CONFIRMATION OF THE PRE-CLEAVAGE EMPLACEMENT OF BOTH THE NORTHERN AND SOUTHERN DIORITES INTO THE CHARNIAN SUPERGROUP

by

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Summary

The Northern and Southern Diorites are intruded into the Charnian Supergroup and their petrographic similarities suggest that they could be essentially coeval. However, previous investigations based on field mapping have generated a variety of opinions on their relative age and on their relationship to structures in the host rock. This paper records, in both sets of intrusions, narrow zones of cleavage (ductile shear zones) separated by domains of virtually unstrained diorite. The ductile shear zones, which are locally mylonitic, are sub-parallel to the slaty cleavage in the host Charnian and the intrusions, therefore, pre-date the main tectonic event in the district. Further confirmation of this timing is seen in the deformation of the contact metamorphic minerals around the Northern Diorites at Longcliffe. Post-Caledonian Rb/Sr whole rock ages on the Northern Diorites can not, therefore, relate to their emplacement particularly as metamorphic evidence points to a Precambrian age for the cleavage.

Introduction

Diorites intruded into the Charnian Supergroup (Fig. 1) show two distinct geographical groupings (Northern and Southern) which also differ in degree of alteration, form of intrusion, and to some extent texturally and mineralogically. A variety of opinions have been expressed in the literature concerning their relative ages and their timing with respect to the one regional cleavage event. Petrographically the two groups are similar and have been thought of as related intrusions (e.g. Wills and Shotton, 1934; Le Bas, 1982). Watts (1947) stated that the Northern Diorites are less affected by regional deformation than the Southern Diorites and were, therefore, considered to be younger. He noted zones of "foliation and cleavage" in the Southern Diorites but interpreted the Northern Diorites as having been intruded along post-cleavage faults. In contrast, Jones (1927) claimed that both groups of intrusions had been through the same number of fracturing episodes and that both pre-dated the regional cleavage. Unfortunately key steps in the argument for the latter conclusion were not given and the basis for the claim is not proven. Also Jones presented no data from the Northern Diorites but in a later paper (Bennett *et al.* 1928) he noted that the Southern Diorites are "conspicuously less crushed" than the Northern Diorites as exposed at Longcliffe, presumably a reference to fault breccias. He also commented that all the diorites (and the Mountsorrel granodiorite) contain "zones of rotten rock" parallel to the cleavage in the country rock. The 1928 account refers to cleavage in the diorites and, though it is certain that this included the Southern Diorites, the reference does not make it clear if the comment applies to the Northern intrusions. Lowe (in Bennett *et al.*, 1928) observed that the Northern Diorites are more altered than the Southern counterparts, and this led him to suggest a reversal of the relative ages proposed by Watts.

Indirect evidence from Nuneaton strongly supports a Precambrian age for both the Northern and Southern Diorites. Wills and Shotton (1934) documented at Boon's Quarry, Nuneaton, a Lower Cambrian quartzite resting with angular unconformity over a volcanogenic sequence intruded by diorites very similar to the Charnian examples. Their detailed petrography showed that the Nuneaton diorites are closest in character to the Northern Diorites and in summary stated that the Charnwood diorites "can now indisputably be regarded as Precambrian". Later K/Ar work (Meneisy and Miller, 1963) supported this view by recording oldest ages of 684±29 Ma from Charnian volcanic rocks and 547±24 Ma from the Southern Diorites. Of interest in this work is the two clusters around the times of the Caledonian and Hercynian orogenies. Also the Northern Diorites gave young ages between 260 and 276 Ma though the associated contact metamorphic rocks show a mean age of 342 Ma. The data demonstrate several episodes of variable argon loss related to deformation and thermal effects. One of the most

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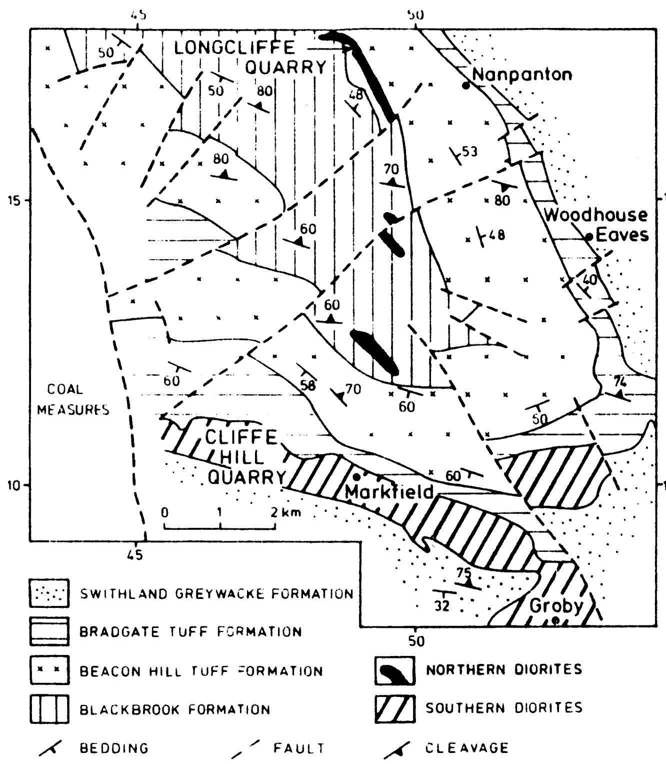

