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Transcrystalline shear fracturing and pseudotachylite generation in a meta-anorthosite (Harris, Scotland)

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Abstract—The meta-anorthosite is locally deformed by brittle shear fracturing, which progressively increases from isolated fractures with little cataclasite to many generations of closely spaced fractures, the intervening rock being highly deformed, in both a plastic and brittle way. In most cases an E–W compression on gently dipping to steep reverse shear planes occurs, which we relate to a Caledonian thrust zone.

In places, the highly deformed rock is cut by pseudotachylite veins, which locally form networks. The pseudotachylite is generally intrusive, but does not appear to be related to movement on major slip surfaces. Very locally it may have formed *in situ*. Pseudotachylite only occurs in highly deformed rock, is only very occasionally deformed itself and, thus, generally represents at each locality the last stage of a complex deformation history, as if its presence welded the rock and prevented further deformation.

These striking differences from the country-rock gneisses (in which pseudotachylite occurs on well developed fractures in very slightly deformed rock) are considered to be due to the low anisotropy of the meta-anorthosite, to its lower shear strength and to the easy propagation and branching of the shear fractures in plagioclase. The source of the heat necessary to generate the pseudotachylite melt is not clear—it may come from crack propagation as well as frictional sliding.

INTRODUCTION

THE BEHAVIOUR of feldspar in brittle or ductile deformation has generally been studied in quartzo-feldspathic rocks, where it is largely masked by that of quartz. Anorthosites are the only common nearly monomineralic feldspar rocks and the Harris meta-anorthosite was chosen for the study of both ductile shear zones (Brown *et al.* 1980) and brittle fracture zones with pseudotachylite. This paper deals with the geometrical relations between transcrystalline brittle fractures and pseudotachylite. Twinning and intracrystalline brittle fracture in plagioclase are dealt with elsewhere.

Pseudotachylites are rare but fairly wide-spread rocks occurring frequently in Precambrian gneisses throughout the world and in important younger fault zones—overthrusts (Outer Hebrides Thrust Zone, Scotland, Sibson 1975) or transcurrent faults (Alpine Fault Zone, New Zealand, Wallace 1976, Sibson *et al.* 1981). They are dark to black glassy-looking discordant veins cutting the fault rocks or the country rock. Though controversy exists over their nature and their mode of formation, all authors on pseudotachylite agree that they are associated with highly crushed rocks (cataclasites), but disagree to what extent actual fusion has occurred (see for example, Wenk 1978).

The Outer Hebrides Thrust Zone of supposed late Caledonian age (Francis & Sibson 1973) cuts Lewisian gneisses and the fault rocks vary from cataclasite and pseudotachylite to mylonite in a general sense from south to north and from west to east (Jehu & Craig 1923, 1925, 1926, 1927, 1934, Sibson 1975, 1977, 1980). Isolated occurrences of pseudotachylite also occur up to 10–20 km to the west of the thrust zone. The main thrust zone just skirts the east coast of Harris, where Lewisian rocks of varied composition including meta-anorthosite occur.

FIELD RELATIONS

The South Harris meta-anorthosite (Witty 1975, Heyes 1978), covers about 10 km^2 and is well exposed (Fig. 1). It is layered, varies in composition from anorthosite to gabbro, and occurs in a tight fold with a nearly vertical axis. It has granulite facies mineralogy of Scourian (Archaean) age and is cut by ductile shear zones of high amphibolite facies and Laxfordian (Proterozoic) age (Witty 1975, Heyes 1978, Borges & White 1980, Brown *et al.* 1980). Sporadic occurrences of later pseudotachylite have been reported (Jehu & Craig 1927, Witty 1975, Heyes 1978). On the coast to the SE, highly crushed and completely saussuritized anorthosite occurs above a thrust fault dipping gently to the SE. Below the thrust, magmatic and metamorphic structures are well preserved, but the meta-anorthosite is highly saussuritized for a distance of about 600 m to the NW from the thrust. Only to the NW of this line is fresh meta-

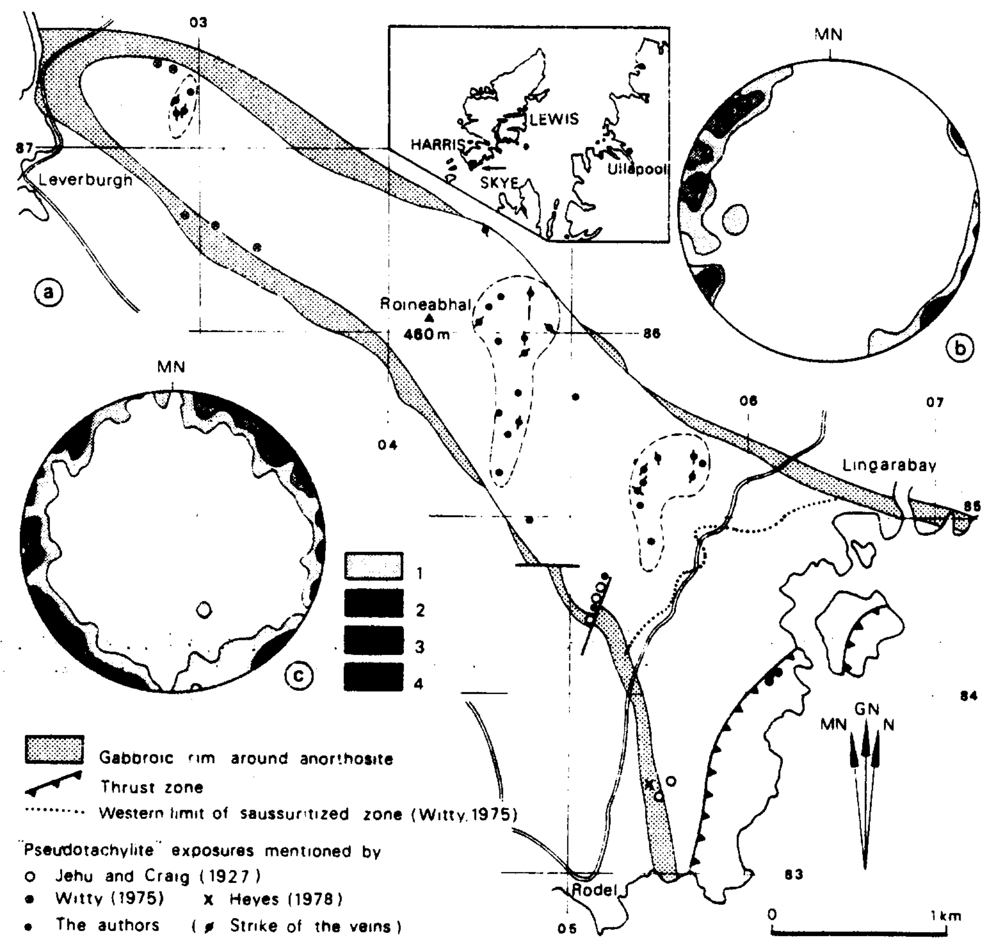

Fig. 1. (a) Geological sketch map of the meta-anorthosite, Isle of Harris, Outer Hebrides (57°46′ N, 6°58′ W shown by arrow on inset map of NW Scotland). MN magnetic North, GN grid North. Metagabbro rim from Witty (1975). The "pseudotachylite" occurrences to the South of the dotted line from Jehu & Craig (1927), Witty (1975), and Heyes (1978), could not be confirmed by the authors, whereas those to the Northwest were. However, Maddock (personal communication 1981) claims to have found true pseudotachylite on the thrust plane at grid reference 058835. (b) Stereogram of mesoscopic pseudotachylite-bearing veins (22 measurements) showing very steep dips and strikes mainly between 0–40° and near 140°. (c) Stereogram of ductile shear zones of Proterozoic age in meta-anorthosite for comparison (205 measurements) [For (b) and (c) upper hemisphere; contours (1) 0.5–1%, (2) 1–1.5%, (3) 1.5–2% and (4) over 2% of the points].

