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Inter-array and intra-array kinematics of en échelon sigmoidal veins in cross-bedded sandstone, Merimbula, southeastern Australia

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Abstract

The kinematics of en échelon arrays of quartz veins hosted by sandstone of the Upper Devonian Worange Point Formation are strongly influenced by bedding and cross-bedding. Bulk deformation recorded by the vein arrays (inter-array kinematics) was influenced by the anisotropy of the host rock, such that, three types of arrays are observed: (1) east-verging arrays parallel to bedding; (2) east-verging arrays oblique to bedding with veins parallel to cross-bedding; and (3) west-verging arrays parallel to cross-bedding with veins parallel to bedding. These three array types correspond to flats, ramps and backthrusts, respectively and represent the earliest stages of thrust fault formation. Flat and ramp arrays form a staircase geometry and conjugate ramp and backthrust arrays form pop-up structures. The interpretation of the morphology of veins and wall-rock (intra-array kinematics) indicates rotation of bridges was the primary kinematic process in the arrays. The opening of vein space by rotation of bridges which maintain constant thickness is predicted from measurements of the orientations of vein–wall-rock interfaces at vein tips and at the array centre. Comparison of the predictions with direct measurement of the proportion of vein to wall-rock along the centreline of arrays demonstrates the applicability of the bridge-rotation model which has been generalised to include the thickening or thinning of bridges during rotation.

1. Introduction

The study of en échelon vein arrays can be subdivided into: (1) inter-array kinematics, which include the combined effects of displacements, senses of movement and orientations of numerous vein arrays commonly differing in the above attributes; and (2) intra-array kinematics, which include fracturing, opening of veins and deformation of both veins and bridges of wall-rock within individual arrays. The former is an important tool in regional structural analysis (e.g. Collins and De Paor, 1986; Diegel, 1988; Mitchell and Forsythe, 1988) and the latter is an important tool for interpreting the mechanics of natural rock fracture (e.g. Roering and Smit, 1987; Craddock and van der Pluijm, 1988; Ohlmacher and Aydin, 1997).

In this paper, vein arrays hosted by cross-bedded sandstone, deformed by shortening approximately parallel to bedding and thus oblique to cross-bedding, are investigated. The paper addresses: (1) the inter-array kinematics which are interpreted as the earliest stages of development of staircase thrust faults; and (2) the intra-array kinematics which demonstrate the applicability of the bridge-rotation model for formation of the sigmoidal veins.

1.1. Thrust fault nucleation

Thrust faults are low-angle reverse faults commonly formed by compression parallel to bedding (American Geological Institute, 1987). Investigation of the nucleation of thrust fault systems is made difficult by the overprinted effects of large thrust fault movements and later deformation (e.g. Connelly and Woodward, 1992). Minor fractures, faults and folds that may have

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formed during nucleation are difficult to distinguish from minor structures associated with the on-going development of the fault system. Although thrust fault nucleation may be characterised by cataclasis (Hyett, 1990) and high fluid pressure (Hubbert and Rubey, 1959), the record of initial structures is obscured in well developed thrust fault systems.

The common occurrence of thrust faults which step through rock layers in a staircase pattern has been interpreted as the result of nucleation of bedding-parallel faults on weak beds, breaking up-section through competent units and continuing as bedding-parallel faults at a higher stratigraphic level (Rich, 1934). An alternative to this 'flat nucleation model' is the 'ramp nucleation model' in which ramp faults initiate first, develop into ramp–flat pairs and then link to form through-going faults (Eisenstadt and De Paor, 1987). Backthrusts form as the conjugate structures to ramps in layer-parallel shortening (Berger and Johnson, 1982). It has also been shown that a number of initial fault segments may link together to form a single fault surface (Ellis and Dunlap, 1988).

1.2. Vein array kinematics

Two models for the kinematics of vein array formation can be distinguished: (1) concurrent propagation of fractures and opening of veins within a brittle–ductile shear zone (Durney and Ramsay, 1973); and (2) opening of veins after propagation of fractures by bending of the intervening wall-rock bridges (Nicholson and Ejiofor, 1987; Nicholson, 1991). In the first model, the veins are relatively competent and their sigmoidal curvature is attributed to differential rotation along their length during fracture propagation (Fig. 1). In the second model the veins or vein-spaces are relatively incompetent and their sigmoidal shape is attributed to the curvature of bent wall-rock bridges. Consequently, these two models can be characterised as the 'vein-rotation' and 'bridge-rotation' models, respectively, although this reflects only the emphasis of the model and does not imply non-rotation of the other component of the array. Nicholson (1991) proposed that differentiation of these processes may be possible by interpretation of vein textures and Smith (1996) proposed that the processes can be distinguished from the morphology of veins and bridges. He indicated that the vein-rotation model is more apt to produce rotational symmetry of veins, whereas the bridge-rotation model is more apt to produce rotational symmetry of bridges.

The kinematics of vein opening in the bridge-rotation model is similar to that described for the formation of kinks (Anderson, 1964; Ramsay and Huber, 1987, p. 427; Ghosh, 1993, p. 291). Where bridges are rotated they present a decreasing dimension along the length of the array causing the opening of vein-space in a process analogous to the way rotation of fold

