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Sense of shear in high-temperature movement zones from the fabric asymmetry of plagioclase feldspars

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Abstract—A new method for determining the sense of shear in plagioclase-bearing tectonites from the (010) orientation of plagioclase feldspar is presented. The method is based on the asymmetry of the (010) plane with respect to the structural frame (foliation and lineation) and the dominant activity of the (010) slip plane in the high-temperature plasticity of plagioclase feldspar. Using examples from the Zabargad gneisses (Red Sea) the method is applied to plagioclases of An25–An45 and compared with other methods of shear-sense determination (quartz *c*-axis fabrics and microstructural criteria).

INTRODUCTION

THE obliquity between the lattice preferred orientation (LPO) and the structural framework defined by mineral-shaped preferred orientation (stretching lineation and flattening foliation) has been shown to be a reliable indicator of shear sense for ductile minerals such as olivine, quartz, ice and calcite (see Bouchez *et al.* 1983 for review and further references). It is now accepted that in polycrystalline aggregates, where grains were deforming due to the dominant activity of a single slip system, the fabric asymmetry is the result of the alignment of the slip planes and directions with, respectively, the shear plane and direction during simple-shear deformation. Hence fabric asymmetries have been applied to determine the shear sense in the kinematic studies of olivine- (Nicolas *et al.* 1973), quartz- (e.g. Bouchez & Pécher 1981) and calcite-rich rocks (e.g. Schmid *et al.* 1981).

Plagioclase is a major rock-forming mineral which occurs in rocks of upper and lower crustal origin. In particular it is common in high-grade metamorphic rocks (e.g. amphibolite gneisses) which may be devoid of the more usual kinematic indicators such as quartz or calcite. Under such high-grade conditions plagioclase is ductile and its LPO should provide a reliable indicator of the sense of shear, providing we understand its plastic behaviour (i.e. slip or twinning systems).

In this paper we present evidence for dominant (010) slip in naturally deformed plagioclase. Optical indicatrix fabrics, and preferred orientations of the (010) trace in *XZ* sections are shown to be an important indicator of shear sense.

GEOLOGICAL CONTEXT AND SAMPLE DESCRIPTION

The plagioclase-bearing tectonites studied in this work are the granulite-amphibolitic gneisses from Zabargad Island located on the western margin of the Red Sea main trough, at the latitude of 23°37′. General geology and detailed mapping within this island have been considered by El Shazly & Saleeb (1979), Bonatti *et al.* (1981, 1983) and Styles & Gerdes (1983), and geometrical, kinematical and dynamical aspects of the deformation have been studied by Nicolas *et al.* (1985, 1986). These gneisses, in contact with the central and northern peridotite bodies, cover an area of only 1 km^2. The gneisses are well banded and homogeneous. Their penetrative syn-metamorphic deformation is marked by the development of a foliation parallel to the banding and a mineral lineation. This deformation is considered as a shear one occurring in the granulite facies conditions, during the intrusion of a mantle diapir elongated parallel to the Red Sea rift direction (Nicolas *et al.* 1986). A maximum shear strain of more than 20 has been estimated from a thinning of diabase dikes (Boudier *et al.* in press). However, the shear sense in the Zabargad gneisses, like almost all the metamorphic rocks deformed at high-grade conditions, is difficult to evaluate from study of the geometry of the schistosity at shear-zone margins, or of deflected marker horizons such as veins or dikes, due to the regional significance and to the paucity of markers. It has also been estimated that during metamorphism the highest temperatures in the area reached 750–950°C at pressures 1.0–1.1 GPa (Nicolas *et al.* 1986).

Seventy specimens were collected from the gneisses in the area, with a sampling grid of about 100 m. Their petrology has been studied by Boudier *et al.* (in press). According to them, the gneisses are three petrological types: (i) mafic gneisses with an andesine plagioclase (An35–An45); (ii) peralkaline gneisses with an oligoclase (An25–An35) and a quartz fraction varying between 10 and 40% and (iii) amphibolites with more than 50% hornblende. Two samples of the mafic gneiss (ZF5 and Z34A) and three of the peralkaline gneiss (Z11B, Z19 and Z36B) were chosen for this study. All of them have the following characteristics: (a) plagioclase is the dominant constituent by volume (>60%); (b) under the petrological microscope with an auxiliary gypsum plate a strong optical fabric is evident; (c) the plagioclase grains display abundant evidence of plastic deformation, such as tapering deformation twins, undulatory extinction, deformation bands, subgrains and small recrystallized new grains (Figs. 1a and 3); (d) deformation is penetratively homogeneous. The structural frame (foliation–lineation) is clearly defined and reflects the finite strain (X–Y–Z frame).

A brief description of the mineralogical and microstructural aspects of the two groups of samples is given below.

Samples ZF5 and Z34A are the mafic gneiss which does not contain any quartz and has a mineral assemblage of plagioclase + pyroxene. The average percentage of anorthite in ZF5 and in Z34A is 34 and 45%, respectively. The plagioclase grains have a bimodal grain-size distribution (Fig. 1a). The larger residual grains constitute the porphyroclasts which have two striking shapes: ribbon and globular ones (see subsection on 'Microstructural evidence'). They have a mean size of about 1.5 mm. Intracrystalline, deformation-induced substructures such as undulatory extinction, subgrains, deformation bands and lenticular and/or bent twins are abundant in all porphyroclast grains (Figs. 1a and 3). These porphyroclast grains, which are about 60% of the whole plagioclase content, are embeded in a recrystallized matrix. The smaller recrystallized grains (40–150 μm) are equant in shape. About 60% of them are twin-free. Optical observation with an auxilliary gypsum plate shows that these new grains have a similar preferred orientation with the porphyroclasts.

