Journal of Structural Geology, Vol. 6, No. 1/2, pp. 183 to 188, 1984
Printed in Great Britain

0191-8141/84 $03.00 + 0.00
Pergamon Press Ltd.

Fracture controlled feldspar shape fabrics in deformed quartzo-feldspathic rocks

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(*Accepted in revised form* 11 *July* 1983)

Abstract—The behaviour of feldspar in the brittle–ductile transition region has often been discussed in models dominated by mechanisms of extension fracturing. In this example, a small Caledonian granitic pluton from NW Ireland, feldspar shape changes are primarily accomplished by small displacements upon numerous shear fractures. These fractures developed as Riedel and anti-Riedel shears as the granite was synkinematically deformed in a regional shear zone. The deformation took place under greenschist facies conditions at strain rates estimated between 10^{-13} and 10^{-14} s^{-1}.

INTRODUCTION

THE DIFFERING rheological responses of the common rock-forming minerals mean that under certain conditions of pressure, temperature and strain rate some exhibit brittle and others ductile behaviour. Two minerals of strongly contrasting rheology are quartz and feldspar. Augen gneisses testify to the competent behaviour of feldspar during deformation over a wide range of geological environments. The brittle behaviour of feldspar has been discussed by Boullier (1980) who concluded that extension fracturing predominates in shear zones deformed under greenschist facies conditions (300–400°C). Mitra (1978) has developed models to account for extension fractures in both quartz and feldspar in ductile deformation zones. Wakefield (1977) described feldspars which have developed both extension and shear fractures under conditions estimated at epidote–amphibolite, falling to low-greenschist facies. Ductile deformation mechanisms in feldspar seem to begin to operate during amphibolite facies conditions (White 1975, Hamner 1982).

The purpose of this contribution is to emphasise the role of shear fracturing in feldspar during the deformation of quartz-feldspathic rocks under low-grade metamorphism conditions. Good examples of fractured microcline and plagioclase feldspar can be seen in the weakly deformed Easky Adamellite, part of the Ox Mountains Inlier, NW Ireland (Fig. 1). This small Caledonian pluton (Pankhurst *et al.* 1976) hornfelsed adjacent metasediments but whilst still cooling was encompassed in a dextral shear zone passing northeastwards through the metasediments (Andrews *et al.* 1978). The shear zone is strongly localized along a mylonite belt in the metasediments but is inhomogeneously distributed through the pluton. The displacement on the shear zone is transferred en échelon across the strike of the zone by a step of about 2 km perpendicular to the strike. A pull-apart at this position may indeed have originally permitted the plutonic intrusion. Shear strain increases in intensity across the pluton and reaches maximum values of $\gamma \sim 1$ (Fig. 1).

The shape fabric of the Easky Adamellite was determined by measuring lengths of quartz and feldspar grains or grain aggregates along a grid overlain on smoothed and etched cut surfaces (Fig. 2c). The strain was computed as the ratio of the average length of quartz/feldspar grains measured along principal strain axes, provided that a large enough number of measurements were made. The method provided data giving semi-quantitative (±20%) estimates of the strains, details of which will be published elsewhere. The transition from megascopically undeformed to relatively highly deformed rock is reflected by similar shape changes for both quartz and feldspars (Fig. 3). Quartz grain shape changes were accomplished by ductile deformation mechanisms. Feldspar exhibits brittle behaviour,

