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A preliminary study on the behaviour of brittle minerals in a ductile matrix: example of zircons and feldspars

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Abstract—The evolution of structures has been studied in mylonitic quartzo-feldspathic rocks across a shear zone in Adrar des Iforas (Republic of Mali). Particular attention has been paid to the brittle behaviour of zircon and mesoperthitic feldspar. The size of these minerals decreases towards the centre of the shear zone but attains an equilibrium size. The grain shapes do not show any strong evolution. The significance of grain size decrease is discussed from a metallurgical point of view. The size of brittle minerals seems to be independent of finite strain but dependent on stress.

Resumé—Nous avons étudié l'évolution structurale de mylonites quartzo-feldspathiques dans une zone de cisaillement en Adrar des Iforas (République du Mali). Une attention particulière a été portée à l'étude du comportement fragile des zircons et des feldspaths mesoperthitiques. La taille de ces miné raux décroit vers le centre de la zone de cisaillement, mais atteint une taille equilibre. Le rapport de forme des minéraux ne montre pas d'évolution particulière. La signification de la diminution de la taille de grain est discutée à la lumière de quelques travaux en métallurgie. La taille des grains fragiles semble être indépendante de la quantité de déformation finie mais dépendante de la contrainte.

INTRODUCTION

Two DIFFERENT mechanisms of deformation in shear zones are expressed by two different kinds of fault rocks (Sibson 1977). The first group represents the cataclastic rocks which show no fabric and have an elastico-frictional behaviour. The second group corresponds to mylonites which have a quasi-plastic behaviour. The microstructural characteristics of plastically deformed minerals in the mylonites have been used by some authors to determine the physical parameters of the deformation. In fact, different minerals can behave differently in polyminerallic rocks. This has been described, for example, in alpine peridotites by Nicolas *et al.* (1971), where olivine is plastically deformed but enstatite is pulled apart. This is generally also the case in quartzo-feldspathic mylonites in which feldspar is comminuted in a ductile matrix of quartz and mica. In this work, we are concerned with quartzo-feldspathic mylonites in which the feldspar and zircon grains exhibit brittle behaviour but the quartz matrix has behaved ductily. The feldspars and zircons show a variation of grain size which could be dependent on the deformation parameters.

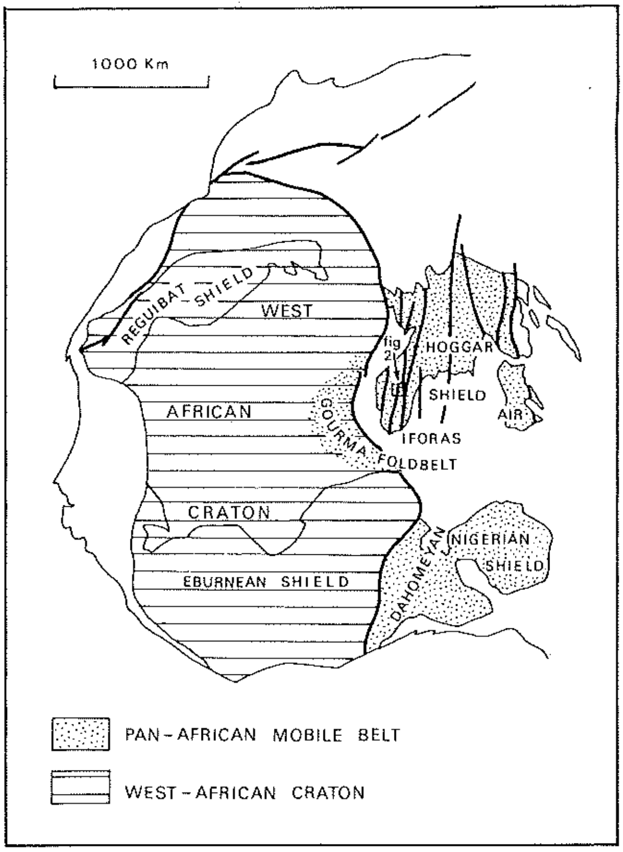

Fig. 1. Location of the studied shear zone in the Pan-African belt.