anorthosite to be seen. We, thus, exclude from this study the strip between the road and the coast (Fig. 1a) as we found no unequivocal pseudotachylite there (i.e. that showed features as described below), in spite of a careful search, and the intense saussuritization precludes study of the fracturing.

Areas of brittle deformation are shown in Fig. 1(a). In the field the transition from undeformed to pseudotachylite-bearing meta-anorthosite takes place over a distance, which varies from less than 1 m to up to 20 m. On approaching such a zone, the pink undeformed meta-anorthosite gradually becomes whitened, its structure becomes more and more masked by the presence of closely spaced fractures and finally single or anastomosing veins of black pseudotachylite appear, generally nearly parallel to the fractures. The pseudotachylite forms only a very small fraction of the deformed volume (10^{-3} to 10^{-6}). The veins are rarely thicker than 10–20 mm and individual veins can be followed up to a few metres, though zones with discontinuous veins can be traced for up to 200–500 m along their trend. In some areas networks and finally breccias with angular or rounded fragments occur, which rarely exceed 200–500 mm in thickness. The veins never occur in completely undeformed meta-anorthosite. The pseudotachylite is definitely later than the ductile shear zones of Laxfordian age, as occasionally such zones are cut at high angles by veins or even brecciated by pseudotachylite networks.

MICROSCOPIC STUDY OF PSEUDOTACHYLITE-BEARING DOMAINS

The Harris anorthosite varies from a meta-anorthosite (sometimes garnet-bearing) to a meta-gabbro (Witty 1975, Heyes 1978). Though the massif is layered, the rocks themselves are only weakly foliated. Plagioclase (An_{80-65} in the meta-anorthosite to An_{55-45} in the meta-gabbro) from 3 to 10 mm with straight or slightly curved grain boundaries is generally twinned on the albite and pericline twin laws with Huttenlocher exsolution, when of suitable composition; these structures can be used as markers for the deformation. Plagioclase is generally transparent and unaltered. The other minerals are garnet (generally with a symplectic rim of amphibole and

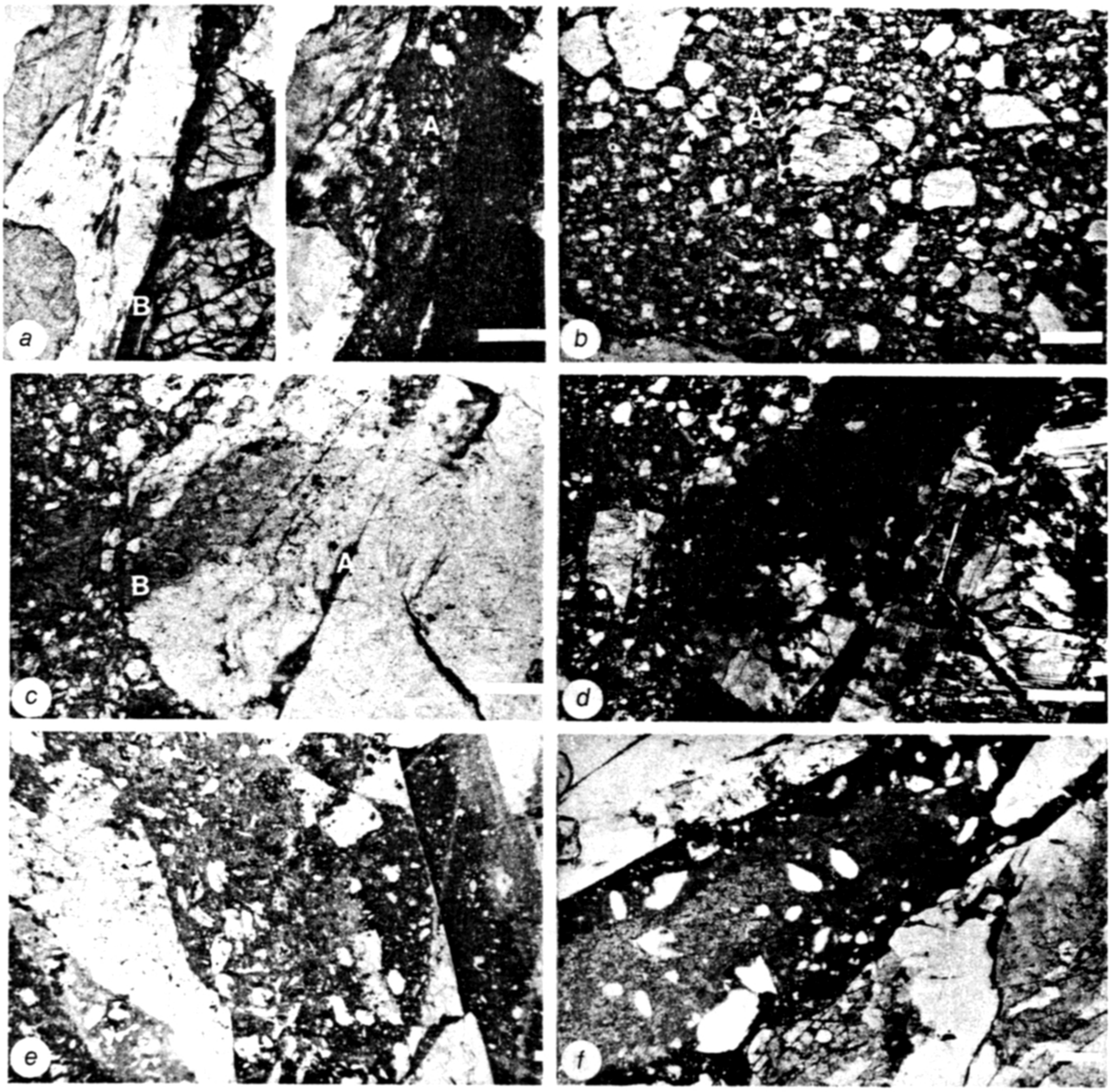

Fig. 2. Different types of deformation products (scale bar 0.2 mm). (a) Isolated shear with a strip of cataclasite (A) and a thin film of pseudotachylite (B) (plane polarised light and crossed polars). (b) Heterogeneous cataclasite with a few clasts with early pseudotachylite just to left of (A) (plane polarised light). (c) Pseudotachylite vein (A) cuts plagioclase crystal, certain parts of which (B) are locally isotropic but undisplaced (plane polarised light). (d) The same view with crossed polars. (e) Variation in colour and clast distribution in pseudotachylite (plane polarised light). (f) Banding and variation in crystallite distribution near the tip of a pseudotachylite vein (plane polarised light).