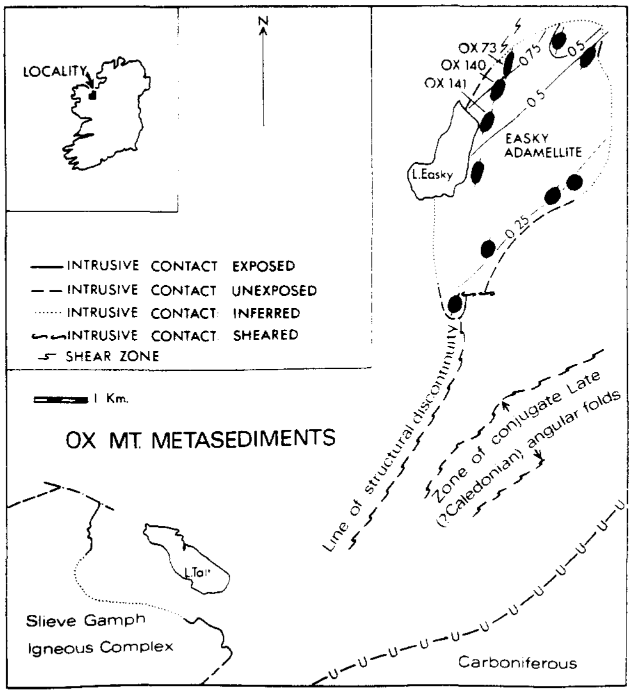

Fig. 1. Locations of specimens studied. Ellipses show the intersection of bulk strain ellipsoids with the ground giving X/Z sections. Deformation in the Easky Adamellite increases towards the northwest margin. Contours of γ at 0.25 intervals trend northeast. The line of structural discontinuity marks a mylonite belt in the host metasediments which passes into the adamellite.

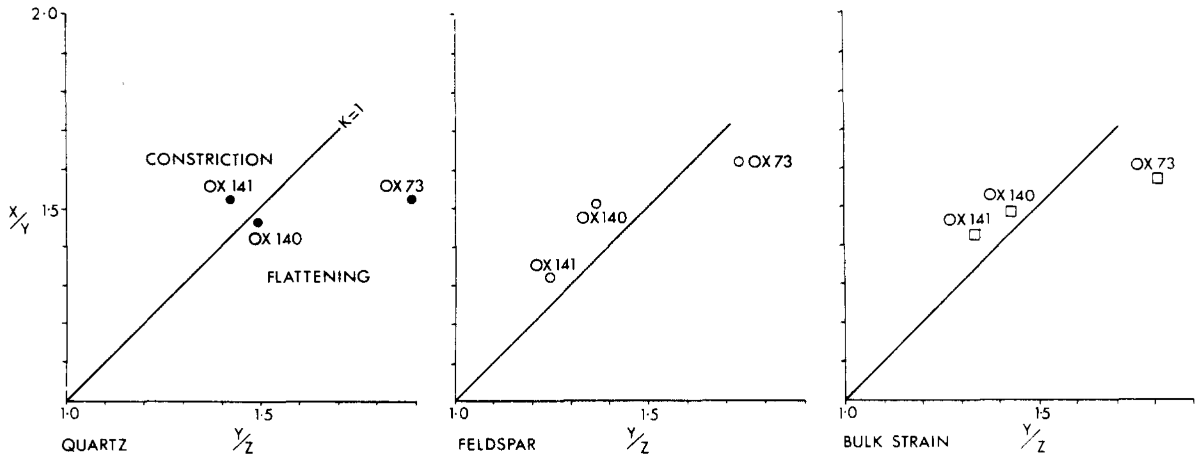

Fig. 3. Flinn plots of the shape fabric of quartz and feldspar grains for the three specimens (numbered) of Easky Adamellite studied in detail. Bulk strain is weighted average of quartz and feldspar shapes.

shape changes being achieved by the incremental sum of at least three processes. Most significant is cataclastic shearing, then separation of fragments via extension fractures and finally buckling perpendicular to the cleavages.

MICROSTRUCTURE

Feldspar

Petrographically, the granite is characterized by an interlocking quartz–oligoclase–microcline–biotite as semblage. Where undeformed, the grain sizes of quartz and oligoclase are similar with a tendency for the microcline to adopt a megacrystic habit. With increasing deformation it becomes possible to discern a vertical foliation and within the foliation, a horizontal stretching lineation. The feldspars retain their igneous petrographic characteristics but are fragmented by brittle fractures.

