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Ductile shear zones in a meta-anorthosite from Harris, Scotland: textural and compositional changes in plagioclase

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Abstract—Small-scale ductile shear zones belonging to several sets in orientation and sense of movement, and including both continuous and discontinuous strain, modify an older granulite facies mineralogy and equilibrium textures of the meta-anorthosite and produce a new schistosity, textures and parageneses. Plagioclase and amphibole recrystallize, garnet and clinopyroxene disappear and scapolite, epidote and sometimes biotite appear. In continuous shear zones, it is possible to relate quantitatively the plagioclase textures produced by the shear strain, γ. The undeformed texture is replaced progressively by protoclastic ($\gamma < 1$), porphyroclastic festoon ($\gamma \approx 1$) or mortar textures ($1 < \gamma < 5$) and finally by heterogeneous or homogeneous polygonal textures ($\gamma > 5$).

In each undeformed rock type the old plagioclase grains are of constant composition ($\pm An_2$). Little or no change of composition is observed in the visibly deformed parts of old grains (bent twin lamellae, slightly misorientated sub-grains). Recrystallized new grains in porphyroclastic and polygonal textures have compositions, however, which differ by up to ±15% An from adjacent old grains and may show continuous compositional zoning. The juxtaposition of deformed old grains at low γ with recrystallized new grains at higher γ excludes late annealing. The very large difference between adjacent old and recrystallized grains also excludes dynamic recrystallization alone and requires in addition strain-induced recrystallization with nucleation and growth in the presence of a K, Cl, S, C... bearing fluid phase. The very high compositional gradients and variation from grain to grain suggest that chemical equilibrium may not have been attained.

INTRODUCTION

DEFORMATION can produce changes in the structure and texture of a rock, as well as changes in the compositions of the minerals or in the mineral assemblages. Bulk compositional changes may also occur by the addition or loss of certain components. In the case of the most studied minerals, quartz and calcite, no compositional changes can occur, whereas for olivine in dunites the changes are probably very small and recent structural work has tended to concentrate on the purely physical aspects of the deformation (preferred orientation, dislocation substructures etc.). Plagioclase, on the other hand, is dominant in anorthosites or gabbroic anorthosites and such rocks are extremely sensitive to mineralogical changes during deformation. In addition to changes in the ferro-magnesian minerals, plagioclase itself may change composition. It is thus necessary to distinguish clearly between the role of physical and chemical effects in the deformation of plagioclase rocks.

In order to relate all stages in the deformational and mineralogical changes to a structural framework, small scale shear zones are most suitable (Ramsay & Graham 1970). The area chosen for study, the Harris meta-anorthosite, contains numerous continuous and discontinuous shear zones and this paper presents data relating the textural and compositional changes in plagioclase to position relative to the shear zone (shear strain) and to the mineralogical changes in the rock.

GEOLOGICAL SETTING AND DESCRIPTION OF THE SHEAR ZONES

Previous work

The Roneval banded meta-anorthosite outcrops to the south of the migmatite complex of South Harris (Outer Hebrides) and occurs in association with paragneisses, meta-norites and meta-gabbro-diorites in SSE–NNW striking bands. It has been interpreted as an early Scourian sheet injected into a sedimentary cover subsequently metamorphosed in the granulite facies (Dearnley 1963, Graham & Coward 1973). Scourian deformation produced an antiform (a syncline according to the magmatic younging directions) with a steep or nearly vertical fold axis. The fold limbs were flattened during folding (Witty 1975).

As has been shown by Witty (1975), the mineral assemblages are of granulite facies: clinopyroxene is invariably partly altered to a magnesio-hornblende and garnet is rimmed by a symplectic intergrowth of plagioclase, amphibole and ore. Plagioclase compositions depend on the bulk rock composition and vary according to Witty, from An_{37-52} in the gabbros, An_{56-69} in the gabbroic anorthosites to An_{64-72} in the anorthosites. Zoning is absent or very weak (3–5% An). Numerous shear zones cut the meta-anorthosite and Witty discussed the mineralogical changes involved.