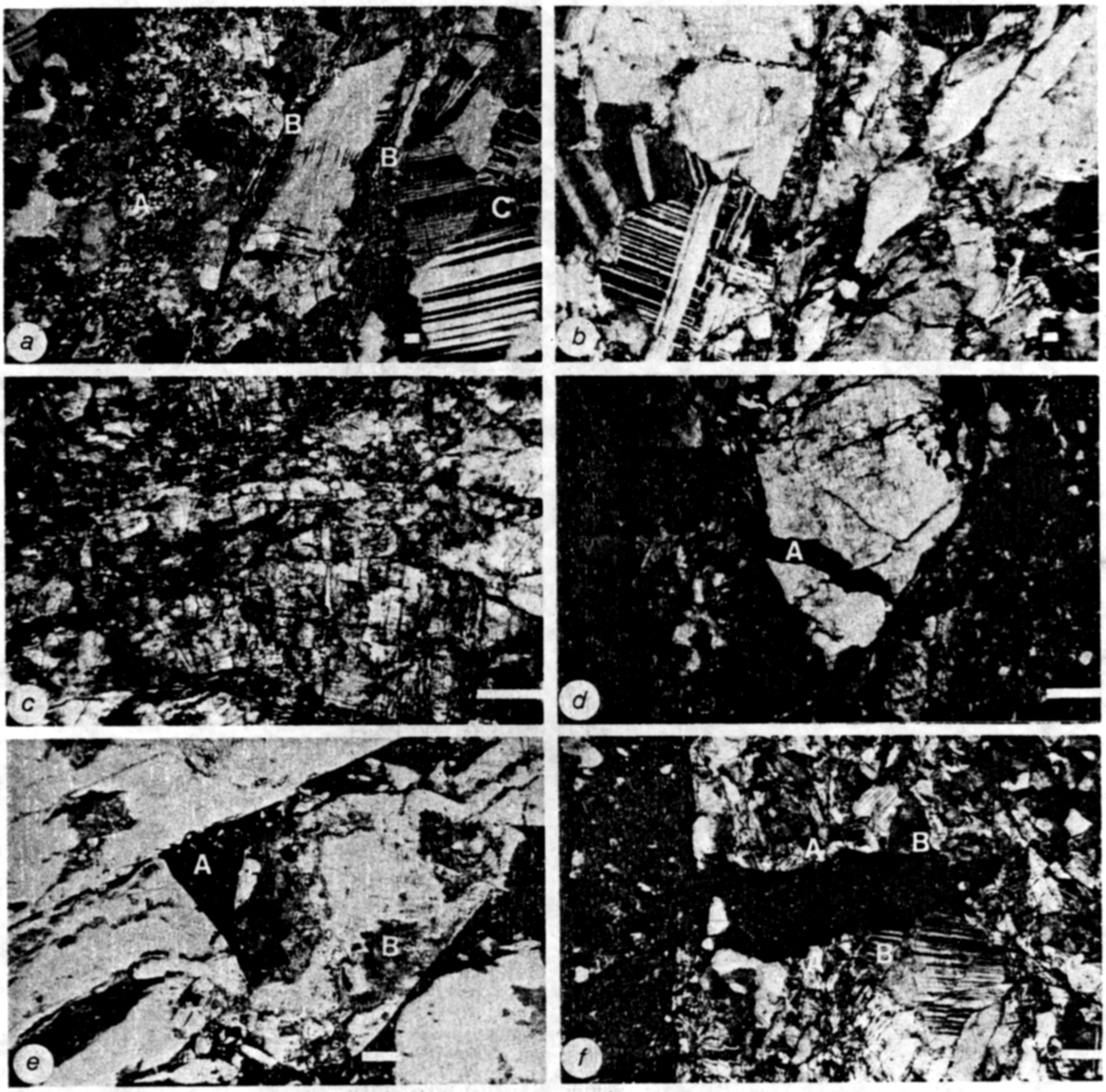

Fig. 3. Stages in the fracturing (scale bar 0.2 mm). (a) Double brittle shear cutting a rock with a ductile Laxfordian shear zone. From left to right: Laxfordian shear zone (A), double shear zone with deformed and broken plagioclase (B), undeformed rock (C). (b) Multiple sets of shears. (c) Brittle deformation affecting the whole rock. Pseudotachylite emplacement. (d) Simple dilatational vein of pseudotachylite (A). (e) Brecciation with more or less rounded clasts in late pseudotachylite (A), one clast contains early pseudotachylite (B). (f) *In situ* replacement of deformed plagioclase in veinlet without displacement of the vein margins as shown by positions of brittle shears (A and B).

plagioclase), amphibole and rare clinopyroxene (partially altered to amphibole) indicating a slight static retrograde metamorphism of the primary granulite facies mineralogy (Witty 1975, Heyes 1978) earlier than the ductile Laxfordian shear zones (Witty 1975, Heyes 1978, Brown *et al.* 1980).

A detailed study of the occurrence of pseudotachylite in the unaltered anorthosite shows that it is not linked to a specific set of megafractures. A microscopic study shows that the whitening of the rock is due to the appearance and development of thin (< 1 mm) cataclastic zones, which progressively invade the anorthosite. Pseudotachylite only occurs in such zones and generally only in the most deformed parts, but even so its occurrence is sporadic. The deformation products can be divided into cataclasites and pseudotachylites.

Cataclasite series (Figs. 2a–c)

The fine grained products in the shear fractures are cataclasites rather than mylonites (Sibson 1977, White *et al.* 1980), as they result from attrition of the minerals. They have highly variable grain size and highly angular grain shape with no shape fabric (Fig. 2b). Contacts with the undeformed rock are generally abrupt. In a few cases there is a gradual transition from highly cataclastic crystals through microfractured crystals to slightly deformed crystals. Movement on the shear fractures is generally very small even on the scale of a thin-section.

Plagioclase has been plastically deformed to some extent, but the main mechanism of grain reduction is brittle fracturing. The material must have recrystallized to a very slight extent to give the rock its cohesion. The cataclasites are always pale in colour in hand specimen and generally colourless in thin section, in marked contrast to the pseudotachylites.

Pseudotachylites (Fig. 2)

The pseudotachylites are characterized by a dark-coloured optically isotropic matrix containing various dispersed objects. The different types in the Harris anorthosite can be classified on the following basis:

(1) The colour of the matrix in unpolarized light (Fig. 2e) varies from pale brown to almost opaque black and may be uniform in the centre of cross-cutting veins or zoned at vein margins or in small veins (Fig. 2f).

