Journal of Structural Geology, Vol. 5, No. 6, pp. 573 to 578, 1983
Printed in Great Britain

0191-8141/83 $03.00 + 0.00
Pergamon Press Ltd.

Stress configurations in conjugate quartz-vein arrays

M. J. RICKARD

Department of Geology, Australian National University,
P.O. Box 4, Canberra A.C.T. 2600, Australia

and

L. K. RIXON

Australian Coal Industries Research Laboratory,
North Ryde N.S.W. 2113, Australia

(*Received* 1 *April* 1982; *accepted in revised form* 15 *April* 1983)

Abstract—Arrays of quartz gash-veins in small angle (40°), conjugate shear zones (type 1 arrays of Beach) are well-developed in the Upper Devonian Merrimbula sandstone of the south coast region of New South Wales, Australia. We argue that vein and cleavage geometry support an origin of the veins as tension fractures in a rotated secondary stress field rather than a primary shear origin as advocated by Beach. We also conclude that the veins develop in dilational shear zones under high fluid pressure.

INTRODUCTION

NUMEROUS conjugate shear zones containing en échelon arrays of quartz veins are developed in thick sandstone beds of the Upper Devonian Merrimbula Group along the south coast of New South Wales, Australia. These sandstones are sharply kinked into wide-spaced (few tens of metres) monoclines with occasional conjugate folds. A spaced (pressure-solution) cleavage is developed throughout the sandstones and a slaty cleavage is developed in mudstone interlayers in the fold hinges. The conjugate shear zones are developed in the region of the monoclinal folds and the geometry of folds, cleavages and shear zones is congruent, implying a simple continuous deformation process (Rixon *et al.* in press).

The shear zones enclose small dihedral angles (*c.* 40°) and the vein tips in each shear zone are oriented parallel to the conjugate zone, that is they are type 1 arrays in the nomenclature of Beach (1975). The maximum principal-stress axes deduced from the shear zones are oriented nearly parallel to the generally flat-lying bedding (Fig. 1). There has been much debate on the fracture mechanism and stress configurations controlling the development of such veins (Roering 1968, Lajtai 1969, Ramsay & Graham 1970, Hancock 1972, Beach 1975, 1977). All agree that where quartz veins lie at about 45° to the shear zone they developed as tension fractures parallel to the maximum principal stress (σ_1). Quartz veins that are parallel to the conjugate zone have been interpreted as initiating as primary shear fractures, subsequently extended under shear strain (Roering 1968, Beach 1975). Intermediate positions have been attributed to surfaces transitional between shear and extension fractures (Hancock 1972). The evidence for the shear origin of these veins is not strong, being based largely on their parallelism with the conjugate zone (Roering 1968, Beach 1975). Beach (1977) and Choukroune & Seguret (1968), however, report small displacements along the vein directions in some examples, as does Hancock (1972) for veins at less than about 30° to a zone. The situation envisaged by Roering and Beach requires that the maximum principal-stress trajectories are essentially constant throughout the system, bisecting the angle between a shear zone and the quartz veins that it contains. Quartz veins parallel to this maximum principal-stress direction occur in the intersection region of shear zones in many examples (e.g. Roering 1968, fig. 3, Choukroune & Seguret 1968, fig. 3, Beach 1975, figs. 2 and 13).

In this type of vein array the veins themselves tend to be planar and a close-spaced (solution-transfer) cleavage is commonly developed perpendicular to them (Beach 1975, fig. 13). The quartz veins in the Merrimbula sandstones show all of these features except that many veins are sigmoidal (Fig. 1) and multiple vein sets are