Field relations

The shear zones have very variable strike, sense of movement, configuration and thickness (a few mm to 10m) and are nearly vertical. All gradations exist between continuous shear zones with drag folding of the early foliation and progressive production of a new schistosity without any clear plane of discontinuity or rupture, to discontinuous shear faults which displace marker horizons on either side of a rupture plane. Figure 1(a) shows four main maxima of the poles to all the measured shear planes; they cannot be directly and unambiguously related to the groups proposed by Witty (1975). Using all the criteria given above, it is possible to divide the shears into several groups:

Maxima A and B represent strike directions between 120° and 160° and include: numerous dextral shears with cm to m dragging and formation of a new schistosity (early Laxfordian group of Witty), shear zones with a new schistosity as above striking 120° without dragging, but sometimes with a small sinistral movement, a few polyphase shear zones with a new schistosity with dextral dragging and sinistral displacement of marker horizons, and dextral shear fractures without dragging.

Maximum C striking 90–100° is relatively homogeneous and includes: very large sinistral shear zones with dragging up to several metres and a new schistosity (late Laxfordian group of Witty). In addition, a few small sinistral shear fractures (conjugate to dextral shears striking 20°–30°) occur.

Maximum D striking 40–60° is very variable and includes: dextral shear zones with cm dragging, dextral shear fractures without dragging, and sinistral shear fractures without dragging.

On the north eastern rim strong deformation of the fold limb occurs. Witty (1975) suggested that this deformation was caused by late Scourian flattening, whereas we consider that it is related to the shear zones of group B (Fig. 1a) for the following reasons: an abrupt dextral rotation of the foliation occurs over 30–70 m with partial coincidence of the foliation and the shear direction; a new schistosity obliterates preexisting structures either gradually or abruptly and can be linked to the shear planes; and textures and parageneses identical to those in the shear zones occur. On the basis of their textures and mineralogy, it is not possible to distinguish between the newly foliated zone on the NE limb of the fold, and the reputedly early and late Laxfordian shear zones of Witty. They all developed in the upper amphibolite facies and there is no apparent reason to separate them in time.

STRUCTURE AND PETROGRAPHY OF THE SHEAR ZONES

As an example of a continuous shear zone we will describe a specimen from a sinistral shear striking N 100° in a meta-anorthositic gabbro (Fig. 1b). From the outside to the centre of the shear zone the following changes are recognized:

Zone 1, primary foliation

A layering (a) (Fig. 1b) is clearly seen, probably of magmatic origin, with alternating bands of anorthosite and meta-gabbro (plagioclase, amphibole with relict clinopyroxene cores, garnet with symplectic rims).

Zone 2, rotation of the foliation

This is recognized between 2 to about 6 cm from the centre of the shear. The old foliation is rotated progressively from its initial position (100°, $\gamma = 0$) to the last

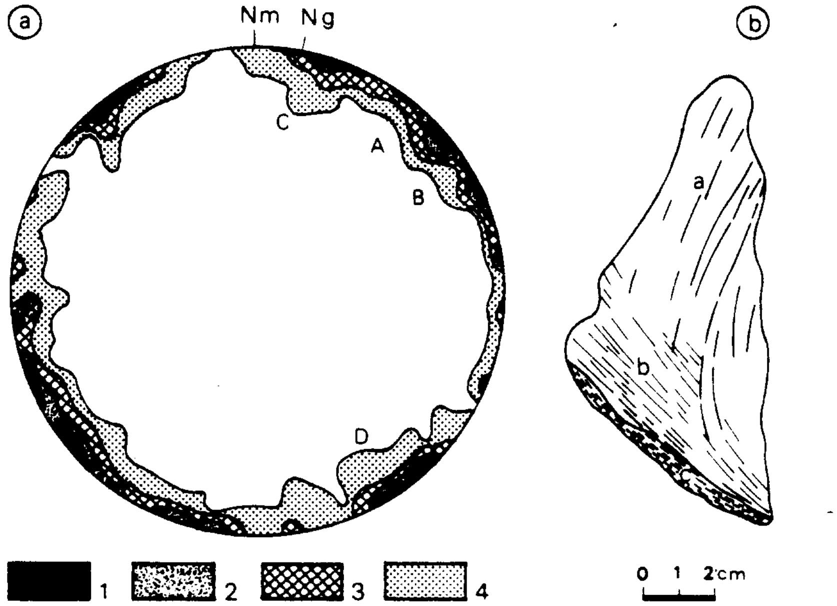

Fig. 1(a). 282 shear zone orientations (1) 3.3–1.8%, (2) 1.8–1.3%, (3) 1.3–0.8%, (4) 0.8–0.4% of the measurements in 1% of the area (upper hemisphere). (b). Rock specimen from a sinistral shear striking N 100° – (a) foliation, (b) new schistosity, (c) schistosity in fine-grained rock. Zone I, (a) alone and straight. Zone 2, (a) progressively bent, (b) more and more conspicuous. Zone 3, (b) alone. Zone 4, (c) alone.