(2) The dispersed objects (Figs 2e & f) consist of debris or clasts of the rock or minerals and crystallites which have grown in the isotropic matrix. The smaller fragments are mainly plagioclase (amphibole and garnet fragments are much less frequent than their modal abundance in the rock would suggest). In pseudotachylite-rich veins or breccias the fragments generally have an angular shape; sometimes they are simply displaced like pieces of a puzzle (Fig. 3d). In networks on the contrary, the fragments are often highly rounded and may be only coated by a thin film of pseudotachylite. Crystallites vary in volume percentage of the pseudotachylite, but their abundance is generally low. They may be found (a) randomly orientated, (b) preferentially orientated giving rise to a flow banding (Fig. 2f), (c) in spherulites, sometimes in mutual contact or (d) radially overgrowing a mineral fragment, generally plagioclase. No evidence of vesicles was found in any of the pseudotachylites.

(3) The structure of the pseudotachylite may be homogeneous or inhomogeneous, layered or with flow banding and with gradational or sharp boundaries.

The development of brittle shear fractures

The progressive deformation of the meta-anorthosite through the development of brittle shear fractures can be divided into three stages depending on the spacing of fractures and the degree of deformation of the rock between the fractures. The shear fractures rarely exceed a few mm in thickness and movement on them is of the order of 1–10 mm. As the spacing of the shear fractures decreases, ductile and brittle deformation of the intervening rock increases rapidly.

(1) First stage—the development of isolated shear fractures in an otherwise undeformed rock. Hand specimens of such rocks show little or no sign of deformation. In thin section, thin isolated shear fractures occur that separate domains which at first are undeformed, but as their spacing decreases to about a few mm, traces of deformation can be seen between shears in plagioclase crystals such as mechanical twins or slight intracrystalline fracturing (Fig. 3a). In some places, the fractures widen and show intense granulation of the minerals resulting in the formation of ultracataclasite. As the deformation increases, subsidiary sigmoid-shaped fractures link the main shear fractures and make an angle of about 20° with them; they are geometrically similar to Riedel fractures (with $\varphi \simeq 40°$ where φ is the angle of internal friction from the Mohr–Coulomb construction) as their angular relations and shear senses are those of R and R' fractures, but formed under conditions very far from those of steady-state plastic deformation required to form true Riedel fractures.

(2) Second stage—the formation of a network of shear fractures accompanied by further intracrystalline deformation (Figs. 3b and 4). This stage is frequently accompanied by the occurrence of isolated veins of pseudotachylite. Many generations of shear fractures occur, often with induced second-order fractures, and their geometric and kinematic interpretation becomes complex (Fig. 4).

(3) Third stage—intense fracturing and comminution of the rock. There are now no undeformed compartments (Fig. 3c) and the rock becomes chalky white in hand specimen. Pseudotachylite occurs at this stage, often as networks of veins or as breccias (Fig. 5). The plagioclase between the shear fractures is intensely deformed through the development of closely spaced mechanical twins and intracrystalline shear fractures (Fig. 3c).

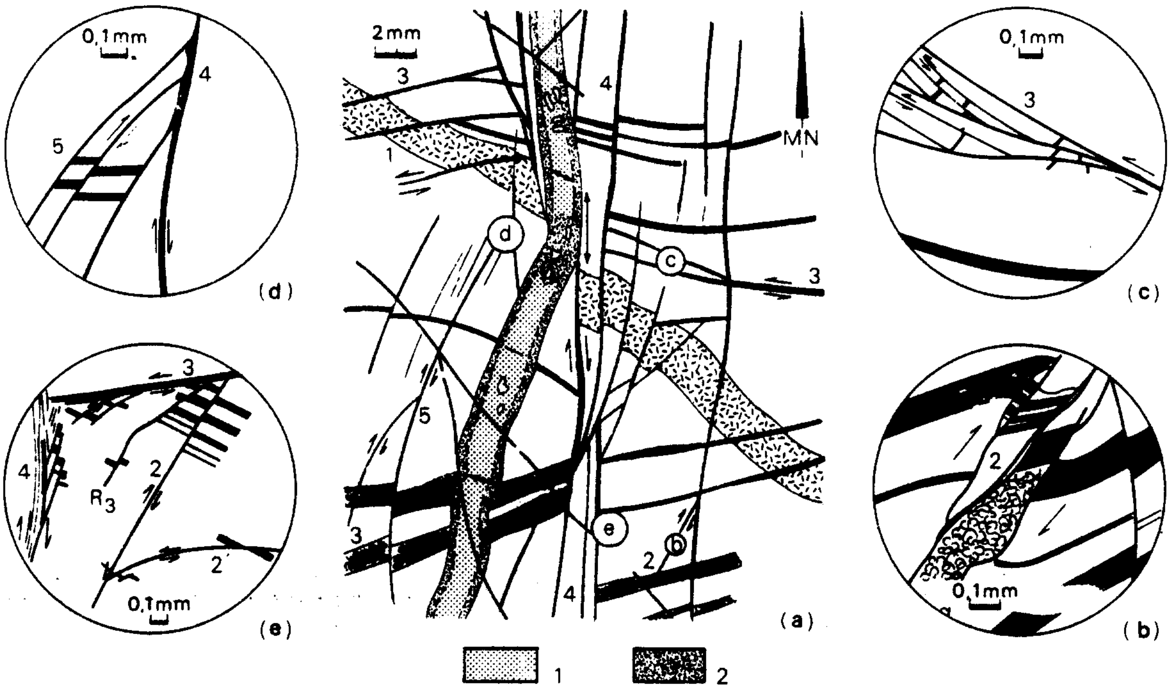

Fig. 4. Development of multiple shears and occurrence of a vein of pseudotachylite. (a) Thin section in a horizontal plane (MN, Magnetic North; ornament 1, light brown pseudotachylite; ornament 2, dark margins). (b) – (e) Details from the thin section leading to the following chronology: (1) a small Laxfordian ductile shear 1 acts as a marker; (2) a weakly developed set 2 of apparently dextral shear fractures is accompanied by its conjugate set 2' [visible in (b) and (e)]; (3) a more well developed apparently sinistral set 3 accompanied by mm thick cataclasites. In some places a single shear is split into a sheaf-like array of fractures before dying out [visible in (c)]. Set 3 induced second-order fractures R_3 which curve in an unexpected way, probably due to the influence of the cleavage anisotropy of plagioclase [visible in (e)]; (4) the main set 4 shows true dextral movement as the section was orientated to show real throw. [visible in (a) (d) and (e)]. It induced set 5 second-order shears on the scale of a crystal [visible in (e)] or on a transcrystalline scale [visible in (a) and (d)]; (5) dilatational N–S pseudotachylite vein follows preexisting shear fractures 4 and 5.

