Generation of Pseudotachylyte by Ancient Seismic Faulting

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Summary

Pseudotachylyte occurs as vein material infilling highly brittle shear and extensional fractures developed along the western margin of the late Caledonian, Outer Hebrides Thrust zone in NW Scotland. Vein geometries and textures show clearly that the pseudotachylyte has been through a melt phase. From the composition of the pseudotachylyte matrix which is close to that of a basaltic andesite, probable melt temperatures of around 1100 °C are inferred. Field and theoretical studies demonstrate that the pseudo-tachylyte was generated by relatively high stress seismic faulting in crystalline sialic crust devoid of an intergranular fluid, most probably at the time of thrust inception and at a depth of around 4–5 km. A study of pseudotachylyte-bearing ' single-jerk ' microfaults shows that the slip (d) is related to the thickness of the pseudotachylyte layer (a) by the equation,

$$d = 436 . a^2$$

where d and a are measured in centimetres. Work–energy calculations based on this empirical relationship suggest that the pre-failure shear stress on the microfaults must have been as high as 1·6 kbar to overcome the initial frictional resistance (τ_f), which decreases with increasing slip during a single movement according to the relationship,

$$\tau_f \propto \frac{1}{\sqrt{d}} \text{ or } \frac{1}{a}$$

which may arise solely from the viscous shear resistance of the melt layer.

Delineation of palaeoseismic zones by the recognition of those cataclastic rocks which are necessarily the products of earthquake faulting, may assist in the determination of ancient plate boundaries.

1. Introduction

In this paper, field and theoretical studies are used to estimate the physical parameters which have governed the production of pseudotachylyte melt-rock in and around the Outer Hebrides Thrust, a complex dislocation zone which disrupts a basement of amphibolite or granulite facies Lewisian Gneiss in NW Scotland (Jehu & Craig 1934). With an eastwards sheet-dip of around 25°, the thrust zone can be
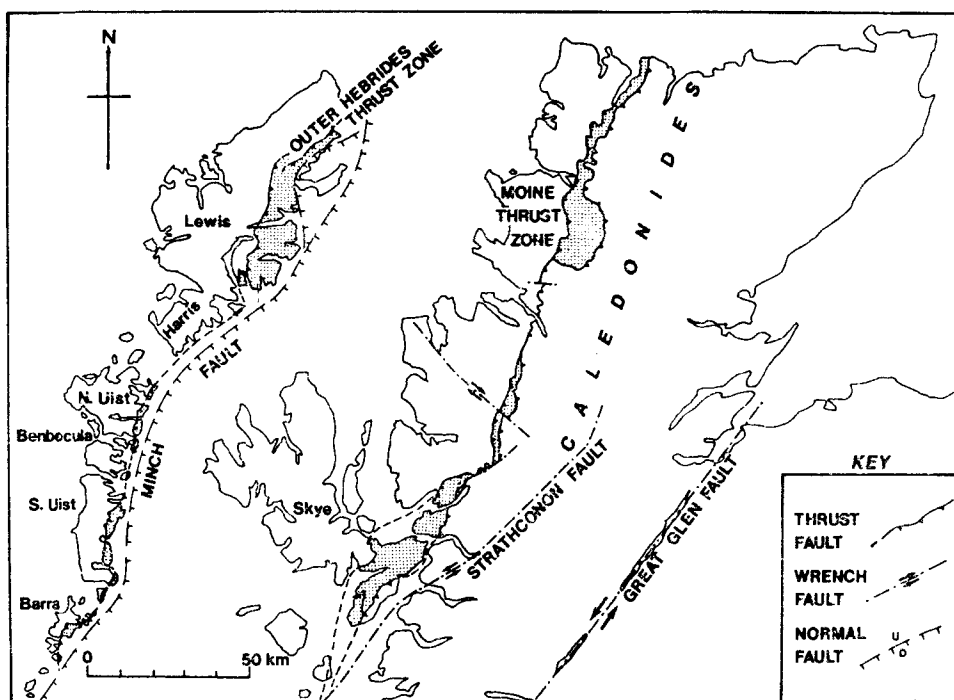
Fig. 1. The Outer Hebrides Thrust in relation to other major faults of NW Scotland.

traced for over 190 km down the eastern coast of the Outer Isles in a series of three linked arcs from Northern Lewis to the islets south of Barra (Fig. 1), and it must rank as one of the major tectonic elements in the fabric of the British Isles. One may infer a late Caledonian age for the thrust from its marked parallelism with the Moine Thrust some 85 km to the east, and this is supported by the results of a K–Ar dating programme carried out on the cataclastic* products of the thrust zone (Sibson, in preparation).

Pseudotachylyte occurs subordinately to ultracataclasite (extremely fine-grained, cohesive rock powder with <10 per cent porphyroclasts) in crush zones along the western margin of the thrust zone, the degree of development of the crush zones decreasing progressively from north to south along the island chain; and also in localized failure zones which may lie as much as 25 km west of the thrust base. Because these minor zones of brittle failure become more common going from west to east towards the thrust base, and the observed displacements are generally consistent with the WNW–ESE compressional regime implied by the presence of the major thrust zone, there is little doubt that most of this localized faulting is associated with the development of the Outer Hebrides Thrust. There are, however, certain steeply inclined crush zones striking NW–SE across the gneissic complex west of the thrust base, which may predate the thrust episode (Francis & Sibson 1973).

The detailed internal structure and deformation history of the thrust zone will be discussed at length in a later publication (Sibson, in preparation). It is sufficient to say here, that by reconstructing the thrust zone in its initial state a picture emerges whereby as a result of semi-ductile deformation in mylonitic shear zones

* The terminology used in this paper to describe cataclastic rocks and their textures is derived from Spry's (1969) standard text, to which the interested reader may refer.
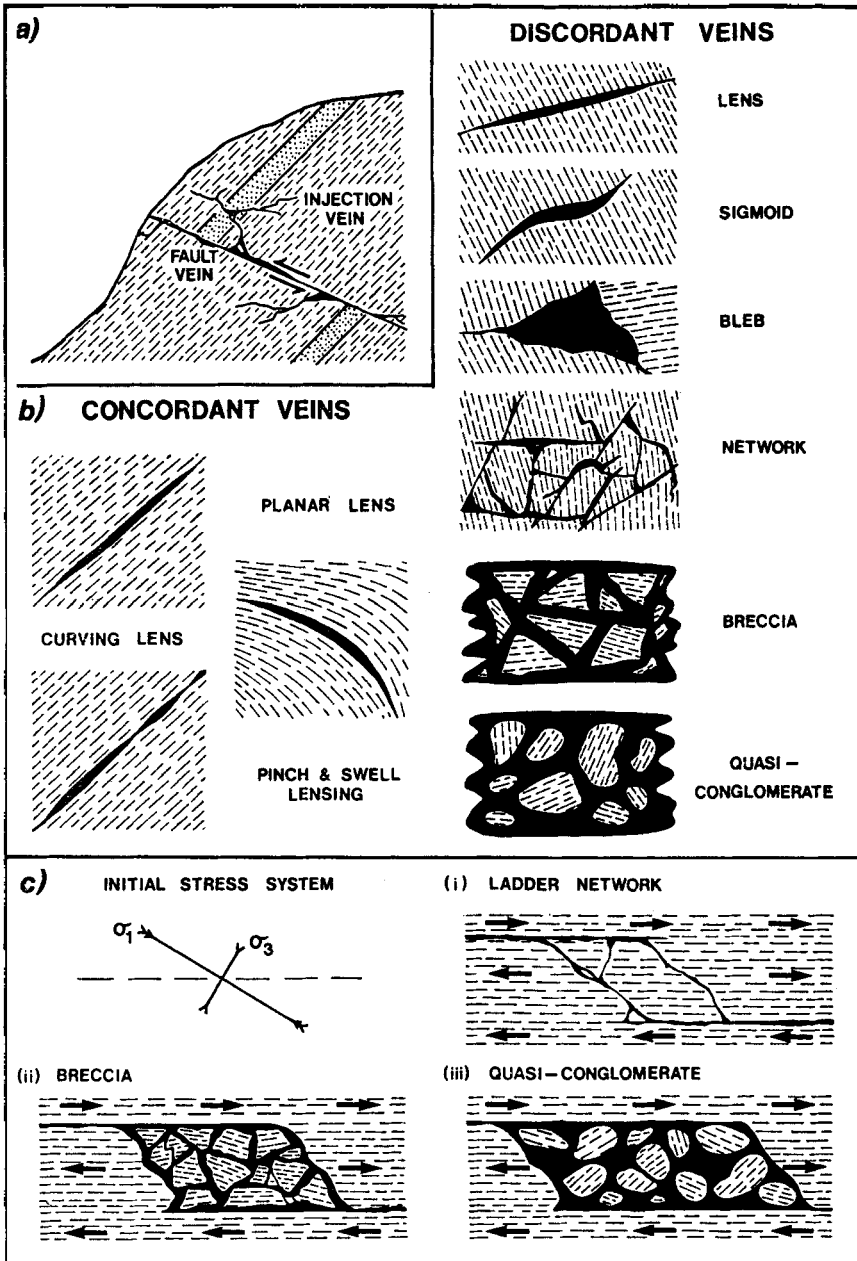
FIG. 2. (a) Fault and injection vein relationships. (b) Geometric classification of pseudotachylyte veining. (c) Mechanism for quasi-conglomerate formation.