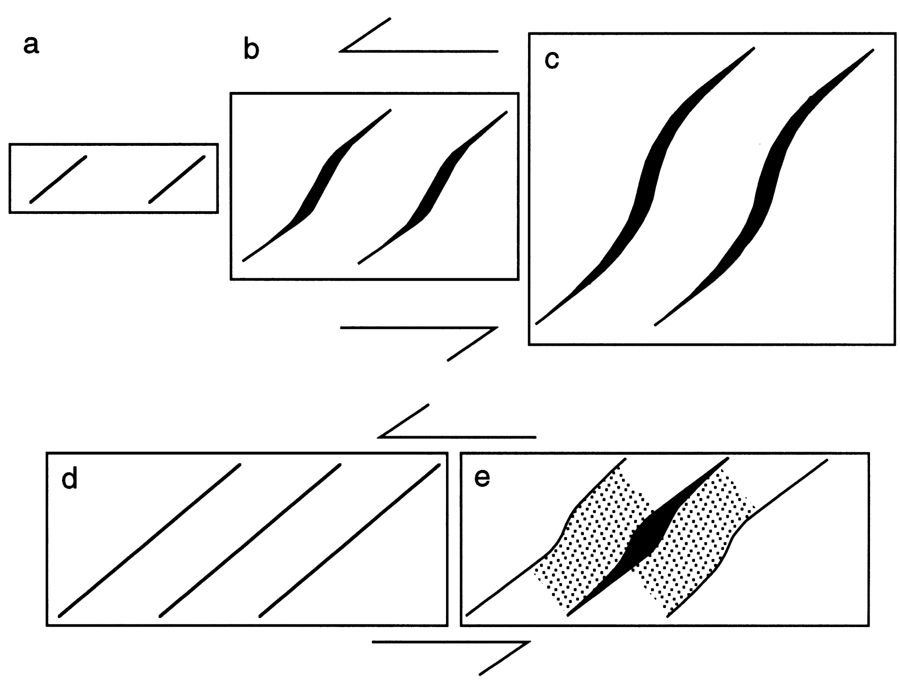

Fig. 1. Schematic illustrations of kinematic models explaining sigmoidal vein shapes. In the 'vein-rotation' model (a), fractures initiate and in (b) and (c), vein centres are rotated as fractures propagate during shearing. In the 'bridge-rotation' model (d) fractures propagate until they overlap. (e) Bridges (stippled) of rock between fractures are bent forming sigmoidal vein-space (black). Arrows show generalised sense of shear, not displacement vectors.

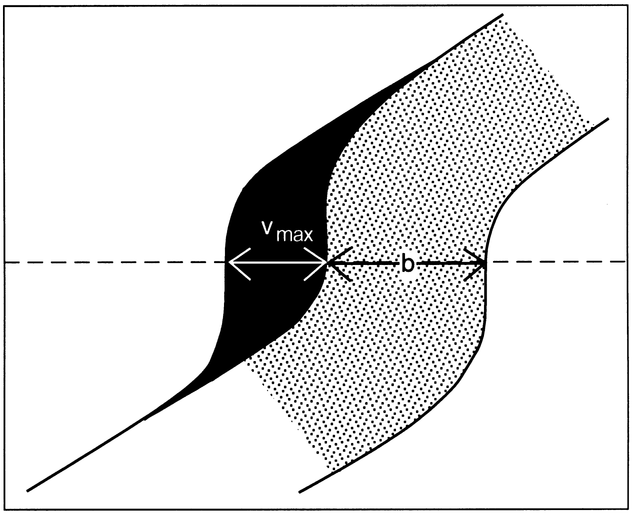

Fig. 2. Schematic illustration of the maximum vein opening (v_{max}) which is achieved when a bridge (stippled) is rotated such that it is perpendicular to the centreline of the array (dashed), while maintaining constant orthogonal thickness at the centre of the bridge (b).

limbs produces saddle reefs in fold hinges (Smith and Marshall, 1993). The maximum vein opening is attained when the bridge has rotated into an orientation perpendicular to the centreline of the array (Fig. 2). Further rotation of the bridge would theoretically lead to a decrease in the vein-space. In vein systems where dilation is accompanied by progressive precipitation of minerals, volume loss by some process such as pressure-solution would be required for rotation to proceed beyond the maximum vein opening configuration.

The presence of anisotropy in the host rock can influence the pattern of structural development. In particular, anisotropy oriented obliquely to the principal compressive stress can result in the formation of conjugate shear structures which may be morphologically dissimilar (Biot, 1965; Cobbold et al., 1971).

2. Inter-array kinematics

Fluvial sandstones of the Upper Devonian Worange Point Formation (Taylor and Mayer, 1990; Lewis et al., 1994, p. 101) on the South Coast of New South Wales, Australia (Fig. 3) are well bedded and have pervasive unidirectional cross-bedding. Abundant and well-exposed en échelon arrays of quartz veins within these rocks have been the subject of previous published (Powell, 1983; Rickard and Rixon, 1983; Rixon et al., 1983) and unpublished (Smith, 1991; Shepherd, 1992) studies. Rixon et al. (1983) recognised the relationship between the vein systems and regional north–south trending kink folds, with minor east-verging thrust faults related to east–west contraction, with an estimated total layer-parallel strain of about 10%.

Abundant en échelon arrays of quartz veins are exposed on a cliff section at Short Point near Merimbula, New South Wales (Fig. 3), that is parallel to the profile plane of the arrays. The host rocks are horizontally bedded and have unidirectional cross-bedding defined by variations in grain size and some mud drapes. The sandstone breaks readily on bedding surfaces and less so on cross-bed surfaces, but the latter are more pervasive so that both are mechanically significant weaknesses. The presence of two planes of weakness, and the curvature of one of these, produces a complex anisotropy in the rock (Fig. 4). Veins and arrays of veins occur in a variety of orientations usually involving parallelism with either bedding or cross-bedding. Three types of arrays were observed: east-verging arrays parallel to bedding with veins oblique to bedding (Type A); east-verging arrays oblique to bedding with veins parallel to cross-beds (Type B); and west-verging arrays parallel to cross-beds with veins parallel to bedding (Type C).

The three types of arrays do not overprint each other but form a compatible set of structures. Type A arrays are linked by relatively short Type B arrays in a staircase pattern between bedding surfaces (Fig. 5a). Type B and Type C arrays locally occur together as a conjugate pair producing box folds (Fig. 5b). All three types locally occur together with Type C being located near the junction of Types A and B (Fig. 5c). Each type of array also occurs independently Fig. 4.

Across the outcrop there are three zones of intense veining which dip toward the west and are dominated by east-verging arrays (Fig. 4g). The intervening intervals are either poorly veined or dominated by west-verging arrays (Fig. 4g). The zones of intense veining dip at approximately 10° and the perpendicular spacing between each of the zones is approximately 10 m.