GEOLOGICAL SETTING

A shear zone in the Pan-African mobile belt of Iforas (Republic of Mali) has been studied. The shear zone (see Fig. 1) is tentatively interpreted as a strike-slip fault due to the collision between the West African Craton and an eastern continent (Black *et al.* 1979, Bertrand *et al.* 1980). It is a very straight lineament trending 010°, approximately 300 km long and readily visible on ERTS photographs. This shear zone separates two different blocks (Fig. 2): a gneissic assemblage of reworked basement with its highly deformed, metamorphosed and intruded cover on the west (Kidal assemblage); and, on the east, the Iforas granulitic unit, which is a basement nappe emplaced at an early stage of the Pan-African event (Boullier *et al.* 1978, Boullier 1979). The study has been concentrated on the eastern part of this

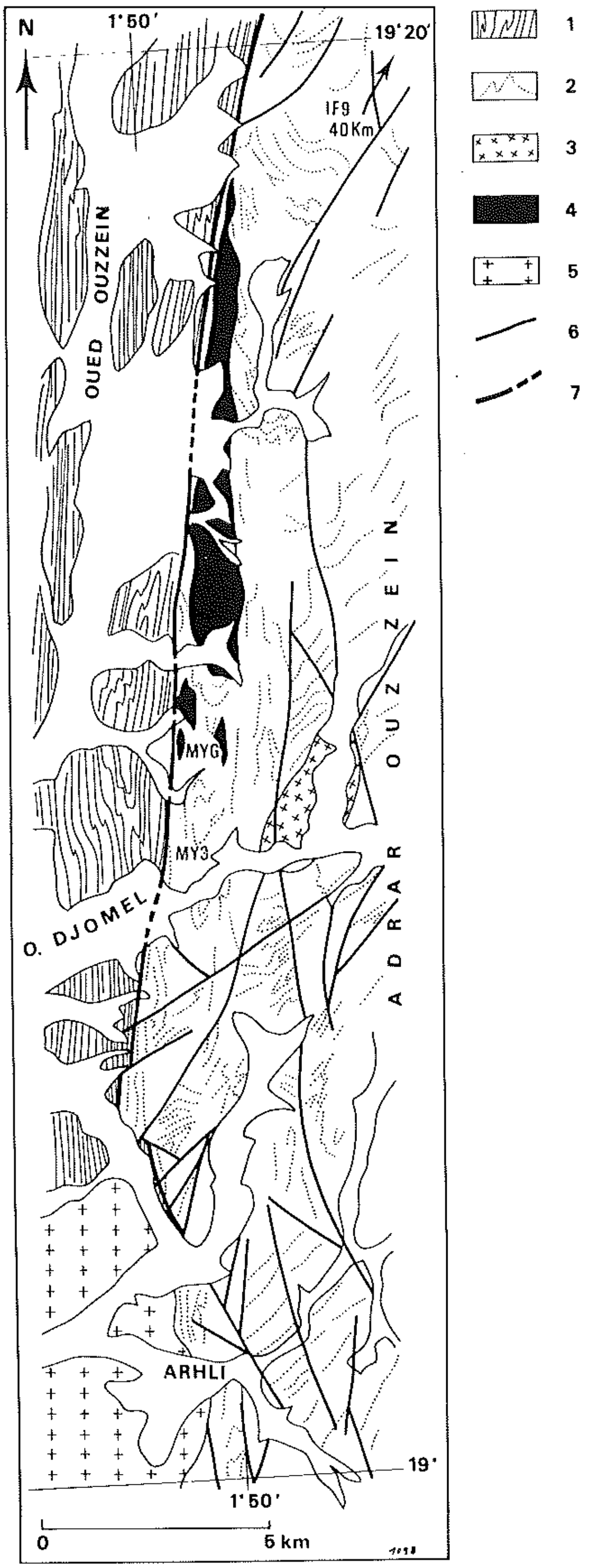

Fig. 2. Schematic map of the studied area: 1. Reworked Eburnean basement and its highly deformed, metamorphic and intruded cover. 2. Trend of foliation in the Eburnean subalkaline leptynites of the granulitic unit of Iforas. 3. Charnockitic intrusion. 4. Pan-African calc-alkaline granite deformed in the shear zone. 5. Post-mylonitic calc-alkaline granite. 6. Fault. 7. Mylonitic shear zone.

mylonitic shear zone i.e. in the granulites. In the studied area, the granulites are represented by a homogeneous banded formation of subalkaline leptynites of Eburnean age (= 2150 Ma, Lancelot personal communication). This formation has been migmatized during the Eburnean event as demonstrated by the quartzo-feldspathic veins which are parallel to or cross-cut the banding and foliation of the leptynites.