at depth, distortional strain energy accumulates in a highly brittle upper crust, which responds intermittently by frictional failure along discrete planes with the consequent generation of pseudotachylyte.

2. Classification of pseudotachylyte veining

Because the dominantly quartzo-feldspathic gneisses west of the thrust base are relatively ' clean ' and uncrushed, it is from localized zones of brittle failure within these rocks that most can be learnt about the generation of pseudotachylyte. The material occurs in a variety of vein types, and in hand specimen is a very dark, extremely hard, fine-grained rock which is invariably closely jointed and fractures in a splintery or occasionally sub-conchoidal manner. On a genetic basis it is possible to distinguish two fundamental classes of vein (Fig. 2(a)).

(i) Fault veins

These are veins lying along markedly planar shear fractures on which the pseudo-tachylyte has been generated by rapid frictional sliding. Fault veins often ' pinch and swell ', presumably as a result of surface irregularities in the fault planes, but individual veins rarely exceed 10 cm in thickness. Estimates of apparent lateral displacement along the shear fractures are sometimes possible when the fault veins cut across the gneissic banding, but accurate correlation of offset bands becomes difficult when the slip exceeds a few tens of centimetres. Many of the calculations presented later in this paper are based on measurements made on pseudotachylyte-bearing micro-faults with displacements of less than one metre apparently resulting from a single slip increment (Fig. 3(a)). Hereafter these will be referred to as ' single-jerk ' micro-faults. It should be noted, though, that not all microfaulting west of the thrust base has generated pseudotachylyte. One possibly significant fact in this regard is that rather more low-grade marginal alteration (chloritization of biotites, epidotization, saussuritization of feldspars etc.) occurs in the gneisses immediately adjacent to barren microfaults, perhaps implying the presence of rather higher local concentrations of pore water than is associated with the pseudotachylyte faulting. More complex fault veins with signs of rebreakage (e.g. disrupted chill margins) are designated ' multiple-jerk ' features. In general, the style of pseudotachylyte-generating faults is extremely brittle (Fig. 3(a)), with virtually no drag effects adjacent to the fault planes, except in the case of the larger, multiple-jerk failure zones, where rather crude drag folding has occasionally taken place by flexural slip along the gneissic foliation.

(ii) Injection veins

In contrast to fault veins, these features tend to be far less regular in form. They can be seen to be dilational veins along which there has been no lateral offset of markers (Fig. 4(b)). Often, they ramify through the gneiss in the most erratic manner, but usually there is a clear association with movement zones, and in many instances they can be traced back to parent fault veins (Fig. 2(a)). It should be noted that because brittle shear fractures in rock generally form at about 30° to the maximum principal compressive stress (σ_1), there is always a tendency for any frictionally generated melt to be squeezed off the fault plane into tension fractures across which the normal stress is locally a minimum; that is, perpendicular to the least principal compressive stress (σ_3). This is especially the case with the larger faults, where some loss of pseudotachylyte from the fault plane into injection veins has almost always occurred. The great irregularity of these injection veins can probably be accounted for in part by the non-static stress conditions prevalent during fast earth-quake faulting, and also by the strength anisotropies within the banded and foliated
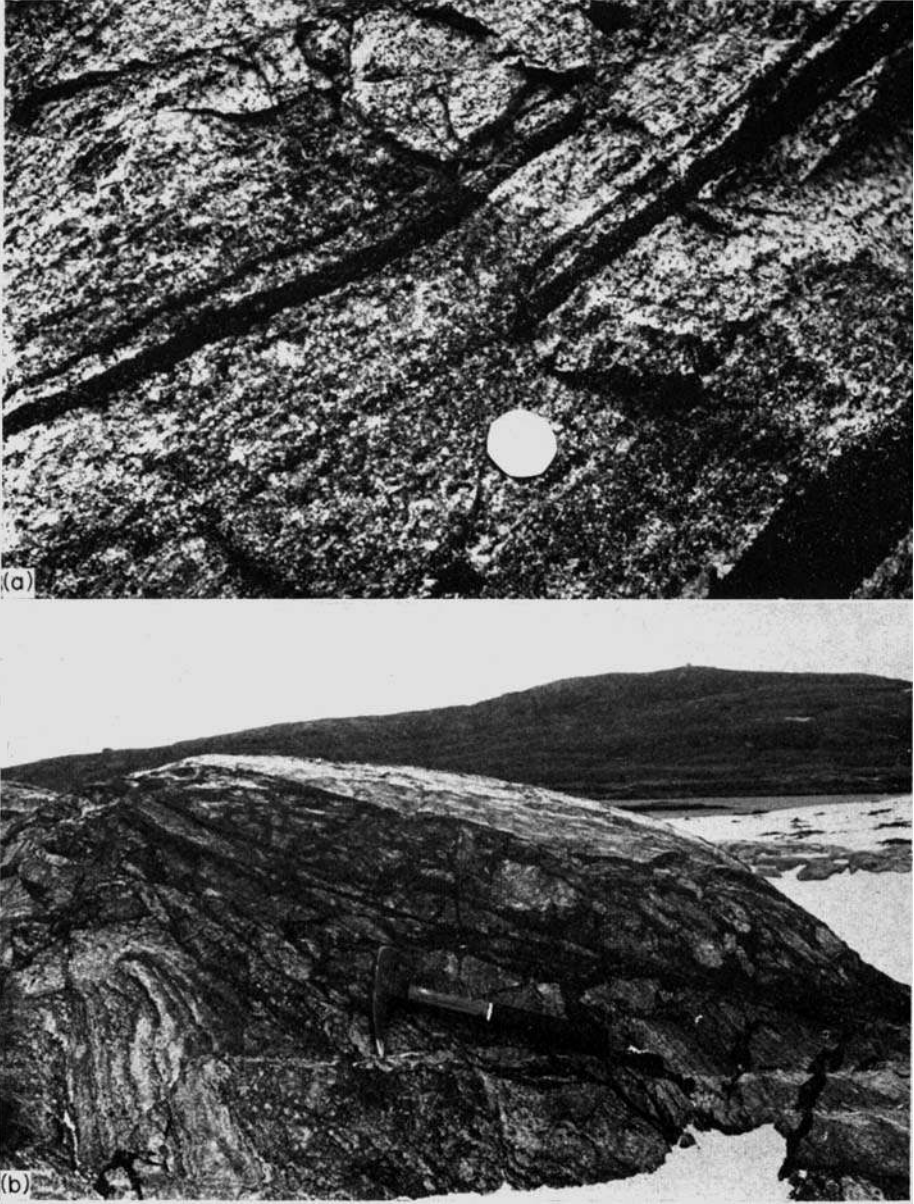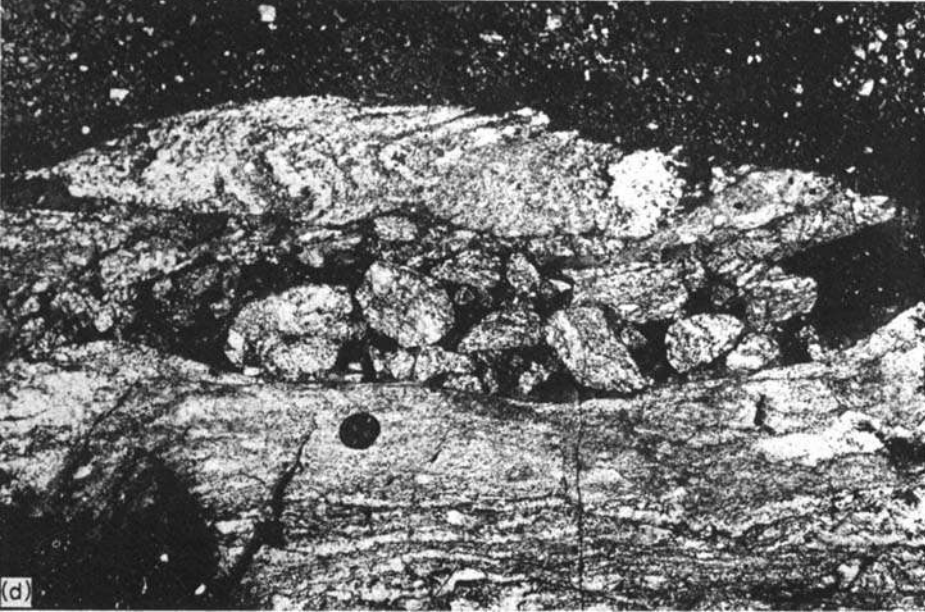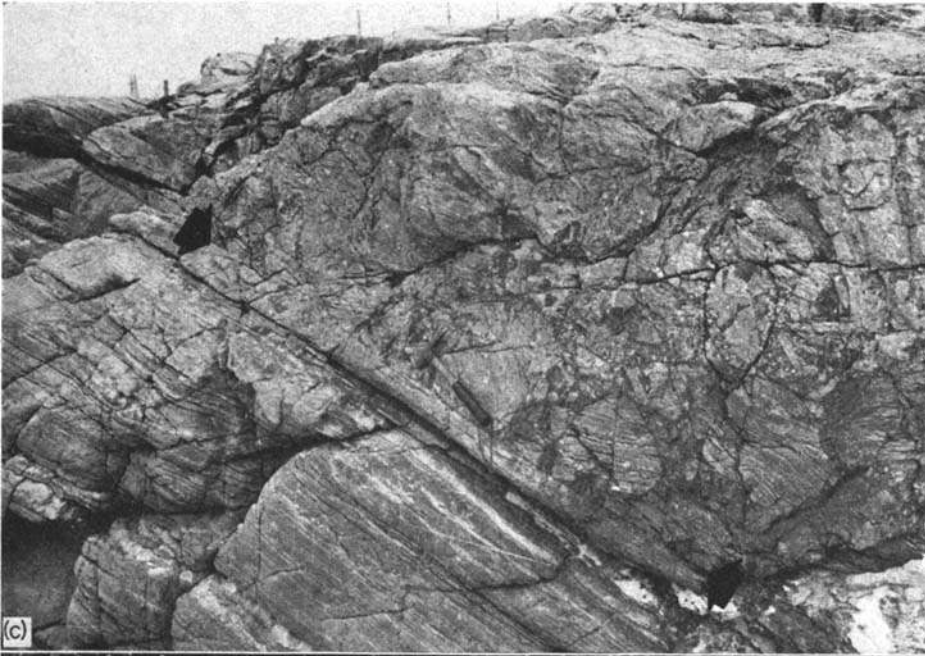
FIG. 3(a) and (b)