Samples Z19, Z11B and Z36B consist of both deformed plagioclase and quartz. The percentage of quartz in Z19 and Z11B is about 10–15%, and in Z36B about 30%. The average percentage of anorthite in plagioclase for Z19, Z11B and Z36B is 25, 30 and 35%, respectively. The quartz ribbons are composed of small new grains/subgrains (20–70 μm) which have almost similar lattice orientation. These quartz grains are well recovered and optically strain-free, with serrated boundaries. Although some quartz-ribbons are observed to be molded to the forms of the porphyroclast grains of plagioclase due to their rheological differences, plagioclase grains particularly in the quartz-free layer are deformed plastically, having sweeping undulatory extinction and tapering deformation twins as well as subgrains. They show typical core and mantle structure (White 1975). Dynamically recrystallized grains, 15–65 μm across, occur mainly along the margins of relict grains, some new grains/subgrains occur in the relict where a crystal is bent or an intracrystalline microshear zone is observed. The new grain boundaries are curved to slightly sutured. The orientation of the new grains is found to be host-controlled.

(010): DOMINANT SLIP PLANE

Structural and dislocation energy considerations

In the framework structure of all feldspars the strongest bonds are the Al–O and Si–O tetrahedra or T–O bonds. To a first approximation, the easiest glide planes will be those intersecting the smallest number of T–O bonds per unit area. Using this criterion the easiest glide planes should be (010) with two T–O bonds per unit cell, followed by (001), (110), $(\bar{1}\bar{1}0)$ and $(10\bar{1})$ with four each, and then (100) and (111) with six (Tullis 1983, Gandais & Willaime 1984). The easy slip direction will be the shortest Burgers vector since dislocations with the lowest energy are the most stable and the energy of a dislocation in an isotropic medium is proportional to $|b|^2$. If we restrict ourselves to possible Burgers vectors in the easy glide plane (010) then in the $C\bar{1}$ structure we would expect 1/2 [001] with b = 0.7 nm, [100] with b = 0.8 nm and 1/2 [201] with b = 0.8 nm; in $I\bar{1}$ and $P\bar{1}$, 1/2 [001] with b= 0.7 nm which is dissociated (see Montardi & Mainprice 1987) and [100] with b = 0.8 nm (all indices are based on a cell with c = 1.4 nm). Hence we would expect easy slip on (010) to be in the $\langle c\rangle$ or $\langle a\rangle$ directions in all plagioclases, and additionally in the [201] direction occurring in the $C\bar{1}$ structure. These conclusions agree with recent LPO studies of bytownite (An70) (Wenk *et al.* 1986) and of intermediate plagioclase feldspars (An25–An48) (Olsen & Kohlstedt 1985), and with TEM studies of $C\bar{1}$ (Olsen & Kohlstedt 1984) and $I\bar{1}$ (Montardi & Mainprice 1987) space groups.

Optical fabric evidence

The knowledge of the LPO allows one to infer the possible dominant slip systems, assuming that the fabric was formed by intracrystalline slip (e.g. Bouchez *et al.* 1983). In the case of triclinic plagioclase one cannot directly infer the LPO from measurements of the optical indicatrix because the positive and negative axes of the indicatrix cannot be distinguished. Hence there are four possible crystal orientations for a given orientation of the optical indicatrix (Jensen & Starkey 1985). However, with the additional information of the (001) and (010) cleavage orientations the complete LPO, including the distinction of positive and negative crystallographic axes, can be obtained (Wenk *et al.* 1986). Such measurements are extremely laborious and require that cleavages are present in a sufficient number of grains to make the measurements statistically meaningful. As a compromise we have recorded the orientation of the optical indicatrix, the poles to (010), and the trace of (010) in the XZ section of the structural frame.

The angular relationship between the optical indicatrix and the crystallographic axes, which changes with composition in the plagioclase series, is shown in diagrams published by Burri *et al.* (1967). For the plagioclase feldspars considered in this work (An25–45), the angle between the optical directions α and [100] progressively varies from 2 to 18°; between β and [001], from 25 to 50°; and between γ and the normal to (010), from 8 to 24°. The optical indicatrix fabrics (α, β, γ) of the plagioclase feldspars are shown in Fig. 2. A strong preferred orientation is evident with α and β forming a girdle in the foliation plane with a maximum of β in samples ZF5, Z34A, Z11B and Z36A or a maximum of α in sample