The shear zone cross-cuts all the pre-existing structures including the banding of the granulites as well as a late Pan-African calc-alkaline granite which intrudes the leptynites. The strong penetrative mylonitic foliation is vertical and is defined by the flattening of quartzo-feldspathic lenses and by green amphibole and/or green biotite layers. The horizontal stretching lineation is defined by the elongation of quartz and feldspar aggregates which form ribbons, by the orientation of green amphibole needles and by stringers of small greenish biotite flakes and ore minerals (magnetite – ilmenite). In the centre of the shear zone, the initial banding of the leptynites is no longer recognizable: very fine ultramylonite containing isoclinal folds forms, with the mylonitic foliation axial planar to the folds. The fold axes are exactly parallel to the stretching lineation. Consequently, it is suggested (see also Quinquis *et al.* 1978) that these structures are produced by high strain progressive simple shear.

No rotation of the foliation was detected in the 500 metres wide strain transition zone. However, assuming that the stretching lineation is close to the movement direction, the shear zone is interpreted as a strike-slip fault with a probable sinistral displacement. A small component of flattening normal to the shear zone is also evidenced by ptygmatic structure in previously horizontal layers in the western section. The magnitude of the displacement is not yet known.

MICROSTRUCTURES

The undeformed leptynites (*Fig.* 3)

These rocks are coarse grained (averaging 1–2 mm) with an inequigranular granoblastic texture (Collerson 1974). No flattening of the primary minerals can be observed and the layering is defined by variations in the proportions or in the size of the minerals (quartz + mesoperthitic feldspar + clinopyroxene + ilmenite ± plagioclase ± green amphibole ± titaniferous biotite). Even in these macroscopically undeformed rocks, there are some indications of slight straining: the quartz grains show undulatory extinction, prismatic sub-grains and lobate quartz–quartz grain boundaries. Dynamic recrystallization is rare (less than 1% in volume). Clinopyroxene and feldspars do not show any evidence of plastic deformation although some cracks are present. The clinopyroxene is surrounded or partly replaced by small crystals of green amphibole which is also undeformed. The minerals are rich in CO_2 and H_2O-filled fluid inclusions which are arranged in trails.