FIG. 3. (a) 'Single-jerk' pseudotachylyte-bearing microfault, Grimsay, Isle of N. Uist. (b) 'Multiple-jerk' pseudotachylyte-bearing fault, Cuier Beach, Isle of Barra. (c) Fault breccia with pseudotachylyte matrix, Cuier Beach. (d) Quasi-conglomerate with pseudotachylyte matrix, Grimsay.
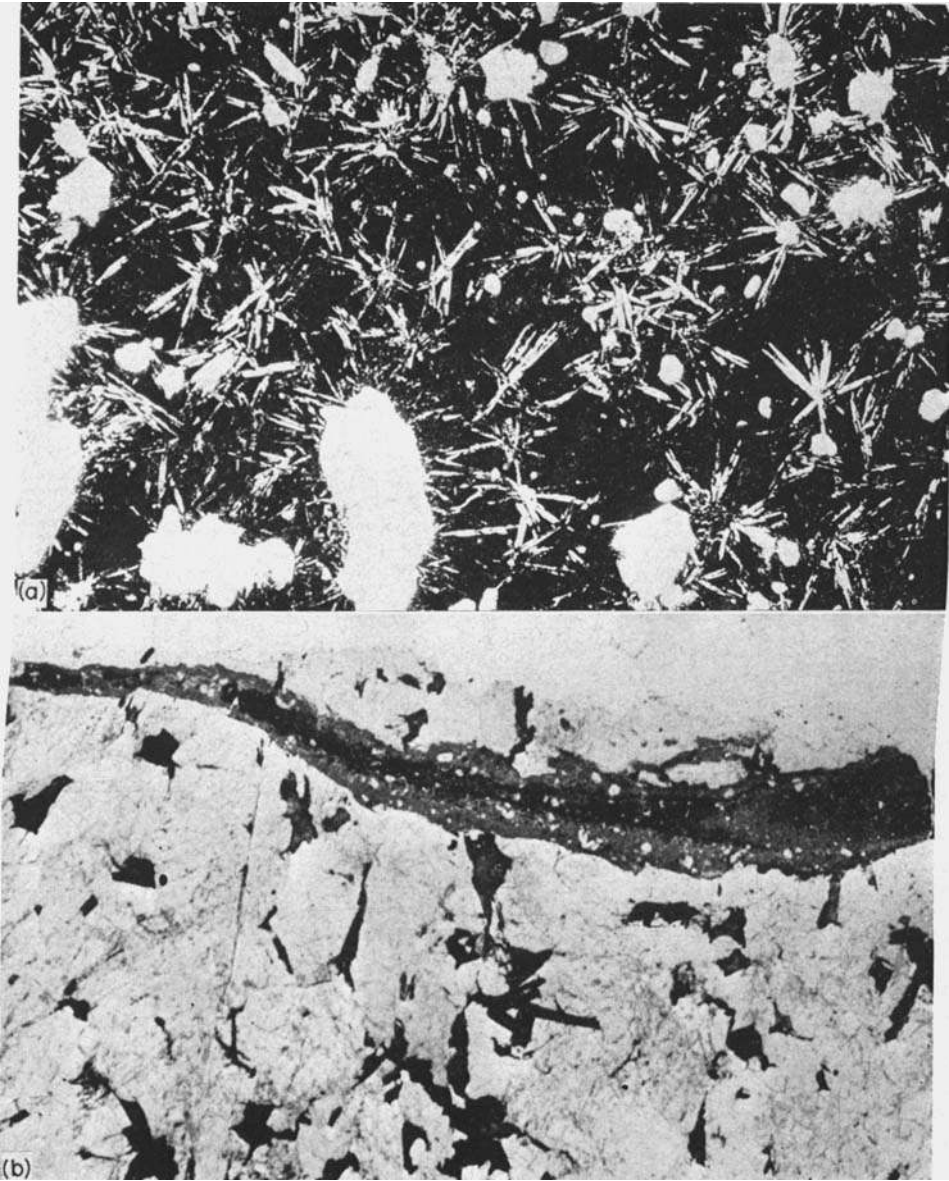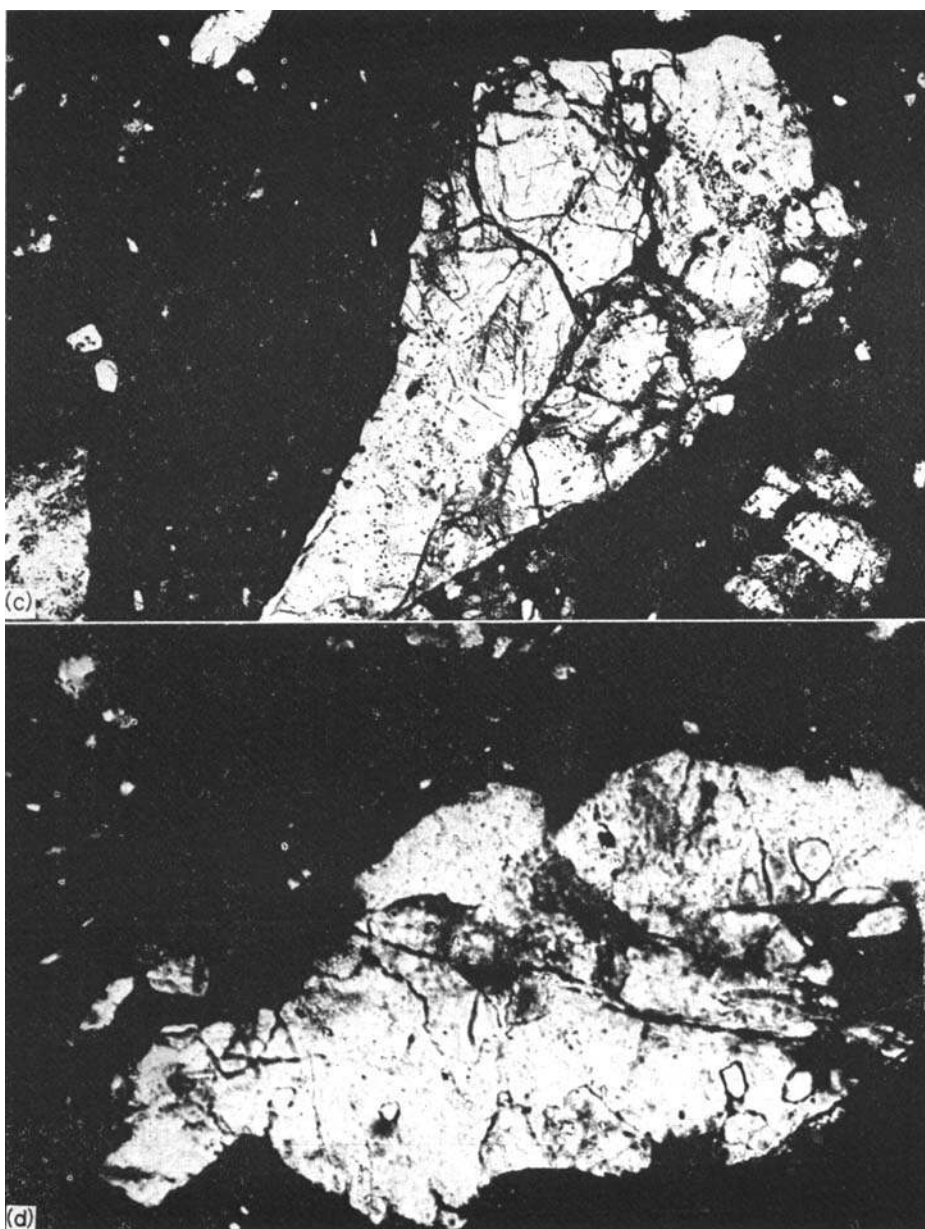
FIG. 4(a) and (b)