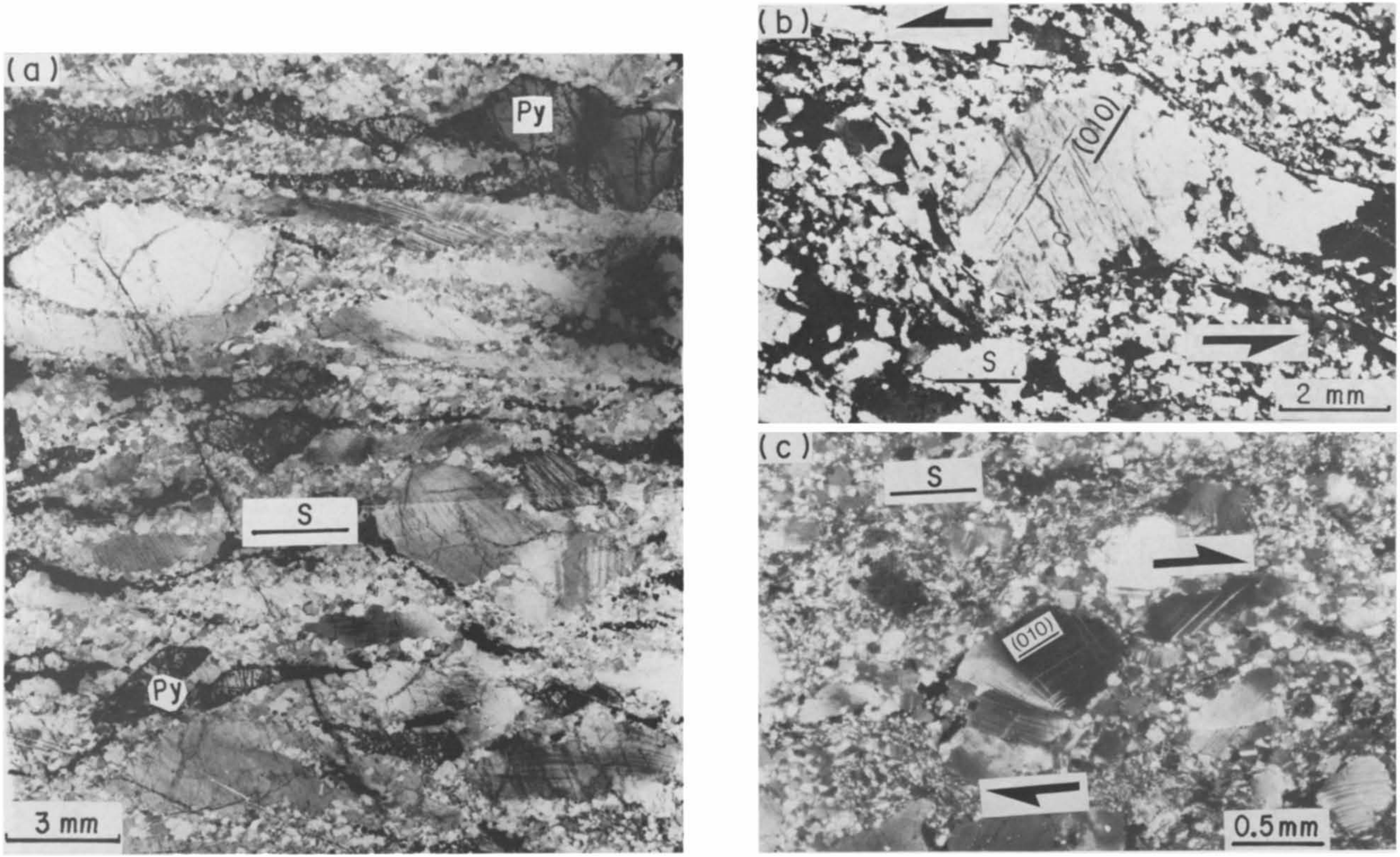

Fig. 1. Typical deformation microstructure of Zabargad gneiss. Optical photograph plane is parallel to *XZ* section and the foliation trace is marked by S. Crossed nicols. Sample (Z34A) from mafic gneiss containing plagioclase (An35–An45) and pyroxene (Py). See text for microstructural description. (b) Optical microstructures indicating non-coaxial shear. Asymmetric pressure shadow in sample Z36B, indicating a sinistral shear. (c) Retort shaped crystal ('cornue') in sample Z11B, indicating a dextral shear.

