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Microfracturing in relation to atomic structure of plagioclase from a deformed meta-anorthosite

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Abstract—Brittle deformation of Caledonian age affects the Harris (Scotland) meta-anorthosite and occurs as restricted areas with penetrative networks of shear fractures, frequently associated with pseudotachylite. Plagioclase is cut by both transcrystalline and intracrystalline fractures, the latter being of two types: those directly induced by the transcrystalline shear fractures and those which appear to be independent of them. Several orientations of intracrystalline fractures may occur in any one grain.

Whereas the orientations of the transcrystalline fractures may be independent of the plagioclase lattice, intracrystalline fractures are clearly crystallographically controlled. The most common intracrystalline fractures follow the main cleavage planes, (001) in all cases, but also frequently (010), $(1\bar{1}0)$ and (110). Other fracture directions, often conjugate, are very common. They include $(0\bar{2}1)$ and others near $(\bar{1}11)$–$(\bar{1}21)$ and $(11\bar{1})$–$(12\bar{1})$ close to the [101] and the [112] and $[1\bar{1}2]$ zones. These latter planes are those which also occur as cleavages in experimentally shocked microcline and as slip planes and deformation bands in experimentally deformed feldspars.

The easy slip and low cohesion in plagioclase can be explained in terms of periodic bond chains in the feldspar structure. The close agreement in orientation between the unusual cleavages developed in the meta-anorthosite and experimentally produced deformation bands in plagioclase suggests that fracture occurs along the deformation bands parallel to dislocation glide planes.

INTRODUCTION

The behaviour of basic plagioclase under deformation conditions near the brittle–ductile limit can be determined from the study either of the products of laboratory experiments or of naturally deformed rocks. The terms brittle and ductile are used here for the microscopic behaviour of plagioclase, which reacts either by fracture or by deformation of its lattice, and not for the bulk behaviour of a continuous medium in the rock-mechanics sense (Paterson 1978).

Both brittle and ductile deformation in the above sense are well developed in plagioclase in a meta-anorthosite from Harris, Scotland. The meta-anorthosite is of early Proterozoic age (Cliff *et al.* 1983) and was later deformed in small ductile shear zones of middle Proterozoic (Laxfordian) age (Borges & White 1980, Brown *et al.* 1980). It is cut by the Outer Hebrides Thrust of Caledonian age (Francis & Sibson 1973), along which is found a great variety of fault rocks including pseudotachylite produced during earthquake movement (Sibson 1975). The meta-anorthosite is affected by brittle deformation of Caledonian age in restricted areas (Macaudière & Brown 1982), where it can be followed in the field from undeformed rock through little fractured rock with isolated shear fractures (with or without cataclasite) to intensely fractured rock with pseudotachylite veins. As deformation increases, the spacing of the shear fractures decreases and the intervening crystals are more and more deformed. This is shown by the occurrence in plagioclase of both ductile (mechanical twins, undulose extinction) and of brittle deformation (intracrystalline fractures).

Pseudotachylite is generally considered to be produced during rapid stress release associated with seismic faulting at moderate depth (Sibson 1975, 1977). The deformed meta-anorthosite contains several apparent generations of shear fractures, which cut each other at low angles. This could be the result of a succession of deformation events with different stress fields (multiple event) or more probably of highly transient and variable stress during a single quasi-instantaneous earthquake (single event). In either case deformation must have occurred at very variable stresses and rates. At high to very high strain rates during earthquakes, microscopic deformation probably occurred mainly by fracture and grain rotation in cataclasites or by the production of a pseudotachylite melt. At low strain rates between earthquakes, deformation probably occurred mainly by mechanical twinning, by translation gliding and kinking and by dislocation movement. This paper deals only with intracrystalline fracture in plagioclase on an optical scale and its relation to atomic structure, the development of twinning is dealt with separately (Brown & Macaudière in prep.).

DESCRIPTION OF THE MICROSCOPIC INTRACRYSTALLINE FRACTURES

The most abundant mineral of the Harris meta-anorthosite is basic plagioclase (Witty 1975). The crystals have a polygonal shape with wide albite or pericline growth twins. Huttenlocher exsolution on the scale of 1–10 μm is clearly seen in most crystals and is younger than the growth twins (Figs. 1a & b). The plagioclase is in a low structural state (Nissen 1974). Other minerals are garnet, amphibole and rare clinopyroxene.