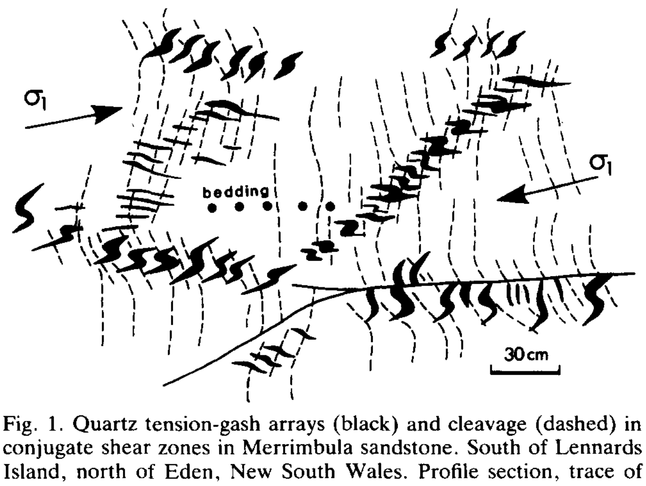

Fig. 1. Quartz tension-gash arrays (black) and cleavage (dashed) in conjugate shear zones in Merrimbula sandstone. South of Lennards Island, north of Eden, New South Wales. Profile section, trace of horizontal bedding indicated. σ_1, maximum principal stress.

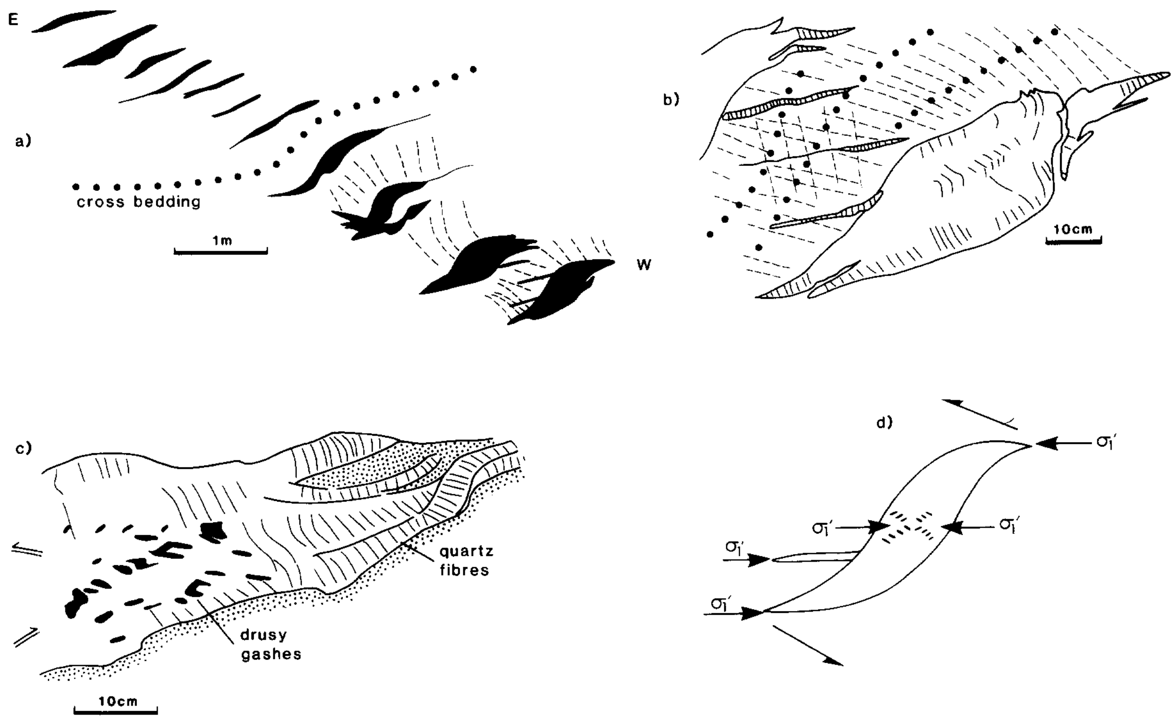

Fig. 2. (a) Quartz-vein array at Haycock Point, near Pambula, New South Wales. (b) Detail of part of (a) to show two generations of cleavage (dashed) in the shear zone. (c) Detail from fallen block of part of a composite quartz vein with internal conjugate arrays of minor drusy gashes (black). (d) Interpretation of stress geometry for veins shown in (b) and (c), see text for details.