Fig. 1. Location and Regional geological map of the Charnwood district showing the position of Loncliffe and Cliffe Hill Quarries. Modified from Worssam and Old (in press).

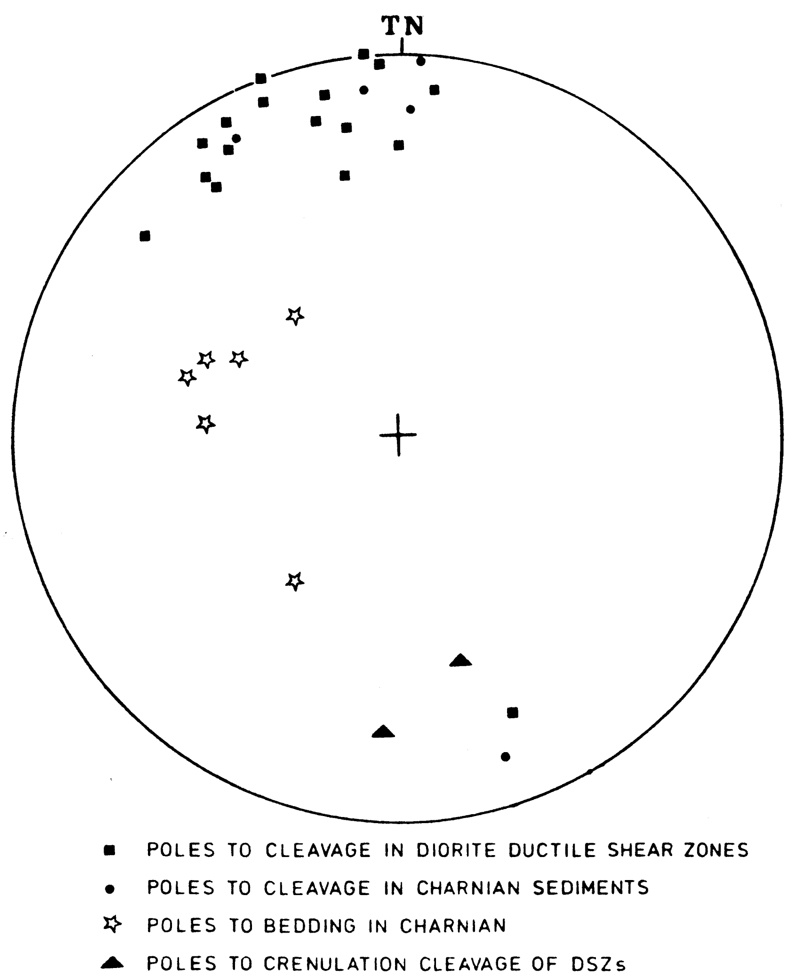

Fig. 2. Lower hemisphere, equal-area projection of structural data from Longcliffe Quarry.

significant disturbances to the isotopic systems appears to have been the Triassic mineralisation episode; Moseley (1979) reported the work of R.J. King who dated clay gouge in a galena + bornite vein from Newhurst Quarry at 232±7 Ma. Though the K/Ar geochronometry did not provide new evidence on the relative age of the Northern and Southern Diorites, nor demonstrate the Precambrian timing of the Northern Diorites, Meneisy and Miller appear to have followed the geological history outlined by Watts. In their summary table they placed the Southern Diorites intrusion at 680 Ma followed by Charnian cleavage and then, still in the Precambrian intrusion of Northern Diorites.