FIG. 4. (a) Stellate clusters of plagioclase microlite nucleated on porphyroclasts in a thick pseudotachylyte vein (×45). (b) Thin injection vein with tongue of glass enclosing spherulites (×15). (c) Cracked quartz porphyroclast in pseudotachylyte (×90). (d)-Embayed feldspar porphyroclast in pseudotachylyte (×90).

gneisses. Veins of pseudotachylyte have also been classified according to their geometric habit, as in Fig. 2(b). A division can be drawn between those veins which lie concordant with the gneissic foliation, and those which cut across it. Thus a vein of pseudotachylyte lying along a fault plane which cuts across the gneissic foliation, would be referred to as a 'discordant fault vein'. Obviously, problems arise in the distinction between concordant fault and injection veins when there are no suitable markers inclined to the foliation, but fault veins generally possess a much higher ratio of length to average thickness.

Larger failure zones are characterized by complex network veining and fault breccias with fragments of gneiss set in a matrix of pseudotachylyte. Not uncommonly, the gneissic fragments are well rounded and the fault breccia takes on a conglomeratic aspect. These pseudotachylyte vein networks, breccias and quasi-conglomerates appear to be mixtures of fault and injection veins, and are frequently bounded by planar fractures (Fig. 3(c) and 3(d)) thought to be the generating surfaces from which the matrix pseudotachylyte has been derived. The envelopes to these larger failure zones may again be concordant or discordant to the gneissic foliation. In both breccias and quasi-conglomerates, but especially the latter, the included fragments show signs of rotation, the amount increasing with the ratio of matrix to fragments. Every gradation is seen in the field between ladder networks of en echelon fault veins linked by arrays of tensional injection veins, breccias and quasi-conglomerates. The implied sequence of development, during a single-slip increment (Fig. 2(c)) is:

(i) Offset, pseudotachylyte-generating shear fractures (either concordant or discordant to the gneissic foliation) are linked by a set of irregular injection veins in a ladder network.

(ii) As slip continues, pseudotachylyte from the bounding fault veins is injected into the growing void, while the fault planes themselves remain almost barren, thereby retaining the frictional resistance necessary for the further generation of pseudotachylyte. Included fragments of gneiss undergo some rotation and are disrupted by further tension fractures.

(iii) Continued injection of pseudotachylyte, tensional fracturing of fragments, attrition brought about by rotational grinding, explosive decrepitation of included material due to fluid expansion under rapid heating (see later) and corrosion by the melt all contribute to the extreme rounding displayed in some quasi-conglomerates.

The very frequent occurrence of concordant fault veins is indicative of a marked strength anisotropy in the gneisses, allowing preferential shear failure along the foliation whenever it is favourably orientated with respect to the stress regime associated with the major thrust (Francis & Sibson 1973). That this should occur is evinced by the work of Borg & Handin (1966), who have demonstrated the existence of such a strength anisotropy in dry Fordham Gneiss, a well-foliated biotite gneiss petrographically similar to hebridean 'grey' gneiss, by a series of triaxial compression tests ($\dot{e} = 10^{-4}/s$; $T = 500\,°C$; $P_{con} = 5\,kbar$). With test specimens cut so that the foliation is at $45°$ to σ_1, failure occurred at a differential strength of $4\cdot2\,kbar$; about half the failure strength when tests were conducted with the foliation perpendicular to σ_1.

3. Textural evidence for a melt phase

Apart from the intrusive habit of many pseudotachylyte veins, there is abundant textural evidence to show that Outer Hebrides pseudotachylyte has been through

a melt phase. In thin section, the pseudotachylyte can typically be seen to consist of about 10–30 per cent by volume of randomly orientated porphyroclasts set in a dense, fine-grained matrix, which very rarely contains optically recognizable glass (Fig. 4(b)), but often displays either microlitic textures resulting from the rapid chilling of a melt (Fig. 4(a)) or devitrification textures, both of which may be more or less obliterated by recrystallization.