These minerals are affected by intracrystalline deformation to various extents. Garnet develops a network of small cracks, but otherwise is little deformed. Amphibole shows undulose extinction and the development of cleavage, sometimes with shear displacement. Deformation is most easily seen in plagioclase because of the presence of earlier twins and exsolution, which act as prominent strain markers, and enable the orientation and nature of intracrystalline fractures to be easily determined optically.

Types of intracrystalline fractures in plagioclase

The intracrystalline fractures in plagioclase can be classified according to their relationship to the transcrystalline shear fractures which affect the rock (Macaudière & Brown 1982). These latter cut across many crystals and are, as a result, unrelated to the crystallographic orientations of the individual crystals. They are frequently delineated by cataclasite and, where the deformation is intense, their spacing decreases below that of the size of individual crystals. Intracrystalline fractures on the other hand are restricted to individual crystals. They may be divided into two groups depending on their geometrical relationship to transcrystalline fractures; namely, those which are closely related to and have been *induced* by movement on transcrystalline fractures, and those for which no such relationship is visible and are *independent* of them.

(1) *Induced intracrystalline fractures.* The transcrystalline fractures may induce sets of parallel fractures at a low angle (15–30°) to the main fracture and with the same sense of movement (Fig. 1c). These induced fractures are often at an oblique angle to the twins, but in some cases they may curve round to become perpendicular to the twins and may coincide with a cleavage (Macaudière & Brown 1982, fig. 4c). The anisotropy of the crystal directly influences the propagation and orientation of the induced intracrystalline fractures.

The orientation of the induced fractures and their sense of movement are those corresponding to Riedel fractures. Though in some cases the plagioclase is noticeably plastically deformed (Macaudière & Brown 1982, fig. 5b), in other cases it is imperceptible apart from the above fractures (Macaudière & Brown 1982, figs. 4e & 5d). The same ambiguity thus exists on the scale of a crystal as on a larger scale, for fractures which can be interpreted as R and R′ shears, although no important plastic deformation has occurred (Macaudière & Brown 1982).

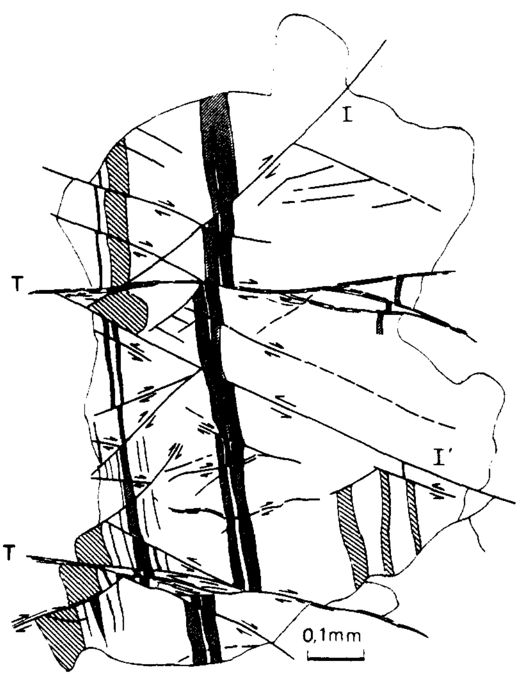

Fig. 2. Drawing of a plagioclase crystal from a pseudotachylite-bearing meta-gabbro-anorthosite (2 mm towards lower right from *b* in Macaudière & Brown 1982, fig. 5). The twins are pericline twins. An important set of transcrystalline shear fractures T produced conjugate sets of intracrystalline fractures, I, near $(\bar{1}11)$ and I′ further from $(1\bar{1}0)$ (see Fig. 4a), the latter dying out before or just beyond the grain boundaries.

(2) *Independent intracrystalline fractures.* Such fractures show no special spatial or geometric relationship with the transcrystalline fractures, but are found in all areas where the deformation is important. They occur as one or several sets of shear fractures, on which movement dies out in general as the grain boundary is approached. In many cases they coincide with a cleavage and are very clear cut; in other cases they are oblique and less well defined (Figs. 1a & d). Frequently, two sets of fractures give rise to lozenge shapes which are more or less symmetrical with respect to a set of twins (Figs. 1b, e & f). Occasionally, the intracrystalline shear fractures are parallel to sets of transcrystalline fractures (Fig. 2) and are thus transitional to induced fractures. In some rare rocks cut only by very widely spaced transcrystalline shear fractures, plagioclase close to such fractures is slightly cloudy, even though the rock shows no other signs of deformation. This is due to the presence of very small fluid inclusions in minute healed intracrystalline fractures, usually cleavage planes; the inclusions are unfortunately too small for study. These rare fluids could perhaps have made a slight contribution to the fracturing or more probably could be later and due to the saussuritization of the meta-anorthosite close to the Outer Hebrides Thrust Zone (Witty 1975, Macaudière & Brown 1982).