A systematic study of the fracturing was made using thin sections. Three oriented specimens exhibiting relatively large strains were selected (Fig. 2c). Sections were cut parallel to the principal planes of strain which were easily located by visual inspection. The orientations of the principal axes were transferred to the sections. Special care was taken to ensure that the correct sense of displacement across fractures was determined as mirror image reversals are easily obtained, either in the section-making process or via the petrological microscope. Fractures were observed along traverses using a micrometer stage. All fractures showing any offset and/or dilation were recorded. Only *XZ* principal plane sections showed a predominance of shear fractures. Extension fractures were observed in the *XY* plane. Shear fractures in *XY* and *YZ* showed little or no offset. In *XZ* the distribution of fractures shows a marked asymmetry (Fig. 4), dextral shears being about three times as numerous as both sinistral shears and extension fractures. Offsets are small, up to 500 μm. Many shear fractures are accompanied by dilation or pull-apart voids in which quartz has crystallized. The absence of any significant offsets in *XY* and *YZ* sections indicates that the dextral and sinistral shears form conjugate sets intersecting along the *Y* axis. The acute angle between the shears varies from 65 to 75°, tending to increase with increasing strain. The data for extension fracture orientation (Fig. 4) demonstrate that the modal values are, predictably, perpendicular to the *X* principal strain axis. Feldspars also change shape by microbuckling of the cleavages (Fig. 2a). In extreme cases, fold rotations in excess of 90° have been produced in zones with high local strain.

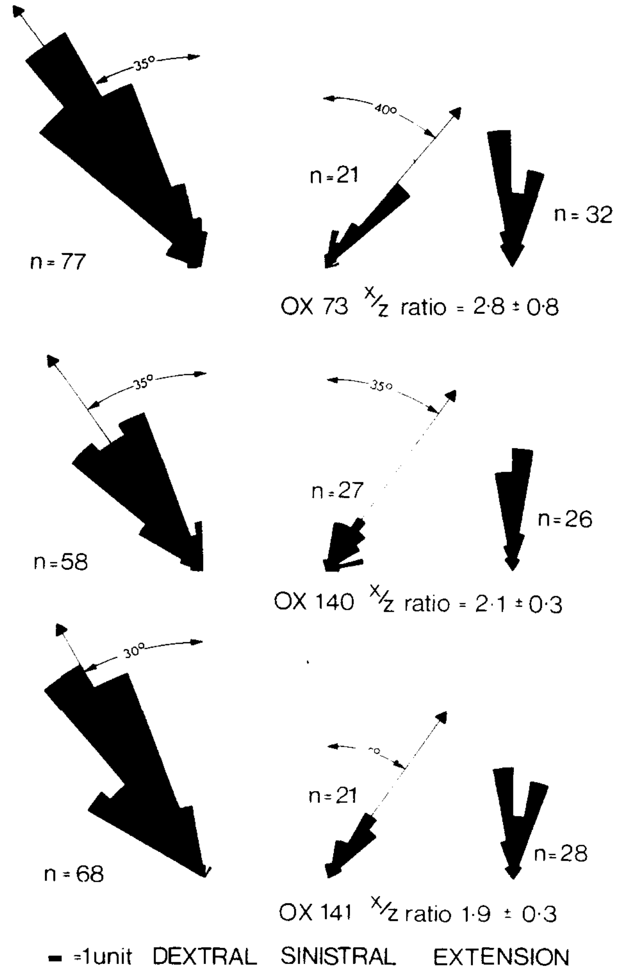

Fig. 4. Fracture pattern displayed by feldspars in three specimens of the Easky Adamellite. Dextral shears outnumber sinistral shears and extension fractures by about 3 : 1. *X*/*Z* ratios are bulk strain estimates.

