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POST-LITHIFICATION DEFORMATION OF SANDSTONE-DIKES: IMPLICATIONS FOR TECTONIC DEWATERING

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ABSTRACT. In two slate-grade metamorphic terrains, the geometry of pre-tectonic clastic dikes shows that strong orientation convergence of dikes and tectonic fabrics occurs during regional deformation. In both examples dike arrays were initially polygonal, but after moderate to high strain very few dikes are inclined at appreciable angles to cleavage. These latter high angle relationships are not anomalous as claimed by some authors but provide unequivocal evidence for pre-deformation dike production. This crucial evidence is unfortunately rarely observed because the most common natural exposure, the ac profile plane, usually approximates the highest strain section of the tectonic strain ellipsoid (XZ) where greatest convergence has occurred. Putative examples of clastic dikes demonstrating tectonic dewatering must show intensive three-dimensional investigation of dike/cleavage geometry before the evidence can be given any weight. Ideally low strain areas should also be sought and studied in detail to minimize the effects of metamorphic and strain overprinting. Because forcefully injected clastic dikes can have initial polygonal configurations, the dikes in the described examples demonstrate that statistical parallelism of dikes with cleavage cannot be used to support the tectonic dewatering hypothesis. Borradaile's sand-dike test for the degree of rotation in the strain history was applied because the material studied provided appropriate data, but problems with the basis of the method were revealed. It is claimed in the method that, in deformed rocks, a great circle distribution of poles to dikes can only be derived from dikes that were initially perpendicular to bedding. However, a good approximation to this distribution was developed by applying a simulated homogenous pure-shear deformation to field data where dikes showed considerable angular variation relative to bedding; only 2 of 23 dikes were initially at right angles to bedding, and most were between 10° and 60°. The validity and applicability of the sand-dike test need further investigation.

INTRODUCTION

Hubbert and Rubey brilliantly pioneered geological work on the mechanical effects of pore-fluid pressures and whilst metamorphic petrologists have long realized the normality of abnormal pore fluid pressures ($P_{fluid} \cong$ hydrostatic pressure) members of the structural fraternity were slow to consider the wide ranging implications of such conditions. A major exception was Maxwell who in his 1962 paper contemplated the fascinating question of what would happen to an over-pressured sedimentary pile if it were to be caught up in regional tectonism. The notion of abnormal pore-fluid pressures pushing clastic grains apart and thus facilitating their rotation as an aid in the production of rock cleavage has only recently been discussed and considered in any detail in the context of grain boundary sliding (g.b.s.) (for example, Borradaile, 1978, 1979, 1981). Maxwell's tectonic dewatering hypothesis sparked a storm of controversy with comments in some of the latest papers being very blunt, for example "there is no substantial evidence for the hypothesis" (Beutner, 1980), and "it does not even seem possible to construct a testable dewatering model" (Geiser, 1976). Clastic dikes and their relation to slaty cleavage figure prominently in this heated debate, and their significance is still interpreted in a wide variety of ways. Geiser (1976, p. 793) states that some geometrical configurations of dikes with respect to cleavage may demonstrate the operation of tectonic dewatering. The present paper takes advantage of two well exposed examples of clastic dikes in slates to demonstrate what happens to dike geometry during strain in lithified rocks. This documentation may then be used as a basis for comparison with areas where tectonic dewatering has been proposed. Deep-sea drilling in presently active tectonic areas could well demonstrate the existence of regional secondary fabrics generated by dewatering, and if this happens an intensive search in the ancient record will be made to find evidence for the operation of such a process. Clastic dikes would again undoubtedly feature highly in this quest, and data of the type presented here could be used as a reference point for tests of the hypothesis.

At our present state of knowledge it seems possible to determine that some dikes clearly pre-date tectonism and thus are unrelated to tectonic dewatering (Maxwell, 1976, p. 791). A major problem in verifying Maxwell's dewatering hypothesis is the generally high degree of overprint attributable to solid state deformation processes (Powell, 1973). If cleavage was initiated by dewatering or if intragranular deformation was significantly inhibited by grain boundary sliding, the evidence for such behavior on the grain scale is often obliterated by strain and metamorphic related effects. Bulk strain markers such as folds or clastic dikes are required to highlight any contribution from intergranular deformation (Borradaile, 1981), and hence the geometry of clastic dikes is an important facet in these studies particularly in connection with the sand-dike test (Borradaile, 1977) which claims to be capable of demonstrating angular differences between cleavage and the XY plane of the tectonic strain ellipsoid.

STIRLING RANGE CLASTIC DIKES

These dikes occur within the low-grade metasediments that outcrop in the Stirling Range National Park, southwest Western Australia (Boulter, 1979). Tectonically the sediments are within the foreland to the Proterozoic Albany-Fraser mobile belt close to its northern margin with the Archaean Yilgarn Block. The host rocks to the dikes are arenites, with varying micaceous contents, interbedded with slate horizons; the latter usually ranging in thickness from a few centimeters to two meters. No thick slate units are known, but apart from this limitation they are often of commercial quality. Metamorphism has been dated at 1150 m.y.b.p., and X-ray diffraction shows that all the white mica is sericite with no illite being present (Richards, ms). At each locality, a single slaty cleavage is the dominant tectonic fabric in the mudrocks, and, whilst one or more weak crenulation cleavages are often present, these later fabrics are only rarely strongly developed.

Clastic dikes in slate beds are common throughout the Stirlings, but they are particularly well exposed on Toll Peak and Talyuberlup (pls. 1 and 2), and at the latter locality are somewhat more abundant than usual. A most significant feature of the outcrops described in detail is their three-dimensional nature; on Toll Peak mesoscopic folds coupled with erosion along bedding planes show all aspects of the beds, whilst on Talyuberlup the beds are nearly horizontal, and the hill outline is stepped along the bedding to an isolated flat-top which is parallel to bedding. In both areas differential weathering has often deeply eroded the slates and left the dikes with positive relief. Plate 1 shows typical views for the region of the clastic dikes on a face at high angles to bedding. In the majority of exposures the plane of observation is nearly parallel to the fold profile on an ac joint, and on these sections the dikes appear to be sub-parallel to the cleavage; figure 1 presents orientation data from such faces to support this statement. A small minority of dikes are found in the acute angle between bedding and cleavage, but most show cleavage in the acute angle between dike and bedding. The former acute angle relationship either means that the dikes were not initially perpendicular to bedding or that the strain history was non-coaxial.

Without very careful investigation the apparent sub-parallel relationship between dikes and slaty cleavage might appear to represent the three-dimensional relations. However, bedding plane exposures at both localities allow complete investigation of the dike geometry relative to the tectonic fabric (pl. 2-A and fig. 2). Plate 2-A is a photograph of a bedding surface on Toll Peak demonstrating that in this section the clastic dikes exhibit a polygonal pattern. Orientation data from this outcrop are presented in figure 2A as is similar information from the flat lying beds at the summit of Talyuberlup in figure 2B. In addition plate 2-A shows that the trace of slaty cleavage on the face is closely related to the elongation of the polygons.