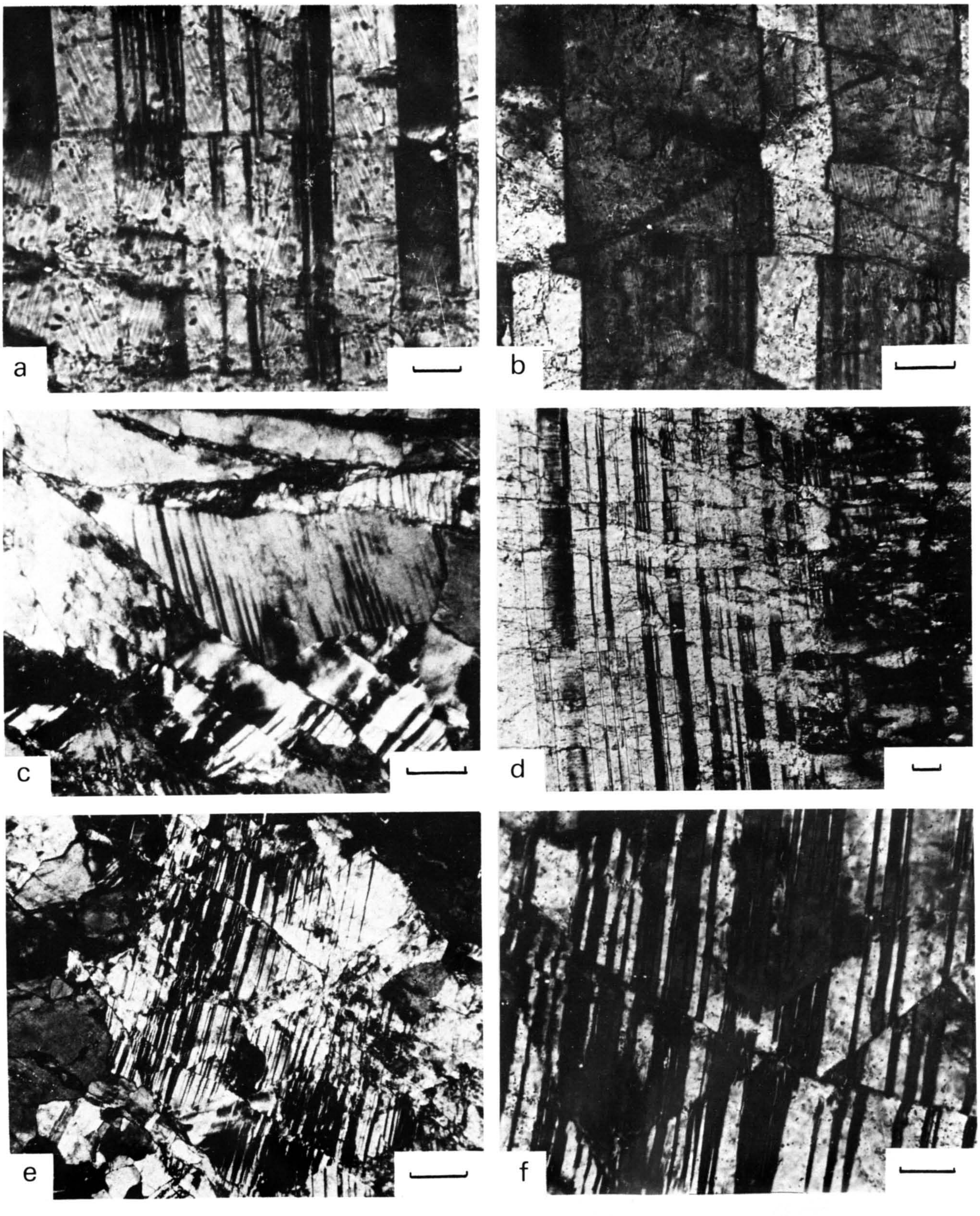

Fig. 1. Photomicrographs (crossed polars) of intracrystalline fractures in plagioclase from the Harris meta-anorthosite. (a) Detailed view of section perpendicular to [100] with vertical trace of albite twins; the faint oblique lines in the twins are Huttenlocher exsolution lamellae which are younger than the thicker growth twins. Horizontal (001) fracture (see d) (scale bar 0.05 mm). (b) Vertical trace of albite twins (one set showing faint oblique lines due to Huttenlocher exsolution lamellae) cut by irregular fractures with E–W trace near $(\bar{1}01)$, with NW–SE trace near $(0\bar{2}1)$ and with NE–SW trace near $(\bar{1}11)$ (scale bar 0.05 mm). (c) Induced fractures in plagioclase (lower centre) at angle of about 30° to and with same sense of movement as main E–W fracture with thin film of pseudotachylite. Induced fractures lie between $(\bar{1}\bar{1}1)$ and $(\bar{2}\bar{2}1)$ and are perpendicular to the trace of pericline twins (scale bar 0.2 mm). (d) General view of large crystal (for detail see (a)) perpendicular to [100] with trace of albite twins vertical and of pericline