Fracturing and pseudotachylite geometry

The complexity of the shear movements which produced only cataclasites possibly suggests a similar complexity for pseudotachylite formation. If each shear movement produced pseudotachylite, one would expect to have many generations of cross-cutting pseudotachylite and early pseudotachylite might often be deformed by later brittle shear zones. The situation is in fact much simpler, as at least 90% of all pseudotachylite is later than all the shearing movements; it is only affected (a) by brittle fractures which cut the whole anorthosite (see Fig. 8c) and have a spacing of about 0.1 m and (b) by closely spaced brittle fractures about 1 mm apart, restricted to the pseudotachylite and probably due to thermal contraction.

Up to two generations of pseudotachylite exist in any one specimen, one early and rare, the other late, varied and abundant, though regionally this may be an oversimplification.

(1) Early pseudotachylite (Pst I, less than 10% by volume of pseudotachylite) is pale brown, often flow banded, cut sometimes by late shear fractures and frequently by late pseudotachylite (Pst II). It is never found in wide veins. It is found (a) in discontinuous streaks or films on planar shear fractures, (b) within banded cataclasites in mm thick shear fractures, (c) in contact with the margins of wide veins of late pseudotachylite (Pst II), (d) as angular fragments in certain heterogeneous cataclasites (Fig. 2b) and (e) in rounded 'pebbles' in late pseudotachylite breccias (Fig. 3e). This early pseudotachylite is thus older than the late pseudotachylite and older than, or of the same age as, the last shear fractures (Figs. 6a & b). It is never plastically deformed as found farther north by Sibson (1980).

(2) Late pseudotachylite (Pst II, more than 90% by volume of pseudotachylite) is pale grey–brown to dark brown. Several (rarely more than two) generations may cut each other, but they are always later than the shear fractures. It occurs in thin networks, in cross-cutting veins (Fig. 4a) or as a matrix to coarse breccias or pseudo-conglomerates (Fig. 5a). Typically two generations of late pseudotachylite occur:

(i) Pst IIa, earlier, often invading highly deformed and fractured zones on thin anastomosing surfaces sometimes to dead-ends, highly charged with debris and of varied and heterogeneous structures and

(ii) Pst IIb, later, in sharp veins cutting Pst IIa, nearly free of small debris, dark in colour with a homogeneous structure and few crystallites. The structure becomes more complicated and the pseudotachylite develops colour and structural zoning in narrow ramifications (Fig. 6a).

There is no way to determine the time interval (seconds or millions of years) between the different

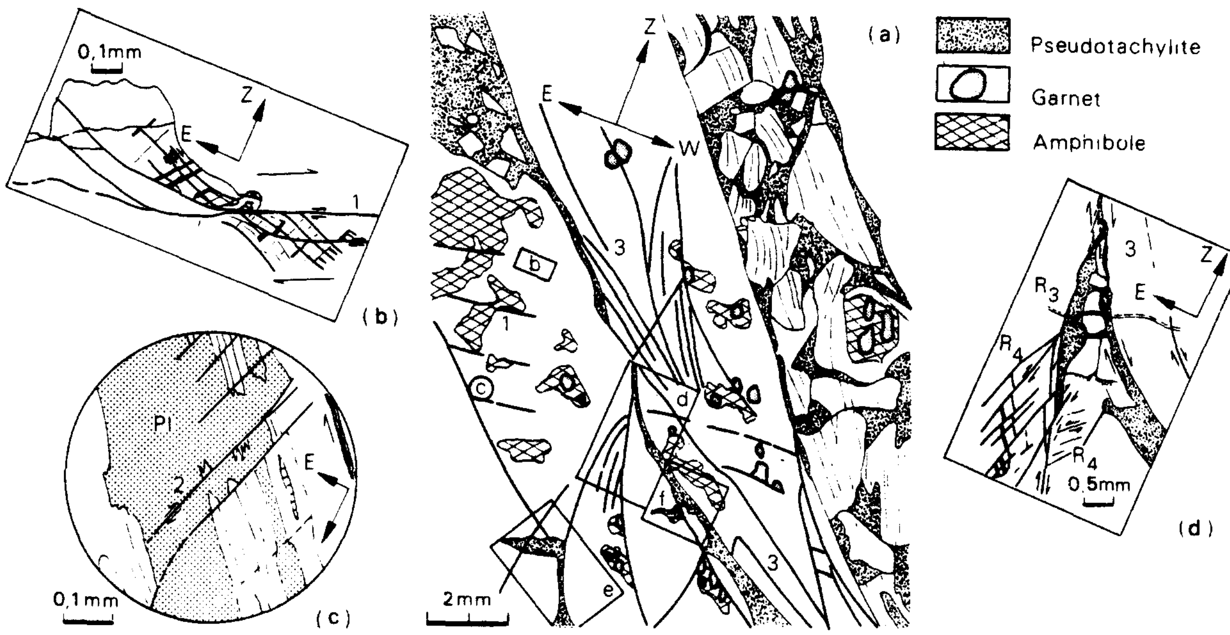

Fig. 5. Multiple fractures and occurrence of a pseudotachylite breccia. (a) Thin section in E–W vertical plane, Z vertically up. (b) – (d) Details from the thin section. (e) and (f) Positions of Figs 6(a & b). The following chronology can be established: (1) An older set 1 of nearly flat reverse shears with apparent dextral movement [visible in (a) and (b)] (2) A well represented set 2 of very thin steep reverse shears [visible in (c)]. (3) The main set 3 of normal dextral shear fractures. It induced R_3 second order fractures which in their turn induced R_4 and R'_4 Riedel-like fractures [visible in (d)]. (4) Emplacement of the main pseudotachylite veins. The pseudotachylite breccia to the right of (a) contains only slightly misorientated clasts with set 3 fractures.

generations of pseudotachylite, but in our opinion they probably belong to the same deformation event. The older may have been emplaced during late shearing and the younger during dilatation at stress drop.

Mechanisms of emplacement of the pseudotachylite

A detailed study of the pseudotachylite has shown that several processes, often simultaneous, have been responsible for its emplacement. The emplacement conditions and the microscopic characteristics of the pseudotachylite argue strongly in favour of its having been molten at some stage.

(1) Simple dilatation in an injection vein. The form of the vein may be simple or complex; if it follows a network of pre-existing fractures, it may jump from one to another, but the opening direction can be determined using markers (Figs. 3d and 4a).

(2) Dilatation and brecciation. The dilatation does not occur on one surface, but the pseudotachylite invades a volume of the rock with varying degrees of movement or attrition of the fragments.

(a) Simple brecciation. The pseudotachylite invades a volume of rock and separates the fragments, which can be fitted back together like a puzzle (Fig. 5d).

(b) Brecciation with attrition and rounding of the fragments. When markers exist which show that movement has been small (e.g. little or no rotation of set 3 fractures in the breccia in Fig. 5a), one can generally not reconstruct the fragments, even in different planes. In highly fractured zones, one can suppose that the smaller fragments are now dispersed in the pseudotachylite. This mechanism cannot be invoked where the fragments are round and it is probable that thermal spalling and melting produced the rounding.

(c) Brecciation and transport. Some of the thick veins with rounded fragments may require transport of up to several metres as fragments from different layers of the meta-anorthosite may coexist, e.g. anorthosite, garnet–anorthosite, gabbro.