Unfortunately the Precambrian rocks at Nuneaton are not cleaved and hence there is no stratigraphic indication for the age of the Charnian cleavage. The lack of cleavage at Nuneaton is shown by a layer of accretionary lapilli in the Precambrian at Boon's Quarry which displays a compaction-fabric parallel to the bedding and no tectonic overprint is visible. Evans (1979) made a case for the Charnwood district cleavage being Caledonian but the evidence is circumstantial and leaves open the possibility of an older age. The cleavage in the Charnian is certainly no younger than Caledonian and, although the three-plate model for the British Caledonides has introduced uncertainty for the timing of suturing and major deformation in Eastern England, evidence from Poland and Germany shows it to be an early Devonian event (Soper and Hutton, 1984). Moseley (1979) discussed the presence of cleaved Cambrian sedimentary rocks close to Charnwood (Rotherwood borehole, 9 km west of Whitwick, and Merry Lees Colliery, Desford) and took this to imply that the Charnian cleavage was post-Cambrian. As a consequence of this inference he stated that "the cleavage may be later than the Southern Diorites" though he also stated (p. 317, p. 323) on structural grounds that they were post-cleavage. Metamorphic studies in progress (Merriman and Pharaoh, pers. comm.) are providing the clearest indication of the Charnian cleavage age. The Cambrian sediments close to Charnwood have a much lower metamorphic grade than the Charnian greenschist assemblages strongly suggesting the existence of a distinct Late Proterozoic tectonic event associated with cleavage generation.

In view of the above evidence it is surprising that Rb/Sr whole rock methods gave very different radiometric dates for the Northern and Southern Diorites (Cribb, 1975). Particularly an Hercynian age of 304±90 Ma (latest decay constants) for the Northern Diorites is difficult to accept. The 540±47 Ma intrusive age for the Southern Diorites is much more reasonable especially considering the present uncertainties surrounding the chronometric age of the base of the Cambrian. A K/Ar age of 547±24 Ma on the Southern Diorite can be regarded as a minimum estimate for the intrusive event. Considering the weight of combined evidene, the Rb/Sr data appears to have had undue influence particularly in view of the method's reputation of being susceptible to resetting by relatively minor events (e.g. Field and Raheim, 1979). Cribb (1975) clearly believed the isochrons on the diorites to be meaningful intrusion ages and that the Northern Diorites are much younger than the southern Diorite. Because Cribb considered that "the relationship of the Northern Diorites to the faulting appears firmly established" he, therefore, concluded that the faults were much younger than previously thought.

The above discussion indicates that the structural state of the diorites needs clarification. Because several authors (Watts, 1947; Jones, 1927) have recorded cleavage in the Southern Diorites, the present work has concentrated on the Northern Diorites. A simple test to determine the tectonic timing of emplacement is to establish whether contact metamorphism associated with their intrusion pre- or post-dates the regional cleavage. The results of such an investigation are reported here.

Structural Geology of the Northern Diorites and Immediate Country Rock

The Longcliffe Quarry (SK 4917) Fig.1 provides extensive exposures of both Northern Diorite and Charnian country rock. The diorite is essentially an elongate body trending NNW sub-parallel to the strike of bedding in the Charnian sediments at the scale of the quarry. Towards the southern end of the quarry, a significant upright fault striking nearly E/W has generated 50 m of sinistral strike separation of the intrusion boundary. Most of the diorite—sediment contacts are faulted but some intact intrusive boundaries are preserved. The diorite intruded a portion of the Charnian relatively rich in fine-grained beds and the resultant contact metamorphism has generated some visually striking spotted slates. In hand specimen the spots are green and the majority appear to be approximately ellipsoidal in shape averaging 3 mm in their longest dimension. The ellipsoids show a very strong preferred orientation in the rock cleavage. The latter is a strong fabric even in freshly exposed quarry faces within metres of an intrusive contact, reflecting the very fine-grained nature of the protolith. On surfaces cut parallel to the cleavage the elliptical outlines of the spots show a good preferred orientation which is close to the dip direction of the steeply inclined fabric.

Thin section examination (Plate 15A) shows the spots to be concentrations of chlorite and white mica with a pronounced enrichment of chlorite as a selvage to each spot. The slaty cleavage at this scale of observation is seen to be spaced at intervals around 0.01 mm. Of considerable significance is that both the chlorite and white mica components of the spots are strongly aligned in the rock cleavage (Plate 15A). Both minerals occur as rectangular grains with high aspect ratios and presumably are tabular in three-dimensions.