deformation twins horizontal on the right and in correctly orientated albite twins. Main E–W fractures are (001). They either die out laterally or sometimes deviate towards oblique NW–SE fractures near $(0\bar{2}1)$ (scale bar 0.1 mm). (e) General view of plagioclase crystal with conjugate fractures symmetrical to N–S pericline twins forming lozenge-shaped areas. The fractures are very close to $(\bar{1}21)$ and $(\bar{1}\bar{2}1)$ (b in Fig. 4b) (Scale bar 0.2 mm). (f) Detail from lower left part of (e). The NW–SE fracture swings round to approach $(\bar{1}\bar{1}1)$ (scale bar 0.05 mm).

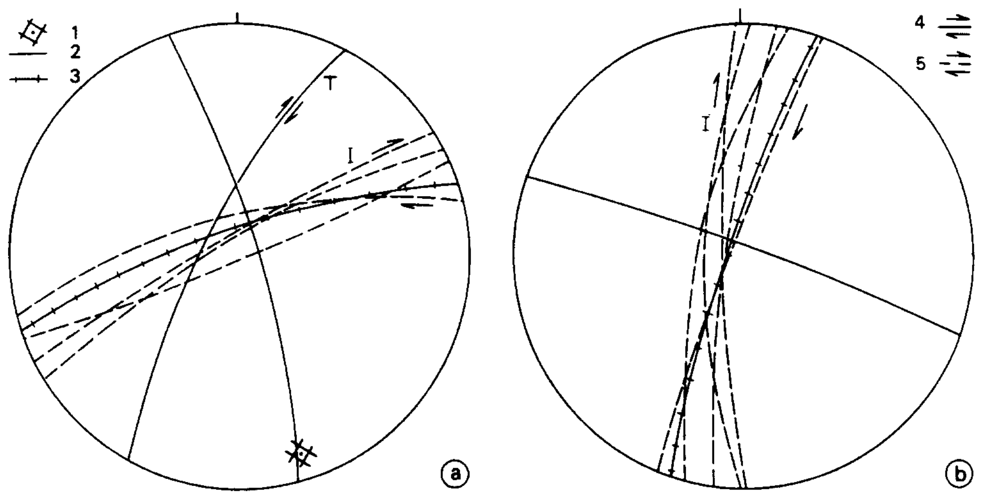

Fig. 3. Stereograms showing the spread of intracrystalline fractures (1) near (001) relative to the twin composition planes in two differently orientated crystals. (a) Intracrystalline fractures, I, linked to a transcrystalline shear fracture, T. (b) Set of isolated intracrystalline shear fractures in a plagioclase not cut by a transcrystalline fracture. (1) cleavage, (2) albite composition plane, (3) pericline composition plane, (4) transcrystalline shear fracture, (5) intracrystalline shear fractures.