Even where recrystallization of the groundmass is well advanced, the distinctive nature of the porphyroclast content renders pseudotachylyte distinguishable from rocks bearing a similar dark, flinty appearance in the field, such as ultramylonites and ultracataclasites, in which feldspar is usually the dominant porphyroclast. In contrast, pseudotachylyte usually contains a roughly equal mixture of quartz and feldspar porphyroclasts, with occasional quartzo-feldspathic rock fragments. Mafic minerals are rarely preserved. Quartz porphyroclasts are typically angular with an intensely cracked and strain-shadowed appearance (Fig. 4(c)), while porphyroclasts of plagioclase feldspar, though often faulted internally with some development of strain-induced twinning, tend to be sub-rounded and embayed with rather blurred outlines perhaps resulting from marginal melting (Fig. 4(d)). Only on rare occasions are the porphyroclasts oriented in other than random fashion, but occasionally a shape alignment indicative of flow is apparent. Rather irregular colour variations subparallel to vein walls may also be a relic of flow banding. No textural features such as quartz basal fractures or high pressure polymorphs, thought to be uniquely attributable to the high transient shock pressures associated with impact structures (Carter 1965) have been observed in Outer Hebrides pseudotachylyte.

The work of Marshall (1961) shows that considering the age of these pseudo-tachylytes, and the P–T conditions under which they developed, it is not surprising that devitrification is well advanced and little optically recognizable glass is evident. What glass is seen, is typically yellow-brown to dark brown in colour with clear evidence for flow, but studies of the groundmass of pseudotachylyte by transmission electron microscope (White 1974) invariably reveal the presence of at least some remnants of vitreous material (which may however, result from intense crushing at high strain-rates). In general, the matrix is brown to black, sub-opaque to opaque, and composed of extremely fine-grained particulate material with an abundance of dusty granular or rod-shaped ores, most of which are probably magnetite though occasional skeletal habit suggests some ilmenite is present. No relict vesicles or amygdules have been observed. Where recrystallization of the groundmass is advanced, fine granular epidote, sericite and chlorite become common, and an exceedingly small brown micaceous mineral is sometimes visible in a fine granular quartzofeldspathic matrix.

The groundmasses of the thicker pseudotachylyte veins, however, are often rather patchily matted with dendritic crystal growths of unknown composition and/or stellate clusters of plagioclase microlites (composition about An_{30-35}) (Fig. 4(a)) which have usually nucleated on plagioclase porphyroclasts, and may grow up to 0·3 mm in length. Such textures are characteristically formed by the incipient crystallization of a rapidly cooling melt (Spry 1969, p. 153), and are typical of glassy volcanic rocks such as pitchstones. Very occasionally, the microlites flow around porphyroclasts in a trachytic manner, demonstrating that some crystallization had proceeded before final solidification of the melt. Because microlites are not found in pseudotachylyte veins less than a centimetre or so in thickness, it seems that cooling 'half-lives' (see Section 6) of the order of minutes are needed for their development. These thicker veins generally possess relatively dark and fine-grained margins without microlites, which are presumably relic chill features. Where microlitic crystallization has not occurred, spherulitic textures characteristic of devitrification are not uncommon, and their form may be preserved where recrystallization of the groundmass is more advanced, by the sub-spherical clustering of granular ores in reaction rims around small porphyroclasts to give a mottled, 'honeycomb' texture.

Margins of pseudotachylyte veins are often very sharp, cutting cleanly across quartz and feldspar grains, but where the country rock contains an abundance of mafic minerals, especially biotite, these tend to be preferentially eroded by the melt and the contact becomes ragged with cuspate offshoots of pseudotachylyte into the host rock. Thin injection veins can be seen plucking fragments of mineral grains off the walls to form new porphyroclasts, and felsic grains adjacent to veins are usually intensely cracked in a manner akin to the included porphyroclasts, with strong strain-shadowing of quartz, for distances up to a millimetre or so from the vein margin.

A mechanism which would contribute to this intense cracking and fragmentation observed in porphyroclasts and vein margins, involves the dramatic rise in pressure to be expected in water held under approximately constant volume conditions, when subjected to sudden heating. Very low, intergranular pore-fluid pressures have been postulated as a necessary pre-requisite for the generation of pseudotachylyte by frictional fusion (Sibson 1973), but there is no doubt that some water was present in the amphibolite facies gneisses of the Outer Hebrides when faulting took place. Typically, the water content of such rocks is about 1–2 per cent by weight, but this water will be locked up, both within the lattice structure of mafic minerals such as biotite and hornblende, and in unconnected fluid inclusions in quartz grains and along grain boundaries. Such ' trapped ' water cannot therefore act as an intergranular pore-fluid, and confining pressure will not be reduced in accordance with the principle of effective stress put forward by Hubbert & Rubey (1959). Assuming that the water in these fluid inclusions was initially at P–T conditions close to homogenization, the pressure rise, ΔP, is related to temperature rise, ΔT (°C), by the expression:

$$\Delta P \approx \frac{\Delta T}{47} \text{kbar} \tag{1}$$

(taken from the steam tables of Burnham, Holloway & Davis 1969)

for water initially at 140 °C and under a confining pressure of 1·3 kbar (corresponding to a depth of 4–5 km), held under constant volume. (If the fluid in the inclusion is initially below its homogenization temperature, the sharp pressure rise is delayed until homogenization is achieved.) Clearly, with a temperature rise of only 50 °C being required to induce local hydrostatic ' overpressures ' of 1 kbar, rapid heating is a powerful mechanism for the promotion of hydraulic fracturing along grain boundaries and lines of inclusions. Presumably the intense grain shattering provoked by such explosive decrepitation would extend back to some critical isotherm in the wall rock or porphyroclast, as heat is lost by conduction from the melt. Such a mechanism also helps to explain the rounding of rock fragments in the quasi-conglomerates with a
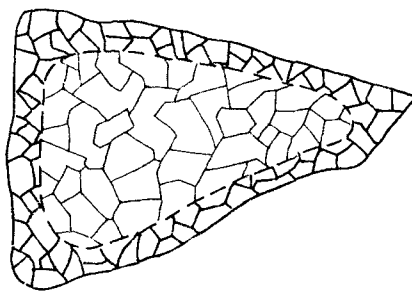

FIG. 5. Thermally induced rounding of angular rock fragments by marginal decrepitation (dashed line represents a transient isotherm).

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Table 1

Analyses of pseudotachylyte and wall rock

	A	B	C	D	E
SiO_2	61·18	60·57	61·92	55·40	55·83
Al_2O_3	17·22	17·45	16·90	19·11	18·01
TiO_2	0·62	0·64	0·57	0·78	0·84
*Fe_2O_3	7·57	7·28	6·65	8·91	6·70
MnO	0·13	0·11	0·11	0·13	0·08
MgO	4·34	4·93	3·88	6·04	5·12
CaO	3·42	3·64	3·47	3·17	7·40
Na_2O	2·91	3·45	3·08	3·26	3·64
K_2O	2·45	2·51	2·19	3·07	1·22
P_2O_5	0·10	0·11	0·10	0·13	0·11
Total	99·94	100·68	98·87	100·00	99·93

* Total iron calculated as ferric

pseudotachylyte matrix, which must occur very quickly. From simple conduction theory, it is obvious that isothermal surfaces while in general subparallel to cooling surfaces or contacts, will tend to be 'rounded-off' adjacent to sharp angular projections and corners (Fig. 5). One can therefore envisage the effect of a rapid succession of episodes of explosive marginal shattering eventually producing a sub-rounded residual rock fragment.

To the author's mind, the textural evidence cited above shows unequivocally that pseudotachylyte associated with the Outer Hebrides Thrust has been through a liquid melt phase. Other postulated origins for pseudotachylyte (e.g. Reynolds 1954) generally involve the entrainment of fine-rock particles in a hot fluidized system, but in the Outer Isles there is no adequate source for the large volumes of gas required. At high temperatures, the main role of the water present in Hebridean 'grey gneiss' will be to lower the viscosity of any melt that forms by promoting depolymerization (Scarfe 1973).