The diorite is cut by a series of narrow (10 cm to 1.5 m) foliated zones of localised ductile deformation (*ductile shear zones*) separated by 2 to 10 m intervals (*lithons*) of igneous textured diorite with no detectable tectonic fabric. Average ductile shear zone (DSZ) spacing is about 5 m. Most of the DSZs are near planar but branching curved examples do occur. Some curvature may be attributed to a later deformation which has folded pre-existing DSZs and crenulated their internal fabrics. However, most observed curvature of the DSZs is initial. Cleavage within the DSZs varies considerably in intensity from zone to zone and also within individual zones. One unusual aspect of these DSZs is that the orientation of the fabric within single zones remains virtually constant even though fabric intensity may be very variable. The fabric also is sub-parallel to the local zone boundary and hence the orientation data on cleavage in the diorite fairly closely reflects the range of attitudes of the DSZ boundaries (Fig. 2). Some imprecision has to be attached to the above comments because many DSZs have gradational boundaries where the cleavage intensity decreases and hence their margins are not sharply defined. Figure 2 also shows the overlap between orientations of cleavage in the diorite DSZs and slaty cleavage in the country rock.

Between the DSZs the diorite is virtually unstrained and igneous textures are well preserved though alteration is commonly well advanced. Within these lithons deformation is limited to the formation of quartz-carbonate-chlorite veins. One prominent set of veins is approximately horizontal with an internal structure defined by fibres of quartz and carbonate (Plate 15B) sub-perpendicular to the fibre walls (therefore, nearly vertically plunging). The fibres contain abundant fluid inclusions which are commonly arranged in planar arrays at high angles to the length of each fibre. These veins show a spatial association with the DSZs being best developed within 2 m of the foliated domains. Several other fibre textured veins occur in the lithons typically containing compound internal fabrics. Most of the vein sets have representatives that show fibres at high angles to the walls for part of their width together with highly foliated portions. The boundaries between these sections typically follow the vein margins. Thin section analysis shows that the foliated zones were derived from the fibre domains by localised high strain. The other alternative was that the fibre portion represented a tensional reactivation of an already foliated vein but the overprinting evidence clearly shows that the first interpretation is correct. Other vein sets have all their fibres at low angles to the vein walls. These could either be shear-veins where the fibres grew following an oblique opening direction or they could represent more uniformly strained fibrous veins such that all fibres have been skewed from the original high-angle to the vein walls. Both categories probably are present but detailed work is required for satisfactory discrimination.

Several vein styles occur within the DSZs displaying a wide range of strain states. Many are parallel or sub-parallel to the cleavage in the zones. These range from unstrained with sub-horizontal fibres to totally recrystallised high-strain examples (Plate 16A), which have mylonitic textures. A minor vein style is found as short segments (5–10 cm) running at high angles to cleavage and sharply truncated at cleavage planes. This type shows no sign of recrystallisation or other strain related features.

Cleavage intensity in diorite within the DSZs is best monitored in thin section by measuring the axial ratios of the opaque grains. In the igneous textured diorite the opaque minerals are largely ilmenite but within the cleaved domains it is transformed to leucoxene. Similarly grains that were once pyroxene become aggregates of small chlorite flakes in the DSZs. Weakly cleaved diorite shows a general alignment of plagioclase laths. Around plagioclase phenocrysts, in low strain examples, the matrix has commonly pulled away from the large grains and generated a fringe of carbonate fibres parallel to the rock cleavage. The same texture occurs within aggregates of phenocrysts where members of a cluster have been separated and the gap filled by carbonate fibres. At such low strains the opaque grains are virtually unaffected remaining approximately equant but at intermediate strains their axial ratios reflect the strain. Plate 16B shows highly strained diorite where the opaques have axial ratios in the highest strain section of around 10 to 1. In the field this is a very fissile rock which has lost all of its igneous texture.

One DSZ, 4 m into the diorite from an intrusive contact, contained compound fabrics. The general cleavage varied from weak to moderate in intensity. At an angle of 25° to the main cleavage, a series of narrow zones (maximum 5 mm in width) of intense cleavage abruptly truncate the overall fabric. These are probably C-planes in the terminology of Lister and Snoke (1984). C-planes typically represent zones of intense shear strain sub-parallel to the boundaries of a DSZ. The oblique, more general fabric, is the result of heterogeneous simple shear within the body of the deforming zone. Unfortunately, the nature of the exposure did not allow definition of the shape of the DSZ.

The deformed DSZs noted earlier have been folded by a distinct later but minor event which has affected the margins of some DSZs and their internal fabric. This superimposed event generated a crenulation cleavage within the already cleaved diorite and a sub-horizontal crenulation lineation on the early cleavage planes. The crenulation cleavage strikes around 100° and dips between 50 and 65° to the north. This is a very weak event which contributes virtually nothing to the bulk regional strain, and in view of the metamorphic evidence suggesting the main deformation is Precambrian, could be an expression of Caledonian deformation.