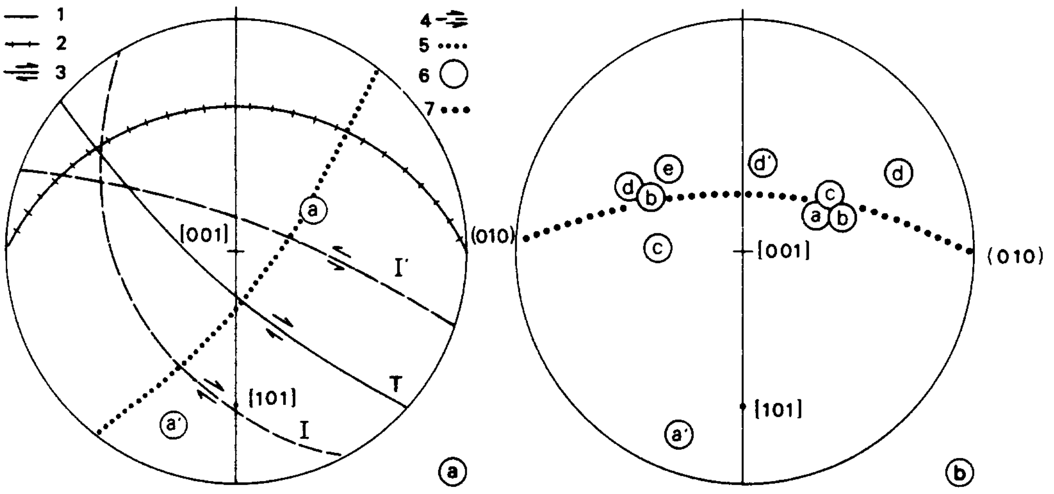

Fig. 4. Stereograms in the standard orientation of poles to conjugate fractures in plagioclase. (a) Crystallographic orientations of the fractures in Fig. 2. A set pseudo-symmetrical to I with respect to (010), if present would be close to parallel to the thin section. (b) Orientations of fractures from five plagioclases including that from Fig. 2(a). The poles lie close to the [101] zone with a weak tendency to be spread out in the [112] and $[1\bar{1}2]$ zones. (1) albite composition plane, (2) pericline composition plane, (3) transcrystalline shear fracture (4) intracrystalline shear fractures, (5) plane normal to zone axis of I, I' and T, (6) poles of maximum fracture concentrations, (7) [101] zone.

Crystallographic orientation of the intracrystalline fractures

Not all plagioclases develop intracrystalline fractures and it is probable that this is due to their position relative to transcrystalline fractures and their orientation relative to the local stress field. As deformation is so inhomogeneous on the scale of a crystal, it is impossible to even guess at the orientation of the transient and instantaneous local stresses which produced the intracrystalline fractures during earthquake movement. Thus, no attempt was made to measure the orientations of individual crystals relative to some external coordinate system.

The crystallographic orientations of the intracrystalline fractures were measured on a universal stage. The indices are quoted in relation to the lattice of the most abundant twin individual. On propagation from one twin to the other, indices will change from (hkl) to $(h\bar{k}l)$. Intracrystalline fractures have preferred crystallographic orientations which are presumed to be parallel to planes of weakness in the plagioclase. Transcrystalline fractures with cataclasite may have any orientation but it is possible that minor ones without cataclasite may follow stepwise crystallographic planes of weakness on a submicroscopic scale. The main planes of weakness are the cleavages and many crystals show intracrystalline fracture on (010) parallel to the albite composition plane. More commonly fracture occurs on or near (001) nearly perpendicular to the albite composition plane (Figs. 1a & d) and more or less parallel to the pericline composition plane (Fig. 1d, 3a & b), which in these

