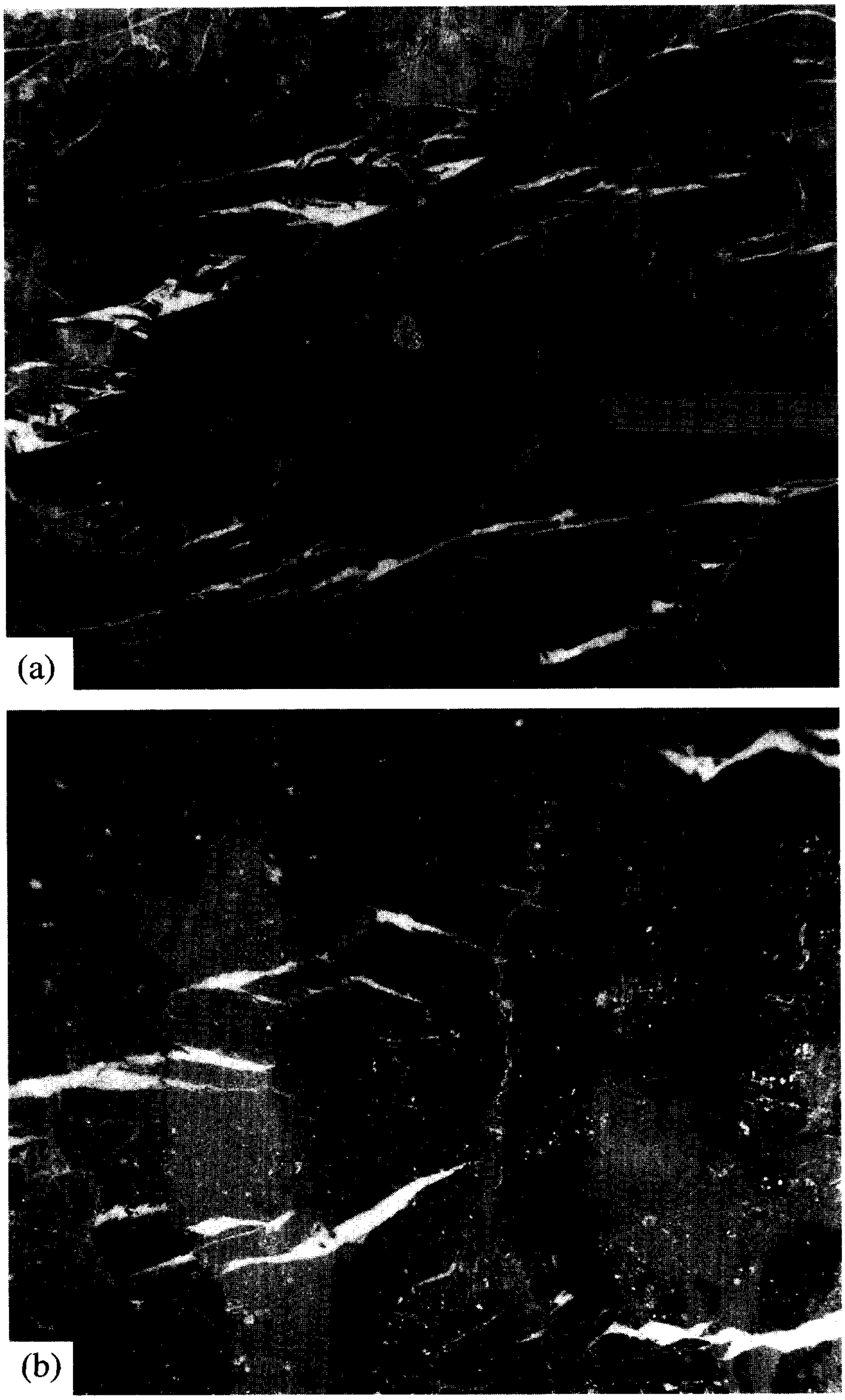

Fig. 2. Photographs of vein arrays from the Jack Limestone. (a) Conjugate vein arrays with a bisector-parallel configuration and (b) conjugate vein arrays with a convergent configuration (field of view is 18 cm top to bottom).

surrogate for shear displacement of the array. The analysis is based on simple shear displacement and due to the relatively small amount of vein opening the rotational effects of dilatancy of the zone are expected to be minor. In the vein system (Fig. 2b), a stylolite crosses both arrays and, although it is irregular, it is clearly deflected in the appropriate sense as it crosses each of the arrays. Assuming that the deflection of the stylolite is entirely due to shear strain, an estimate of the shear displacement is obtained (Fig. 3). Geometric analysis shows that shear strain of the array can only account for a rotation of 10–13° (Fig. 3).