common (Fig. 2). The amount of shear in each zone is small and generally distributed throughout the zone, apart from an occasional narrow fault zone (Fig. 1); also quartz filled, incremental shears are not generally developed. Cleavage in the shear zones is stronger and more closely spaced than in the adjacent sandstone, and solution-transfer processes have provided the quartz for the veins (Beach 1974). The cleavage shows various relationships to quartz veins demonstrating that it developed throughout the growth of the shear zone. In some examples cleavage developed early and was rotated with the quartz veins during shearing, in others the cleavage is planar, crossing the sigmoidal quartz veins, and in a few places a new weak cleavage has developed perpendicular to the youngest straight quartz veins and crossing earlier cleavage (Figs. 2a & b).

MECHANISM OF VEIN FORMATION

We find it difficult to accept a shear origin for these structures for the following reasons.

(1) Beach (1975, p. 262) has argued that 'if veins originated as fractures in a secondary stress field following stress relief within the shear zone, it is unlikely that the geometric relation between veins and zones would occur'. We argue conversely, that because the shear zones were initiated before the quartz-vein fractures (Beach 1975, Ramsay 1980, Rixon *et al.* in press) it is more difficult to explain how the sheared rock retained a 'memory' of its earlier frictional properties to enable it to develop shear fractures parallel to those that developed in the sound rock.

(2) There is no evidence for shear displacement at vein tips and veins do not continue as shear fractures. Veins are commonly restricted to the shear zones, but where they do extend outside they turn into the direction of the conjugate-zone bisector, that is, parallel to the external maximum principal-stress axis.

(3) If the quartz veins initiated in shear, then the associated perpendicular cleavage, especially at the newly formed vein tips, should also be a surface of high shear stress. However, no offsets are apparent beyond those attributable to mild pressure-solution across the cleavage seams (cf. Beach 1974, 1977). In the low strain position at the margin of the shear zone, stress and strain were probably orthogonal, a conclusion agreeing with an interpretation of the cleavage as a compressional pressure-solution effect, and the quartz veins as tension gashes (Figs. 1 and 2). Support for this interpretation is provided by Rispoli (1981) who mapped the stress fields associated with wrench faults in limestones using tension gash arrays and perpendicular stylolitic cleavage.

(4) The pattern of quartz fibres should be different for the two situations (Hancock 1972, Durney & Ramsay 1973). If the gashes originated as tension fractures, the fibres growing during extension should be perpendicular to the walls, although subsequent passive rotation into sigmoidal forms would tilt the fibres in the zone-shear direction (Figs. 3a & b). If the gashes originated as shear fractures oblique to a primary maximum principal stress, the initial fibres should be tilted and the oblique extensional opening would produce fibres tilted in the opposite sense to the zone-shear direction (Fig. 3c).

We have not yet made a detailed study of the fibre geometry, and clearly there was complex multistage vein