(3) Replacement. In some cases the pseudotachylite occurs without dilatation and injection and it appears to have formed *in situ* by the replacement of more or less deformed crystalline material by isotropic material (Figs. 2c & d). This can also be seen in certain dead-end veinlets in highly deformed material (Pst IIa, Fig. 3f) or even on the edges of wide veins (Pst IIb) which are corroded, the pseudotachylite occurring in undeformed crystals.

GEOMETRIC ANALYSIS

Microscopic observations described in the previous section showed that late pseudotachylite is dilatational and does not usually follow shear fractures. The orientations of shear fractures and pseudotachylite veins for one specimen are given in Fig. 7. Shear fractures of all generations range in strike from about 55–100° (Fig. 7a), whereas pseudotachylite veins of all generations are spead out with a weak maximum near 30–40° in strike (Fig. 7b).

On separating shear fractures with early pseudotachylite (Pst I, Fig. 7c) from dilated fractures with late pseudotachylite (Pst II, Fig. 7d), it can be seen that there is a good correlation between early

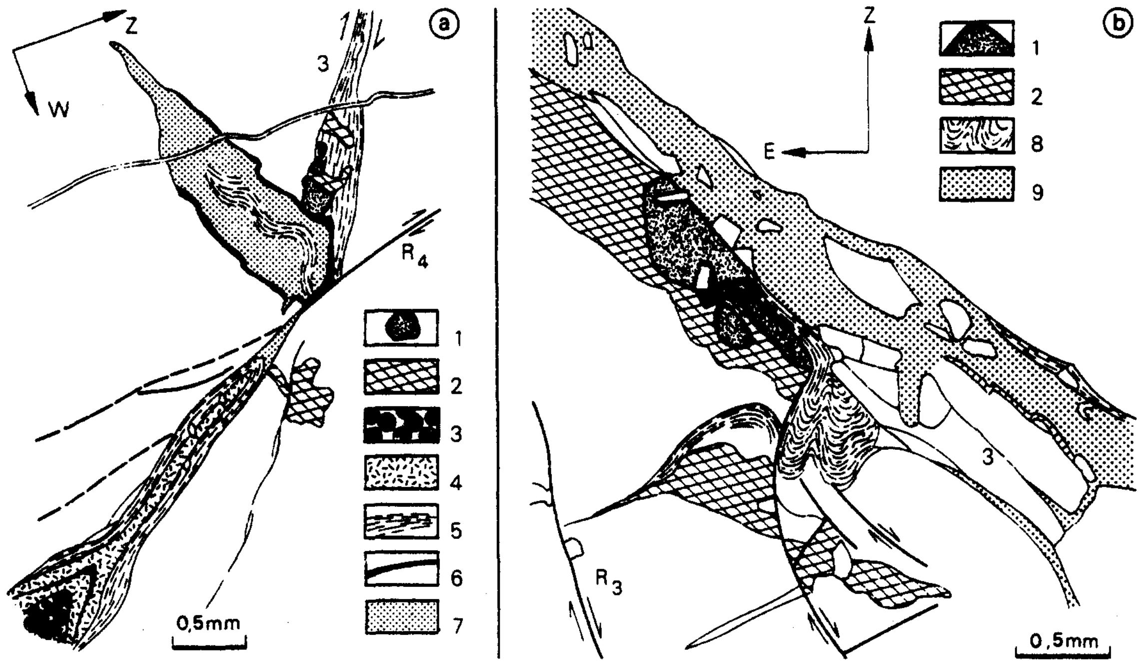

Fig. 6. Detail of pseudotachylite veins drawn from thin section. Symbols: (1) garnet; (2) amphibole; (3) - (9) various pseudotachylites—(3) spherulitic; (4) microlitic; (5) orientated microlitic; (6) homogeneous dark; (7) homogeneous light; (8) early light banded and (9) undifferentiated. Z; E, W, 3, R_3 R_4 as in Fig. 5. (a) Located at e in Fig. 5(a); details of a zoned pseudotachylite vein. The pseudotachylite is later than the shear fractures, which it cuts or follows. (b) Located at f in Fig. 5(a); early banded pseudotachylite, linked to 3 and R_3, is cut by later pseudotachylite which follows and dilates set 3 shears.

pseudotachylite (in spite of the small number of measurements for Fig. 7c) and shear fractures suggesting that the early pseudotachylite follows the shear fractures. This is not the case for dilated fractures with late pseudotachylite, the exact orientations of which (Fig. 7d) are in detail mainly different from those of the shear fractures (Fig. 7a). In other cases dilated fractures with pseudotachylite may coincide in direction but not age with certain shear fractures (Figs. 8a & b).

Figures 7(d) and 8(b) for microscopic dilatational pseudotachylite veins in two hand specimens should be compared with measurements for macroscopic veins from the whole anorthosite massif in Fig. 1(b). A good correlation at these two-scales exists (apart from the existence of a maximum near 100° in Fig. 7d).

Kinematic analysis

From a detailed study of the geometry of the shear fractures, one obtains a certain number of different movement patterns, some simple, some more complex. The following deformation sequences were found locally in different areas:

(1) a single set of gently dipping reverse shears with an E–W compression direction;

(2) a set of gently dipping reverse shears cut by steep reverse shears with an E–W compression direction, on which are superposed normal shears indicating extension in the same direction;

(3) a set of steep strike-slip shears with E–W compression cut by a second set with NE-SW compression and

(4) a set of strike-slip shears with N–S compression cut by a second set with NE–SW or E–W compression.

The only common feature is the presence of a compression direction near E–W, which can probably be related to the Outer Hebrides thrust zone. In detail, however, each domain may have a sequence of compressional and extensional movements in a horizontal direction. No single set of movements can account for the complexity of the fracturing linked to the pseudotachylite-bearing specimens. This complexity may result from different causes simultaneously:

(i) a cascade of induced fractures from the main fracture for a fixed stress field due to mineral anisotropy (see below),

(ii) short-term multiple fluctuations in the stress field during earthquake rupture leading to complex orientations and distributions of the fractures (single event) (Sibson personal communication 1981) and

(iii) long-term changes in the stress field leading to successive shear fractures of different orientation and movement (multiple events).

DISCUSSION

It has been shown above (1) that the late pseudotachylite is never deformed and (2) that pseudotachylite never occurs in undeformed rocks, but only in rocks which have a complex deformation history. The following discussion will deal firstly and very briefly with the nature of the deformation before pseudotachylite formation, secondly with the problem of the age and origin of the pseudotachylite and, thirdly, the role of rock and mineral anisotropy.