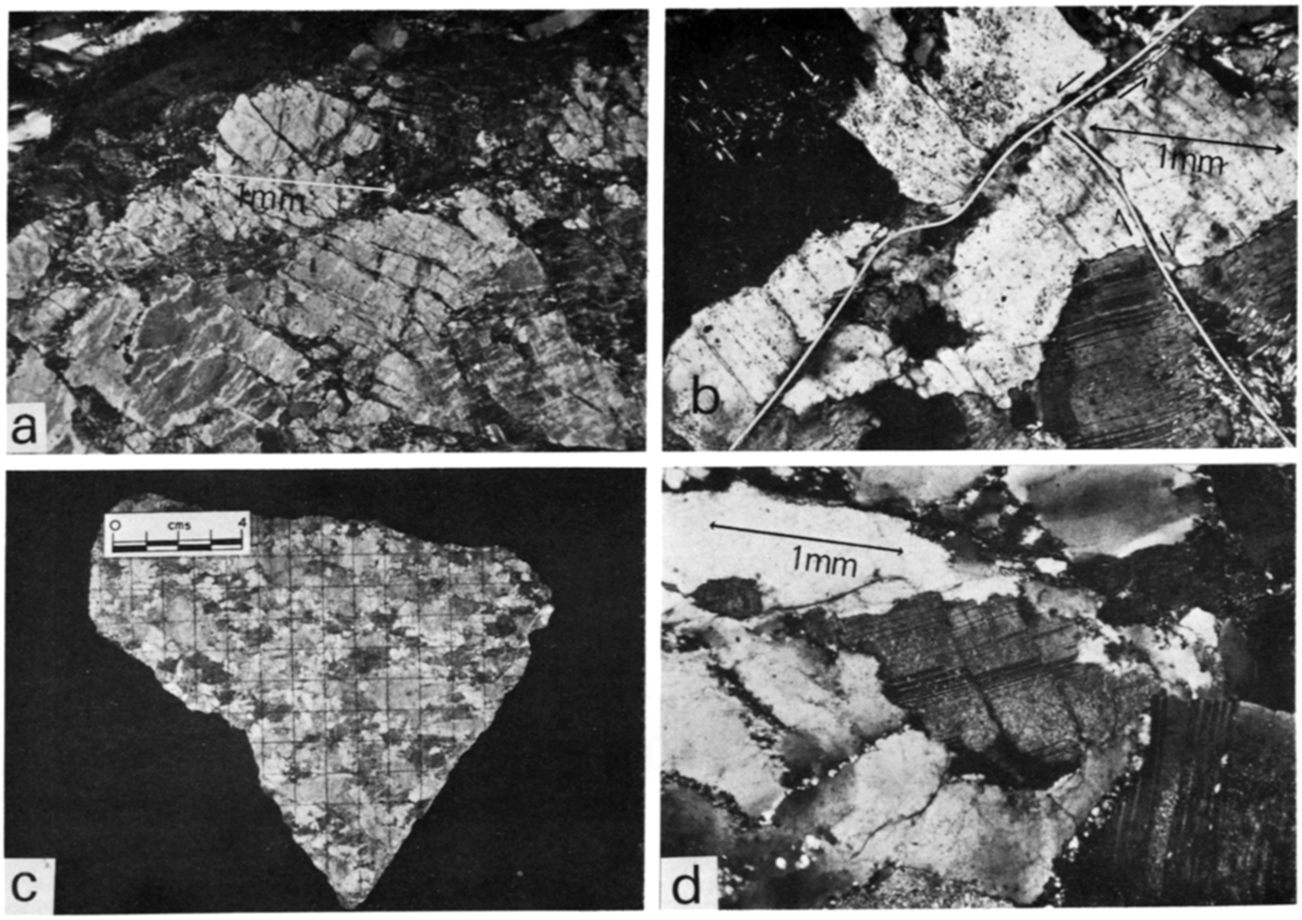

Fig. 2. Easky Adamellite (OX 141). Scale-bar parallel to extension direction. Photomicrographs are of *XZ* sections. (a) Feldspar displaying a characteristic pattern of close-spaced buckled dextral shears. Spaces between shears are infilled by quartz. (b) Feldspar displaying shears with both sinistral and dextral offsets. The dextral shears are inclined at 44° and the sinistral at 38° to the shortening direction. The dextral shear continues across a biotite crystal. (c) Etched *XY* surface of Easky Adamellite. Quartz and feldspar grain shapes and sizes are similar. Measurements were made upon this (OX 141) and two other specimens. (d) Feldspar affected by dextral shears inclined at 34° to the shortening direction. No trace of the shears is visible in the adjacent quartz grains, which have changed shape by ductile mechanisms. Quartz grains show strong undulose extinction and are beginning to recrystallize, especially along grain boundaries.