Structural Geology of the Southern Diorites and Immediate Country Rock

Previous workers have commented on the tectonised condition of the Southern Diorites. The clearest statement is found in Worssam and Old (in press) who describe schistose textures and shear zones up to 25 m in width. Though not specified, it seems they were referring to a ductile shear zone rather than a brittle one. Other references in the memoir to 'shearing' are not particularly helpful as it is unclear whether they are discussing shear fractures or zones of cleavage development. However, the pre-cleavage age of the Southern Diorites is well documented.

The somewhat more advanced weathering in the quarries at Newton Linford (e.g. SK5108) allowed better definition of DSZ shape and internal fabric patterns. One example showed well developed C-planes (80/092 right-hand-rule) sub-parallel to the zone margin. A moderate to strong S-fabric (62/076) runs obliquely through the zone and contains a mineral lineation on the cleavage planes. The lineation plunges towards 357° demonstrating that the zone evolved by north-block-down motion relative to the south block. Because the S-surfaces curve into and out of the C-planes, these S-C tectonites are easily classified as being Type 1 following Lister and Snoke (1984).

At Cliffe Hill Quarry (SK4710), (Fig. 1) cleavage in the diorites is much more restricted. It occurs in widely separated zones commonly a few 10s of centimetres wide. These zones dip between 20 and 40° due north but, as the entire quarry was not surveyed, upright DSZs as seen elsewhere may be present. Intact intrusive boundaries occur at Cliffe Hill and extensive metasomatic activity is obvious in the Charnian country rocks. However cleaved sediments were not found in the contact aureole and hence it was impossible to study the textural relations between contact minerals and deformation fabrics.

Discussion and Conclusion

The presence of highly cleaved zones in both the Northern and Southern diorites, sub-parallel to slaty cleavage in the Charnian Supergroup, clearly demonstrates their pre-cleavage emplacement. For the Northern Diorites unequivocal evidence is also provided by the deformation of the contact metamorphic minerals. The alignment of the spots could be a mimetic texture where post-cleavage growth was controlled by the fabric heterogeneity. That this is not the case is shown in thin section (Plate 15A) where all the contact minerals are deformed by the cleavage event; a simple test for pre-tectonic intrusion.

A block of well cleaved spotted slate was cut parallel to the cleavage (approx equal to XY plane tectonic strain ellipsoid) and the elongation lineation define by the spots was located (X direction where X>Y>Z). Two sections perpendicular to the cleavage were also cut, one containing the lineation (XZ) and the other perpendicular to the spot long axes (YZ). Many spots are rhomboidal in shape with longest edges oriented near the bedding plane and with the longest diagonal skewed towards the cleavage. These are taken to be spots whose growth was controlled by the compositional anisotropy of the sedimentary layering and modified in orientation by the tectonic strain. Less than 20% of the spots are regular ellipsoids in shape and these were measured in each principal plane of the tectonic strain ellipsoid. These spots must have been sub-spherical post-contact metamorphism and pre-tectonism, hence the contact metamorphic event introduced into the rock regularly shaped strain markers after the compaction transformations which probably were considerable in such a pelitic rock. The 3-D strain state indicates that the X dimension has been extended by 105%, the Z direction shortened by 48%, and that Y has barely changed at 4% shortening; this is very close to plane strain. This strain symmetry may reflect bulk plane strain on the regional scale or it could have been produced by flexural flow during folding localised in incompetent beds.

As determined by Jones (1927), the diorites have been through several fracturing events. Some of the vein sets in the Northern Diorite at Longcliffe either pre-date the DSZs or were initiated early in the evolution of these zones. The early veins include the totally recrystallised veins within the DSZs and the partly mylonitised examples in the lithons. The steeply plunging longest dimension of the ellipsoidal spots shows this to be the maximum stretching direction during the cleavage forming event; a common situation in very-low grade metamorphic rocks. Such an elongation orientation probably was responsible for the sub-horizontal fibre veins adjacent to the DSZs. The quartz fibres are traversed at high angles by abundant arrays of fluid inclusions and an origin by cyclic crack-seal (Ramsay, 1980) seems likely with the several centimetre thick veins having undergone 100s to 1000s of such cycles. Fluid-pressure gradients established at each microcrack event provide a considerable driving force to move fluids through even 'tight' igneous rocks thus accounting for the altered state of the Northern Diorites. The K/Ar studies clearly show several episodes of disturbances to the isotopic systems and it seems likely that the network of foliated zones and vein arrays assisted fluid flow in these later events. Careful sampling of a variety of deformation states from the diorites linked to further isotopic work might help to define the structural parameters influencing perturbation to isotopic systems.