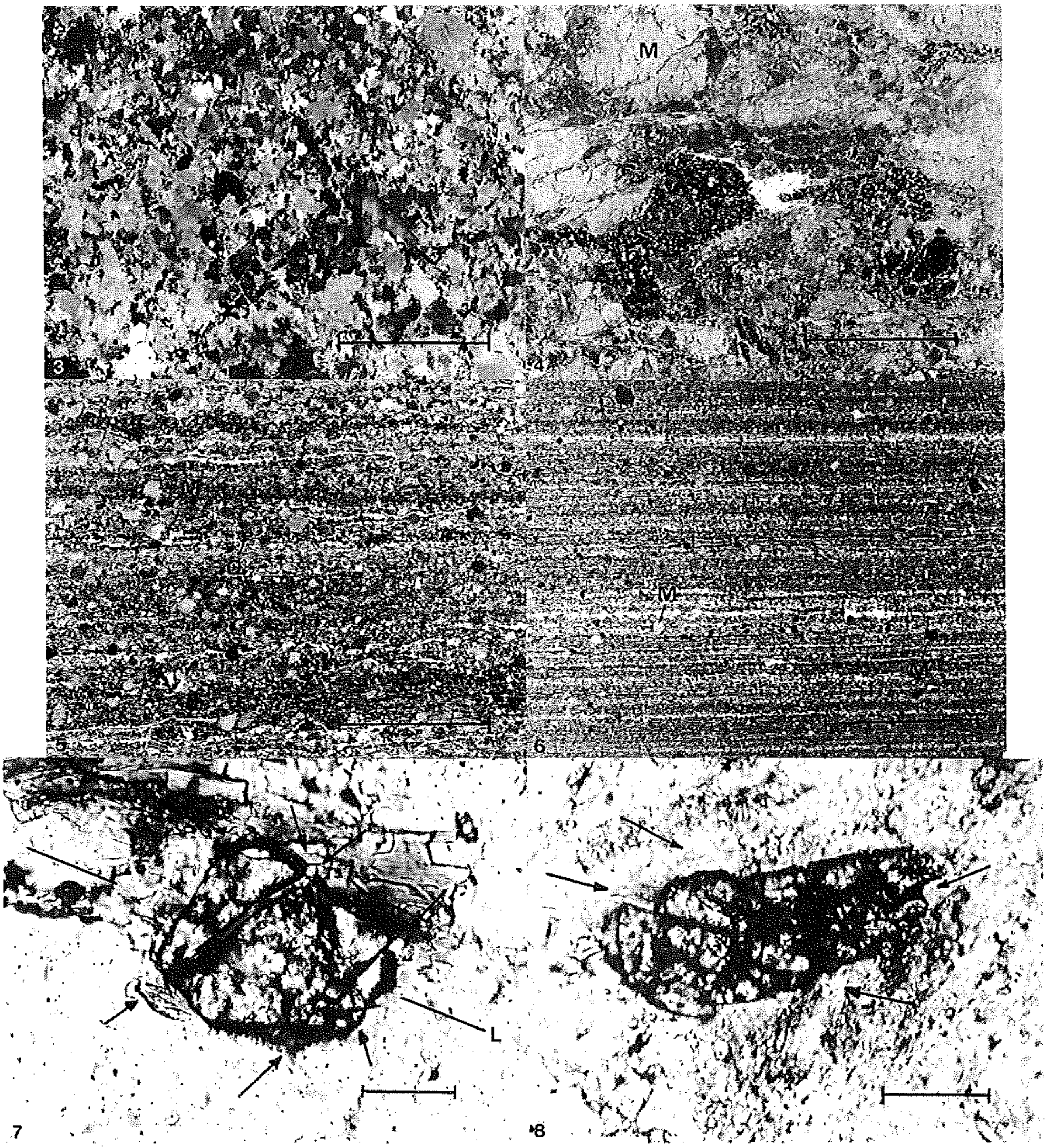

Fig. 3. Photomicrograph of an undeformed subalkaline leptynite. Negative print. Scale bar: 5mm.

Fig. 4. Photomicrograph of a protomylonitic subalkaline leptynite. Note the fracturing of mesoperthitic feldspars M and the dynamically recrystallized quartz aggregates Q. Scale bar: 5 mm.

Fig. 5. Photomicrograph of a mylonitic subalkaline leptynite. Note the round shaped clasts of mesoperthitic feldspars M, the polycrystalline quartz ribbon Q, and the tectonic layering. Scale bar: 5 mm.

Fig. 6. Photomicrograph of an ultramylonitic subalkaline leptynite. Note the very fine grain size and the persistence of mesoperthite clasts M. Scale bar: 5 mm.

Fig. 7. Photomicrograph of a fractured zircon. The fracture (arrows) are nearly normal to the stretching lineation L. Ordinary light. Scale bar: 20 μ.

Fig. 8. Photomicrograph of a fractured zircon. The scale bar (20 μ) is parallel to the stretching lineation. The cracks (arrows) are nearly parallel to the lineation. Ordinary light.

The protomylonites (*Fig.* 4)

In the protomylonites (see the classifications of Higgins 1971 and Sibson 1977), i.e. in the first stage of deformation, a penetrative foliation appears. It is defined by the flattening of quartz lenses, the alignment of green amphibole, which grows syntectonically from relicts of pale green clinopyroxene, and by stretched opaque minerals. Quartz crystals are almost completely polygonized and a mosaic of small equant crystals (≃ 50μ in dia.) replaces the highly deformed porphyroclasts. The plastic behaviour of quartz can be contrasted with the more brittle behaviour of other minerals such as mesoperthite, zircon and apatite in which cracks are very common.