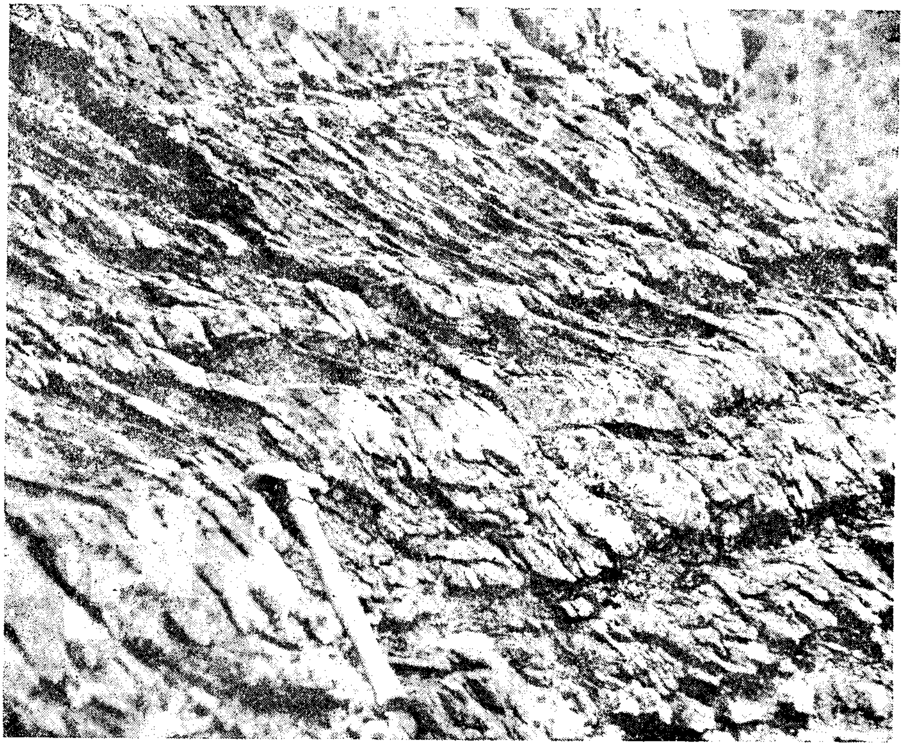
Polygonal clastic dike arrays are normally attributed to subaerial desiccation or more rarely in the case of small dikes to sub-aqueous synaeresis. The pattern could, however, also be produced by dewatering of equal volumes of sand during shock induced liquefaction by a process akin to that which produces polygonal joints in dolerite sills by cooling of equal volumes of magma. Unfortunately in the present examples the exact mechanism of formation of the dikes is equivocal; no clear disrupted feeder zones have been observed for a forceful injection mechanism, nor have truncated dikes been noted as might be expected if they were neptunian in origin. Some potential feeder zones could equally be entirely the result of pressure solution, and mudrock veneers over the tops of some dikes are never completely continuous. The vast majority of dikes taper downward, and no examples of stratigraphic upward injection have been observed. On balance a passive infill of sun-cracks is favored, but little weight can be attached to this evidence. Some sedimentary structures, particularly interference ripples, suggest very shallow water conditions perhaps emergent at times, and the general palaeocurrent pattern is consistent with a deltaic environment (Richards, ms).

Almost all the dikes have been boudinaged with individual boudins having square cross sections (pl. 2-B) suggesting a high viscosity contrast between dike and host slate. Fibrous quartz and specular hematite infill the space between the boudins; the fibers between the pulled apart segments of the sand-dikes being mainly straight (fig. 3 and pl. 2-B). The fibers of quartz lie either within or close to the plane of slaty cleavage and sub-parallel to a mineral lineation on the cleavage. The geometry of the relationship between the fibrous veins and the sand-dikes is akin to the boudinaged calcite veins of Beutner, Jancin, and Simon (1977). Where variably oriented polygonal dikes can be fully examined, dikes of all orientations have been boudinaged, and the veins of fibrous quartz and the internal fibers maintain a reasonably constant attitude. The fibrous quartz veins may extend into the adjacent slate as rapidly tapering and perhaps bifurcated offshoots (fig. 3). Within these extensions, which deflect toward the slaty cleavage, the fibers make a higher angle with this fabric than in the boudin necks. Curvature of the fibers is also largely restricted to these offshoots.

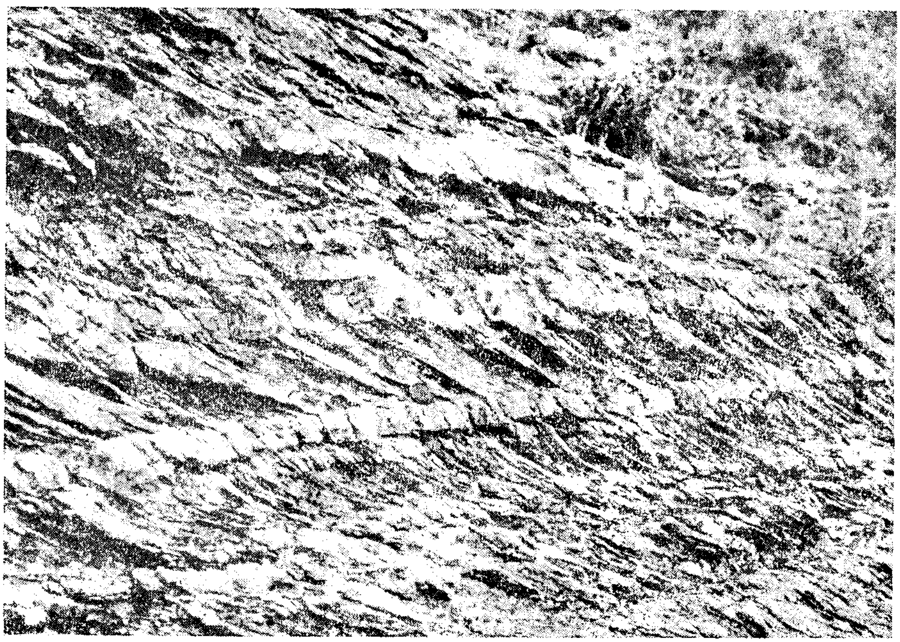
Microscopic examination of the straight quartz fibers shows that undulose extinction is common and that individual fibers do not show continuous optical orientation, rather they are a mosaic of polygonal subareas, 0.1 to 0.2 mm in diameter, showing only a few degrees of optical mis-match (pl. 3). Contacts between adjacent fibers are rarely planar, usually being irregular on the scale of 0.05 mm new grains or sub-grains. The intensity of optical deformation effects varies mainly with the thickness of the fibers; thin fibers near the walls of the veins are more affected than thick fibers found in vein centers. Where curved fibers occur there is also an intensification of optical strain effects proportional to the degree of curvature, suggesting that most if not all the bending of the fibers is superimposed and not a growth feature (White and Wilson, 1978). The folding deformation of the fibers is too intense to be related to the formation of the weak crenulation cleavages which are often present in the slate beds. As will be argued later the veins formed early in the strain event that produced the slaty cleavage and were progressively modified through that deformation event.