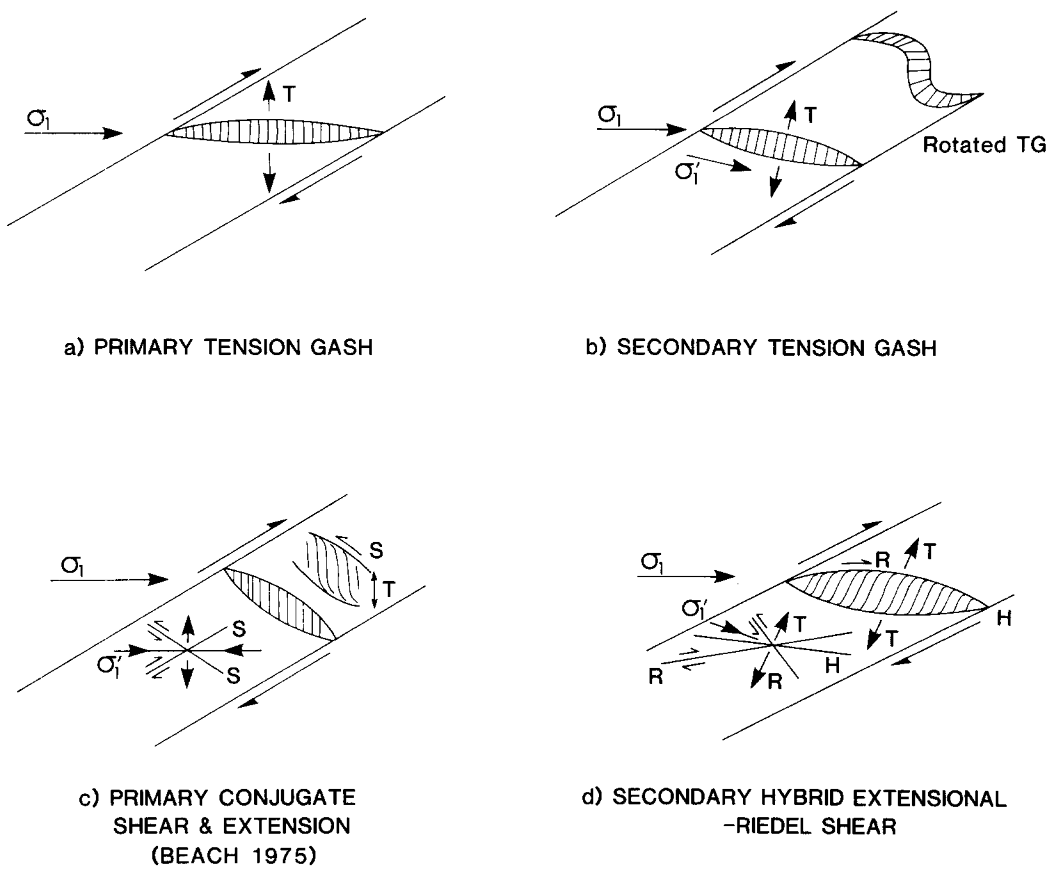

Fig. 3. Quartz-vein fibre arrangement for extensional opening of veins formed by primary and secondary tension and shear mechanisms. See text for details.

development especially where early veins have been rotated into sigmoidal forms (Fig. 2). Nevertheless, in most of the examples investigated we observed that the syntaxial quartz fibres (Durney & Ramsay 1973) in planar veins and in the tip portions of sigmoidal veins are perpendicular, or tilt at 70–80° to vein margins in the direction of the main shear (Fig. 2b). Thus the quartz-fibre geometry accords with a secondary tension origin (Fig. 3b), rather than a primary shear origin (Fig. 3c).

The quartz fibres would also tilt clockwise if the gashes originated as Riedel shears (Fig. 3d). Nevertheless, Riedel shears do not fit the observed geometry since they generally form at angles at about 20° to a shear zone (Hancock 1972), therefore, a larger stress reorientation would be necessary to develop them at 40°. The lack of shear offsets across the cleavage planes [point (3) above] is an additional observation which does not accord with a Riedel-shear hypothesis. A small-angle hybrid (shear-extension) fracture (Fig. 3d) would satisfy the geometric constraints, however.

(5) In complex multiple-vein arrays thin planar veins branch off sigmoidal veins or cut across them (Fig. 2b). If developed synchronously such branch veins may be taken as evidence for a shear origin for the primary vein (Beach 1980) but these are developed later against rotated early veins and have younger vein fillings (Fig. 2b).

Two or three sets of veins are common and the newer veins are parallel to the tips of the older sigmoidal veins (Fig. 2b). This indicates that the maximum principal-stress directions, and the maximum incremental extensions (Durney & Ramsay 1973, fig. 16, Ramsay & Huber 1983), remained constant during the development of the shear zones—or, at least, the stresses had the same orientation at each critical failure threshold.