4. Composition of the melt

In Table 1 are listed major element analyses of a pseudotachylyte fault vein (column B) and its associated wall rocks (columns A & C), carried out by XRF on ignited dry material. The analysed fault vein was selected because it lies concordant with gneissic foliation and banding for over 20 m, so that variation in the composition of the wall rocks was kept to a minimum. In this locality, the quartzo-feldspathic host gneisses are of a variety recognized as aluminous metapelites by Coward et al. (1969), being particularly rich in biotite and garnet. As often noted for other pseudo-tachylytes (Philpotts 1964), there is no significant change in composition between the pseudotachylyte vein and its host rock, and further analyses show that there is little lateral variation along the same vein. However, a modal analysis of the same pseudo-tachylyte by point counter gave a porphyroclast content of 9 per cent quartz and 11 per cent plagioclase (with composition about An_{30}) by volume. The composition of the pseudotachylyte's groundmass has thus been calculated by subtracting the porphy-roclast content from the whole rock analysis, and the results (column D) show that the groundmass has a composition close to that of a typical basaltic andesite (column E) from the Cascades Volcanic Province (Turner & Verhoogen 1960, p. 285).

These results demonstrate that the melt phase generated is by no means a selective low melting-point fraction of granitic composition, but this is unsurprising considering the comparatively low water content of host gneisses and pseudotachylyte (typically about 1 per cent by weight), and the short time available for mutual reaction between

mineral phases, which probably means that the minerals tend to melt individually in order of increasing melting-points. Certainly the high apparent mobility of the melt is more readily understood if it is of a composition which tends to the basaltic rather than the granitic. Precise estimates of the likely melt temperature are difficult to make, but Spry (1969, p. 111) suggests that under the somewhat analogous conditions of contact metamorphism, melting of quartz-rich metamorphic rocks begins at about 950 °C. The total absorption of micas and hornblende by the melt points to temperatures in excess of this figure, while the embayment of plagioclase prophyroclasts perhaps indicates temperatures as high as 1100–1200 °C, though this will be critically dependent on water content (Philpotts 1964). In later calculations, the melt temperature is taken as 1100 °C, which is within a few tens of degrees of the liquidus determined at 1 bar for a melt of this composition (Thompson 1973), and is about the temperature at which a basaltic andesite becomes comparatively mobile with a viscosity in the range 10^3–10^4 poise (Scarfe 1973).

5. The depth range of pseudotachylyte faulting

The mylonitic shear zones, mentioned previously as having initially underlain the level of pseudotachylyte generation, developed under lower greenschist conditions in a temperature regime within the range 250–350 °C (Turner 1968, p. 366). Thus, assuming a continental geothermal gradient of 30 °C km^{-1}, one may infer a lower depth bound of around 10 km for pseudotachylyte faulting. Some idea of an upper bound can be gained from the fact that in contrast to some pseudotachylytes described from the Himalayas (Scott & Drever 1954) and elsewhere, those from the Outer Hebrides are non-vesicular. For a typical water content of 1–2 per cent by weight, a minimum cover of perhaps 1 km may be inferred for the time of their formation (McBirney 1963).

Unfortunately, no further direct evidence is available for narrowing this 1–10 km depth range for pseudotachylyte faulting. However, in Section 8 it will be shown that empirical stress estimates, derived from a study of pseudotachylyte microfaults west of the thrust base, are consistent with the stress magnitudes required to overcome the frictional constraints on dry thrust faults at a depth of around 4–5 km. It should be borne in mind, though, that if the localized faulting west of the thrust base occurred early in the development of the thrust zone as is suspected, the faults could then have been carried down to lower structural levels by the continued thrusting.

6. The nature of faulting involved in pseudotachylyte generation

Two lines of evidence suggest that the shear failure which gave rise to pseudotachylyte took place at slip-rates well in excess of 10 cm s^{-1}, within the range characteristic of earthquake faulting.

(i) Injection veins of pseudotachylyte range from a few centimetres to as little as a millimetre or even less in width, but the latter may still extend for several centimetres through the country rock. By considering the conductive cooling of an infinite planar sheet of melt of width, a, instantaneously injected at a uniform temperature, T_0, relative to the country rock, one can place an upper limit on the time available for the intrusion of injection veins of a given thickness. In this model, assuming that pseudotachylyte and country rock have the same thermal properties, and that because the pseudotachylyte is formed as a glass, there is no significant release of latent heat, the temperature in the centre of the vein relative to the country rock after time, t, is given by:

$$T = T_0 \, \text{erf} \left(0 \cdot 25 a (Kt)^{-\frac{1}{2}} \right) \tag{2}$$

where K is the thermal diffusivity (Jaeger 1964). It is now useful to define the cooling ' half-life ', $t_{\frac{1}{2}}$, of a vein, being the time in which the temperature difference between the centre of the vein and the country rock away from the vein falls to one half of its initial value. Then,

$$t_{\frac{1}{2}} = 0 \cdot 27 a^2 K^{-1} \qquad (3)$$

and if $K = 0 \cdot 007 \text{ cm}^2 \text{ s}^{-1}$ (Jaeger 1957),

$$t_{\frac{1}{2}} \simeq 40 a^2 \text{ cgs units.} \qquad (4)$$

Thus for injection veins 1 cm and 1 mm in width, the cooling half lives will be respectively 40 and 0·4 s. Clearly, the time available for the injection of a vein of finite extent and given thickness will be considerably less than the appropriate half-life for the conductive cooling of an infinite sheet*. If, for example, one considers the arrays of tensional injection veins often found linking en echelon fault veins, and also the frequent occurrence of injection veins leading back to near-barren fault veins, there is a clear implication that generation and injection of pseudotachylyte melt took place more or less simultaneously during episodes of fault slip. It is therefore reasonable to suppose that the time intervals involved in pseudotachylyte injection were of the same order as those required for the generation of the melt during a slip increment. One can therefore conclude that the injection and generation of the pseudotachylyte melt took place within a few seconds at the very most, implying slip-rates of 10 cm s^{-1} or more for the commonly observed ' single-jerk ' displacements of 10–100 cm.

(ii) Supporting evidence comes from a simple analysis of the temperature rise induced by frictional sliding on fault planes at various slip rates and depths in the crust. Now it has been shown (Sibson 1973) that melting on fault planes is inhibited by the presence of an intergranular pore-fluid such as water, because the first increments of frictionally generated heat create a transient localized increase in fluid pressure which drastically lowers the effective normal stress across the fault plane, and thus the capacity of the fault to generate further heat during continued slip. It is only necessary, therefore, to examine the case of dry frictional sliding, that is to say, sliding under conditions of zero pore-fluid pressure. For ease of calculation, a simple model is considered in which faulting takes place at constant velocity, v, on a horizontal plane so that the normal stress across the fault plane z , is equal to the overburden pressure given by:

$$\sigma_v = \rho g z \qquad (5)$$

ρ being the crustal density, g the acceleration due to gravity, and z the depth to the fault plane. It is also assumed that Amonton's Law remains approximately true for frictional sliding over the depth range considered (the work of Byerlee (1968) suggests that this will be so), so that the frictional resistance to shear is given by:

$$\tau_f = \mu_k \cdot \sigma_n \qquad (6)$$

μ_k being the coefficient of kinetic friction. Then the rate of heat production per unit area of the fault plane is given by:

$$\left. \begin{array}{l} Q = \mu_k \cdot \sigma_n \cdot v \\ \\ = \mu_k \cdot \rho g z \cdot v \end{array} \right\} \qquad (7)$$