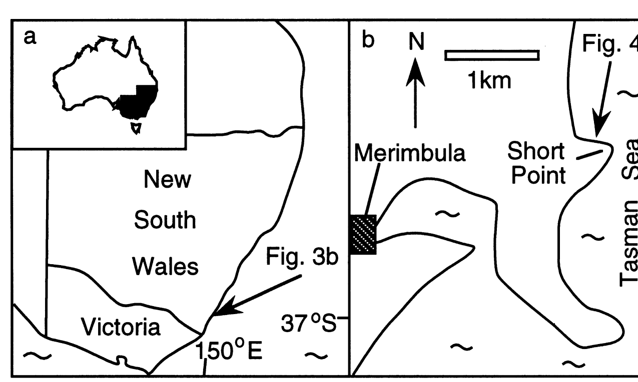

Fig. 3. (a) and (b) Location of study area in southeastern Australia.

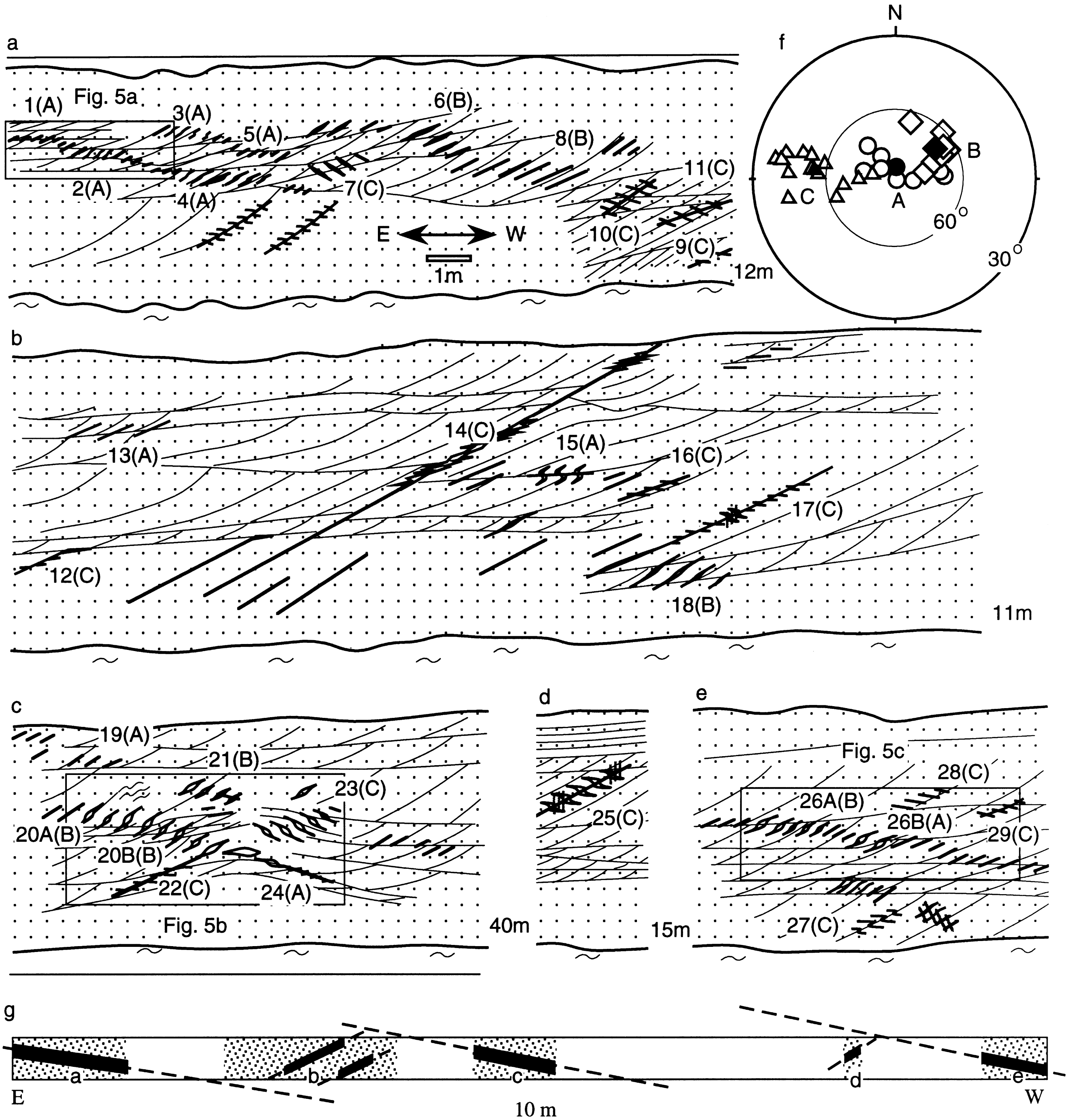

Fig. 4. (a–e) Quartz vein array systems hosted by unidirectional cross-bedded sandstone exposed in the cliff profile at Short Point, Merimbula. Intervening sections (given in metres) are poorly veined. Array types A, B and C, as defined in the text, are labelled in brackets. (f) Partial equal angle stereograph (from 30° to 90° plunge) of orientations of the 29 numbered arrays. The arrays are classified as types A (circles), B (diamonds) and C (triangles). Mean orientations of pole (solid symbols) are Type A = 85°–007° (0.015), Type B = 73°–051° (0.006) and Type C = 63°–278° (0.018). Spherical variances are in brackets. (g) Schematic overview of the distribution of veining (black) on the continuous cliff exposure. East-verging (Types A and B) arrays are predominant in sections (a), (c) and (e). These sections are separated by sections which are poorly veined (blank) or dominated by west-verging (Type C) arrays, that is, sections (b) and (d). The inferred east-verging incipient thrust faults are shown as dashed lines.