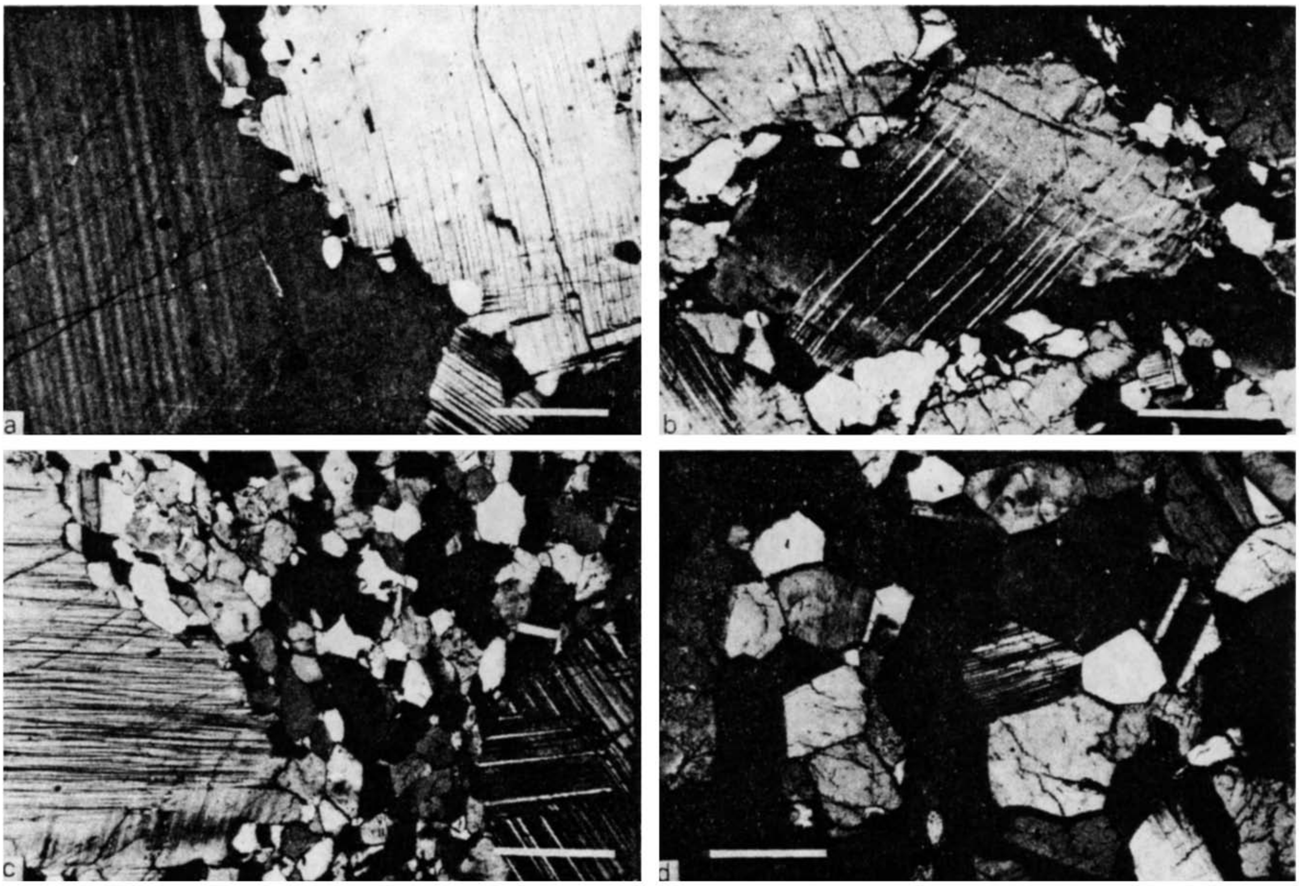

Fig. 2. Plagioclase deformation and recrystallization textures – (a) porphyroclastic festoon texture, some scattered new grains and bulges along the old grain boundaries, (b) porphyroclastic mortar texture, thick walls of new grains with polygonal shape, (c) heterogeneous polygonal texture (two old grains are present), (d) homogeneous polygonal texture. The scale bar is 0.5 mm long.