* Owing to the very strong temperature dependence of silicate melt viscosities (Clark 1966; Scarfe 1973), the cooling range of melt temperatures over which injection can continue is likely to be a small fraction of the initial temperature difference, perhaps 900–1000 °C, between pseudotachylyte melt and country rock. However, because of uncertainties in estimating the temperature/viscosity range for injection, it has been thought preferable to use the ' half-lives ' calculation, which makes few assumptions about the properties of the melt, and gives an upper limit to the possible injection time.
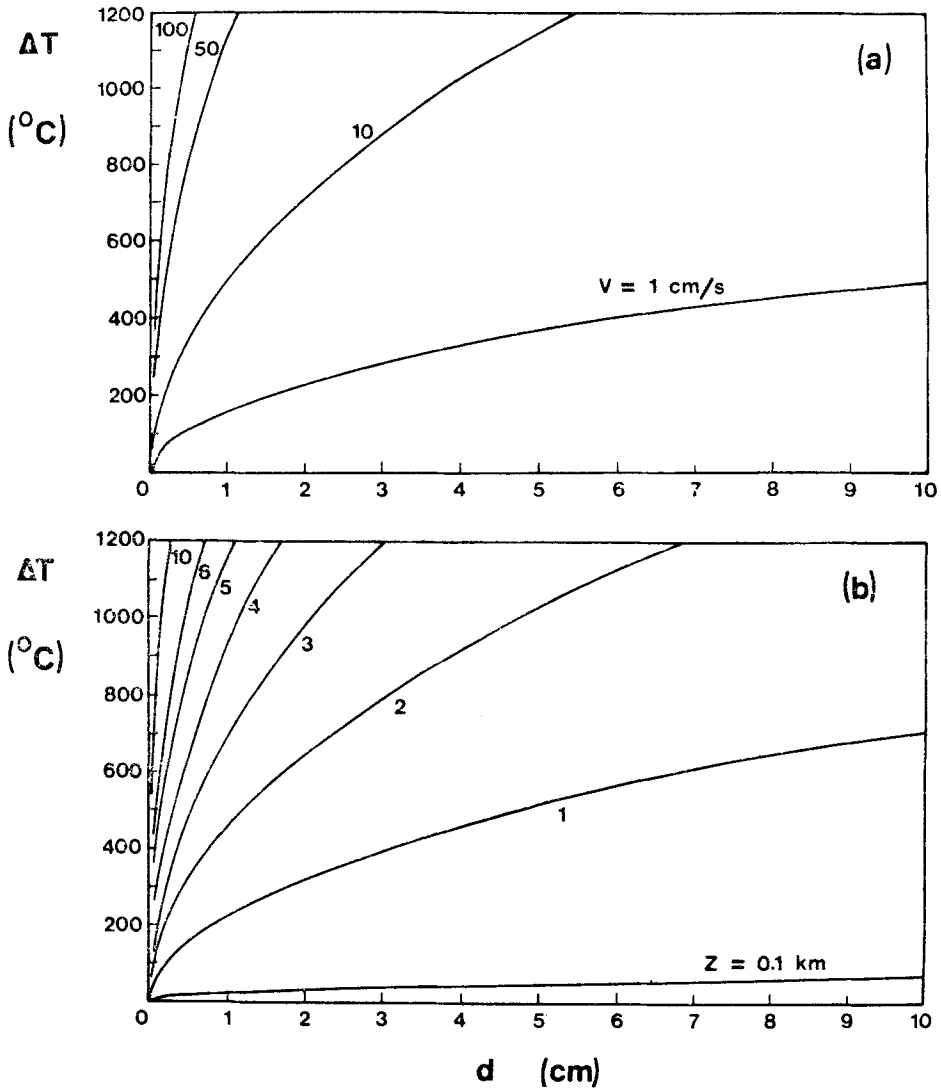
FIG. 6. (a) Temperature rise (ΔT) versus displacement (d) on a horizontal fault at a depth of 5 km for various sliding velocities (v) ($\mu_k = 0 \cdot 5$). (b) Temperature rise versus displacement for dry frictional sliding at 50 cm s^{-1} at various depths $\mu_k = 0 \cdot 5$).

and the temperature rise after a displacement, d, at constant velocity can be calculated from the equation for constant heat production along a plane in an infinite medium (Carslaw & Jaeger 1959, p. 76). Thus,

$$\left. \begin{aligned} \Delta T &= \frac{Q}{k} \sqrt{\frac{K.d}{\pi v}} \\ &= \frac{\mu_k \cdot \rho g z}{k} \sqrt{\frac{K.dv}{\pi}} \end{aligned} \right\} \tag{8}$$

where K is the thermal diffusivity and k the thermal conductivity. Reasonable values

Table 2

Data from pseudotachylyte microfaults

d(cm)	a(cm)	d/a
0·7	0·05	14
*0·34	0·020	17
2·8	0·125	22
1·8	0·005	36
6·7	0·15	44
8·8	0·175	50
8·2	0·15	54
7·1	0·125	57
5·8	0·10	58
11·7	0·20	59
6·8	0·075	91
24·3	0·225	108
129·0	0·75	172
91·0	0·325	280

* Measured microscopically

for the parameters involved are:

$$\mu_k = 0·5 \qquad K = 0·007 \text{ cm}^2 \text{ s}^{-1} \qquad g = 980 \text{ cm s}^{-2}$$
$$\rho = 2·8 \text{ g cm}^{-3} \qquad k = 2 \times 10^5 \text{ erg cm}^{-1} \, {}^{\circ}\text{C}^{-1} \text{ s}^{-1}$$

Using equation (8), temperature rise has been plotted against displacement for various slip-rates at a depth of 5 km in the crust (Fig. 6(a)), and also for a typical seismic slip-rate of 50 cm s^{-1} (Ambraseys 1969; Brune 1970) at different crustal depths (Fig. 6(b)). Such curves are of course meaningful only up to the onset of melting ($\Delta T \sim 800\,°C$), when the frictional properties of the fault surface may be expected to change abruptly. It should also be noted that for a more typical, inclined thrust fault in a compressive stress regime, the normal stress across the fault plane will exceed the overburden pressure. For a thrust fault in the optimum orientation for frictional sliding with a static coefficient of friction equal to 0·75, the normal stress is 1·6 times the overburden pressure, so that the rate of heat generation and consequently the temperature rise will be greater than for the model of a horizontal fault by this factor.

In thin-section, Outer Hebrides pseudotachylyte can be seen microscopically as having just started to form on microfaults with a finite apparent slip of less than 0·5 cm. Thus, despite uncertainties in the validity of application of simple frictional laws, and the lack of detailed knowledge of velocity–displacement relationships during seismic faulting, one may infer from the curves in Fig. 6 that pseudotachylyte was produced by faulting at slip-rates in excess of 10 cm s^{-1}, at depths greater than 2–3 km.

7. Work–displacement relationships on pseudotachylyte microfaults

By measuring the displacement, d, and the thickness of the melt layer, a, on pseudotachylyte-bearing microfaults, much can be learnt concerning the decrease of heat-generating capacity and frictional resistance with progressive slip on a melt-lubricated fault plane, during a 'single-jerk' displacement. Unfortunately, there are severe limitations on the accuracy of the field data, because:

(i) Some microfaults are devoid of pseudotachylyte and these have to be ignored. (It may be that such structures are the product of slow, aseismic faulting, or that generation of pseudotachylyte has been inhibited by the presence of local concentrations of pore water, as suggested earlier.)
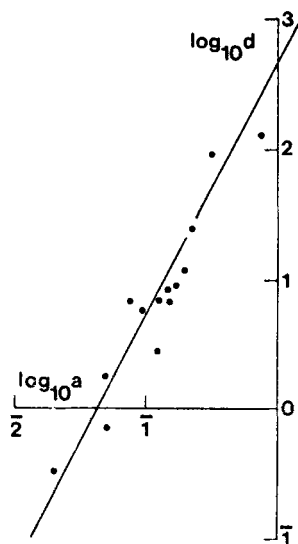
Fig. 7. Displacement (d) versus thickness of the pseudotachylyte layer (a) on microfaults (both d and a are measured in cm).

(ii) It is only possible to measure apparent displacements from offset gneissic banding etc., as there are usually no definitive indicators of true slip direction. Field measurements have been rejected where the relative orientation of microfault and marker banding is such that the probable true displacement, usually consistent with WNW–ESE shortening, is likely to differ greatly from the apparent displacement.