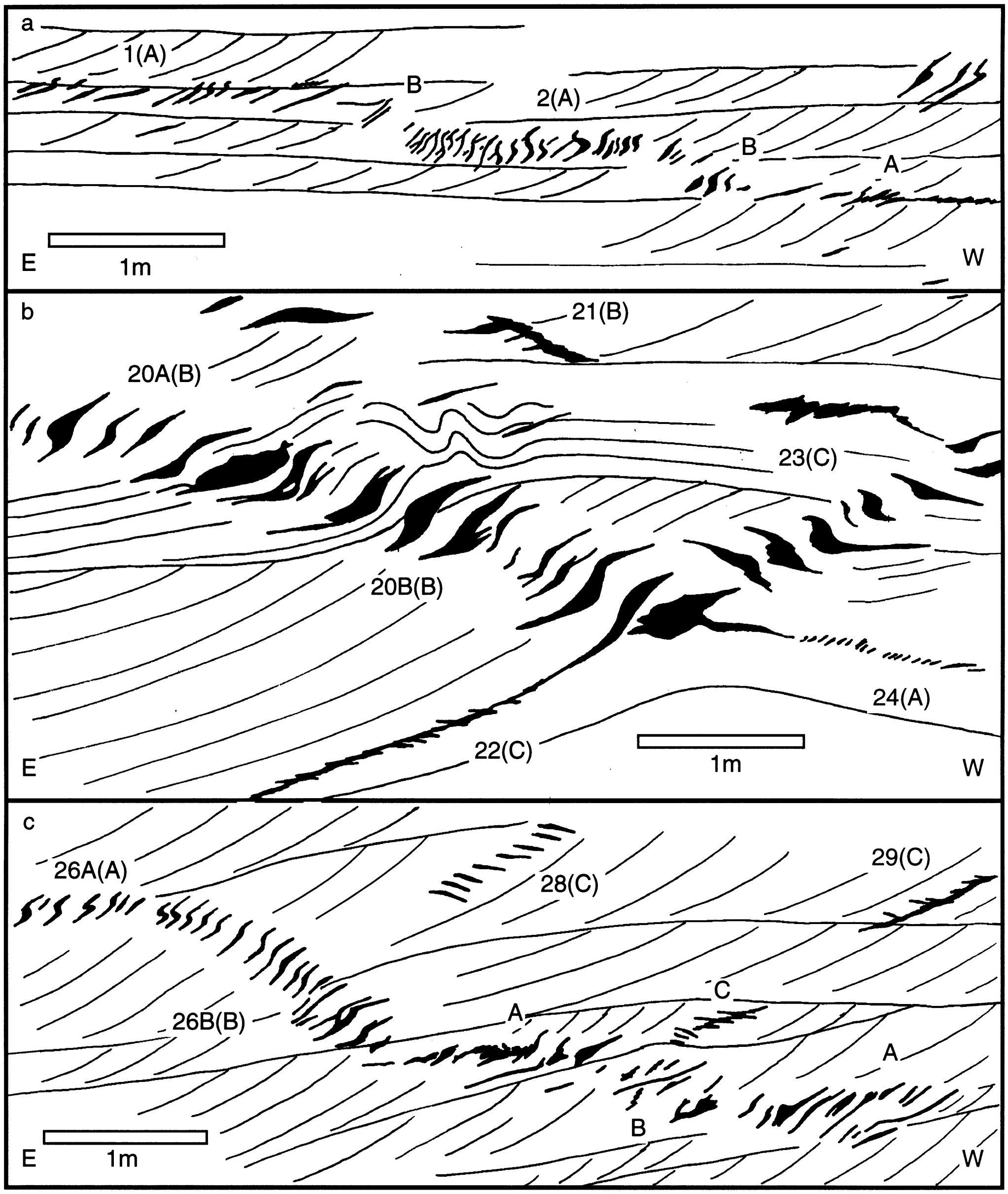

Fig. 5. Detail of vein arrays showing (a) continuity between Type A and Type B arrays, (b) a conjugate system of Type B and Type C arrays with a Type A array forming the arm in the lower right and (c) continuity of Type A and Type B arrays with Type C arrays located near intersections of Type A and Type B arrays. Locations shown on Fig. 4.

3. Intra-array kinematics

Previous studies have differed in their interpretation of the intra-array kinematics of en échelon veins in the Worange Point Formation. Powell (1983) considered they may have been initiated as shear fractures based on obliquity between the inferred principal stress and the vein tips. The morphology of the veins and vein fibres is consistent with the veins being hosted by extension fractures (Rickard and Rixon, 1983) and that interpretation is followed here.

Veins in the field area are variable in size but in profile are typically tens of centimetres in length and have aperture widths of a few centimetres. The veins are usually filled with fibrous quartz but small growth cavities remain in some of the larger veins. Vein shapes vary from planar in the case of veins with little opening to strongly sigmoidal where more opening has occurred. In many arrays the individual veins are discrete, but partial and complete linkage of veins has occurred in some arrays by slip on bedding in Type A and cross-bedding in Type C. The strain of arrays can be determined, by the method of Nicholson and Pollard (1985), from the sigmoidal bending of rock bridges between veins. Shear strains up to $\gamma = 1$ are recorded in arrays of discrete veins and greater strains are recorded where veins have become linked.

The morphology of the arrays varies with the relationship to the rock anisotropy. Type A arrays are commonly linked by slip on bedding interfaces and tend to have poor symmetry, the latter being due to the angle between the array and cross-beds being high below the arrays and low above the arrays (Fig. 5a). Veins in Type B arrays are generally larger with good symmetry and relatively regular fracture spacing due to their occurrence on cross-beds. Since the rock is coherent, fracturing is not always precisely parallel to the cross-beds, particularly where cross-beds curve into unfavourable orientations. Veins in Type C arrays are commonly linked by slip on cross-bed surfaces. Bridges in Type B arrays tend to have approximately constant orthogonal thickness (Fig. 6a) although some hourglass-like thinning of bridges is observed (Fig. 6b). Bridges where high strain has occurred have well developed spaced cleavage by pressure-solution (Fig. 6c). The development of cleavage in bridges is most apparent in Type A and Type C arrays, but less apparent in Type B arrays where relatively long bridges have more readily accommodated the displacement of the arrays.