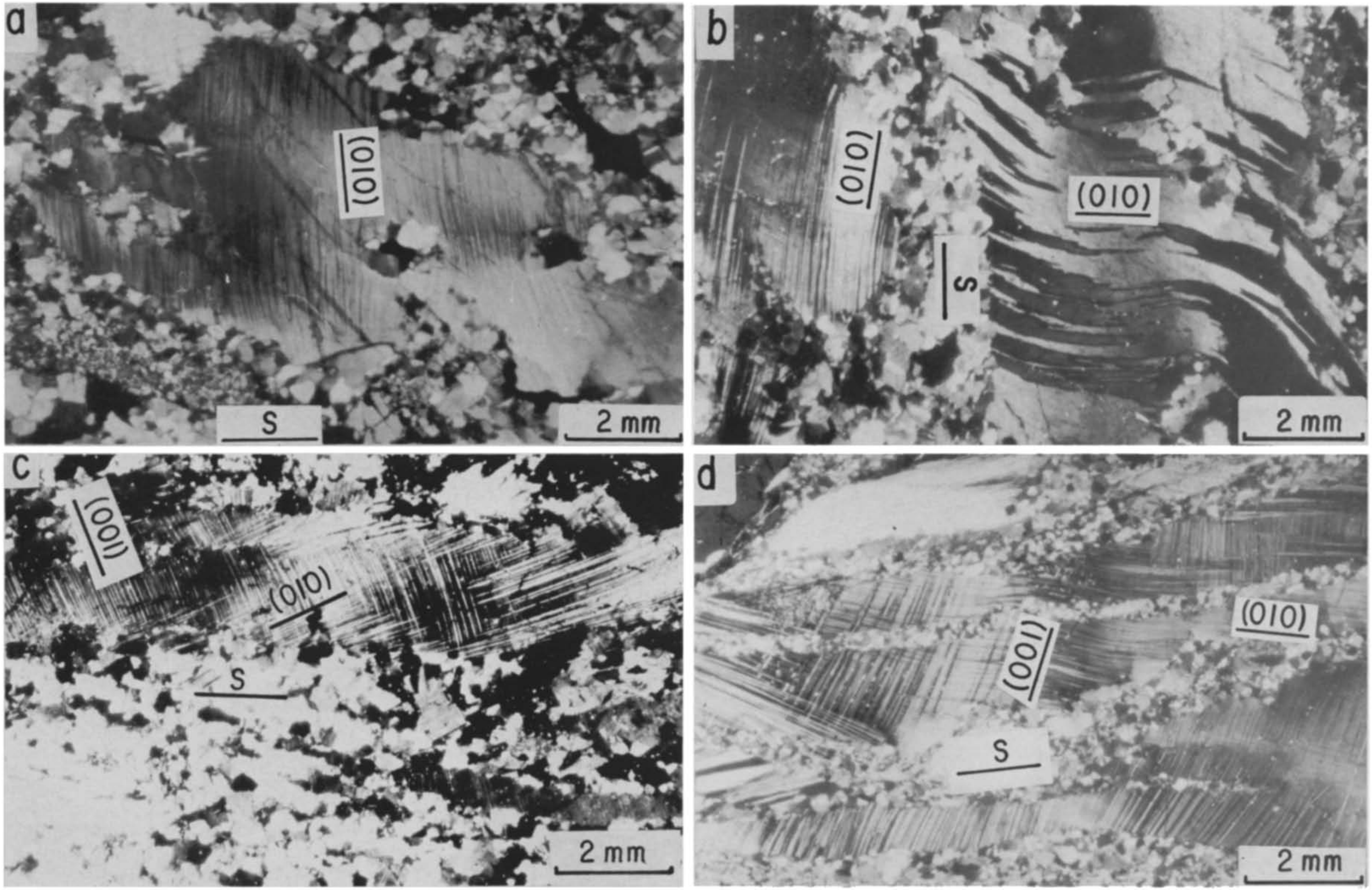

Fig. 3. Micrographs of plagioclase porphyroclasts from sample Z34A. *XZ* section is parallel to the plate and the foliation trace is marked by S. (a) and (b) Globular porphyroclasts whose (010) planes are at a high angle to the lineation. (c) and (d) Ribbon porphyroclasts whose (010) planes are at a small angle to the lineation.