Quartz and mica

Ductile quartz deformation can be followed from almost undeformed to relatively highly deformed adamellite during which quartz grains of a similar grain size to feldspars undergo internal deformation and have just started to recrystallize (10–20%) to polygonal aggregates along grain boundaries (Fig. 2d). In the least deformed rocks evidence of internal strain is manifested by strong undulose extinction with deformation band and large subgrain development. At higher strains original grain shapes can still be distinguished, though the quartz now contains high dislocation densities manifested by subgrain recovery. Brittle fractures in feldspar do not continue across grain boundaries into quartz. Clearly the quartz was able to accommodate by ductile mechanisms the displacements of feldspar along shear fractures. As quartz is not fractured, offsets along shears were probably achieved by small increments of slip or slow creep during progressive deformation. Alternatively the quartz may have fractured, the fractures subsequently healing over during slower ductile deformation.

Biotite, more or less altered to chlorite, is severely disturbed by buckling and kinking of the 010 cleavage and is also transected by shear fractures (Fig. 2b). These occur both parallel and oblique to the cleavage. Occasional muscovite grains are seen with chlorite beards growing as pressure-shadow fibres. Some boudinaged apatites also developed chlorite fibre fringes.

FRACTURE PATTERN INTERPRETATION

The feldspar fracture orientation shows a precise relationship to the rock fabric. There are sharp modal peaks in the shear fracture distribution at 30–35° to the finite shortening direction (Fig. 4), that is at 55–60° to the trace of the foliation. The bimodal distribution represents conjugate sets of shears developed in response to local stresses assumed to be parallel to the principal strain axes. The preponderance of dextral offsets suggest an origin as Riedel and anti-Riedel shears (Hills 1972) developed within a dextral shear zone. Figure 3 shows the shape fabric of quartz and feldspar crystals in the specimens studied. Both lie close to a plane-strain deformation path assuming no volume loss. For a granite this is generally a valid assumption. Though some migration of quartz into fractures has taken place there is no sign of truncated quartz grains indicative of widespread pressure solution. If pressure solution was a significant quartz deformation mechanism the shapes of quartz and feldspar might be expected to evolve along different deformation paths. The shape fabric analysis suggests this has not happened.

The shape of the granite and the orientation of its internal fabric (Fig. 1) show it to have been deformed in a NE-trending dextral shear zone. The geographic orientation of the Riedel and anti-Riedel fractures in the feldspars is that which would be anticipated (Fig. 5) for secondary shear fractures. Because of their initial orientation during progressive deformation the subordinate sinistral shears will rotate towards the shear plane faster than the dextral set. This probably accounts for the increase in the acute angle between the shears from the initial 65 to 75° in the most highly deformed example (OX 73).

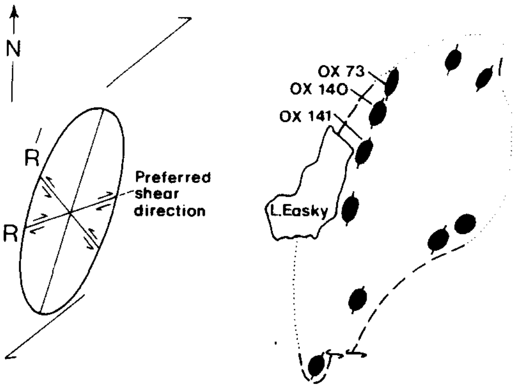

Fig. 5. Geographical relationship between the bulk strain ellipsoid (OX 73) and the modal values of shear fracture orientation determined in three specimens of the Easky Adamellite. The best fit for the dextral shear orientation was determined from the inclination of long axes of the bulk strain ellipses. R, Riedel shears; R', anti-Riedel shears.