Deformation conditions.—The clastic dikes clearly predate tectonism being cut at all angles by the cleavage (pl. 2-A), and, where dike cleavage angles are high, the dikes show cleavage intensity comparable to or greater than that of the host arenite beds. Dikes show no preferential location on fold limbs or closures further arguing against a syn-tectonic timing.

PLATE I



A.



B.

(A) and (B) are both bedding perpendicular views from Talyuberlup illustrating the restricted sub-parallel relations seen between clastic dikes and slaty cleavage in such sections. The hammer handle in (A) is 40 cm long.

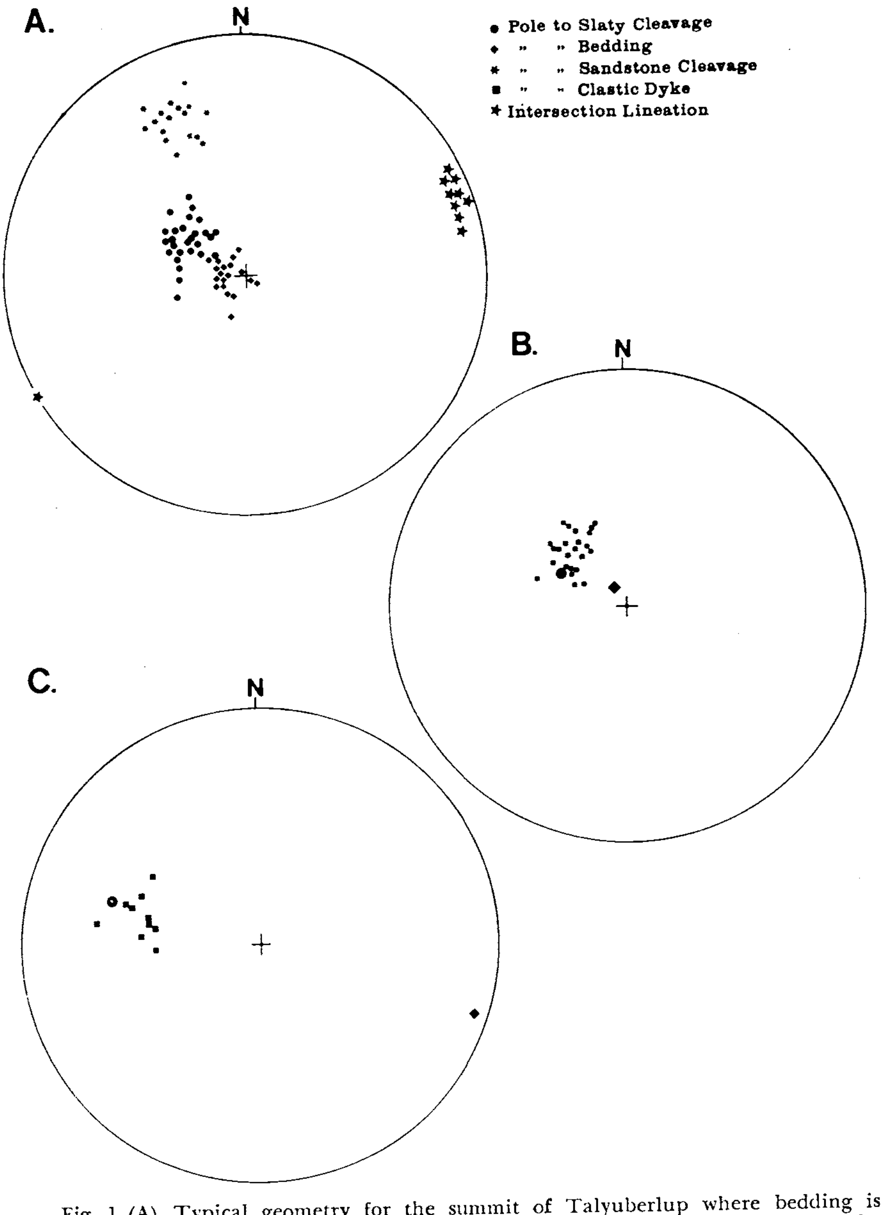
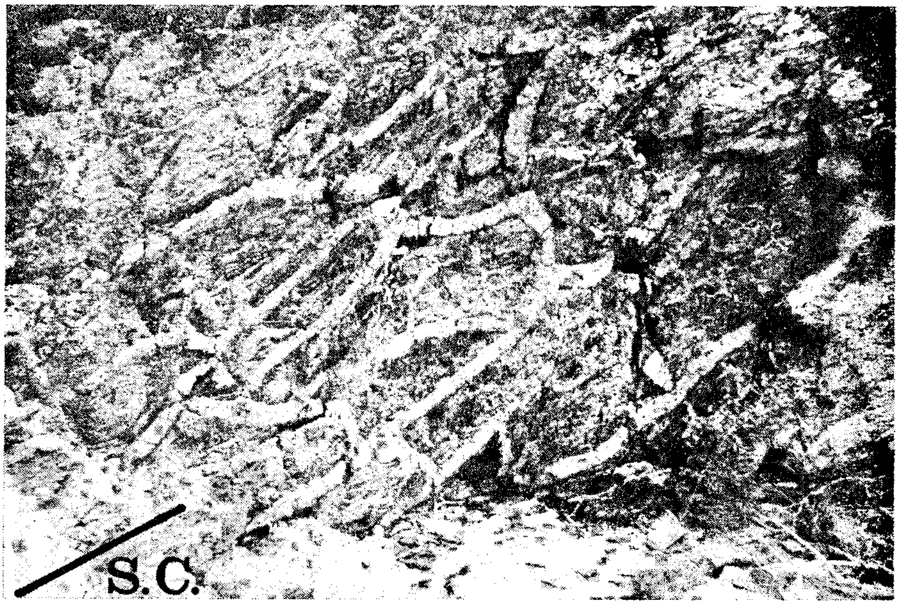


Fig. 1 (A). Typical geometry for the summit of Talyuberlup where bedding is gently dipping and cleavage is strongly refracted from slate to sandstone layers. The lineation is formed by the intersection of the sandstone cleavage and bedding. (All stereographic data are presented on equal-area lower hemisphere projections.) (B) Clastic dike slaty cleavage relations as gathered from the faces shown in plate 1, Talyuberlup. Each dike pole has been rotated so that the pole to the cleavage measured next to the dike has been brought into alignment with the mean cleavage pole (black circle). The mean bedding pole is shown. (C) Clastic dike/slaty cleavage relations from another bedding perpendicular face (Toll Peak). Data are plotted, using the method described in (B).

PLATE 2

A.



A. A view (from Toll Peak) looking onto a bedding plane, showing the flattened polygonal trace of clastic dikes on bedding. The exposed face is 3 m high and the heavy black line labelled S.C. shows the trace of the slaty cleavage.

B.

B. Clastic dikes in a slate bed seen in a bedding-perpendicular section. The quartz veins have formed in the necks between pulled apart segments of dikes. The fibers within the veins are straight in this example. The coin is 2 cm in diameter.