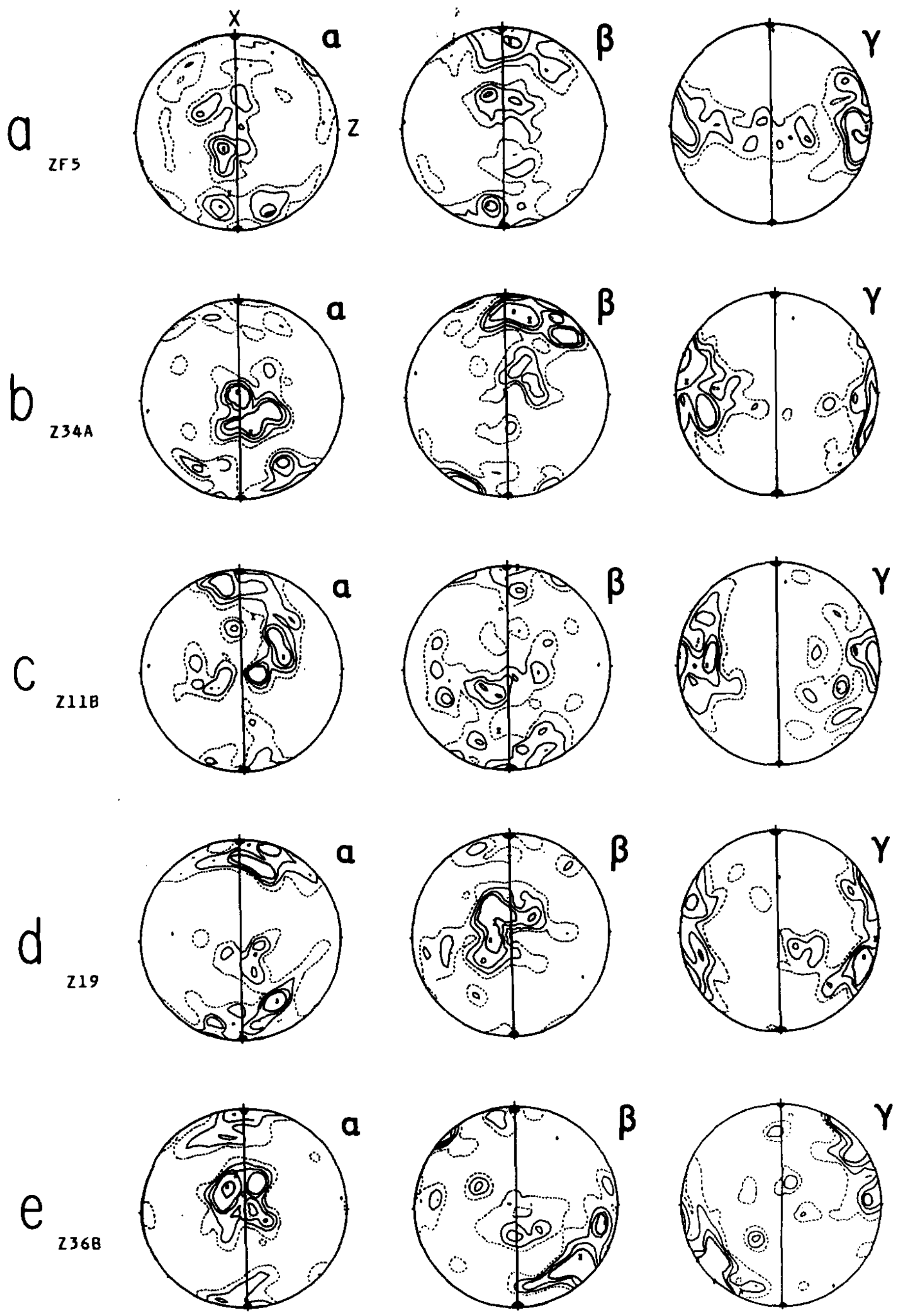

Fig. 2. Preferred orientation of plagioclase indicatrix axes (α, β, γ) from Zabargad gneisses. The *XY* plane (foliation) is the N–S (solid line) perpendicular to the page; the *X*-direction (lineation) is N–S; the *Z*-direction is E–W. Schmidt projection, lower hemisphere; counting area: 1% of the hemisphere area. (a) Sample ZF5, An34: 150 measurements; contours: 1, 2, 3, 4, 8%, maximum 9%. (b) Sample Z34A, An45: 100 measurements; contours: 1, 2, 3, 4, 8%, maximum 11%. (c) Sample Z11B, An30: 100 measurements; contours: 1, 2, 3, 4%, maximum 6%. (d) Sample Z19, An25: 100 measurements; contours: 1, 2, 3, 4%, maximum 8%. (e) Sample Z36B, An35: 100 measurements; contours: 1, 2, 3, 4, 8%, maximum 10%.

Z19 at small to moderate angles to the mineral lineation, and γ a partial or complete girdle normal to the lineation with a maximum at a high angle or normal to the foliation. These fabrics are entirely consistent with slip in the [001] and [100] directions as shown by the high concentration of β and α in the foliation plane close to the lineation. Slip on (010) is strongly indicated by the high concentration of γ normal to the foliation plane. We conclude that [001] (010) and [100] (010) slip produced these fabrics. However, these indicatrix fabrics do not represent the exact crystallographic preferred orientations and so no sense of shear can be deduced.

Microstructural evidence

In experimentally deformed rocks, in which the relationship between grain orientation and imposed deviatoric stress is known, a clear microstructural distinction can be made between grains in an easy slip orientation and those in an unfavourable one (Nicolas *et al.* 1973, Tullis *et al.* 1973). The undeformed globular-shaped grains are in unfavourable orientations for slip, commonly with the easy slip plane normal to or at a high angle to the compression direction, whereas the extensively deformed ribbon grains are in an easy slip orienta-