The internal kinematics of vein arrays was investigated by making direct measurements of the proportion of vein material (Fig. 7, v) relative to the amount of wall-rock (Fig. 7, b) along the centreline of arrays. This measure is essentially a record of the apparent longitudinal strain of the wall-rock bridges along the array centreline:

$$e_{\mathrm{m}} = v/(v+b). \tag{1}$$

The apparent longitudinal contraction of bridges, that results from bridge rotation relative to the orientation of the array, is compensated by the vein space which opens to maintain strain compatibility with wall-rock outside the array.

It is possible to predict the amount of vein opening that would occur along the array centreline if the bridges maintained constant thickness during rotation. Prior to rotation, a bridge presents the dimension T (Fig. 7) in the direction of the incipient array centreline, this being equivalent to

$$T = t/\sin\alpha, \tag{2}$$

where t is the orthogonal thickness of the bridge and α is the angle between the centreline and the outer tip of the fracture (Fig. 7). As a bridge within the array is rotated to an angle α', it presents a reduced dimension t' parallel to the centreline:

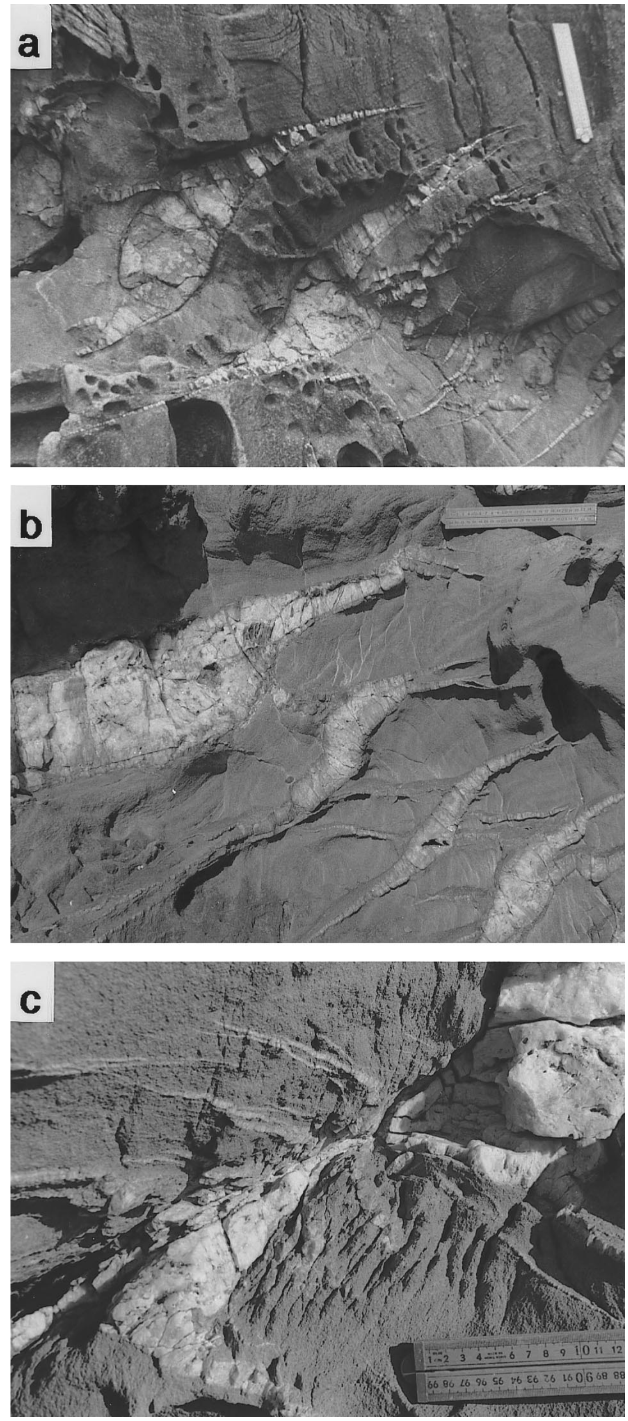

Fig. 6. Photographs of vein arrays. (a) Bridge with approximately constant thickness (array 20A). Scale bar in top right is 25 cm. (b) Highly asymmetric vein (left) accommodating differential bridge rotation (array 6). Note thinning of bridge in bottom right. Scale bar in top right is 25 cm. (c) Type C array with extreme pressure-solution thinning in bridges and affecting veins (array 25).

$$t' = t/\sin\alpha'. \tag{3}$$

Thus, the longitudinal strain as related to the rotation of the wall-rock bridge, has potential to open vein

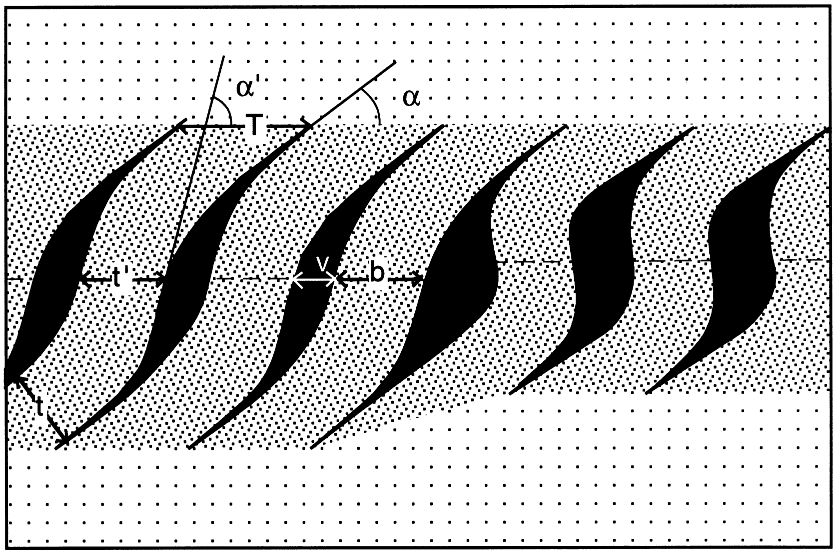

Fig. 7. Schematic representation of a vein array with shear strain variation accommodated by an asymmetric vein (centre). Parameters are shown for direct measurement of the proportion of veining (v) to wall-rock bridges (b) along the centreline (dashed) and for predictions of vein opening based on the orthogonal thickness of bridges (t), the dimension (T) of unrotated bridges parallel to the array centreline, and the dimension (t') of rotated bridges parallel to the array centreline which are derived from the angle between the array centreline and the outer tips of veins (α) and the inflection of the vein margin (α').