One remarkable example confirms this conclusion and the validity of the secondary tension-gash hypothesis. In the central part of one complex vein, we have noted conjugate arrays of small drusy cavities that reflect the geometry of the parent array (Fig. 2c). Maximum principal stress during drusy-vein development was parallel to the vein tips of the older veins (Fig. 2d) and therefore must have been reoriented into the 40° position with respect to the shear zone.

DISCUSSION ON MECHANISM OF DEVELOPMENT

From the arguments given above we reject the primary-shear hypothesis of Beach (1975) for the origin of the conjugate quartz gash-vein arrays in the Merrimbula Sandstone and favour a standard stress-reorientation hypothesis (Lajtai 1969, Hancock 1972). In considering a mechanism of development, we must explain the small dihedral angle (40°) between conjugate shear zones, the parallelism of quartz veins in each zone to the complementary conjugate zone, the parallelism of vein tips through successive vein developments, the lack of internal shear planes, the enhanced development of cleavage in the shear zones and its curving geometry.

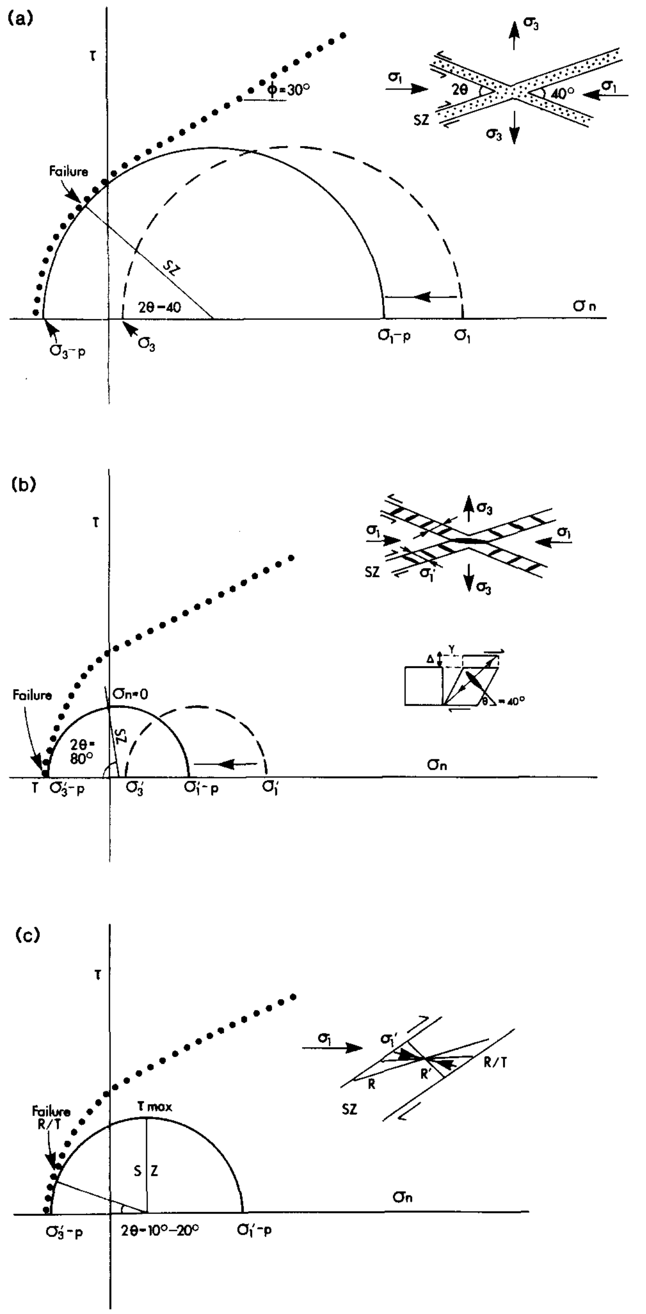

Fig. 4. Mohr-circle representations of critical stress conditions for failure. (a) Failure of sandstone in low-angle conjugate shears (SZ) under principal stresses σ_1 and σ_3 and fluid pressure, p. (b) Failure in extension (T) under reoriented stresses σ_1' and σ_3' in the dilating shear zone; see text for details. (c) Failure on hybrid extensional-Riedel (R) shears at 10–20° to σ_1' axis. σ_1, primary maximum principal stress; σ_1', reorientated maximum principal stress; σ_3, primary minimum principal stress; σ_3', reorientated minimum principal stress; σ_n, normal stress across failure plane.