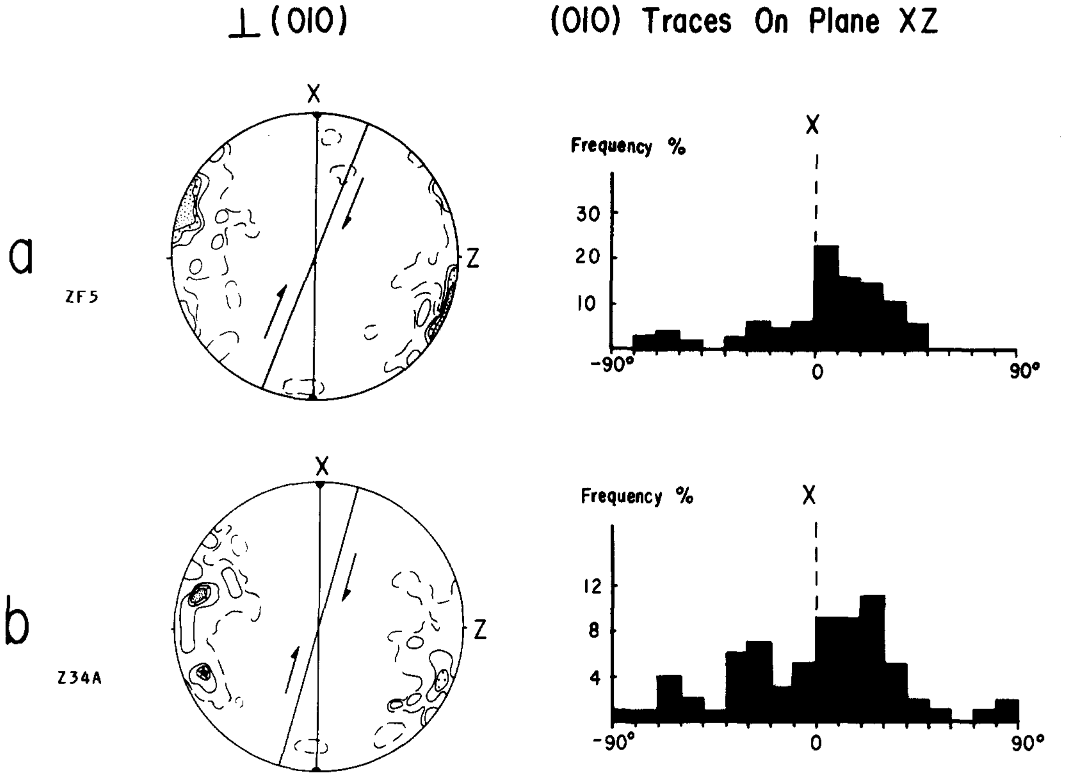

Fig. 4. Preferred orientations of (010) in Zabargad gneisses devoid of quartz. Poles to (010) (left) and angular distribution histograms of (010) traces (right). *XZ* plane with *X* (dots) in N–S of the plate. (a) Sample ZF5. Poles to (010): 50 measurements; contours: 2, 4, 6, 8% per 1% area. (010) traces on plane *XZ*: 100 measurements. (b) Sample Z34A. Same as (a). See note on figure.

tion. One can use these considerations to deduce the slip plane from the microstructure, as shown by Bouchez (1977) in the case of naturally deformed quartz. We have, therefore, made systematic observations of both the globular and ribbon-shaped porphyroclasts in the samples collected for this study.

(a) Globular porphyroclasts typically have an equant shape. Their (010) plane is at a high angle to the lineation (*X*-direction) (Fig. 3a). In *XZ* section histograms they populate their minima inclined at +70–90° from the *XY* plane (Figs. 4 and 5). Some grains show extensive lattice bending, especially near their margins (Fig. 3b); in others, grain-boundary recrystallization occurs with twins or deformation bands in the cores.

(b) Ribbon porphyroclasts typically have an elongated shape (Fig. 3c & d). Their aspect ratios vary from 10:1 to 50:1, depending on the strain intensity. The (010) plane is at less than 30° from the trace of the *XY* plane forming a maximum subparallel to this plane (Figs. 4 and 5) and the (001) plane is at a high angle to the *XY* plane.

These orientation relationships provide indirect evidence for dominant slip on the (010) plane and minor activity on the (001) glide plane. The presence of ribbon porphyroclasts whose (010) and (001) cleavages are both observed in the *XZ* section implies that the [001] direction lies close to the stretching lineation, further implying that the dominant slip direction is [001] in those grains. We conclude that the deformation microstructure of the porphyroclasts is consistent with the dominant activity of (010) slip.

ASYMMETRY AND SHEAR SENSE IN THE ZABARGAD GNEISSES

If the (010) plane acted as the dominant slip plane in the plagioclase grains, then asymmetric fabrics of (010) in plagioclase can be used as an indicator of shear sense in the high-temperature movement zones, just as the basal plane (0001) in quartz can be used at low temperatures.

Plagioclase (010) *fabrics in the samples without quartz*

The orientation of the poles to (010) and the angular distribution of the trace of (010) planes, measured in the *XZ* section, show a marked asymmetry of (010) with respect to the foliation and the lineation in samples ZF5 and Z34B (Fig. 4). The asymmetry of the fabrics and the geometry of the sheared plagioclase porphyroclasts (Fig. 3) suggest a strain path essentially non-coaxial, say closely approximating that of simple shear. Then its shear sense can be deduced from the asymmetry (e.g. Bouchez *et al.* 1983, Simpson & Schmid 1983). On the analogy of the asymmetrical fabric of quartz at low temperatures one can determine the shear sense to be dextral in sections ZF5 and Z34A.

Comparison between plagioclase and quartz orientations

Samples (Z11B, Z19 and Z36B) consist of both deformed plagioclase (An25–An35) and quartz so that quartz and plagioclase fabrics can be compared. Figure