space (as measured along the centreline of the array) given by:

$$e_r = 1 - \sin\alpha/\sin\alpha'. \quad (4)$$

Twelve arrays (or parts of arrays), for which accurate three-dimensional measurements could be made, were selected in order to compare direct measurement of the vein opening ratio (e_m) with predictions of vein opening by the bridge-rotation model (e_r). The orientations of: (1) the central plane of each array (Fig. 8, open circles); (2) outer tips of vein margins (Fig. 8, squares); and (3) inflection of the vein margins (Fig. 8, diamonds) were measured. Poles to veins and arrays were found to lie approximately along a vertical WNW–ESE girdle (Fig. 8).

The field measurements were used to determine an average vein tip-array angle (dihedral angle between orientations 1 and 2) and a vein inflection-array angle (dihedral angle between orientations 1 and 3). The variation of these angles from east to west along arrays is shown graphically with the array orientation as zero (Fig. 9). The graphs show a mixture of smooth and step-wise changes in rotation and thus shear strain. Abrupt changes in rotation of bridges are evidenced by asymmetric veins flanked by differently deformed bridges as illustrated in Fig. 7. The direct measurements and predictions of vein opening by the bridge-rotation model have been plotted (Fig. 10) and, except for array 25, show a general clustering around the line of equivalence between the two forms of measure. The implications of the scatter of the results will be discussed below.

4. Discussion

4.1. Vein arrays as incipient thrust faults

The three types of arrays are kinematically related in an analogous way to flats (Type A arrays), ramps (Type B arrays) and backthrusts (Type C arrays) of a thrust fault system and the arrays at Short Point are interpreted to be an incipient thrust fault system. The incipient flats, ramps and backthrusts occur either in isolation or as groups of associated structures, such as conjugate pairs with opposite shear sense (Fig. 11). The three types of array are kinematically compatible with a bulk deformation characterised by a component of west-over-east shear and a bulk shortening axis which plunged gently to the east (Fig. 11).

Individual arrays may have had multiple points of initiation, particularly where the arrays are hosted by planes of weakness. During propagation, arrays may have transformed between types with the same shear sense (flats and ramps) or propagating arrays may have intersected and linked together to form a through-going fault. In the case of structures with opposing shear senses (notably ramps and backthrusts), simultaneous initiation as a conjugate pair and/or interaction during propagation locally caused the formation of pop-up structures and associated folding.

The concentration of veining in west-dipping zones approximately 3 m wide separated by zones approximately 10 m wide with local backthrust arrays is interpreted as the result of the nucleation of approximately