The possibility of vein rotation must also be assessed in terms of the kinematics of vein opening as indicated by

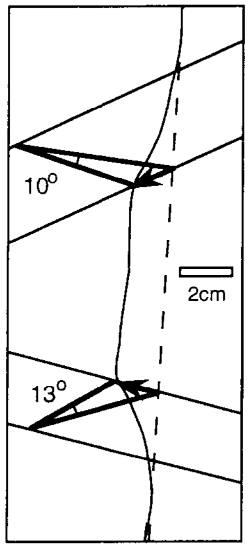

Fig. 3. Line drawing of the shear displacement (arrows) of arrays estimated from the deflection of a stylolite (Fig. 2b). A maximum of only 10–13° rotation is possible.

the morphology of the veins. The three main shapes observed are planar, lens-shaped and wedge-shapes linked by array-parallel veins, all locally modified by stylolites. The possibility of rotation of planar and lens-shaped veins is difficult to assess, whereas the linked wedge-shaped veins record more detailed evidence of their kinematics. The margins of the linked wedge-shaped veins (right of Fig. 2b) indicate opening of the veins by displacements sub-parallel to the linking fractures and at a high angle to wedge-shaped parts of the veins. These array-parallel displacements account for a significant component of the shear displacement of the arrays and decrease the potential for vein rotation.

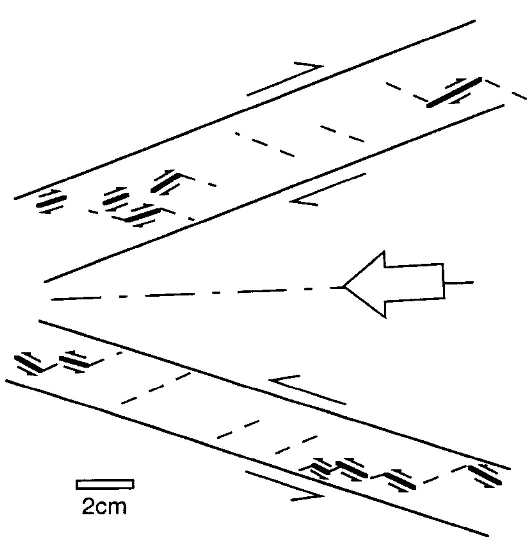

Fig. 4. Line drawing of the inferred early fault segments (thick lines) which result from compression (open arrow) and control the kinematics of the developing arrays and extension fractures at terminations and between segments (dashed lines).

It could be suggested that dissolution on stylolites after the formation of arrays could have imposed pure shear or similar bulk deformation on the rock to account for the rotation of the veins. However, the morphology of stylolites indicates that significant deformation ceased with the development of the arrays. This evidence includes a greater amplitude of stylolite teeth within arrays compared to host rock; more significantly, the orientation of the stylolite teeth is perpendicular to veins within arrays, and there is no indication of reorientation of teeth toward the array bisector as would be expected if a later distributed deformation had been imposed on the rock.

A mechanism of formation must reconcile the role of brittle fracture at initiation, as indicated by the acute conjugate angle, with the convergent configuration of veins, which implies that zones of stress re-orientation existed prior to brittle fracture initiation. If the process were controlled by the initiation of extension fractures, they would be expected to form in a bisector-parallel configuration, whereas if stress re-orientation occurred before initiation of brittle fracturing, the acute conjugate angle is unexplained. A reconciliation of these points comes from consideration of the array-parallel vein segments that link some of the en échelon veins. The linking veins could be interpreted as later features caused by brittle failure of the rock bridges. However, an alternative interpretation is that they are early discontinuous fault segments that initiated in response to compression. The kinematics of similar segmental faulting during the initiation of thrust faults has been described previously (Ellis and Dunlap, 1988). Figure 4 shows the distribution of these structures without the vein material or extension fractures being shown. Displacement on the fault segments creates localised stress concentration and re-orientation leading to the formation of extension fractures as pinnate structures at fault segment terminations and as en échelon fractures between fault segments. The orientation of the extension fractures depends on the kinematics of the faults and happens to be approximately equal to the conjugate angle between the initiating fault zones; hence, an approximately cross-parallel convergent configuration is produced. The pattern of initial fractures may have been controlled by lithological contrasts within the limestone; for example, the clastic facies seen as pale grey in Fig. 2(b) appears to host many of the shear fracture surfaces.

CONCLUSIONS

Conjugate vein arrays exposed in limestone of the Jack Hills Gorge display a range of conjugate angles from 60° to 30°. Both bisector-parallel (Type 2) and convergent (including cross-parallel, Type 1) configurations of vein arrays occur. Analysis of a convergent vein system indicates that there is insufficient shear strain to support a model of vein convergence by rotation of veins from an initial bisector-parallel configuration. The morphology of veins suggests that much of the shear displacement was accommodated by wedge-like opening of veins without vein rotation. Array-parallel vein segments linking en échelon veins are interpreted as early fault segments, which controlled the kinematics of the developing arrays. Thus, zones of brittle discontinuous faulting, possibly controlled by competence contrasts, were initiated with an acute conjugate angle. Slip on these fault segments produced extension fractures at fault segment terminations and discrete en échelon extension fractures between fault segments.

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