The mylonites (*Fig.* 5)

In the mylonites, the foliation is continuous and defines a tectonic layering. Quartz forms ribbons of type II.2 of Boullier & Bouchez (1978), i.e. polycrystalline ribbons composed of an equant mosaic of grains with constant grain size (around 50μ). The quartz *C*-axes do not show any clearly preferred orientation in these ribbons which are deflected by mesoperthite augen which recrystallize into albite in their margin. The green amphibole is syntectonically replaced by green microcrystalline biotite and calcite grains appear in the feldspathic layers. The fluid inclusions in quartz ribbons are concentrated in the grain boundaries. They seem to contain only water.

The ultramylonites (*Fig.* 6)

Ultramylonites are present in the centre of the shear zone; the average grain size is very small (about 20μ) except for some round-shaped relicts of mesoperthites (about 100μ in dia.) from the original granulitic material. At this stage of large strains the amphibole is entirely replaced by greenish microcrystalline biotite which is itself partially chloritized. In places, the mineral phases no longer define a tectonic banding but are mixed together.

THE BRITTLE MINERALS

Zircon

No flattening or plastic elongation can be seen in zircon grains, but cracks appear. Some cracks are open and close to a plane normal to the stretching lineation defined in the sample (Fig. 7). In this case they can be interpreted as tensional cracks. But others are nearly parallel to the stretching lineation indicating a crushing mechanism (Fig. 8). After fracturing, zircon grains are dispersed in the ductile matrix and seem to be passively rolled. Some measurements have been carried out on zircons in samples representing different stages of strain on three sections across the shear zone. These measurements were carried out on *XZ* thin sections relative to

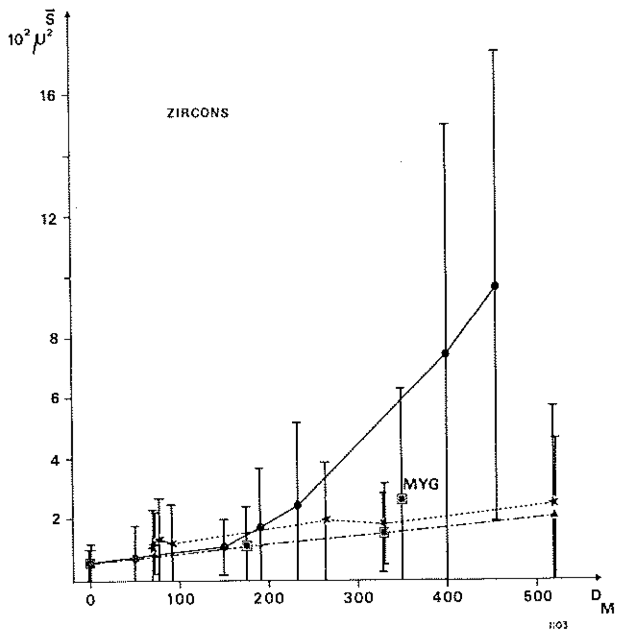

Fig. 9. Graph of average zircon grain size versus the distance from the centre of the shear zone. Vertical lines represent the standard deviations. Surfaces of grains have been measured in thin section. 60 measurements per sample. The different lines represent three different sections across the shear zone. MYG is a calc-alkaline granite intrusive in the leptynites and deformed in the shear zone.

the strain ellipsoid (*X*> *Y*> *Z*). Figure 9 indicates that two initial size groups exist. In rocks with large initial zircons, the size decreases rapidly by fracturing of grains and then behaves the same as the fraction with a small grain size. In the shear zone where the qualitatively estimated strain is increasing, the zircon size does not change very much, indicating that the zircons have probably attained an equilibrium grain size. There is no clear variation in the shape ratio $\bar{r}$ with increasing strain (Fig. 11). The average ratio is constant at 1.4.