visible position (150°, $\gamma = 1.54$). A new schistosity (b) (Fig. 1b) begins to be obvious and shows a fan from 30° to a few degrees from the shear plane. There is disagreement between the shear strain calculated from the rotation of the original foliation and that from the angle of the new schistosity (Ramsay & Graham, 1970), which in this case always gives a higher value. This may be due to volume reduction in the shear zone which reduces θ' (Durney 1980). The Zone 1 minerals persist — plagioclase, ferroan pargasitic hornblende, garnet with its symplectic rim, but the new schistosity (b) is weakly outlined by small 0.1 mm polygonal plagioclase, by small ferroan pargasitic hornblende and by scapolite.

Zone 3, dominant new schistosity

In this zone 1–2 cm wide, the new schistosity (b) (Fig. 1b) obliterates the pre-existing foliation and it is impossible to determine the shear angle by the first method mentioned above. Large relict plagioclase, and relict magnesio-hornblende occur in a mosaic of new 0.1 mm plagioclase, magnesio-hornblende and scapolite, which define the schistosity.

Zone 4, centre of the shear zone

The schistosity (c) (Fig. 1b) is well developed and parallel to the shear plane, the grain size is small (~ 0.04 mm), and the contact with Zone 3 is sharp. Plagioclase occurs in polygonal granoblastic texture with biotite and magnesio-hornblende. This zone has been subsequently fractured and partly altered (chlorite, sericite).

All the shear zones in the meta-anorthosite with drag folding and a new schistosity are roughly similar. One can relate the shear strain, $\gamma = 2/\tan 2\theta'$ (where θ' is the angle between the shear plane and the new schistosity) to the disappearance of the old foliation and old minerals and, to the appearance of a new schistosity, new minerals and new plagioclase textures. The new schistosity is clearly seen when θ' is less than about 30° ($\gamma \approx 1$), and the old foliation is no longer visible when θ' is less than about 10° ($\gamma \approx 5$). Garnet disappears at $\theta' \approx 25°$ ($\gamma \approx 1.7$), clinopyroxene at much lower strain and amphibole and plagioclase relict grains are still seen when γ is greater than 10.

TEXTURAL AND CHEMICAL MODIFICATION OF THE PLAGIOCLASE

Textural evolution of plagioclase

The meta-anorthosite, away from the shear zones and unmodified by later deformation or alteration, has a simple granoblastic texture here called primary. Described below are the textural modifications produced in plagioclase (following in part the nomenclature of Kehlenbeck 1972). These textural changes are progressive and can be related to the value of the shear strain.

(I) *Primary granoblastic texture.* Coarse equigranular (up to 5 mm) polygonal mosaic of pink plagioclase crystals with straight or generally curved grain boundaries. Twinning on both the albite and pericline laws occur. In the rocks with plagioclase richer in anorthite than about An_{65}, all favourably oriented crystals show well developed Huttenlocher exsolution lamellae, which extend to the grain boundaries and are clearly younger than the twins. This implies that most of the twins now seen are probably growth twins and that the exsolution occurred under static conditions. This primary texture is slightly disturbed around symplectic rims to garnet and by the development of myrmekite.

(II) *Protoclastic texture.* The primary plagioclase grain boundaries become serrated and bulge and contain a few new grains (≃ 20–40 μm). The host grains show limited internal deformation: bent old twin lamellae, new wedge-shaped mechanical twins, sub-grains on the boundaries with low to medium misorientation (up to 15°).

Two types of porphyroclastic textures are distinguished.

(III) *Porphyroclastic festoon texture,* (*Fig.* 2a). Strings or festoons of zoned polygonal new grains (40–120 μm) occur along the limits of the old grains and form up to 5% by volume. The old grains have fewer sub-grains, which tend to be larger than in II. Sometimes they show a thin rim up to 50 μm thick, which has a continuous variation in extinction angle up to a few degrees; Huttenlocher exsolution is not optically visible in this rim.

(IV) *Porphyroclastic mortar texture,* (*Fig.* 2b). The festoons of new grains are replaced by continuous multiple walls of polygonal new grains of larger size (80–300 μm), which form up to 20% by volume. The zoned new grains are frequently twinned, either with two individuals of nearly equal thickness or a few thin lamellae. A very few new grains have undulose extinction with sub-grains suggesting later deformation. The relict grains are as in III.