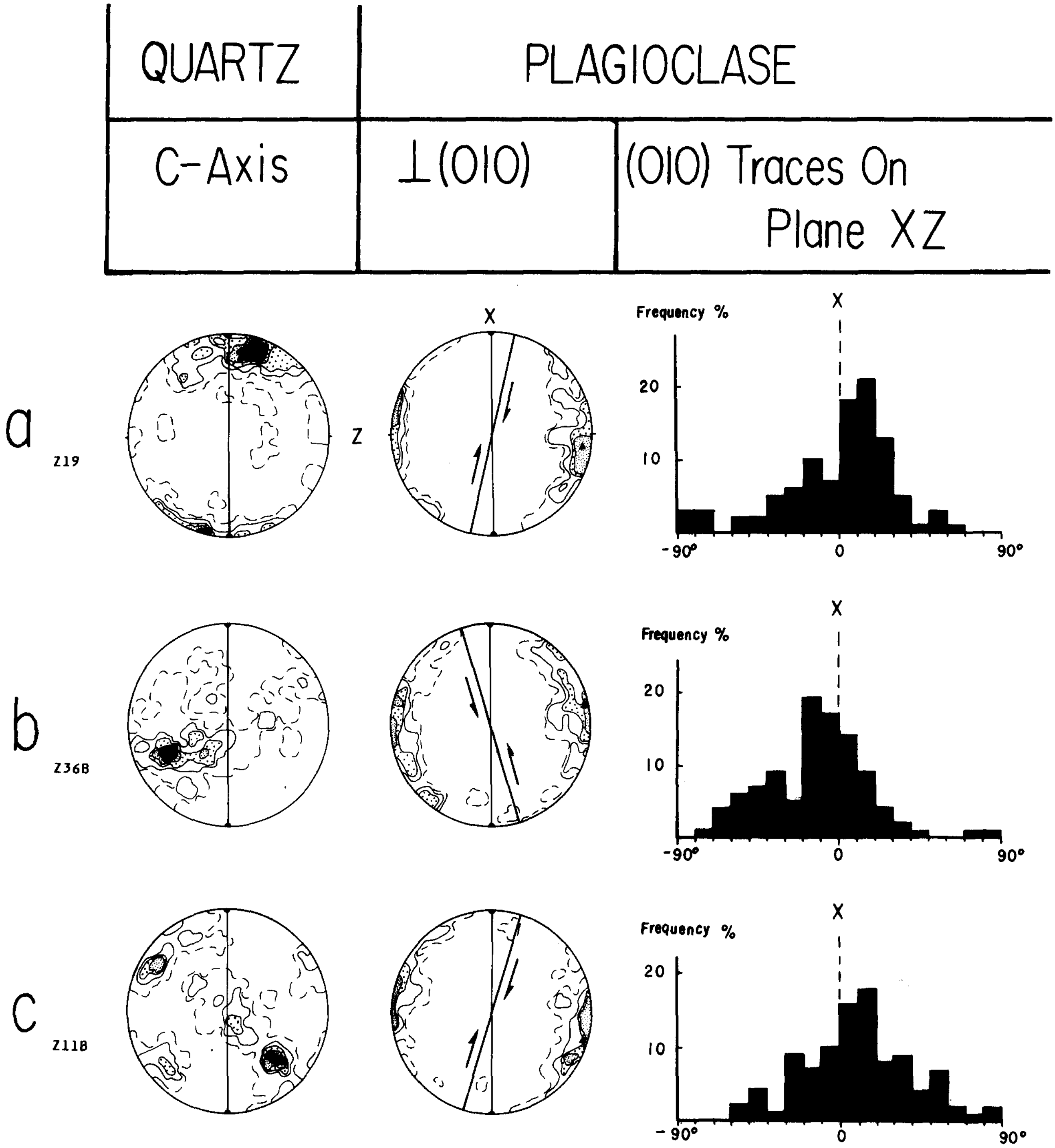

Fig. 5. Comparison between quartz and plagioclase orientations in quartz-bearing plagioclase-rich gneisses of Zabargad. (a) Sample Z19. Quartz: 100 measurements; contours: 1, 3, 5, 7, 9% per 1% area. Poles to (010) of plagioclase: 50 measurements; contours: 2, 4, 8, 12% per 1% area. (010) traces on plane *XZ*: 100 measurements. (b) Sample Z36B. Same as (a). (c) Sample Z11B. Quartz: same as (a). Poles to (010) of plagioclase: 100 measurements; contours: 2, 4, 8, 12%. (010) traces on plane *XZ*: 100 measurements.

5 shows the plagioclase (010) orientation, (010) trace orientation on the *XZ* section and quartz *c*-axis orientation measured in these samples. The following characteristics are clearly illustrated.

(a) (010) planes in plagioclase feldspars have a strong concentration at a low angle to the *XY* plane (foliation), indicating that (010) is indeed the dominant slip plane.

(b) Quartz *c*-axis preferred orientation patterns vary from one sample to another. In sample Z19, the *c*-axis maximum falls close to the stretching direction (*X*) of the finite strain frame, no girdle is present normal to the point maximum. Sample Z36B has a strong maximum of *c*-axes intermediate between the *Z* and *Y* axes within the girdle, being markedly asymmetric. And the *c*-axis pattern in sample Z11B is defined by unequally populated crossed-girdles with high opening angles.

(c) Both quartz *c*-axes and plagioclase (010) fabrics have a marked asymmetry with respect to the foliation and lineation. In addition, the preferred orientation of (010) traces in the *XZ* plane has an obliquity of the maxima to the *XY* plane.