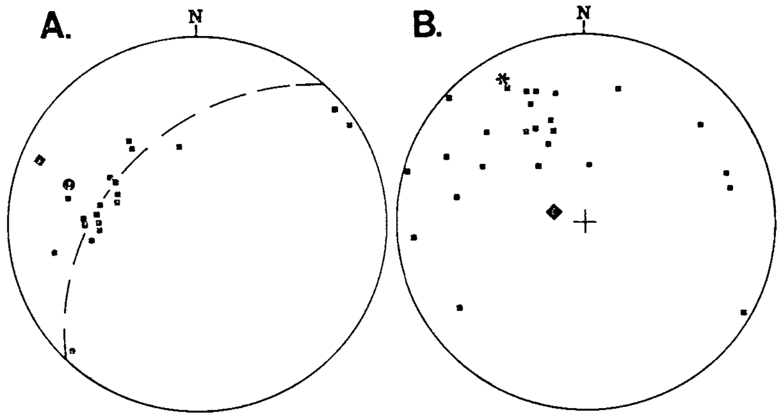


Fig. 2 (A). Clastic dike geometry from the outcrop shown in plate 2-A (Toll Peak). The dashed line is a best fit great circle to the dike poles. Mean slaty cleavage and bedding poles are shown. Symbols are as for figure 1 and data are treated as in figure 1B. (B) Clastic dikes in arenite from the summit of Toll Peak. Here strain is low, and the wide spread of poles to dikes suggests an original non-orthogonal relation to bedding.

Variably cleaved dolerite dikes demonstrate that the surrounding sediments were solid enough during the deformation to transmit stress difference through coarse-grained and relatively dry igneous rocks (Wood, 1974). At the foot of Talyuberlup, 1 km to the south, a strain analysis on ellipsoidal mafic clots (once pyroxene and now partly altered to chlorite) in a dolerite gave a result of +87 percent X, −11 percent Y, and −40 percent Z ($X \geqslant Y \geqslant Z$). Considering the likely viscosity contrast between an arenite/slate multilayer and a coarse-grained dolerite, the strain within the dolerite is compatible with that in the sediments. Reduction spots are rare within the slates, but on Toolbrunup, 6 km west-southwest of Toll Peak, Richards (ms) found a concentration of spots that allowed an estimate of strain to be made. The result was +250 percent X, +10 percent Y, −74 percent Z, and though errors are difficult to gauge, the shortening in Z is at least 60 percent. The nature of the slate fabric on Toll Peak, Talyuberlup, and Toolbrunup is identical in hand specimen and thin section. Strains of the magnitude recorded here can readily explain the dike configurations observed (Boulter, 1974; Groshong, 1976; Beutner, 1980). Within the Stirlings, a mineral lineation typically runs down the dip of the slaty cleavage and on Toolbrunup was always within a couple of degrees of the reduction spot longest axes. This lineation is taken to approximate closely the X direction of the tectonic strain ellipsoid which means that most exposures of clastic dikes (for example pl. 1) are in a plane not far from XZ the highest strain section. Following the analysis of Groshong (1976, p. 1135, pure shear perpendicular to cleavage), dikes on the lower slopes of Talyuberlup gave an 8.4 to 1 strain ratio for the exposed face perpendicular to bedding. The method assumed that the dikes were originally orthogonal to bedding, and whilst this is not necessarily true (see later), an approximate value is obtained. For the reduction spots on Toolbrunup the XZ strain ratio is 13.5 to 1 which would cause convergence of all but the originally highest angle dikes to the strain ellipsoid's XY plane.

Despite the simplicity of the boudin shapes in the pulled apart dikes it appears that the boudin formation with attendant growth of fibrous quartz veins did not occur throughout the strain history. What meager strain data are available suggest that strain symmetry hovers around plane strain which means that dike/bedding/cleavage relations of plates 1 and 2-B and figures 1 and 3 must be associated with extensions of about +200 percent in X. The quartz fiber veins typically account for only 10 to 20 percent of the presently observed length of the dikes. Marjoribanks (1976) has attributed optical features such as those seen in the quartz fibers (pl. 3-A) to strains of approx 40 percent shortening in Z with a flattening symmetry. Boulter (ms) showed that similar features develop between 30 and 40 percent shortening, and perhaps, in a fluid-rich vein, a lower strain value may have brought about the intracrystalline deformation features observed (Kerrich, 1976). The quartz veins have taken up a moderate amount of deformation demonstrating that they were largely formed in the early stages of the strain history, and that viscosity contrasts between dikes and host mudrocks decreased during the deformation. This agrees with other observations in the region where the initial response to stress difference in arenite layers was the production of widely spaced mica-band cleavages without any associated pervasive cleavage formation (Boulter, 1979).

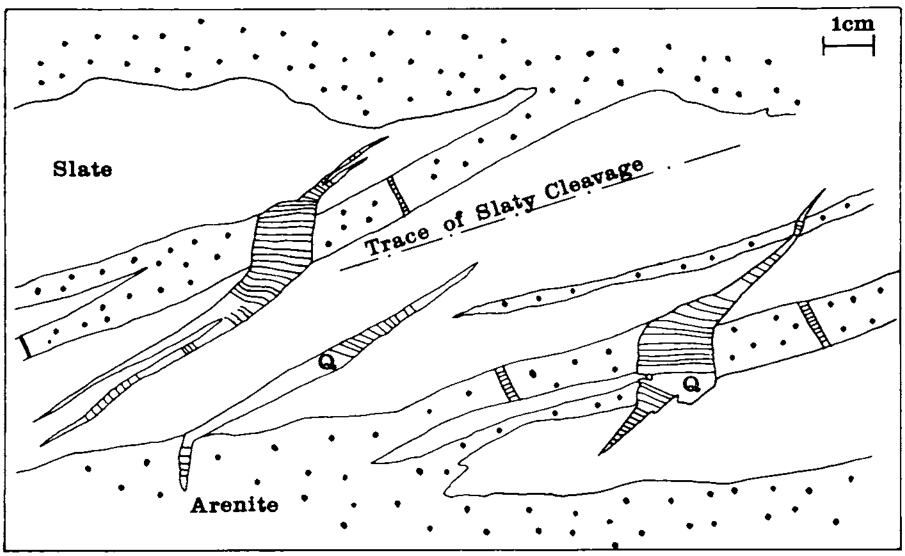
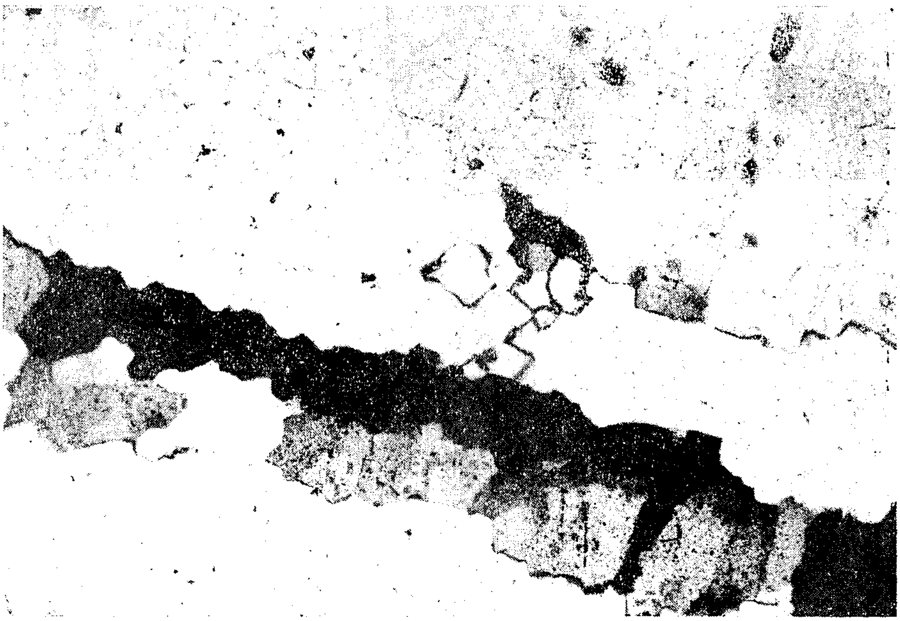