An understanding of the dynamics of the ductile shear zones must await a more detailed study. Some zones appear to be fairy straightforward concentrations of heterogeneous simple shear. Others (e.g. Longcliffe) may have nucleated on dilatant fractures (Segall and Simpson, 1986). Also the role of volume changes in their evolution needs to be assessed both structurally and geochemically. The above features need to be studied before the likely propagation mode of the DSZs into the Charnian country rock may be assessed. Some Post-Triassic faults have been localised along diorite DSZs but separations recorded to date are only on the metric to decametric scale.

Acknowledgments

A study of this type is entirely dependent on gaining access to quarries. Messrs D.F. Campbell and S. Jones of ARC, Shepshed and Mr D. Smith of Tarmac, Cliffe Hill, proved extremely generous in the assistance they provided. Discussions with R. Stanczyszyn, geologist ARC, were useful at the start of the project.

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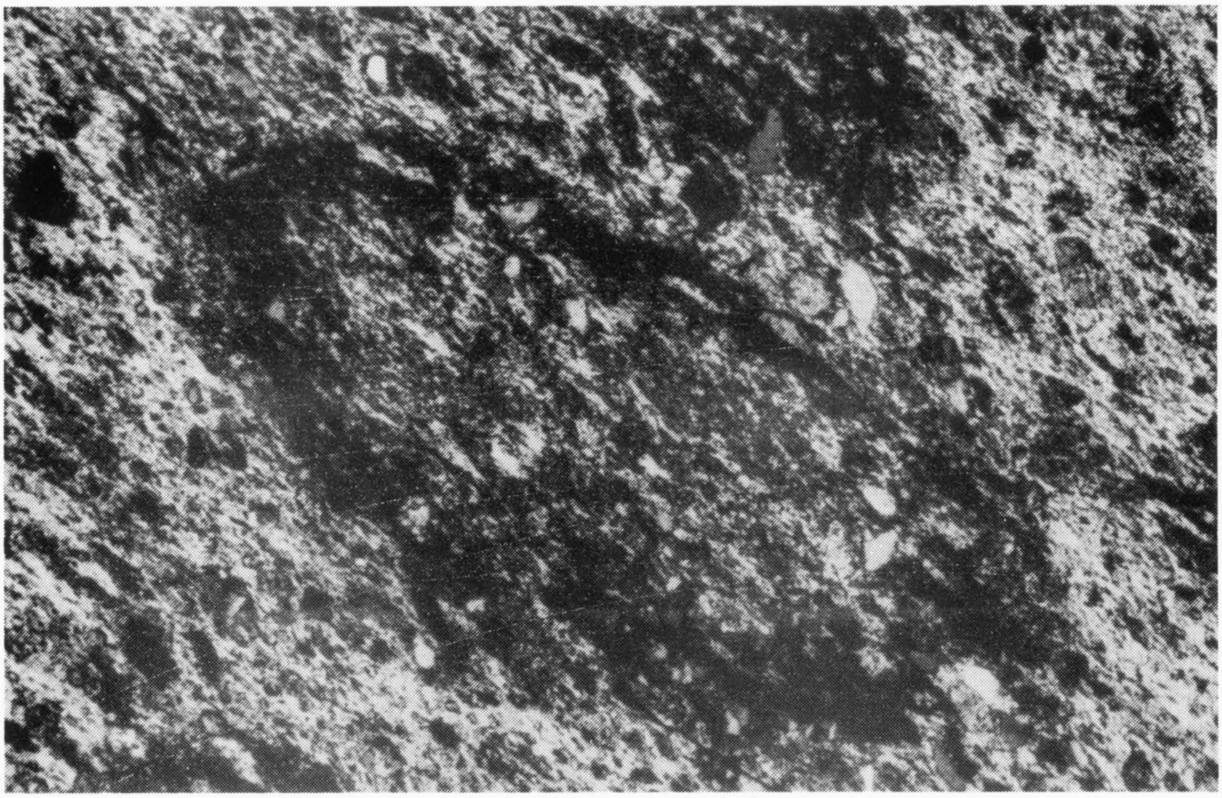

Plate 15A. Photomicrograph (crossed polars) of a contact metamorphic chlorite + white mica spot. All the mineral components of the spot are aligned in the rock cleavage as is the overall shape of the spot. The contact metamorphism is pre-cleavage. Longcliffe Quarry, field of view 2.0 mm.