The similarity of the plagioclase (010) fabrics indicates that these samples have similar deformation histories and the obliquities reflect non-coaxial strain paths. Hence it seems reasonable to suppose that the *c*-axis fabrics of quartz are related with the operative dislocation slip systems in the samples studied. The quartz fabric pattern having ⟨*c*⟩ mainly disposed close to the stretching direction (*X*) has been well documented by Bouchez *et al.* (1985), O'Hara & Gromet (1985), Blumentfeld *et al.* (1986) and Mainprice *et al.* (1986a). TEM studies show that this pattern is in fact produced by the dominant activity of the slip on $\{11\bar{2}0\}$ and/or $\{10\bar{1}0\}$ planes along the ⟨*c*⟩ axis (Mainprice *et al.* 1986a). The quartz *c*-axis fabric pattern in sample Z11B, defined by unequally populated crossed-girdles, can be attributed to a combination of $\{10\bar{1}0\}$ ⟨*c*⟩ and (0001) ⟨*a*⟩ systems together with a possible ⟨*c* + *a*⟩ slip direction (Lister & Dornsiepen 1982, Schmid & Casey 1986, Tubià & Cuevas 1986). Then it is an intermediate fabric pattern caused by the basal ⟨*a*⟩/prism ⟨*c*⟩ switch. It is well known from the experimental deformation studies that quartz, at lower temperatures and/or faster strain rates, has a dominant activity of the slip on (0001) along the ⟨*a*⟩ axis so that its aggregate develops a *c*-axis maximum parallel to the maximum compression direction (Tullis *et al.* 1973). However, at higher temperature and/or slower strain rates, and in hydrous conditions experimental studies demonstrate that $\{11\bar{2}0\}$ ⟨*c*⟩ or $\{10\bar{1}0\}$ ⟨*c*⟩ slip system become more important and a transition from basal ⟨*a*⟩ to prism ⟨*c*⟩ dislocation glide takes place (Tullis *et al.* 1973, Blacic 1975, Linker *et al.* 1984). In fact, all the tectonites with prism ⟨*c*⟩ slip and the basal ⟨*a*⟩/prism ⟨*c*⟩ switch fabric patterns are deformed at high-grade metamorphic conditions such as amphibolite or granulite facies. The fabric pattern in sample Z36B has been interpreted as due to predominantly ⟨*a*⟩ slip, possibly along (+) $\{10\bar{1}1\}$ or (−) $\{01\bar{1}1\}$ planes (Bouchez & Pêcher 1981, Lister & Dornsiepen 1982). We suggest that the pattern should be developed at high temperature. When quartz changes from the trigonal alpha phase to the hexagonal beta one, the glide on the rhomb planes becomes more important because the (+) rhomb $\{10\bar{1}1\}$ ⟨*a*⟩ system and (−) rhomb $\{01\bar{1}1\}$ ⟨*a*⟩ system are symmetrically equivalent (Starkey 1979, Lister & Dornsiepen 1982). This pattern (Fig. 5b) of quartz *c*-fabric was also found in the Saxony granulite terrain around a gabbro body (Behr 1964). Therefore, it seems to be certain that the Zabargad gneisses deformed at temperatures higher than 570°C, where quartz is in the beta-phase stability field. The basal ⟨*a*⟩/prism ⟨*c*⟩ mechanism switch takes place at 600–700°C (Lister & Dornsiepen 1982) and the dominant *c*-slip operates at 700–800°C (Mainprice *et al.* 1986a). In such conditions plagioclase feldspars, the dominant constituent in the tectonites, are deformed plastically by the dominant activity of dislocation slip on the (010) planes along the ⟨*c*⟩ and/or ⟨*a*⟩ direction (Mainprice *et al.* 1986b). If coexisting in a non-coaxial deformation field, the fabric asymmetries of both quartz *c*-axis and plagioclase (010)-plane with respect to the foliation and lineation, should give a consistent sense of shear for each sample. In fact, in terms of the model of Etchecopar (1977), Bouchez *et al.* (1983) and Simpson & Schmid (1983), we infer that the shear sense determined from the (010) fabric asymmetry of plagioclase feldspars is in concordance with those determined from quartz *c*-axis fabric. The shear sense is dextral in sections Z11b and Z19 and sinistral in Z36B (Fig. 1b & c).

Microstructures

The feasibility of (010) fabric asymmetry in plagioclase feldspars as an indicator of shear sense is supported by some microstructural observations in the Zabargad gneisses.

Asymmetric pressure shadows and retort-shaped crystals ('cornue grains') are frequently described as due to progressive deformation under a regime close to simple shear (Etchecopar 1977, Nicolas 1984), and these features allow the shear sense to be determined. Asymmetric pressure shadows indicating a sinistral shear have been observed in Z36B (Fig. 1b) and retort-shaped crystals indicating a dextral shear have been observed in Z11B (Fig. 1c). These shear senses correlate well with those determined both from the (010) fabrics of plagioclase and quartz *c*-axis fabrics.

CONCLUSIONS

Various arguments based on plagioclase crystal structure and considerations of likely slip systems, as well as LPO and microstructures, indicate the importance of the (010) slip plane in the high-temperature plasticity of plagioclase feldspars. Predominant glide on (010) has led us to develop a technique for directly determining the sense of shear from either (010) pole figures or histograms of the (010) trace in the *XZ* section, using the asymmetry of the (010) plane distribution with respect to the structural framework (foliation and lineation).

Measurements have been made on plagioclase feldspars (An25–A45) from the Zabargad gneisses (Red Sea) which were deformed at high temperatures of 750–950°C. A consistent sense of shear has been found using the (010) fabrics of plagioclase, quartz *c*-axis fabrics and other microstructural criteria. The method, quick and easy to apply, should be particularly useful in high-grade rocks where plagioclase feldspar is abundant and plastically deformed by dislocation movements.

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