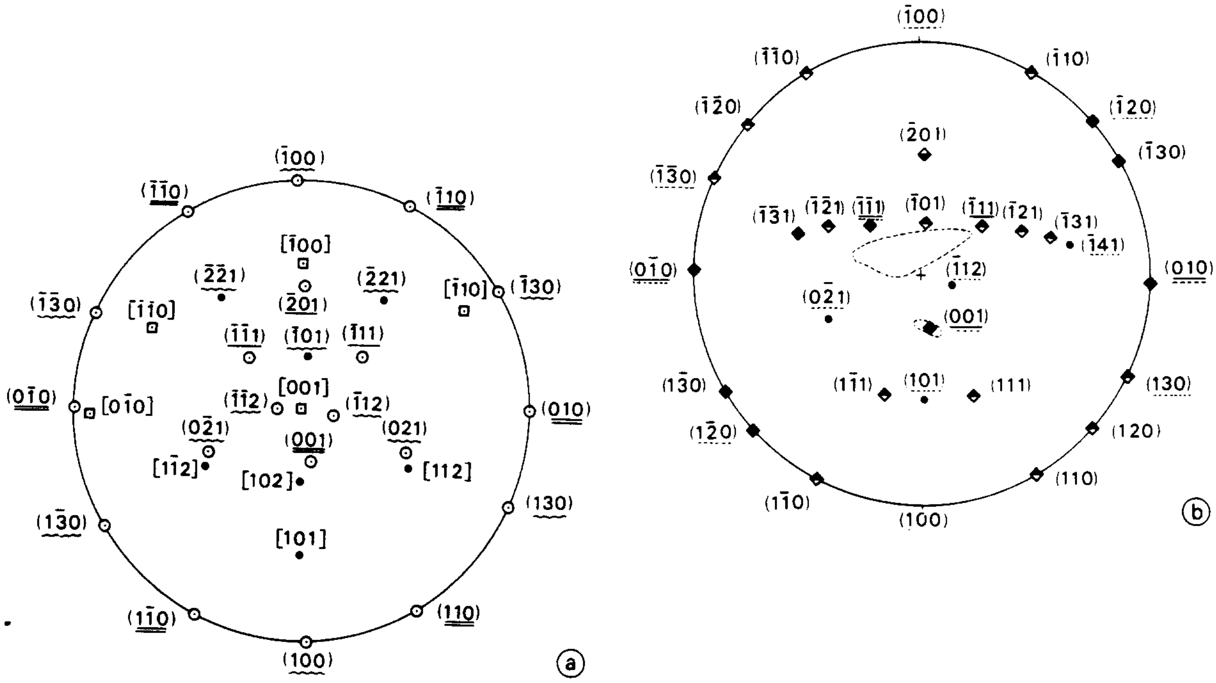

Fig. 5. (a) Stereogram of orientations of PBC directions ([ ]) and of predicted F_1 (—) and F_2(~) faces from Woensdregt (1982) for the orientation of An_{70} from Burri *et al.* (1967, p. 294) indexed on a $C\bar{1}$ cell with $c \approx 7$Å. For the 14Å average cell, all *l* indices should be doubled i.e. $(\bar{2}01)$ becomes $(\bar{2}02)$ and $(\bar{1}21)$ becomes $(\bar{1}22)$ etc. The composition planes of normal twins (0) and the twin axes of parallel twins (□) are shown for plagioclase. Common F_1 cleavages are shown by (=). (b) Stereogram of cleavages (—) and deformation lamellae (....) from shocked feldspars (data from Smith, vol. 1, 578–589). The slip planes observed by TEM from experimentally deformed feldspars (references in the text) are also shown (◆ plagioclase only, ◆sanidine only, ◆ both). For sanidine there is ambiguity when placed in a triclinic diagram as (*hkl*) and $h\bar{k}l$ are the same in a monoclinic lattice. Dashed fields show regions of optical deformation lamellae from Borg & Heard (1970, fig. 9).

plagioclases of composition An_{60-75} is very close to (001) (Brown & Macaudière in prep.). Intracrystalline fracture occurs rarely on $(0\bar{2}1)$ (Figs. 1b & d).

In the case of conjugate sets of fractures, a twin composition plane frequently occurs as a diagonal to the two sets, but the crystallographic orientations of the fractures may vary from specimen to specimen. Two such sets occur in the plagioclase shown in Fig. 2, their traces being approximately symmetrical with respect to the twins. The two sets of intracrystalline fractures (I and I′) are symmetrical with respect to the pericline composition plane, P; the transcrystalline fracture, T, is perpendicular to it. Their geometrical relations are shown in Fig. 4(a). Their indices are, however, not simple, as all these planes lie in the [110] zone (Figs. 4a & b). In most cases (Fig. 1e, f & 4b) the intracrystalline cleavage planes are more or less symmetrical with respect to (010), most of them lying close to the [101] zone.

DISCUSSION

Deformation features of plagioclase

Experimental deformation of feldspar single crystals (plagioclase, Borg & Heard 1970; sanidine, Willaime *et al.* 1979) has shown that most of the deformation occurs by fracture and cataclasis on or near cleavage planes at temperatures up to 700°C and strain rates of 10^{-4} to $2 \times 10^{-6}s^{-1}$, whereas at highter temperatures mechanical twinning (albite and pericline laws in plagioclase), slip and deformation lamellae are important (Fig. 5b). Plastic deformation was observed in these latter crystals by transmission electron microscopy (Marshall & McLaren 1977a & b, Willaime & Gandais 1977, Willaime *et al.* 1979, Kovacs & Gandais 1980, Scandale *et al.* 1983) and the slip systems determined (Fig. 5b). Most slip planes occur in the [001] and [101] zones. Similar features have been observed in feldspar-bearing rocks deformed naturally at lower temperature and strain rates (Debat *et al.* 1978, Sacerdoti *et al.* 1980).