The small dihedral angle of these shear zones indicates that failure occurred by shear when the effective minimum stress was negative; that is failure occurred on the parabolic part of the Mohr failure envelope (Fig. 4a). This situation is best achieved when there is a small differential stress and low total and effective confining pressure (Fig. 4a). Relevant mechanical analyses have been published by Secor (1965), Hancock (1972), Phillips (1972), Hancock & Kadhi (1978) and Sibson (1981). Stratigraphic considerations indicate that there was less than 3 km, and possibly only 1 km, of overburden (Rixon *et al.* in press), so that confining pressure would be low. In addition, fluid pressure would have been high because mudstones interlayered with the sandstones would provide impermeable barriers. Quartz veins in bedding planes indicate vertical extension, and fluid pressure is likely to have approached lithostatic load at the initiation of flexural-slip folding (Price 1975).

The formation of shear zones, would relieve the horizontal stress temporarily (Lajtai 1969), and the effective confining pressure would increase as water escaped from the system up faults. Thus the differential stress would decrease and the Mohr circle would move to the right (Fig. 4b). The shear zones represent small planar lenticular zones of more ductile material with a slightly different Mohr failure envelope from the unsheared sandstone (Fig. 4b). As tectonic stress built up again, the fluid pressures evidently also increased so that failure occurred in extension (Mohr circle moving to the left) before the differential stress built up enough to cause Riedel-shear failure (Fig. 4b).

The maximum principal stress in the shear zone (σ_1') is reoriented by the shearing of the ductile material. The optimum angle is 45° to the shear zone (Lajtai 1969, Hancock 1972) perpendicular to the maximum incremental strain (Ramsay 1980), but in this case the dilational nature of the shear zone (Fig. 4a) allows extensional failure at lower angles (Ramsay 1980, Ramsay & Huber 1983) and this explains the observed 40° attitude between the quartz veins and the shear zones. Garnett (1974) has considered a similar problem for gash veins in kink bands; in terms of his analysis, it is apparent (Fig. 4b) that the normal stress (σ_n) across the shear zone approaches zero (the optimum condition for the development of tension gashes) when the gashes, and hence σ_1' are oriented at less than 45° to the shear zone. The dilation across the shear zone must remain approximately constant throughout the successive vein developments, which may be taken to imply that deformation was essentially continuous and that successive gash veins developed when the rotated early-formed veins could no longer accommodate the strain (Ramsay & Huber 1983), although, there may have been fluid-pressure fluctuations as fissures drained the adjacent rock (Phillips 1972). Stresses do not appear to have built up sufficiently [that is an increase in σ_1 to enlarge the Mohr circle (Fig. 4b)] to allow Riedel shears to develop in the zone, but, in some zones, 'jamming-up' or a local increase in strain rate allowed shear failure along a central plane that disrupted the quartz veins (Fig. 1).

In the intersection zones between coeval conjugate arrays, pure shear (flattening) predominates and the tension gashes develop at 20° to each zone, parallel to the primary maximum principal-stress axis (σ_1). In some cases, both at Merrimbula (Fig. 1) and elsewhere (e.g. Beach 1975, fig. 2, Hancock 1973, plate 5) veins fan and reduce angle progressively towards the intersection zone. Presumably this indicates a progressive reduction in stress reorientation (Garnett 1974) due to increase in dilation towards the intersection zone.