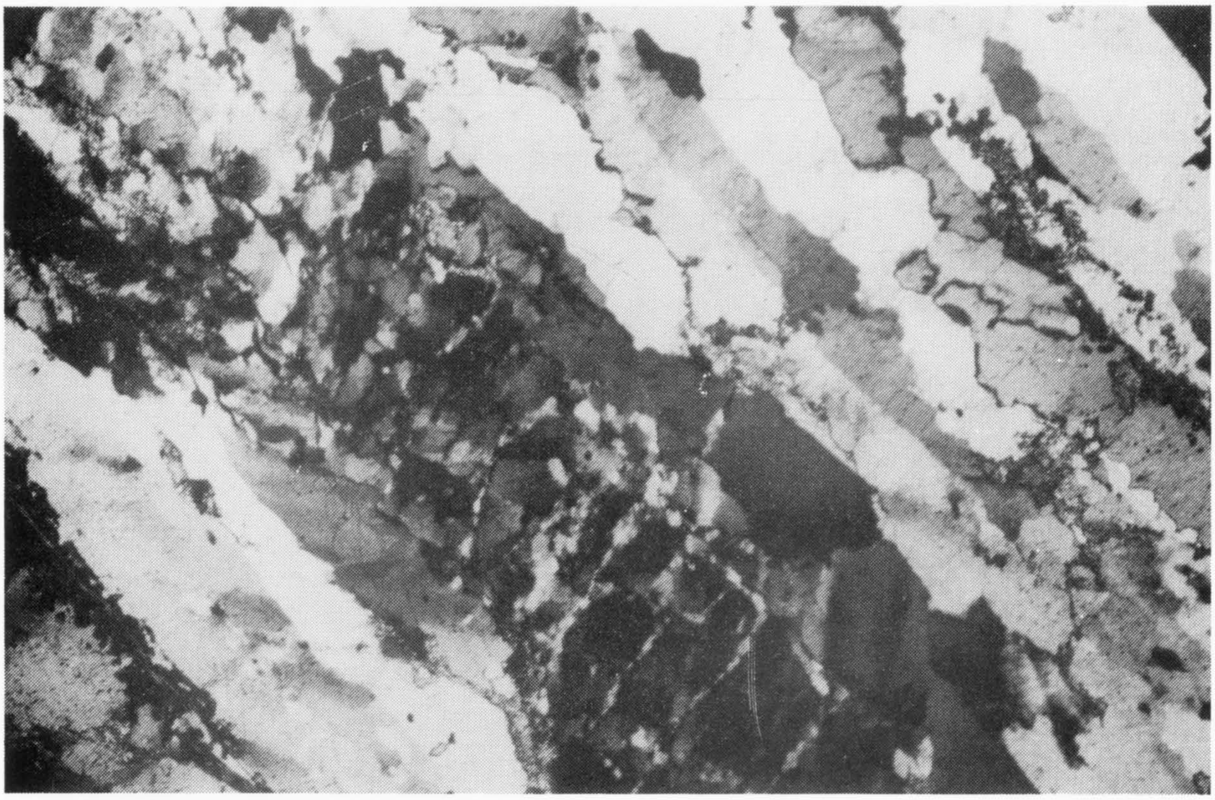

Plate 15B. Photomicrograph (crossed polars) of quartz fibres showing some strain induced recrystallisation. Fluid inclusion arrays trend at high angles to the length of the fibres. Longcliffe Quarry, field of view 3.5 mm.