Fig. 3. A sketch from a field photograph showing clastic dikes in a slate bed and details of the quartz veins (Q) that infill necks between pulled apart dike segments. Individual fibers are shown by the lines within the veins.



A.

A. Photomicrograph showing optical features within fibrous quartz veins that are strain induced. Each fiber has been subdivided into a network of subgrains and new grains, undulosity is common, and the original fiber boundaries have become irregular through grain boundary migration. Field of view is 1.35 mm wide.

B.

B. Photomicrograph of the margin of a neck vein (V) and the adjacent clastic dike. The clastic texture farthest from the vein shows the normal tectonic fabric in the dikes whilst the central part of the photograph shows detrital grains considerably elongated by crack/seal veins. Field of view is 3.2 mm.

The presence of primary fluid inclusions in the fibrous veins of the boudin necks allows measurement of syntectonic temperatures. Fifty primary inclusions gave homogenization temperatures in the range 110° to 350°C, but only 6 readings were outside the range 150° to 250°C. The two readings above 300°C were probably brought about by deformation induced leaking (Kerrich, 1976). All specimens were from Talyuberlup, and the data suggest that there was some variation in timing of the initiation of vein opening, but detailed sampling of small intervals across single veins was not carried out. Boiling did not occur during formation of the veins, and as the pressure correction is unknown the recorded temperatures are minimum values. Homogenization temperatures for the final infilling of the veins are in the 200° to 250°C range, and actual temperatures at inclusion entrapment in excess of this. As the veins record

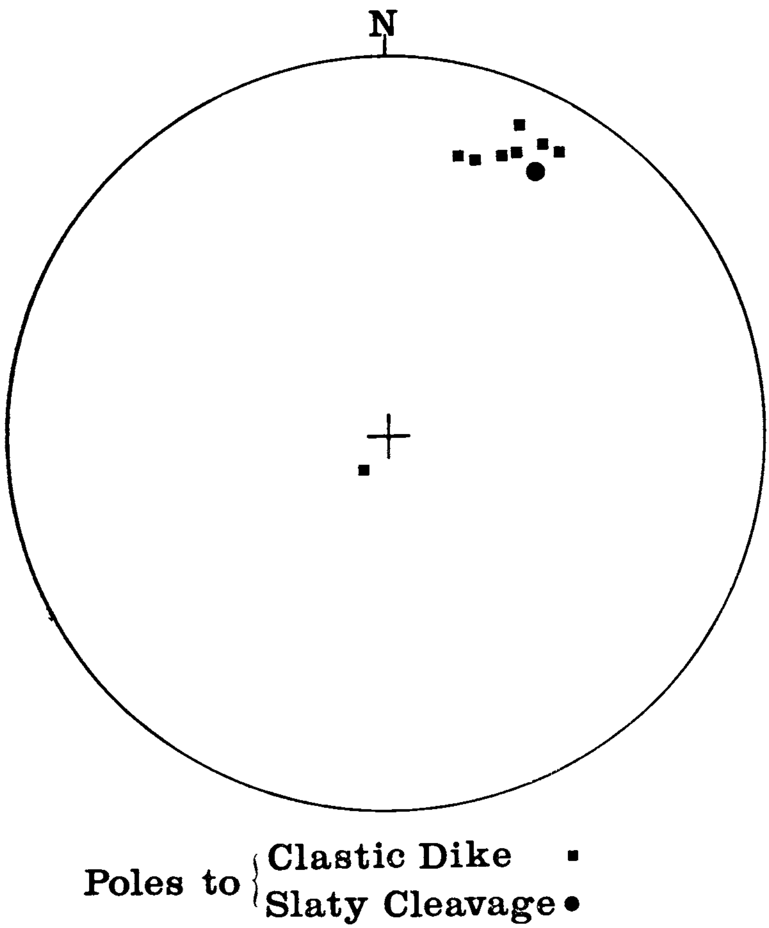


Fig. 4. Typical dike/slaty cleavage relations seen in natural exposures perpendicular to bedding at Scotts Peak.

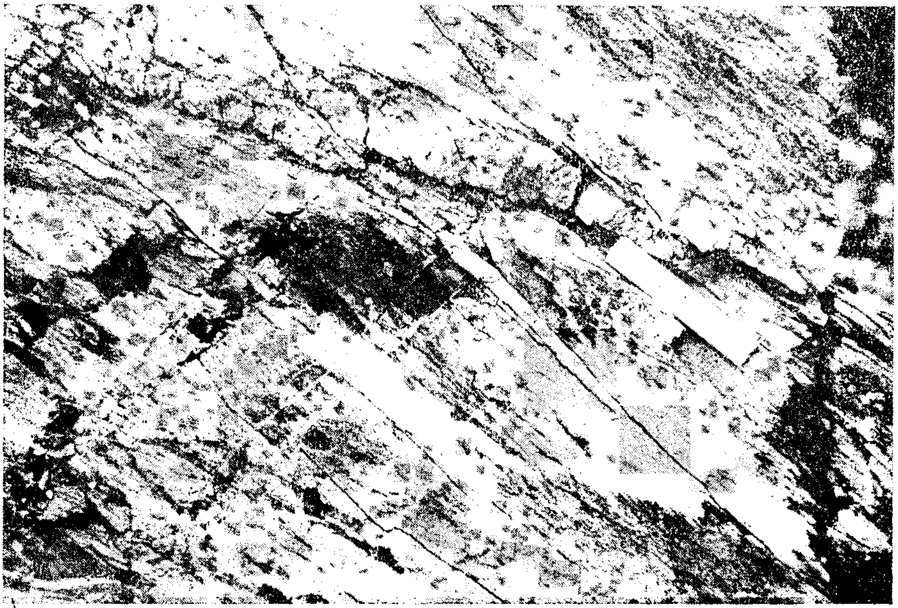
the early part of the deformation, the temperature during the middle and late stages of cleavage development was in excess of 250°C. The lack of evidence for boiling during vein formation is puzzling as there is clear evidence (pl. 3-B) that the veins grew by the crack/seal mechanism (Ramsay, 1980) which involves pressure drops at each cracking event. The presence of sericite as the only white mica indicates that the metamorphism was in Winkler's (1976) low-grade category and that peak temperatures exceeded 300°C.