The parallelism of veins with the conjugate zones results from the coincidence of the 40° stress reorientation and the 40° angle between the initial shear zones. We would anticipate that as shear angles widened up to the normal 60–70° for compressive shear failure, dilation would reduce (Beach 1975, Durney 1981) and the tension gash angle should approach 45° to the shear zone. Published examples (e.g. Roering 1968, fig. 3, Ramsay & Graham 1970, fig. 1, Hancock 1973, fig. 1, Beach 1975, fig. 2) show that veins depart considerably from parallelism with the conjugate array. Irregular stress reorientation might explain these variations, or, as postulated by Hancock (1972, 1973) hybrid fractures could be expected to develop under failure conditions represented by the steeper part of the Mohr envelope (Fig. 4c). The possibility that shear fractures may open in extension (Hancock 1972, Beach 1975, 1980, Burg & Harris 1982, Gamond 1983) means that it is impossible to use the simple form of a gash vein to predict the direction of maximum principal stress unless vein fibres are present perpendicular to the vein walls. Thus in variably oriented veins within an array (e.g. Garnett 1974) the possibility of extensional-shear fracture must be discounted before attempting a stress analysis.

Beach's type 2 arrays, where gash veins are parallel to the intersection axis throughout (Beach 1975, fig. 2) remain difficult to explain. Beach has postulated that the veins originated before shearing by some unexplained nucleation mechanism; later shearing then affected the central part of each array producing sigmoidal veins. This hypothesis does not explain how the veins become localized in conjugate arrays in the first place. An alternative interpretation is that the veins initiated in narrow shear zones at about 45°, then as deformation proceeded they propagated outwards, faster than the shear zone widened, turning into the direction of primary maximum principal stress. We have noted this geometry where occasional veins extend beyond the shear zone in the Merrimbula examples. If our suggested hypothesis proves to be correct then calculations of shear strain for such vein arrays could be seriously in error.

The cleavage pattern is simple; cleavage maintains a perpendicular relationship to straight quartz veins within the shear zones and is perpendicular to the maximum principal-stress axis outside the shear zones (Fig. 1). Early-formed cleavage may be rotated with sigmoidal veins and younger cleavages cross them. The increase in number of cleavage planes in the shear zone is undoubtedly related to the ductile deformation itself and probably to the behaviour of fluids in the shear zone. The likelihood of high fluid pressure during folding has already been mentioned. Faulting associated with the folding would provide channelways to dewater the system locally. The increased ductility in the local shear zones decreases permeability (Brace, 1968) and allows build up of fluid pressure to hydrofracture levels (Raybould 1975, Beach 1977, Sibson 1981) especially where differential stress is low (Phillips 1972). We have noticed that shear zones in very coarse sandstones do not contain quartz veins, presumably because fluids were able to escape. On failure, the development of extensional fissures facilitated dewatering and reduced the fluid pressures in the shear zones. The reduced fluid pressure would enhance pressure-solution, thus explaining the increase in cleavage development in the shear zones. The dewatered parts of the shear zone would eventually drain fluid from the sandstone outside the shear zones until pressure built up again to fracture level. Such a process would help explain the successive vein developments and complex internal vein arrangements. The addition of fluid would also maintain the dilatancy in the shear zone (Beach 1975) by bringing in quartz from the surrounding sandstone where there are generally few quartz veins.

Acknowledgements—We are indebted to Chris McA. Powell who drew our attention to the conflicting hypotheses on tension gashes. We also thank him, D. Durney and P. Hancock for numerous discussions and the anonymous reviewers for their useful critical comments.