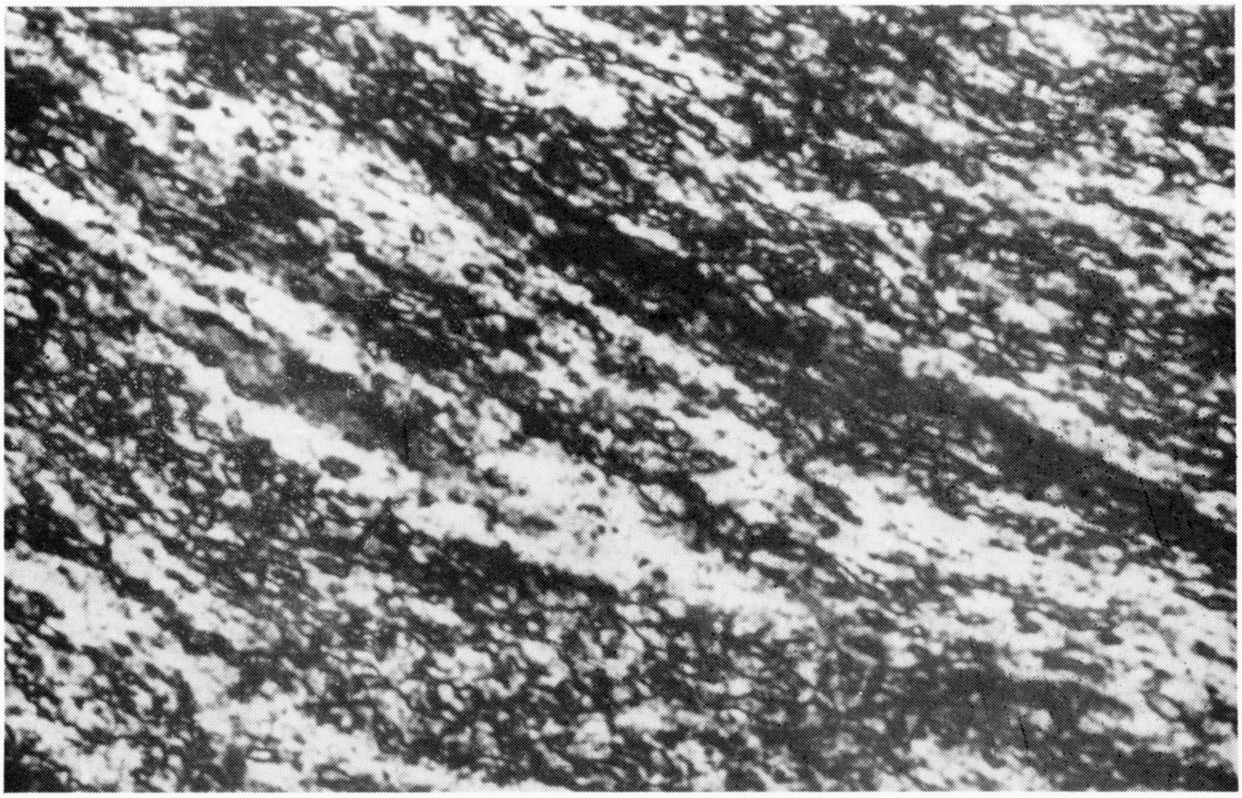

Plate 16A. Photomicrograph (crossed polars) showing intense recrystallisation of a quartz rich vein within a ductile shear zone to create a mylonitic style fabric. Longcliffe Quarry, field of view 0.7 mm.

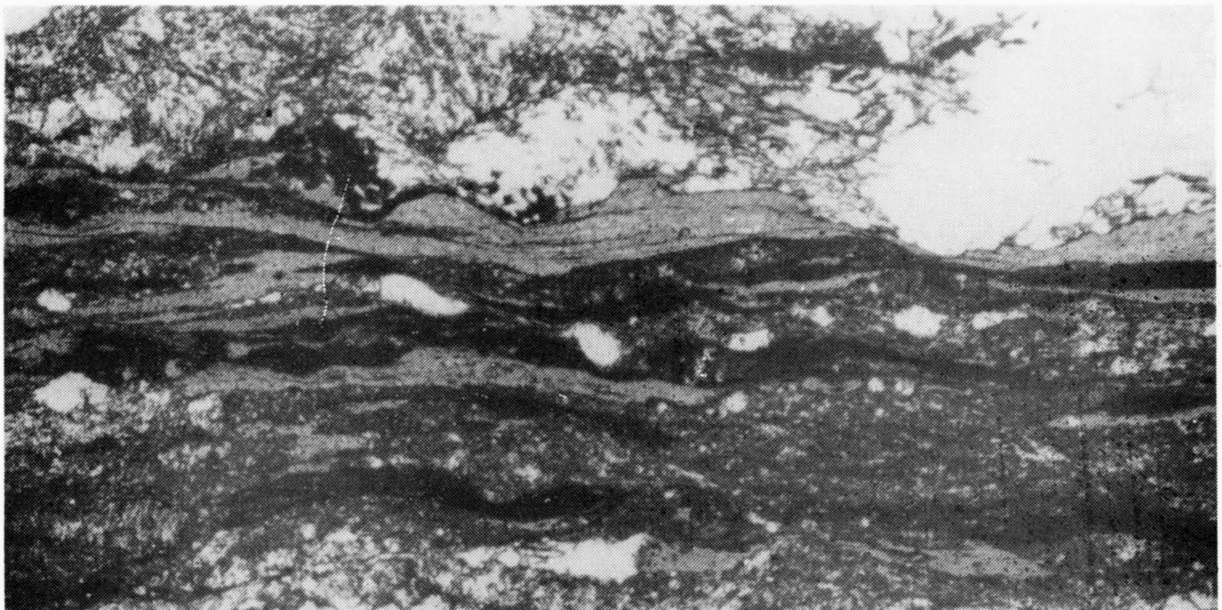

Plate 16B. Photomicrograph (plane polarised light) of very highly strained diorite. Once near equant ilmenite grains are now showing axial ratios around 10 to 1. Longcliffe Quarry, field of view 3.5 mm.