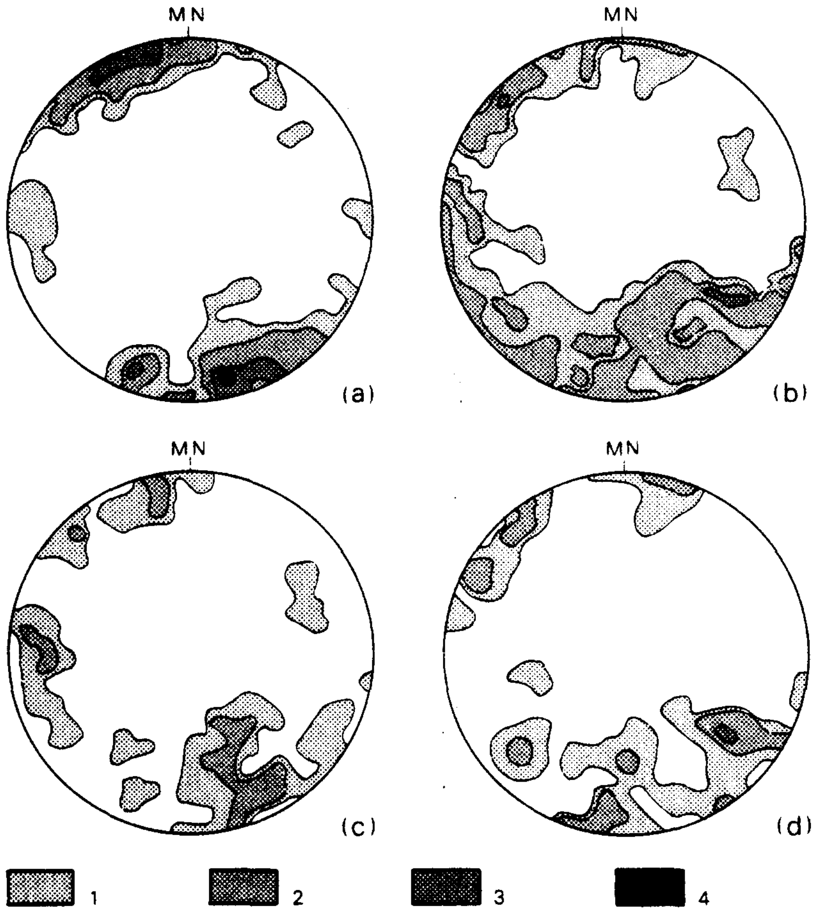

Fig. 7. Fracture orientations in a hand specimen with pseudotachylite. MN, magnetic North. (1) 1.5–3%, (2) 3–6%, (3) 6–9%, (4) > 9% of points on 1% of the hemisphere. Upper hemisphere Schmidt net. (a) All shear fractures (157 points). The trans- and intracrystalline shear fractures are spread out in strike from 55–100°. (b) Fractures with pseudotachylite (70 points) including both shear fractures with early pseudotachylite (Pst I) as well as vein margins with late pseudotachylite (Pst II); the points are highly spread out but a weak maximum occurs near 20–40°. In spite of the small number of points, the stereogram was split into two [(c) and (d)]. (c) Shear fractures with pseudotachylite. Two predominant preferred orientations exist near 70° with variable dips and 0°. (d) Dilatation fractures with pseudotachylite. A well developed maximum near 20–40° occurs which is absent in (c) and in (a). This direction does not correspond to previously existing shear fractures, but to new extensional ones. Two other weaker maxima exist of which at least one near 100° corresponds to a weak shear fracture maximum in (a).

The nature of the deformation

Large volumes of the meta-anorthosite have suffered weak to intense grain comminution, which is mainly located along shear fractures filled with various cataclastic materials. As the spacing of the shear fractures decreases, the deformation of the intervening rock volumes increases. The main mechanism of grain comminution is undoubtedly brittle fracture, but individual crystals inside and outside the cataclasites show variable degrees of plastic deformation: undulose extinction, mechanical twins, etc. (Figs. 2d, 3a, c, f and 5c). The deformed rocks have not lost cohesion; their cohesion may be due to slight recrystallization of the crystal grain boundaries in the cataclasites. A transmission electron microscope study of the deformed rocks is in progress.

Age of the pseudotachylites

Pseudotachylites are abundantly associated with the eastward dipping Outer Hebrides thrust zone (Jehu & Craig 1923, 1925, 1926, 1927, 1934, Sibson 1975, 1977, 1980) of presumed Caledonian age and E–W movement (Francis & Sibson 1973); furthermore the above kinematic analysis of the movement directions in pseudotachylite-bearing meta-anorthosites mainly showed an E–W compression direction. It is natural to assume a Caledonian age for the pseudotachylites in the meta-anorthosite.

On the other hand we found no unequivocal pseudotachylites after careful search to the E or SE of the dotted line on Fig. 1(a) showing the limit of intense saussuritization of the meta-anorthosite. This presumably means either (1) that pseudotachylite which existed in this area has been subsequently saussuritized and is, thus, older than this alteration, or (2) no true pseudotachylite was formed in this area as the saussuritized rocks were too water rich (Sibson 1973, 1975); thus, if only one major period of deformation occurred, the pseudotachylite formed outside this zone must be younger than the alteration.

The saussuritization must be linked with the circulation of large quantities of hot fluids along the thrust zone. As the thrust rises to the NW at an angle of 20–30°,

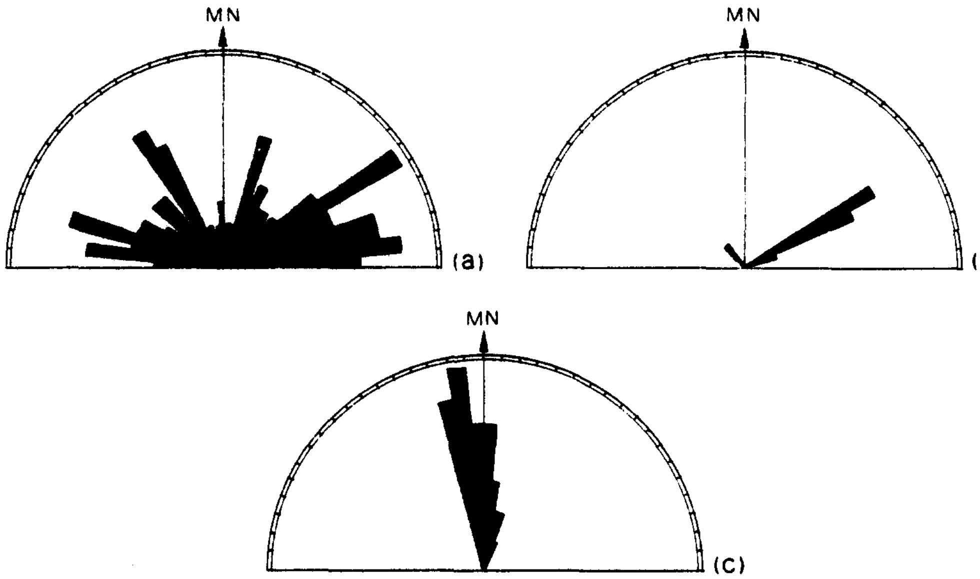

Fig. 8. Fracture orientations in a second hand specimen with pseudotachylite. (a) All shear fractures showing a very large spread in strike (143 points). (b) Dilatation fractures with pseudotachylite with a strong maximum near 50° close to that in Fig. 7(d) (14 points). (c) Late brittle fractures cutting the rock. These have a limited range even on the scale of the whole massif (32 points). (MN, magnetic North).

the saussuritized zone may pass only a few hundred metres above the fractured rocks near the summit of Roineabhal (Fig. 1a). These rocks are almost entirely unaltered, though an incipient saussuritization sporadically affects the anorthosite and the pseudotachylites to the NW of the road. It does not seem possible to fix an age precisely but point (1) above, which seems most probable, and the incipient saussuritization lead us to suggest a Caledonian age for the pseudotachylites. If this is true, the low permeability implied for the fractured rocks suggests a depth of formation in agreement with the 4–5 km proposed by Sibson (1975). The saussuritization could be associated with later and more shallow movements in the complex thrust zone.