REFERENCES

Beach, A. 1974. A geochemical investigation of pressure solution and the formation of veins in a deformed greywacke. *Contr. Miner. Petrol.* **46**, 61–68.
Beach, A. 1975. The geometry of en-échelon vein arrays. *Tectonophysics* **28**, 245–263.
Beach, A. 1977. Vein arrays, hydraulic fractures and pressure-solution structures in a deformed flysch sequence, SW England. *Tectonophysics* **40**, 201–225.
Beach, A. 1980. Numerical models of hydraulic fracturing and the interpretation of syntectonic veins. *J. Struct. Geol.* **2**, 425–428.
Brace, W. F. 1968. Mechanical effects of pore-pressure on fracturing of rocks. In: *Proceedings, Conference on Research in Tectonics* (edited by Baer, A. J. & Norris, D. K.). *Geol. Surv. Pap. Can.* **68–52**, 113–123.
Burg, J. P. & Harris, L. B. 1982. Tension fractures and boudinage oblique to the maximum extension direction: an analogy with lüders' bands. *Tectonophysics* **83**, 347–363.
Choukroune, P. & Seguret, M. 1968. Exemple de relations entre joints de cisaillement, fentes de tension, plis et schistosité (autochtone de la nappe de Gavarnie—Pyrénées Centrales. *Revue Géogr. phys. Geol. dyn.* **10**, **Fasc. 3**, 239–246.
Durney, D. W. 1981. Dilatancy and the angle of obliquity of en-échelon fractures. International Conference on deformation processes in tectonics. *Geol. Soc. Aust. Abstr.* **4**, 38.
Durney, D. W. & Ramsay, J. G. 1973. Incremental strains measured by syntectonic crystal growths. In: *Gravity and Tectonics* (edited by De Jong, K. A. & Scholten, R.). Wiley, New York, 67–96.
Gamond, J. F. 1983. Displacement features associated with fault zones: a comparison between observed examples and experimental models. *J. Struct. Geol.* **5**, 1–13.
Garnett, J. A. 1974. A mechanism for the development of en-échelon gashes in kink zones. *Tectonophysics* **23**, 129–138.
Hancock, P. L. 1972. The analysis of en-échelon veins. *Geol. Mag.* **100**, 269–276.
Hancock, P. L. 1973. Shear zones and veins in the Carboniferous limestone near the observatory, Clifton, Bristol. *Proc. Bristol Nat. Soc.* **32**, 297–306.
Hancock, P. L. & Kadhi, A. 1978. Analysis of mesoscopic fractures in the Dhruma–Nisah segment of the central Arabian graben system. *J. geol. Soc. Lond.* **135**, 339–347.
Lajtai, Z. 1969. Mechanics of second-order faults and tension gashes. *Bull. geol. Soc. Am.* **80**, 2253–2272.
Phillips, W. J. 1972. Hydraulic fracturing and mineralization. *J. geol. Soc. Lond.* **128**, 337–359.
Price, N. J. 1975. Fluids in the crust of the earth. *Sci. Prog. Oxf.* **62**, 59–87.
Ramsay, J. G. 1980. Shear zone geometry: a review. *J. Struct. Geol.* **2**, 83–99.
Ramsay, J. G. & Graham, R. H. 1970. Strain variation in shear belts. *Can. J. Earth Sci.* **7**, 786–813.
Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern*

Structural Geology, Volume 1, Basic Techniques—Strain Analysis. Academic Press, London.

Raybould, J. G. 1975. Tectonic control on the formation of some fibrous quartz veins, Mid-Wales. *Geol. Mag.* **112**, 81–90.

Rispolet, R. 1981. Stress fields about strike–slip faults inferred from stylolites and tension gashes. *Tectonophysics* **75**, T29–36.

Rixon, K. L., Bucknell, W. R. & Rickard, M. J. in press. Mega kink folds and related structures in the Upper Devonian Merrimbula Group, South Coast, New South Wales. *J. geol. Soc. Aust.*

Roering, C. 1968. The geometrical significance of natural en-échelon crack-arrays. *Tectonophysics* **5**, 107–123.

Secor, D. T. 1965. Role of fluid pressure in jointing. *Am. J. Sci.* **263**, 633–646.

Sibson, R. H. 1981. Controls on low-stress hydro-fracture dilatancy in thrust, wrench and normal fault terrains. *Nature, Lond.* **289**, 665–667.