Feldspars may also have been deformed at very high strain rates either naturally during earthquakes and shock deformation or in the laboratory. Such feldspars develop unusual cleavages, planar deformation features and twin-like features (Fig. 5b, data from Smith 1974, vol. 1, pp. 578–589).

Deformation of plagioclase in the Harris meta-anorthosite may also have occurred at high strain rates during earthquakes and it is interesting to compare these fracture directions with deformation features described above. The main intracrystalline fracture directions observed are parallel to normal cleavages, especially (001) (Fig. 3) but also to (010), $(1\bar{1}0)$, and (110). The unusual fracture directions lie close to $(0\bar{2}1)$ or to the planes $(\bar{1}01)$, $(\bar{1}11)$ to $(\bar{1}21)$ and $(\bar{1}\bar{1}1)$ to $(\bar{1}\bar{2}1)$ (Fig. 4b) in the [101] to [102] zones. They are thus very close to shock induced cleavages and to the dislocation glide planes in experimentally deformed feldspars (Fig. 5b).

It is probable that the unusual fracture directions, like the glide planes, are closely related to the lattice and structure of feldspar.

Structural considerations and conclusions

The *discontinuous* properties of feldspar such as morphology, twinning, cleavage and fracture, slip and dislocation movement intimately depend on the atomic structure. Feldspars are three-dimensional tektosilicates all with the same topology, as far as the main tetrahedral bonds, T–O–T, are concerned. The framework structure can best be understood in terms of chains of strong bonds and can be analysed into a small number of such periodic bond chains (PBC). Although the PBC theory was introduced to explain crystal morphology (Hartmann & Perdok 1955), it can equally well be used to explain all discontinuous properties. The crystal structure of high sanidine has recently been interpreted in terms of two types of PBC's, those involving only strong T–O bonds, and those involving K–O bonds as well (Woensdregt 1982). This analysis can be extended to triclinic feldspars which involve the same T–O PBC's (type 1), whereas the second type involves (Na, Ca)–O bonds in addition.

The discontinuous properties of basic plagioclase, indexed for convenience on a 7Å *c*-axis, are shown in Fig. 5(a). Following Woensdregt (1982) the main type-1 PBC's in order of increasing length are [001], $\frac{1}{2}[1\bar{1}0]$ and $\frac{1}{2}[110]$, [101], [100], $\frac{1}{2}[1\bar{1}2]$, and $\frac{1}{2}[112]$, [010] and [102]. F-type lattice planes parallel to two PBC's can be divided into two groups, F_1 having chains with only T–O bonds and F_2 having one chain with only T–O bonds and a second with (Na, Ca)–O bonds in addition. F_1 planes or faces in order of decreasing *d*-value are $(1\bar{1}0)$, $\frac{1}{2}(010)$, (001), (110), $(\bar{1}\bar{1}1)$, $(\bar{1}11)$ and $(\bar{2}01)$ and F_2 planes or faces are $(0\bar{2}1)$, (021), $(1\bar{3}0)$, $\frac{1}{2}(100)$, (130), $(\bar{1}\bar{1}2)$, $(\bar{2}\bar{2}1)$, $(\bar{1}12)$, $(\bar{2}21)$ and $\frac{1}{2}(\bar{1}01)$. The predicted F_1-planes are all very important observed faces (see Smith 1974, vol. 2, pp. 247–274) of which (001), (010), (110) and $(1\bar{1}0)$ are observed cleavages. The predicted F_2 planes are also frequently observed faces but none corresponds to a common cleavage. Furthermore, all F_1 and F_2 faces are composition planes of normal twins in plagioclase (Fig. 5a) except for $(\bar{2}\bar{2}1)$, $(\bar{2}21)$ and $(\bar{1}01)$ (Burri *et al.* 1967).

The unusual cleavage or fracture directions observed in plagioclase from the meta-anorthosite (Fig. 4b) are close to predicted F_1 or F_2 faces $\{\bar{1}\bar{1}1\}$, $\{\bar{1}11\}$ and $\{\bar{1}01\}$ and contain or nearly so the [101] and [102] PBC's, as shown in an [010] projection (Fig. 6a). A [101] projection is given in Fig. 6(b). It can be seen from these two projections that $(\bar{1}01)$, $(\bar{1}11)$ to $(\bar{1}21)$ and $(\bar{1}\bar{1}1)$ to $(\bar{1}\bar{2}1)$ are very reasonable fracture directions, as they break only a small number of T–O–T bonds. They may correspond to very poor cleavages which have as yet escaped detection in plagioclase, but occur in artificially shocked microcline. There is thus very good agreement between PBC theory and observed faces, composition planes to normal twins and cleavage or fracture planes.