Origin of the pseudotachylites—the role of rock and mineral anisotropy

Pseudotachylites frequently occur in dry granulite and amphibolite facies gneisses or associated with major fault zones. It is clear in many cases from field relations that generation is by frictional sliding (Scott & Drever 1953, Sibson 1973, 1975, 1977, 1980, Allen 1979, Grocott 1981). Sibson has argued strongly in favour of the absence of a fluid phase during fault movement, which produced pseudotachylite rather than cataclasite. Furthermore Sibson demonstrated that under dry conditions, the 0.1–1 m s^{-1} slip rates characteristic of seismic faulting were likely to induce frictional melting at depths greater than a kilometre or so, provided slip was restricted to a narrow zone.

Both Sibson (1975) and Grocott (1981) suggested that in many gneisses it is possible to determine the slip surface on which pseudotachylite was generated and that almost all the pseudotachylite is undeformed and found in injection veins ramifying from this surface. If the pseudotachylite did not leave this surface, frictional heating would drop drastically as the melt lubricates the surface (Sibson 1975). Such simple relations imply that locally pseudotachylite generation is a unique event. Furthermore, most isolated pseudotachylite occurs in gneisses which show little non-penetrative strain (Sibson 1975, Grocott 1981, unpublished personal observations from quartzofeldspathic gneisses of Lewisian age from the Barra Isles, Outer Hebrides).

It has been shown in previous sections that most of the pseudotachylite studied in the meta-anorthosite occurs in dilatational veins and is undeformed. The field relations and microscopic characteristics imply a melt origin for the pseudotachylite in the meta-anorthosite. The more or less clear relation between generation surface and injection veins described by Sibson (1975) and Grocott (1981) has not been found in the meta-anorthosite. In no cases could the pseudotachylite veins be related to any major movement surface, but in many cases sem to invade the highly fractured meta-anorthosite. On the other hand injection vein/generation surface relations similar to those described by Sibson (1975) occur in well-banded biotite gneisses about 1 km NW of Rodel (just off map, Fig. 1a) and 2 km W of the meta-anorthosite. Grocott (1981) suggested that the fracture geometry he described in shear belts from Greenland only occurs in strongly foliated rocks. We propose to extend such arguments to the formation of pseudotachylite and suggest the degree of rock anistropy will fundamentally affect pseudotachylite generation and geometry.

(1) *Rock anisotropy*. The ultimate shear strengths of rocks depend on many factors including the mineralogy, the fabric including cracks and microcracks, the pressure, the water pressure, the temperature and the rate of stress increase. It is probable that the presence of

cracks and microcracks plays a dominant role in laboratory experiments, especially at low temperatures and high strain rates. In dry deep-seated rocks which have never been to the surface and suffered pressure relaxation, such cracks may be rare or nearly absent, so that experiments on relaxed rocks may not be fully typical of crustal conditions. Experiments at low temperatures and moderate confining pressures, however, suggest that though the ultimate strength is very sensitive to defects, unaltered granites tend to have higher strengths than biotite-poor gneisses, which in their turn may possibly have higher strengths than anorthosites (Griggs *et al.* 1960, Handin 1966, Borg & Handin 1966, Seifert 1969). In foliated rocks, brittle failure will occur on or near the foliation plane for a large range of stress orientations (Borg & Handin 1966). Failure will occur, in addition, in such rocks at lower resolved shear stresses than in more homogeneous rocks.

(2) *Mineral anisotropy*. In experiments at low temperature and confining pressure and high strain rate, quartz has very much higher strength than plagioclase (Griggs *et al.* 1960, Handin 1966, Borg & Handin 1966, Borg & Heard 1970, Tullis & Yund 1977). Such experiments are much closer to conditions during pseudotachylite generation than those at higher temperatures and pressures in which quartz suffers hydrolytic weakening). Brittle failure will, thus, occur at lower shear stresses in plagioclase than in quartz. Once failure in plagioclase has started in an anorthosite, it will propagate from crystal to crystal. Furthermore, failure will tend to make use of the well developed planes of weakness in plagioclase crystals, which are not all parallel to the initial plane of shear failure. As meta-anorthosites tend to be rather more isotropic than gneiss, the initial fracture may split into numerous secondary fractures, thus deforming a large volume of rock.

In quartzo-feldspathic rocks brittle failure may occur in plagioclase (or in feldspar in general) nearly as easily as in anorthosites. As the felspar is in contact with quartz which is much stronger, brittle failure may not propagate through the quartz. Rock failure will only occur at much higher shear stresses (unless the rock is highly foliated and biotite-rich) and such higher shear stresses might be expected to be infrequent.

CONCLUSIONS

On the basis of the above discussion we suggest that:

(1) In dry quartzo-feldspathic rocks brittle shear failure initiated in the weaker minerals (feldspar, mica, etc.) does not propagate through quartz which acts as a crack-stopper except at higher shear stresses. If the rock is strongly anisotropic (gneiss), failure is guided by the anisotropy and occurs on fractures very close to, or in, the foliation plane, and at lower shear stresses than in granites. Failure generally occurs only on a small number of important shear planes and, if movement is fast enough, frictional melting may occur and pseudotachylite may be found in only slightly deformed rocks.

(2) In anorthosites brittle shear failure initiated in plagioclase propagates easily from crystal to crystal at lower shear stresses than in quartzo-feldspathic rocks. As anorthosites are generally not highly anisotropic and fracture in plagioclase is strongly guided by the crystal structure, failure may give rise to closely spaced intersecting shear planes, especially in high-speed earthquake processes. Pseudotachylite only occurs in such highly fractured anorthosites, which have suffered many cycles of fracturing without pseudotachylite formation. Once pseudotachylite is formed it is only rarely deformed, so that fracture initiation and propagation must be extremely difficult in pseudotachylite as it is probably stronger than cataclasite at low temperature, and further deformation can only occur in other parts of the rock, as yet without pseudotachylite. This argues against the origin of pseudotachylites by ultracrushing (Wenk 1978), as ultracataclasites should have lower strengths than more coarsely crystalline anorthosite (strain softening), and argues in favour of melting. If pseudotachylites in anorthosites passed through a melt stage, frictional heating may be only partly responsible for the temperature rise. Energy dissipation at the tips of moving fractures may significantly contribute to the temperature rise (Richards 1976, Sibson 1981, personal communication).

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