Mesoperthite

In mesoperthitic feldspar, only a few indicators of plastic strain can be observed such as slight undulatory extinction and sometimes a thin rim of dynamically recrystallized small grains (≃ 20μ). The main feature is cracks which generally appear nearly normal to the stretching lineation and which result in pulling apart of the crystals. These cracks are then infilled by quartz and by very small grains of albite. The appearance of cracks in a crystal seems to be dependent also on the crystallographic orientation of the grain relative to the foliation and to the lineation.

The size distribution diagram (Fig. 10) shows that the grain size of feldspars decreases drastically with increasing strain. It seems that the evolution of grain size is the same for feldspars and zircons (compare Figs. 9 and 10). But some irregularities arise in the curves which can be explained by the effect of initial grain size variation in leptynites. Some samples show pegmatitic veins and grain size measurements in and outside the vein show different values (see for example sample My2 in Fig. 10).

Figure 11 indicates that the shape ratio does not show

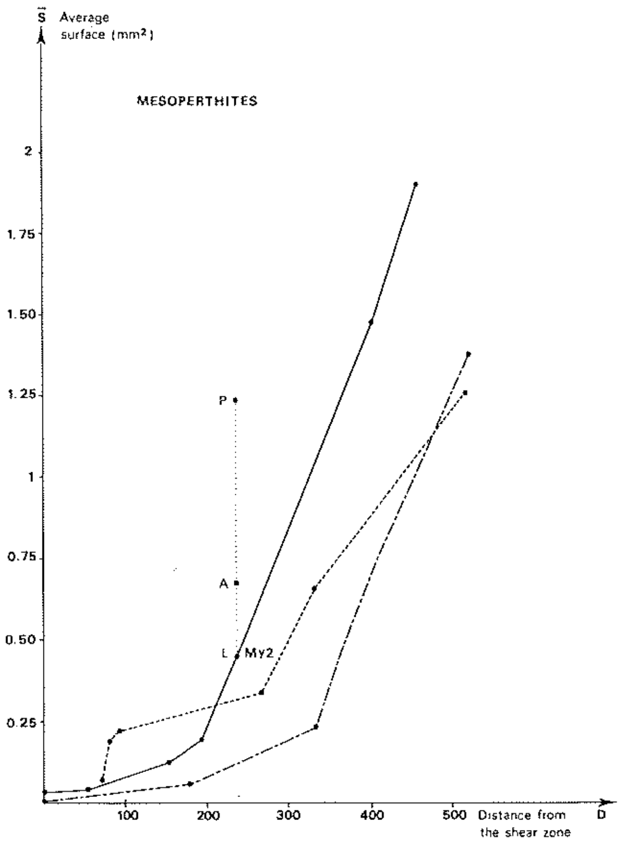

Fig. 10. Diagram of average grain size of mesoperthite versus the distance from the centre of the shear zone. Sizes have been measured on photomicrographs; 100 measurements per sample. The different lines represent three different sections across the shear zone. My2 is a sample showing a pegmatitic vein (see Fig. 4): *P* and *L* are the average grain size inside and outside the pegmatitic vein respectively; *A* is the bulk value.