The important role of these cleavage or fracture planes in the brittle deformation of plagioclase in the meta-anorthosite is shown by their frequent occurrence as intracrystalline fracture directions. Furthermore, they are close to important dislocation glide planes in plagioclase (Fig. 5b and Marshall & McLaren 1977a & b). In the case of (010) dislocation bands, microfractures have in fact been observed by TEM parallel to these bands (Marshall & McLaren 1977b). It is thus possible that rupture occurred along those same planes which occurred as deformation bands produced by dislocation glide at lower strain rates or higher temperatures. A TEM study of these feldspars is planned.

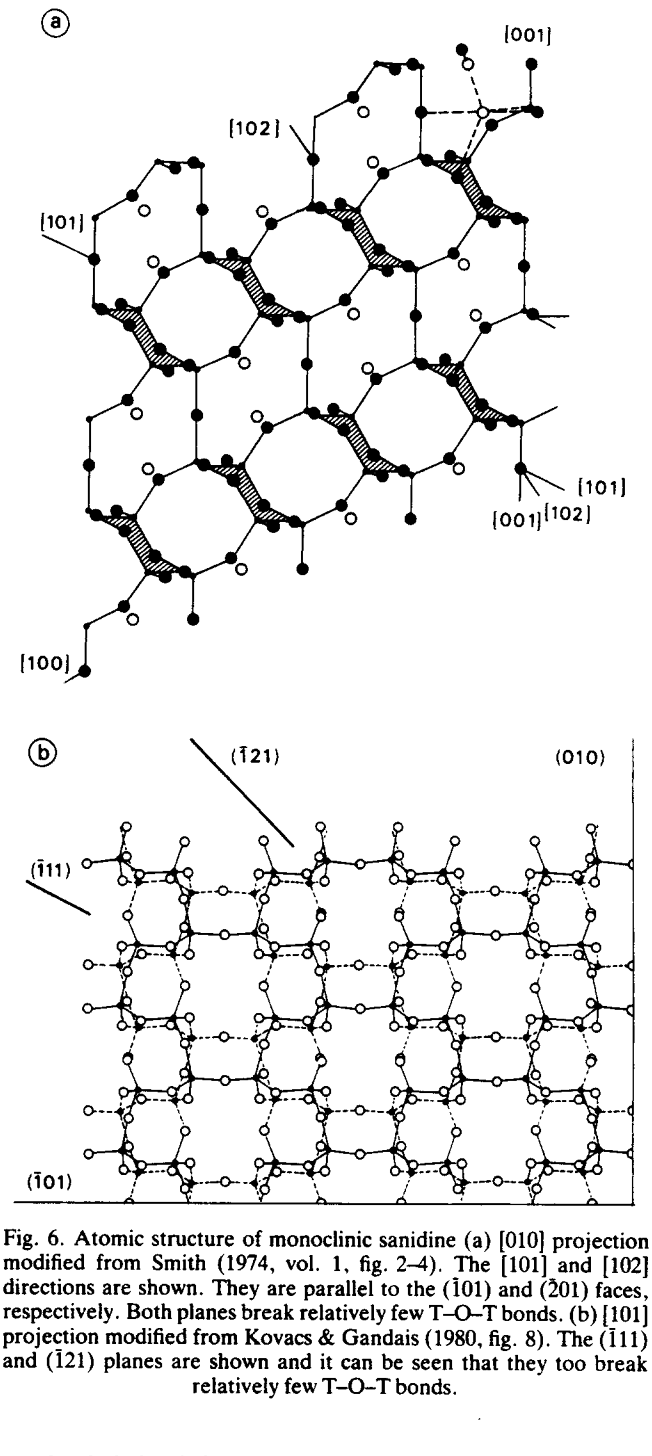

Fig. 6. Atomic structure of monoclinic sanidine (a) [010] projection modified from Smith (1974, vol. 1, fig. 2–4). The [101] and [102] directions are shown. They are parallel to the $(\bar{1}01)$ and $(\bar{2}01)$ faces, respectively. Both planes break relatively few T–O–T bonds. (b) [101] projection modified from Kovacs & Gandais (1980, fig. 8). The $(\bar{1}11)$ and $(\bar{1}21)$ planes are shown and it can be seen that they too break relatively few T–O–T bonds.

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