Polygonal textures. The polygonal new grains form more and more of the rock. Two textures are recognized called *heterogeneous* or *augen* (V) (Fig. 2c) and *homogeneous* or *granoblastic* (VI) (Fig. 2d) depending upon the presence or absence of large rounded plagioclase grains. In the heterogeneous texture these grains, sometimes with internal deformation, are relict plagioclase as shown by their pink colour and by the presence of optically visible Huttenlocher exsolution. The new grains can be strongly zoned; they form either an equigranular (200–500 μm) isometric polygonal texture or a tabular one (200–600 μm) defining a new schistosity, which is also marked by the presence of amphibole, epidote, biotite and scapolite, the last occasionally in nearly monomineralic layers.

Later deformation characterized by very thin closely spaced mechanical twins and subgrains can be sporadically observed in new grains in porphyroclastic and polygonal textures types III to IV.

One can trace an evolution of the plagioclase textures from I to V or VI. Several textures can coexist at different shear strains in the same thin section. The protoclastic texture occurs when $\gamma < 1$ and the porphyroclastic festoon texture occurs when $\gamma \approx 1$. The mortar texture (IV) can be seen when the new schistosity is just locally visible and persists as long as the old foliation ($\theta' =$ 30–10°, $\gamma = 1$–5). The augen and polygonal textures (V and VI) appear when the schistosity becomes penetrative ($\theta' \leq 10°$, $\gamma > 5$). In discontinuous shear zones the evolution from one texture to another is abrupt. II or III and V or VII side by side is a common feature.

Compositional variation in plagioclase grains

Several hundred complete analyses of plagioclase and other minerals in undeformed and deformed rocks have been carried out by microprobe, taking care to distinguish between relict grains, the rims of relict grains, subgrains and new grains of plagioclase in the different textural types (Fig. 3). The precision in the plagioclase compositions is about ± 1% An. A detailed description of the mineral parageneses of the shear zone is in preparation.

The relict grains have compositions in any one rock and in one textural and mineralogical situation which are remarkably constant, varying only by ± An_2 (Fig. 3, a1, d7, d8, f9, f10. Sightly misorientated subgrains or bent twin lamellae, particularly abundant in the shear zone margins (texture II), show no significant compositional change. Some old grains, however, clearly recorded in texture III, have a homogeneous core and a rim with a drop of An_{6-8} related to the disappearance of optically visible Huttenlocher exsolution lamellae (Fig. 3 b3, b4).

The new grains, on the contrary, show a wide range of compositions up to 30% An for a given old grain composition. Several phenomena are superimposed and give unpredictable analyses. (1) In all the textures from III to V, the new grains can be strongly reverse zoned with a core richer in Ab than the adjacent old grain and a rim richer in An. Reverse zoning is also known in polygonal texture VI but can obviously not be linked to relict grain composition, because of the large displacement in the core of the shear. (2) The new grains in immediate contact with relict grains in festoon or mortar porphyroclastic textures (III and IV) show very large differences and may show a spread of up to at least 30% An. (3) There is, however, a general tendency clearly visible on the Fig. 3. When the old grains have a high An content (An_{75}), the new grains are richer in An than the old ones. When the old grains have a composition between An_{30} and An_{50}, the new grains tend to be richer in Ab than the old ones. Between these values the new grains show a large spread of composition, either richer or poorer in An than the old ones. Vernon (1975), White (1975) and Marshall & Wilson (1976) have shown that new grains in deformed andesine, oligoclase and albite can be more Ab-rich than old grains by only a few per cent Ab. Borges (oral communication) found a drop of a few per cent in An content in plagioclase from a shear zone in the Roneval anorthosite. Our results show quite clearly that in these shear zones, plagioclase new