SCOTTS PEAK CLASTIC DIKES

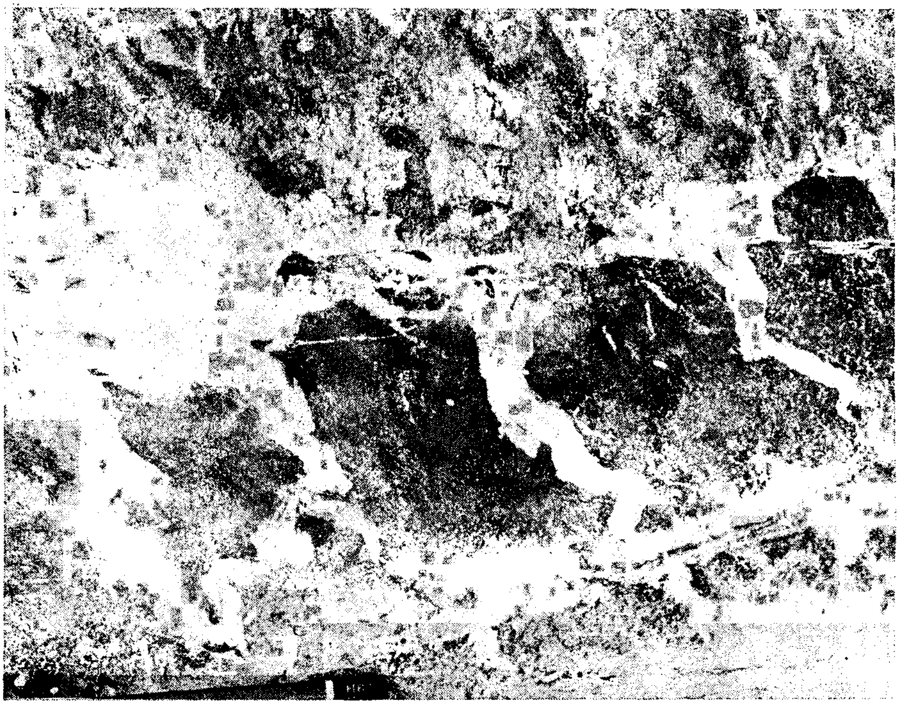
The regional geology of the Scotts Peak district in southwest Tasmania is poorly known, being summed up by Williams and Corbett (1977) as "relatively unmetamorphosed rocks of probable Precambrian age." More detailed information for the area immediately around the dike localities has been provided by Roberts, Cole, and Barnett (1975); all of the dikes come from the Metasiltstone, Argillite, Quartz Sandstone Formation of Roberts, Cole, and Barnett (their fig. 2). Other units in the local stratigraphy are limestone, dolomite with argillite, quartzite, and quartz sandstone. The local structure is dominated by sub-upright macroscopic open to close folds that plunge at about 30° toward 290°. A slaty cleavage is well-developed throughout the mudrocks which are variably crenulated though never intensely. No data are available on metamorphic mineralogy, but a very weak phyllitic sheen to cleavage surfaces indicates a low or very low grade.

When clastic dikes are seen in situ in natural or man-made exposures the faces are usually at high angles to bedding (pl. 4-A), and dikes are almost exclusively within a few degrees of the cleavage (fig. 4). However, extensive quarrying for a large rock-fill dam has broken many large blocks along bedding planes. This has exposed many polygonal clastic dike arrays (fig. 5), clearly showing that the slaty cleavage cuts the dikes at almost any angle and hence that the dikes are pre-tectonic. Whilst the wide range of strain states evident in figure 5 could be due to varying bedding angles with respect to the principal tectonic strain axes, the bedding perpendicular views confirm that the bulk strain varies considerably (compare pl. 4-A with -B). In plate 4-B compaction folds are still partly preserved and were not totally overprinted by the tectonic strain as probably happened with the example in plate 4-A. Ellipsoidal reduction spots are present within the slates, but unfortunately the friable nature of the rock prevented their detailed analysis.

The slates are red, and their association with shallow-water carbonates may indicate a sub-aerial desiccation origin for the polygonal clastic dikes. Some outcrops do, however, display upward and downward penetrating dikes which demonstrate, for these cases, an origin by forceful injection. An injection mechanism is also supported by the presence of the Scotts Peak Fault which is a major strike-slip fault with tens of kilometers of horizontal displacement and which was active during sedimentation of the sequences that host the clastic dikes. Seismic activity


A.

A. Planar clastic dikes in a bedding-perpendicular section from Scotts Peak. Strain in the slate is high. The scale is in 2 cm subdivisions.


B.

B. Clastic dikes in a low tectonic strain area at Scotts Peak. The dikes at high angle to bedding show remnants of compaction folds, while offshoots sub-parallel to bedding have been affected by tectonic folds. The clastic dikes have an average length of 12 cm.

associated with movements on the fault could readily account for injection of dikes, and the evidence at Scotts Peak supports the contention made earlier that shock-induced dewatering could affect equal volumes of material by developing polygonal fractures.

STRAIN HISTORY DURING DIKE DEFORMATION

In addition to Maxwell's approach to tectonic dewatering, clastic dikes have figured prominently in the debate concerning the geometrical relation between cleavage and the XY plane of the tectonic strain ellipsoid. Borradaile (1977) developed an ingenious test using sedimentary dikes to determine whether or not cleavage was produced in a coaxial strain history. The test uses initially orthogonal features whose geometry after strain can be used to determine, within broad limits, the orientation of the XY plane of the tectonic strain ellipsoid. In practice the deformed orientations of once orthogonal features are used to define an area on a stereogram in which Z lies; the angular size of the area may be quite large, and in these cases the precision is low. If the pole to cleavage does not lie in the field predicted for Z, then it is claimed that the deformation was non-coaxial and that the cleavage could not be parallel to the XY plane. The well exposed and abundant dikes in the Stirlings prompted use of the method. The presence of the fibers, which allow the incremental strain history to be followed (Durney and Ramsay, 1973), was seen as a possible test of the method as two independent means were available to measure the degree of rotation in the strain history.