DISCUSSION

The brittle behaviour displayed by feldspar in the Easky Adamellite corresponds very closely to that described in feldspars in the Lethakane shear zone (Wakefield 1977, cf. plate 1C). Wakefield ascribed conjugate shears in feldspar to failure under constantly directed regional stress with subsequent displacement on antithetic shears tending to counter rotational forces exerted by the matrix. The explanation was advanced to account for a preponderance of antithetic shears. In the Easky Adamellite it is the synthetic shears which predominate, suggesting the Riedel shear model.

Brittle deformation of hornblende porphyroclasts (Allison & Latour 1977) shows some similarities to the pattern of fractures in the Easky Adamellite. Allison & Latour (1977) drew an analogy between displacement in hornblendes along cleavages and ductile deformation by translation gliding. Though slip upon favourably oriented cleavages is often utilized in the feldspar, it is not uncommon to see fractures transecting the cleavages, emphasising the brittleness of the feldspar behaviour.

The metamorphic conditions under which feldspar behaves in a brittle fashion are primarily encompassed by the greenschist facies (Boullier 1980, Wakefield 1977). Petrographic evidence from the Easky Adamellite also indicates greenschist facies conditions during the deformation. Biotite is sometimes but not always altered to chlorite. Chlorite, sericite and epidote frequently develop in or peripheral to shear fractures. Chlorite fibres form fracture infillings between apatite, and beards in pressure shadows around muscovite.

Despite a careful search, none of the features of ductile feldspar behaviour (Hamner 1982) characteristic of higher temperature amphibolite-facies conditions have been seen.

An estimate of the order of magnitude of the strain rate may be made by assuming that deformation took place whilst the Easky Adamellite cooled through the greenschist facies temperature range (about 500–350°C, Winkler 1979). The time taken for the centre of the pluton to cool through this range (117,000 years) has been computed from Jaeger (1957, p. 311, fig. 1). This assumes a planar infinite granite sheet 3 km wide. The margins meanwhile will have cooled to the slightly lower temperature of 310°C. Integration of shear strain across the pluton using the method of Ramsay & Graham (1970) gives about 2 km of dextral offset. If the granite was deformed continuously the bulk strain rate would be about $7 \times 10^{-14}\ \mathrm{s}^{-1}$. At the more intensely deformed northwestern margin, higher strain rates up to an estimated maximum of $2 \times 10^{-13}\ \mathrm{s}^{-1}$ would have occurred. These rates are underestimates as the granite is of finite extent laterally and probably vertically, and would have cooled more rapidly than the model supposes. Little is known about the dependence of the brittle behaviour of feldspars upon strain rate. It seems likely that at greenschist facies temperatures, brittle behaviour is characteristic over a wide range of strain rates as fractured feldspars seem to be relatively common in granitic rocks deformed under these conditions.

The data presented above suggest that the relative importance of the roles of shear fracturing and extension fracturing during relatively low temperature deformation need reassessing. Shear fractures are four times more common than extension fractures in feldspars in the Easky Adamellite. Subsequently some of the shear fractures have dilated to allow migration of quartz into the voids. It seems likely that the contribution of shear fracturing in the brittle behaviour of feldspar has been underestimated during previous studies (e.g. Boullier 1980), perhaps because some shear fractures undergoing subsequent dilation have been interpreted as extension fractures. In the Easky Adamellite fibre loading (White *et al.* 1980) may be the cause of some extension fracturing as some feldspars are clearly broken into fragments of lower aspect ratio. Nevertheless shear fracturing is clearly the dominant feldspar deformation process.

Acknowledgements—The author would like to thank J. Green for carrying out preliminary studies. Initial field work was supported by University College, Dublin.

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