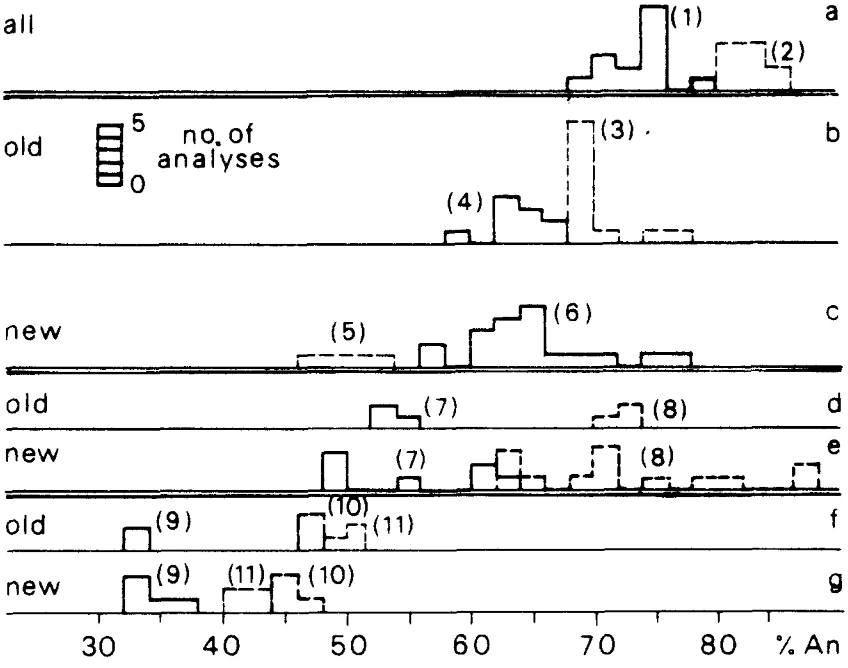

Fig. 3. Histograms of plagioclase compositional variation in old and adjacent new grains from single thin sections from four rocks (a, b and c, d and e, f and g). (a) heterogeneous polygonal texture (V), old grains (1), adjacent new grains (2); (b) and (c) porphyroclastic festoon texture (III), old grain cores (3) and rims (4); adjacent new grain cores (5) and rims (6); (d) and (e) textures ranging from porphyroclastic (III) to polygonal (VI). Comparison between old (d) and adjacent new grains (e) in two compositional bands (7) and (8); (f) and (g) comparison between old (f) and adjacent new grains (g) across a 2 cm wide shear: (9) polygonal augen texture in the core of the shear, (10) porphyroclastic texture in the margin of the shear, (11) porphyroclastic texture between the above two.

grains can be richer and poorer by up to An_{15} than the old grains and are in addition strongly and continuously zoned.

DISCUSSION AND CONCLUSIONS

If the new grains of plagioclase arose by a purely physical mechanism (static or dynamic strain-induced recrystallization), they would have the same composition as the old grains as described by Marshall & Wilson (1976). Shear zones, however, are the site of important chemical and mineralogical changes (Beach 1976). A detailed description of the reactions occurring in these shear zones is in preparation. The composition of the new plagioclase grains will thus depend on the composition of the old plagioclase and on the mineral reactions occurring in the immediate vicinity. It does not seem possible to relate the compositions of the new grains to the Bøggild or Huttenlocher exsolution in plagioclase. In addition, the presence of a fluid phase which can vary in its Na/Ca ratio could affect the composition of the new plagioclase grains.

New grains of variable composition only occur at values of $\gamma >$ about 0.7 (the approximate limit for the appearance of the new schistosity) suggesting that this recrystallization has been superimposed on the earlier plastic deformation in the central parts of the shear zone by fluid penetration, which permitted the elimination of the strained parts of the old grains and the growth of new minerals. The new grains are optically undeformed or only slightly deformed. The new grains increase in volume per cent as γ increases and surround the old grains which persist up to high values of γ. It is thus probable that the plastic deformation of the old grains occurred mainly in their mantle and that only the almost undeformed core resisted recrystallization.

The following conclusions can be drawn.

(1) The mineralogical and textural changes described occur only in the shear zones and can be directly related to shear strain, γ. Recrystallized plagioclase only occurs at values of γ greater than about 0.7, and the degree of recrystallization increases directly with γ.

(2) Relict plagioclase grains with optically visible internal strain occur generally at values of γ less than about 1. Optically visible strain is very rare in relict or new grains at $\gamma > 1$. The existence of strained relict plagioclase within a short distance (a few mm to m) of unstrained grains and the restriction of the mineralogical changes to the shear zones allows one to exclude late annealing.

(3) The inverse relation between internal and total strain suggests strain-induced recrystallization and in particular dynamic recrystallization.

(4) The great variation in the composition of new plagioclase grains in contact with relict grains and their reverse zoning suggests that dynamic recrystallization cannot be the only mechanism. It is perhaps necessary to invoke a superimposed nucleation and growth of new plagioclase grains in contact with a fluid phase.

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