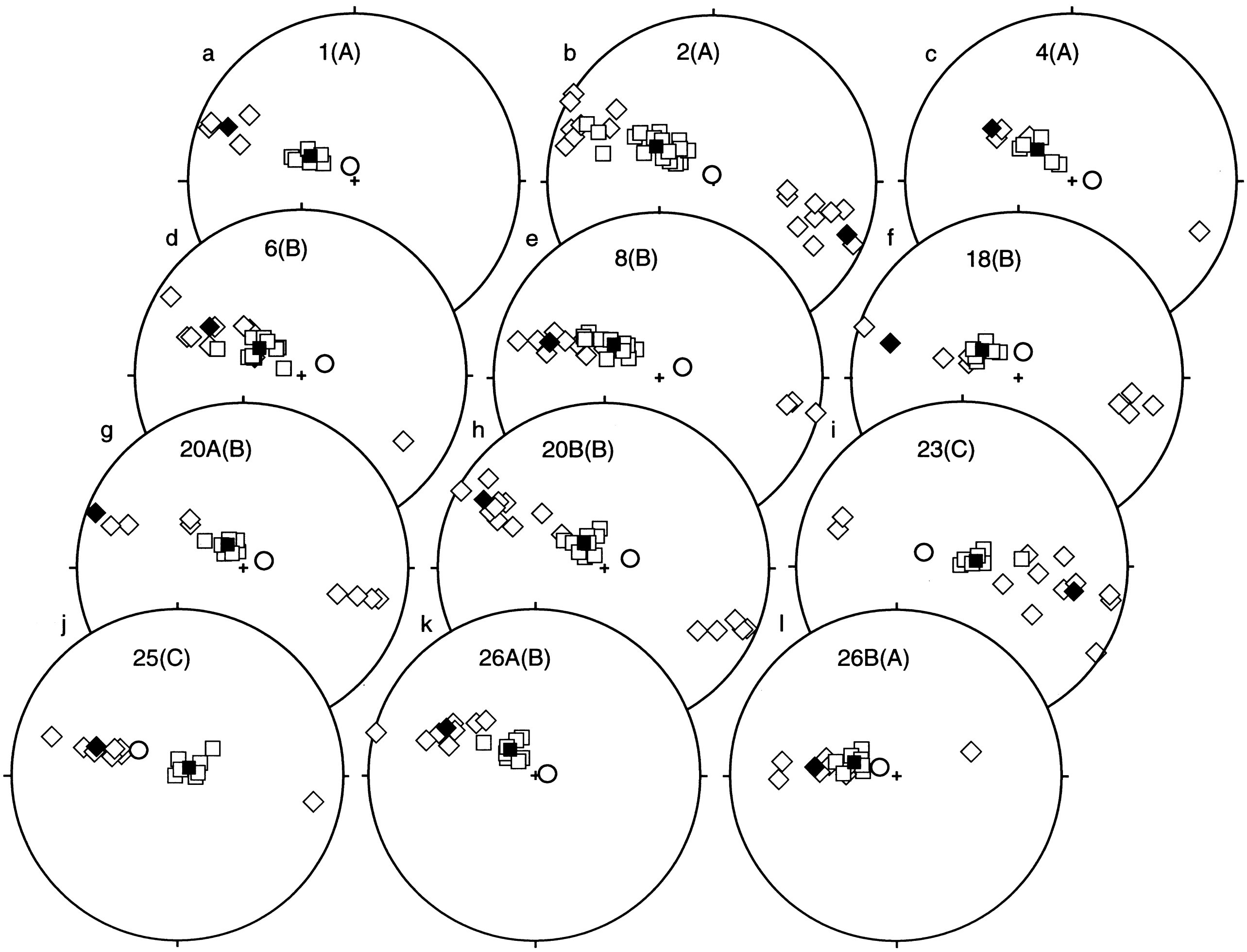

Fig. 8. Equal angle stereographs showing data from 12 well-exposed vein systems. Pole to arrays (open circles), vein tips (open squares, mean shown as solid square) and vein inflections (open diamonds, mean shown as solid diamond) are plotted.

evenly spaced thrust faults. All three zones are preserved at an equivalent stage of development implying that they were initiated contemporaneously rather than progressively as is implied in some models of imbricate thrust fault development (e.g. Ramsay and Huber, 1987, p. 525).

4.2. Bridge-rotation model

The comparison of direct measurements of the proportions of veining and wall rock (e_m) with predictions of apparent bridge contraction based on bridge rotation (e_r, Fig. 10) has implications for the morphology of the arrays, in particular the shape of wall-rock bridges (Fig. 12). Precise equivalence between the bridge-rotation prediction and direct measurement occurs if bridges maintain constant orthogonal thickness. If the predicted value is greater than the measured value, the bridges are thicker at the centre of the array than near the vein tips. If the predicted value is less than the measured value, the bridges are thinner in the centre than at the vein tips. The predicted value is less than zero when the acute angle between bridge centres and the array is less than the acute angle between vein tips and the array.

There are two possible explanations for the occurrence of non-constant thickness bridges: (1) initial non-parallelism of fractures; and (2) ductile deformation of bridges during rotation. The first possibility may occur if some propagation of the fractures occurs during rotation of the bridges. This process has not been considered to be important in the bridge-rotation model, but it should not be ignored. The second possibility is considered to be more significant since pressure-solution cleavage was observed in many of the bridges with thin centres, particularly in the case of extreme thinning in array 25 (Fig. 6c).

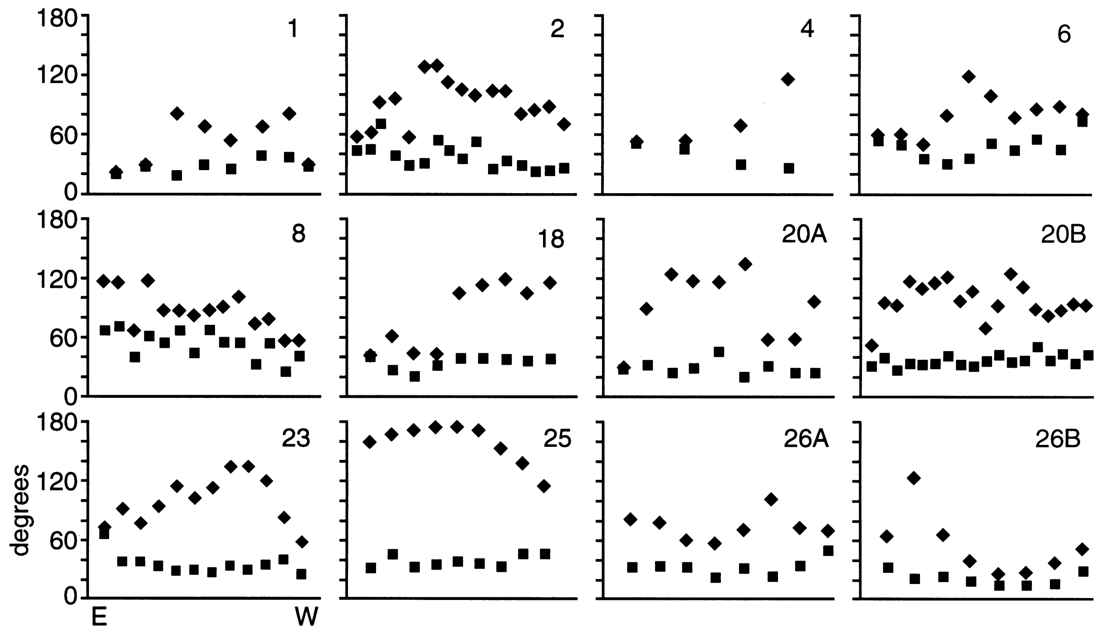

Fig. 9. Graphs of the veins within arrays (east to west) showing the dihedral angle (degrees) between vein tips (squares), vein margin inflections (diamonds) and arrays (zero degrees). Pairs of measurements from the same vein margin are vertically aligned. Spacing of veins along the array is arbitrary.

Interestingly, both bridge thickening and bridge thinning are consistent with compression parallel to vein tips; the former can result from barrelling of the bridge by intergranular flow and the latter from formation of spaced cleavage perpendicular to the compressive stress. Intergranular flow has occurred in many of the host sandstones and is evidenced by pervasive mica beards between grains; however, the kinematic analysis of this flowage is beyond the scope of the present work.