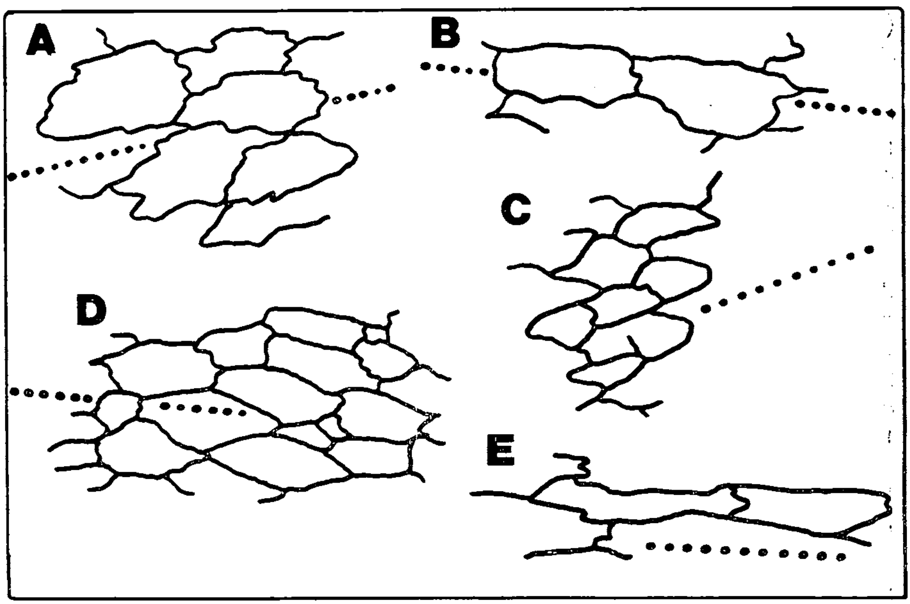


Fig. 5. Traces from field photographs of clastic dikes seen in bedding-parallel sections at Scotts Peak. Part E shows the highest strain ratio recorded for this plane. The dotted line in each part shows the trace of slaty cleavage on the planes illustrated.

Borradaile's method depends upon the expected behavior of planar structures during homogeneous deformation. In order for the method to be successfully applied, the dikes must have been originally bedding perpendicular, and Borradaile (1977, p. 151) claims that, in cleaved rocks, poles to dikes on or near a great circle must have been close to bedding-orthogonal initially. Several authors (for example, Borradaile, 1977, p. 152) have argued from poorly substantiated mechanical grounds that dikes produced by soft-sedimentary deformation or desiccation should be nearly at right angles to bedding. Contrary observations have been made in unstrained rocks, and several publications clearly illustrate clastic dikes with a wide range of orientations relative to bedding including clastic sills. Truswell (1972) illustrates several sets of sheeted sandstone dikes making angles of between 20° and 40° with bedding. Hiscott (1979) in a rare piece of documentation presents orientation data for sand intrusions from an apparently uncleaved turbitite sequence which shows that only 2 of 23 dikes are perpendicular to bedding and that most are between 10° and 60° from bedding. Because the necessary conditions for the sand-dike test are lacking in some cases the method itself had to be investigated. This was done by applying a simulated deformation history on Hiscott's dike population and comparing the results with patterns expected from bedding perpendicular dikes. Bedding was rotated about a horizontal line trending 287° to give a dip of 40° to the east-northeast to simulate a flexural-slip folding episode, and the dikes were subjected to the same rotational displacement. A homogeneous pure-shear transformation was then applied using the strain observed in the Stirlings reduction spots (+250 percent X, +10 percent Y, −74 percent Z). The XY plane of the strain ellipsoid was vertically oriented trending 107° with X down the dip. The final attitudes of the clastic dikes and bedding were calculated and plotted on a stereographic projection (fig. 6) where 21 out of 23 dike poles lie fairly close to a great-circle distribution. If the dikes in figure 6 are assumed to have once been bedding perpendicular, the sand-dike test shows that the strain was non-coaxial even though the applied strain was coaxial; the discrepancy of 6° between where Z should fall and its actual location is, however, not significant considering the scatter of dike pole data. The major conclusion from this exercise is that dikes with very dispersed initial orientations during deformation can converge in such a way that a near great circle distribution is obtained. In view of this behavior one must be very skeptical about using two or three dikes to demonstrate either coaxial or non-coaxial deformation as was done by Borradaile (1977).

Quartz fibers, linking the boudinaged segments of dikes in the Stirlings, are very close to being straight and presumably tracked the incremental strain history for that portion of the deformation that caused the opening. It was argued earlier that the fibrous veins were formed in the initial stages of deformation and that they have probably undergone about 30 percent superimposed shortening which equates to approximately a 2 to 1 strain ratio for the XZ plane. Only minor curvature of the quartz fibers could have been flattened out by such strain ratios, and, therefore, separation of the dike segments took place under almost coaxial conditions. Subsequent modification is uncertain though the common example illustrated in figure 3 must involve some rotational strain. This is demonstrated by the deflections of the vein extensions in the slate and also by the angle between the slaty cleavage trace and the fibers in the boudin neck veins. It is probable that the angle, between the fibers and the length of individual dike portions, was originally somewhat greater (fig. 3). The degree of noncoaxiallity of the strain history still, however, remains impossible to quantify. A plausible but unproven deformation history for the dikes is that their near coaxial segmentation took place during layer

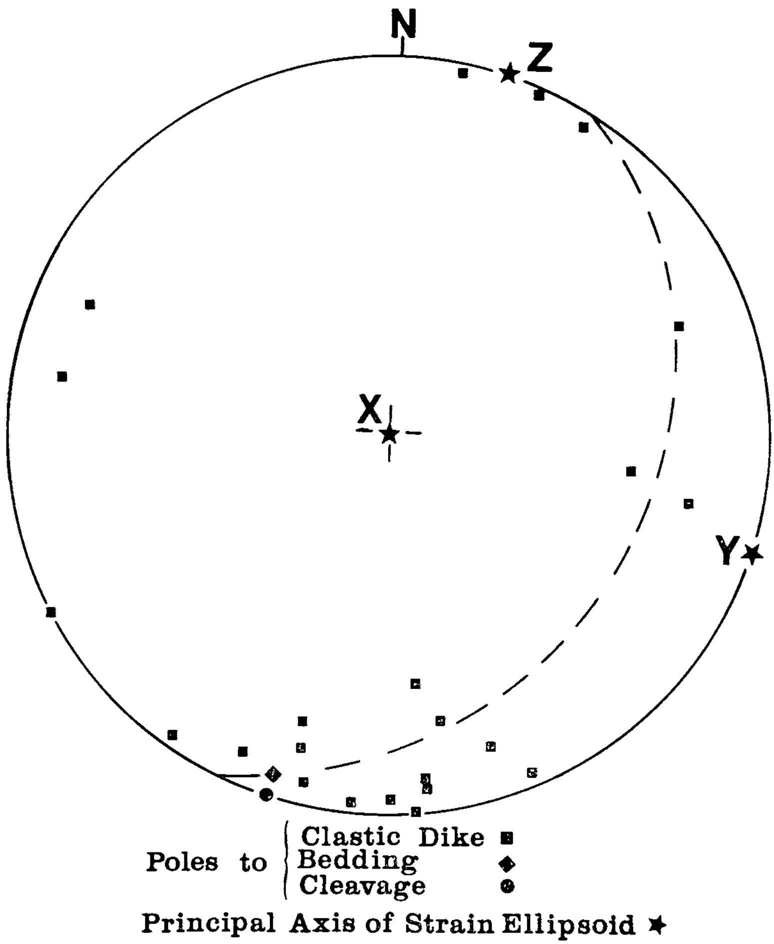


Fig. 6. The clastic dike data of Hiscott after being subjected to a body rotation of 40° about a horizontal axis trending 287° and a homogeneous pure shear transformation of +250 percent X, +10 percent Y, −74 percent Z. The dashed line is a best fit great-circle to the clastic dike poles.

parallel shortening and that the dike/bedding angle was reduced during folding by simple shear along the bedding planes.