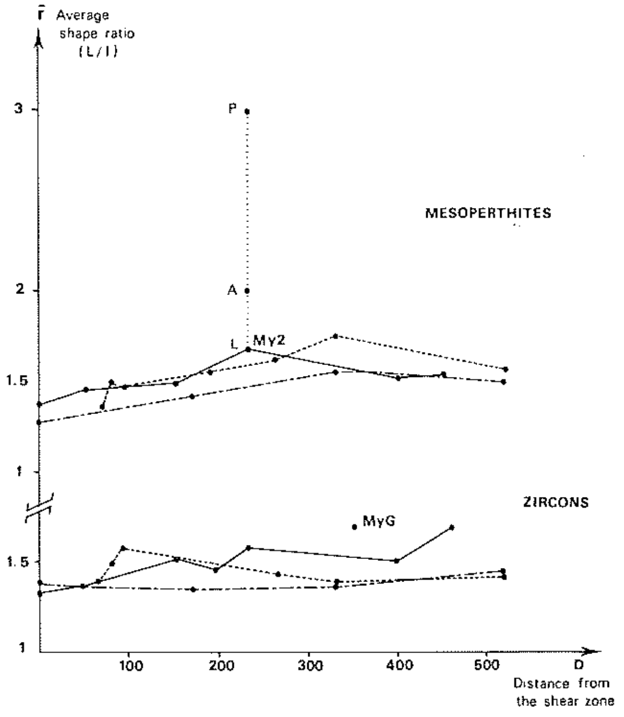

Fig. 11. Graph of average shape ratio of brittle minerals versus the distance from the centre of shear zone. MyG: calc-alkaline granite deformed in the shear zone. My2: sample of subalkaline leptynite showing a pegmatitic vein (see Fig. 4). *P* and *L* are the average shape ratio inside and outside the pegmatitic vein respectively; *A* is the bulk value.

any marked variation but may increase slightly at first and then decrease towards the shear zone. For the sample My2 three values of $\bar{r}$ have been plotted: inside and outside the pegmatitic vein, and a bulk value. The initial increase of $\bar{r}$ probably reflects the pulling apart of the crystals into slightly elongated fragments which then rotate and are fractured again, inducing a progressive decreasing of shape ratio.

Summarizing we can deduce the following from the microstructural observations.

(i) The deformation temperature is relatively low and corresponds to greenschist facies conditions (300–400°C). It seems to decrease towards the centre of the shear zone and therefore to indicate a decrease in temperature with time.

(ii) The strain is accompanied by the change in fluid inclusions composition in the minerals. CO_2 which is very common in granulitic rocks (Touret 1972), is replaced by H_20 which could have an important role in plastic deformation of these rocks (Griggs & Blacic 1964).

(iii) The average grain size of the rocks decreases drastically towards the shear zone. It is due to dynamic recrystallization in the case of quartz and to fracturing of grains in the case of feldspars and zircons. The latter attain an equilibrium size which does not change very much with increasing strain, and their shape ratio is almost constant.

(iv) Many characteristics of the mylonites and ultramylonites (high strain, very fine grain size, no lattice preferred orientation at least of quartz *C*-axis, and mixing of mineral phases which prevent grain growth) suggest a bulk superplastic behaviour of the rocks as proposed by Boullier & Gueguen (1975) even if some minerals have a brittle behaviour and despite the low temperature.

DISCUSSION

A recent review by Goods & Brown (1979) indicates that two main mechanisms are involved in the process of particle fracturing in a ductile matrix (see White *et al.* 1980):

(1) the fibre loading mechanism which is dependent on the aspect ratio of the particles and on their orientation with respect to the applied stress and

(2) local work hardening around the particles which is due to local dislocation storage. The latter is a process involving stress; a critical value of stress is necessary to break the interface or to fracture the particle itself. This critical value is dependent on the particle size.

In the case described in this work, it was found that the shape ratio of zircons does not change clearly with increasing strain and keeps a mean value of 1.4 (Fig. 11). Thus fibre loading is not the mechanism involved in the zircon fracturing. However the shape ratio of mesoperthites shows a slight evolution with increasing strain (Fig. 11). The first small increase of $\bar{r}$ is attributed to the fracturing of feldspars by cracks nearly normal to the extension direction. Then the individual grains which are pulled apart, rotate and are fractured again making $\bar{r}$ smaller. Thus, the fibre loading mechanism seems to be partly involved in the process of grain size reduction in the case of mesoperthites. But it is suggested that, this mechanism may not apply at high strains and therefore, as for zircon fracturing, we have to look for another mechanism.

The second mechanism (Para 2 above) satisfies the observations reported for zircons namely that the fracturing process operates irrespective of the aspect ratio and a critical size of particle seems to be necessary for fracturing to take place.

We may reasonably assume that differential stress is constant across a shear zone after it has developed. Is there a relation between the equilibrium grain size of zircons and that stress? This problem has been dealt with recently by Mitra (1978) who calculates a non-dimensional stress which is necessary to cause overall grain-size reduction in a rock. It is dependent on the ductile matrix fraction and on the brittle grain size. Although more work is necessary to obtain quantitative results, the work reported here indicates that paleostress may be estimated from the equilibrium size of brittle grains in a ductile matrix.

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