Pressure-solution could potentially occur at any time during deformation but is likely to be favoured by: (1) high angles of rotation, particularly beyond 90° which represents the point of maximum vein opening; and (2) low bridge aspect ratios. As these parameters vary

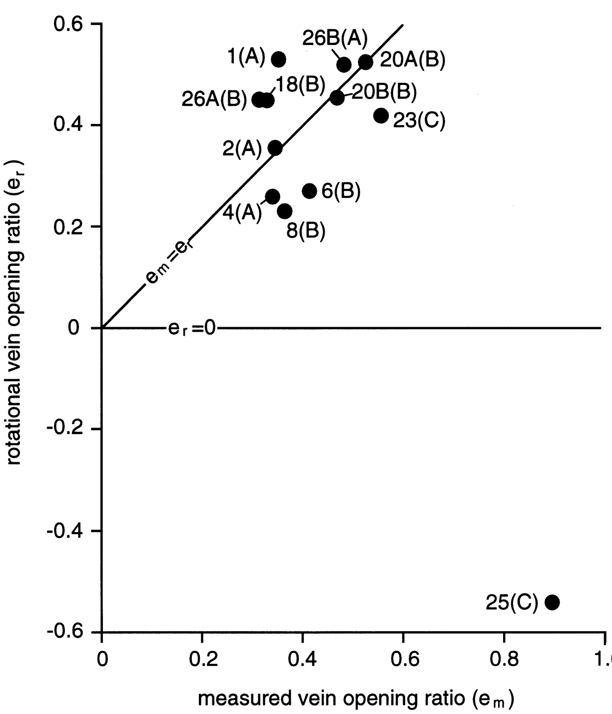

Fig. 10. Graph of directly measured (horizontal axis) and predicted (vertical axis) values of vein opening from 12 vein arrays. Parameters are defined in the text.

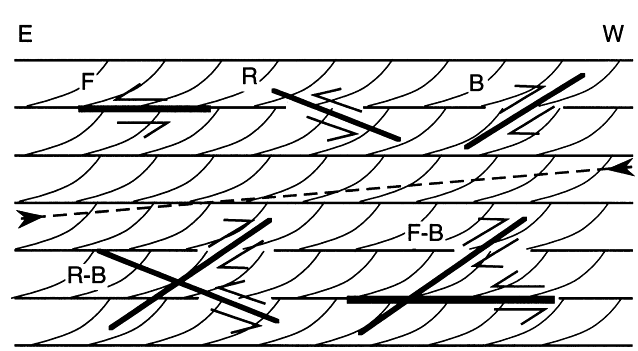

Fig. 11. Schematic representation of the assemblage of vein array types with respect to bedding and cross-bedding. These structures can nucleate in isolation as flats (F), ramps (R) or backthrusts (B) or as conjugate pairs comprising a ramp and a backthrust (R–B) or a flat and a backthrust (F–B). The inferred bulk shortening direction is shown schematically as a dashed line.

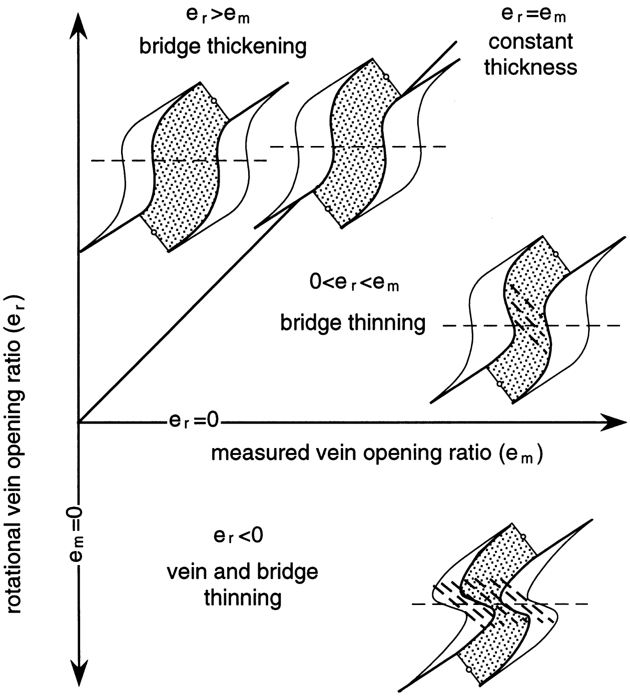

Fig. 12. Shapes of bridges (stippled) defined by relationship between direct measurements and predictions of constant thickness bridge-rotation model. Morphological fields are defined and illustrated. Bridge thinning is commonly associated with the development of pressure-solution cleavage (heavy dashed lines).

within arrays, a detailed study of individual bridges would be required to establish the link between pressure-solution processes and bridge geometry. The most intense pressure-solution cleavage was observed in Array 25 (Fig. 6c) which also displays extreme bridge rotation, well beyond an orientation perpendicular to the array.

5. Conclusions

En échelon quartz vein arrays at Short Point on the South Coast of New South Wales, Australia are strongly influenced by the presence of rock anisotropy in the form of bedding and cross-bedding. Three types of arrays occur: (1) east-verging arrays parallel to bedding; (2) east-verging arrays oblique to bedding with veins parallel to cross-bedding; and (3) west-verging arrays parallel to cross-bedding. The inter-array kinematics involves the two types of east-verging arrays combining to form a staircase geometry of ramps and flats, and thereby suggests that they represent the nucleation of a thrust fault system. The west-verging arrays occur either as isolated arrays or together with ramp arrays to form pop-up structures. Previous models of thrust fault nucleation have favoured nucleation of faults either on flats or on ramps but this study suggests thrust faults can form by initiation of flats, ramps and backthrusts contemporaneously followed by linkage to form through-going faults. Three approximately evenly spaced zones of intense veining across the 140 m outcrop indicate that multiple, parallel thrust faults can nucleate contemporaneously within a single layer.

The intra-array kinematics primarily involves bridge-rotation and some ductile deformation of bridges, as indicated by direct measurement of veining (e_m) along the array compared to predictions of vein opening (e_r) based on the orientation of bridges at the edge and centre of the array. Using these parameters, the generalised bridge-rotation model can describe the morphology of wall-rock bridges, in particular the thickening and thinning of bridges at the centre of the array. Where the direct measure of veining and predictions from bridge rotation are equivalent, the morphology of the array is one of constant bridge thickness. Divergence from equivalence indicates array morphologies in which bridges are either thickened ($e_r > e_m$) or thinned ($e_r < e_m$). Although the precise mechanisms by which bridge deformation occurs during rotation is yet to be determined, the development of pressure-solution cleavage is implicated in bridge thinning.

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