DISCUSSION

Since Geiser's (1975) re-investigation of the dewatering hypothesis there has been some relaxation of the requirement that clastic dikes be parallel to cleavage to prove the operation of the mechanism (Alterman, 1976). Powell (1976) maintains that dikes should be statistically parallel to cleavage if both structures were produced by tectonic dewatering, and Geiser (1976, p. 793) accepted such a configuration as the one piece of evidence that "cannot be interpreted in terms of a solid state origin." In contrast Beutner (1980) has pointed out that statistical parallelism of dikes and cleavage is of no help to the cause of tectonic dewatering as the same relationship may be derived from the solid-state strain transformation of equant polygonal dike arrays. As many clastic dikes in undeformed areas have fairly regular polygonal shapes the geometry sought by Powell should be common but of no use to the dewatering cause. Upright symmetrical folds could also produce statistical parallelism of dikes and cleavage on the scale of several folds; the scale of observation has not been specified too carefully in the earlier discussions but presumably is restricted to individual fold limbs.

From recent discussions of dewatering (Alterman, 1976; Maxwell, 1976; Powell, 1976) it would seem that clastic dikes at high angles to cleavage demonstrate a pre-tectonic origin for the dikes. For both the Stirlings and Scotts Peak examples, dikes are cut at all angles by the slaty cleavage, though in fold profiles the dike/cleavage angles are invariably very low. These sections often approximate XZ of the tectonic strain ellipsoid and as such represent the highest strain ratio where pre-tectonic angular relations are most modified. The same sections are also those most commonly found in natural exposures in the form of ac joints. Early proponents of tectonic dewatering did not provide quantitative data, simply resting their case on written descriptions or two-dimensional views, and under these circumstances the more frequent exposure of the highest strain section was probably misleading. Before any data on cleavage/dike relationships can be accepted authors should demonstrate, as in this work, the three-dimensional nature of their investigation. This may not be possible without extensive quarrying or sawing of very large pieces of rock. Beutner (1980) with careful chisel work exposed dikes for measurement but because of the size of the exposures could not be sure of statistical analysis. An examination of figure 5E shows very little of the flattened polygonal dikes at high angles to cleavage in an example at the upper end of the slaty-cleavage strain range; faces sub-parallel to XZ would only rarely intersect the high angle dikes. A feature of the debate on tectonic dewatering has been the tendency to reject geometrical data from "anomalous" dikes that made a large angle with cleavage (Powell, 1976; and Geiser, 1975). In moderate to high strain such dikes will be rare, but they are key features in deciding the non-tectonic origin of the dike (Wood, 1974). Obviously problems exist in determining the significance of features at some variance with the main population; for example, if the data shown in figure 6 had been collected from a deformed terrain what weighting would have been placed on the two poles a long way off the great circle? Would these constitute key data to reject the proposition that the dikes were originally bedding perpendicular? Obviously gathering enough data to satisfy statistical sampling is a difficult task, and it would appear that many data are required to produce a meaningful result (compare Borradaile, 1977).

The wide range of strain states in the Scotts Peak example provided another highly desirable condition of any study of deformation behavior. In this region, the low strain states displayed clear polygonal dike intersections on bedding, partly preserved compaction folds, and readily recognizable dike offshoots that were at high angles to cleavage. The widespread and often high, strain overprints in slaty terrains cause problems for anyone attempting to interpret the early history of tectonic fabrics. At Scotts Peak, however, a low strain domain clearly shows that the clastic dikes originally had a wide range of orientation. This situation can be followed through to high strain states where virtually all planar dike segments become sub-parallel to the cleavage. It seems that the supporters of tectonic dewatering need to produce a set of strongly oriented dikes with a zero vector sum relative to a weak-cleavage in rocks with non-existent intragranular deformation. Strain shadows exist in many terrains for a variety of reasons and should be fully searched out if a tectonic dewatering hypothesis is to be demonstrated. Also, in view of the discussion in this paper, the dikes would have to be perfectly exposed to demonstrate their geometry.

The remaining part of this discussion is based on the Stirling Ranges where, of the two areas considered, the greater body of data exists. The evidence presented here and by Boulter (1979) most strongly supports the contention that the rocks were lithified prior to deformation. Bedding-parallel quartz veins predate any folding and occur on arenite/mudrock contacts where the wallrocks were sufficiently coherent to maintain vein walls; fluid inclusion studies show high temperatures early in the deformation history which are not compatible with an unconsolidated nature for the rocks; diagenetic cement in quartz arenites (the most likely reservoir unit) and arenites are recrystallized by strain-induced intracrystalline mechanisms; pressure solution produced mica-bands in arenites during layer-parallel shortening and perhaps pre-folding; dolerites within the sediments are moderately cleaved demonstrating coherent host rocks. Undoubtedly pore-fluid pressures were high during the regional deformation/metamorphism, but the mechanical effects of such a condition and the role of grain boundary sliding are poorly understood in well lithified rocks.

CONCLUSIONS

1. Clastic dikes in both areas described are clearly pretectonic as cleavage cuts the dikes at a wide range of angles, and several other lines of evidence support this contention.

2. In highly strained slates the geometry was only revealed by excellent natural three-dimensional exposures or extensive quarrying.

3. Strong convergence of dikes toward the cleavage during strain produces dikes that are largely sub-parallel to cleavage with only minor portions of the dikes at high-angles to cleavage. These latter orientations should not be regarded as anomalous, in fact they are key features but are rarely exposed, because they represent a small portion of total dike length. One of the more common orientations for natural exposures, the ac plane, is often the highest strain plane where most convergence has taken place.

4. A range of strain states down to low values is necessary to determine the early stages in a deformation history because high strain obliterates many delicate structures produced by incipient deformation.

5. A major problem with Borradaile's sand-dike test for coaxial deformation was revealed in that a natural population of variably oriented dikes with respect to bedding, when put through a simulated deformation process, produced a pattern very similar to that proposed for strained initially bedding-perpendicular dikes. In view of this problem it would seem that larger amounts of data should be required for the test and also that more geometrical data are needed on untectonized clastic dikes to allow further testing of the method. Very few data are available on the angular relations of dikes and bedding prior to deformation though it is known that dike patterns are very variable, for example, the rectangular dike arrays of Von Brunn and Hobday (1976) in comparison to the more normal polygonal patterns. Donovan and Archer (1975) record rectangular and polygonal types of dike traces on bedding from a single surface showing the complexity possible.

6. The apparent uncertainty in the sand-dike test requires a closer look at the evidence for grain boundary sliding in the production of fabrics in slaty terrains. The mechanical effects of high pore-fluid pressures must be very variable and for well lithified rocks are poorly known under metamorphic conditions.

7. Many clastic dikes were initially in polygonal arrays so that after deformation they will show a statistical symmetry about the XY plane of the strain ellipsoid, and, hence, such a relationship cannot be used to support the action of tectonic dewatering.

8. I support Geiser (1976) and Beutner (1980) in stating that there is no evidence that tectonic dewatering has played a significant role in the production of regional slaty cleavage.

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