(iii) Fault veins of pseudotachylyte usually 'pinch and swell', which makes it difficult to estimate the average layer thickness.

(iv) Pseudotachylyte melt has often been lost from fault veins by injection into tension fractures, especially on faults which have slipped more than a few centimetres.

(v) Accurate correlation of displaced gneissic banding becomes difficult when the bands are offset by more than 10 cm or so.

Measurements were therefore restricted to those pseudotachylyte-bearing microfaults with no visible associated injection veins, along which slip could be estimated. All quoted measurements were made in the area west of the thrust base in North Uist. Apart from very small fault veins on which measurements were made microscopically, a calibrated draper's lens was used in the field to estimate the thickness of pseudotachylyte fault veins, the average of several measurements (each to the nearest 0·25 mm) being taken to eliminate the effects of 'pinch and swell'. The results are tabulated in Table 2, and from a plot of $\log_{10} d$ against $\log_{10} a$ (Fig. 7), the following straight line was obtained by least squares.

$$\log_{10} d = 1·94\,(\pm 0·2)\log_{10} a + 2·64\,(\pm 0·07)\ \text{cgs units.} \qquad (9)$$

To a close approximation, this corresponds to the parabolic relationship:

$$d = 436a^2 \qquad \text{cgs units.} \qquad (10)$$

Surface fault displacements up to several metres in extent have been produced by the largest historical earthquakes. If equation (10) held for large individual displacements, a slip increment of 5 m would have given rise to a uniform layer of melt just over 1 cm
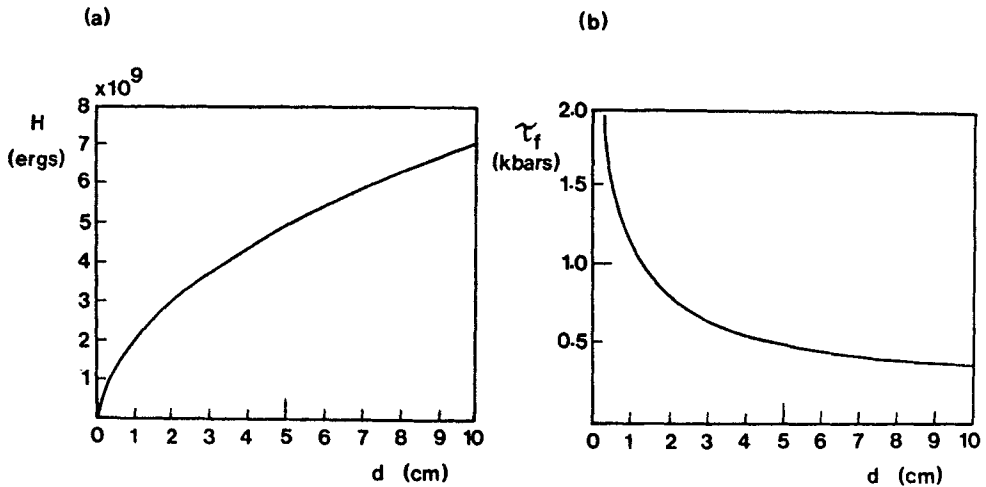
FIG. 8 (a) Cumulative generated heat (H) versus displacement (d) on pseudo-tachylyte-bearing microfaults. (b) Frictional resistance (τ_f) versus displacement for pseudotachylyte generating microfaults.

in thickness. This is in reasonable agreement with the work of McKenzie & Brune (1972), who calculated that a 1-cm layer would be the maximum thickness generated by the mathematical models for earthquake faulting which they considered. However, fault veins of pseudotachylyte 10 cm or more in thickness are not uncommon in the field, though they can rarely be traced far and exhibit 'pinch and swell' on a wave-length of a few metres. It should be remembered that equation (10) was derived from microfaults where it was thought that no melt was lost from the generating fault planes, and the wavelength of 'pinch and swell' was such that an average layer thick-ness could be established over comparatively short distances. It seems likely that thick, 'single-jerk' fault veins probably result from surface irregularities in the fault plane (in a manner akin to the suggested origin of the breccias and quasi-conglomerates), so that partial contact between opposing walls and concomitant heat-generating capacity is always maintained over some parts of the fault surface, with the accumu-lation of pockets of melt elsewhere.

Further implications of this empirically derived equation are explored in the following analysis, which is founded on two assumptions. First, it is reasonably assumed that all pseudotachylyte-bearing microfaults developed under approximately the same initial stress conditions; second, that because individual seismic displacements took place very quickly, virtually all the frictionally generated heat went into melting the gneissic country rock. It follows that the cumulative heat, H, generated per unit area of the fault surface after a displacement, d, should be proportional to the thickness of the molten layer. Thus,

$$H = \int_{x=0}^{x=d} \tau_f . dx = q . a \qquad (11)$$

where τ_f is the frictional resistance and q is the quantity of heat required to melt a unit volume of acid gneiss, hereafter taken to be $4 \cdot 75 \times 10^{10}$ erg cm^{-3}. (Of this value for q, about 4×10^{10} erg cm^{-3} is the energy needed to raise the temperature of acid gneiss over the interval 150–1100 °C (Goranson 1942), while the remainder is the latent heat of fusion (Daly 1933 p. 64).) Note that if τ_f had remained constant during

slip, one would have expected to observe the linear relationship:

$$d = \frac{q}{\tau_f} \cdot a \tag{12}$$

and the cumulative heat generated would increase linearly with displacement. However, from the field derived relationship (10) we obtain:

$$H = \int_{x=0}^{x=d} \tau_f \cdot dx = q \sqrt{\frac{d}{436}} = 2 \cdot 26 \times 10^9 \sqrt{d} \ \mathrm{erg \ cm}^{-2} \tag{13}$$

so that the heat generating capacity of fault movement decreases progressively with increasing slip (Fig. 8(a)).

8. Estimates of stress magnitude

It follows from (13) that the frictional resistance to shear falls off with increasing displacement according to the relationship:

$$\tau_f = \frac{1 \cdot 13 \times 10^9}{\sqrt{d}} = \frac{5 \cdot 4 \times 10^7}{a} \ \mathrm{dynes \ cm}^{-2} \tag{14}$$

which is illustrated in Fig. 8(b). This drastic decrease in frictional resistance with progressive displacement is what might be expected to occur as a molten layer develops and thickens on a fault plane during seismic slip, smothering the low amplitude asperities to decrease the contact area between opposing walls. Indeed, assuming the melt to be a Newtonian fluid, the form of the relationship suggests that once a molten layer has formed, further movement is opposed only by its viscous resistance to shear. This would be directly proportional to the rate of shear straining, which is in turn inversely proportional to the layer thickness.

Because of the many assumptions made, and the imperfect nature of the field data, these results have to be treated with considerable caution. However, they are open to indirect checking from the implied magnitude of the initial shear stresses. Clearly as $d \to 0$, this empirical relationship for τ_f becomes meaningless, but assuming the relationship to hold from the first appearance of melt on the fault plane, and bearing in mind that pseudotachylyte has apparently just started to form on microfaults with a finite slip of 0·5 cm or less, an initial value of at least 1·6 kbar may be inferred for τ_f. It follows that the pseudotachylyte microfaults were probably initiated under differential stresses in excess of 3·2 kbar, as they apparently formed in intact rock possessing a cohesive strength of which so far no account has been taken. The general curve for rock friction presented by Byerlee (1968) enables one to suggest that a first approximation, frictional failure on existing planes is adequately described over the depth range 1–10 km by the simple criterion:

$$\tau > \tau_f = \mu \cdot \sigma_n \tag{15}$$

where μ is the coefficient of static friction, having a value of about 0·75(Fig. 9(a)). Using this criterion, it has been shown (Sibson 1974) that in an ' Andersonian ' thrust regime where $\sigma_v = \sigma_3$ (Anderson 1951), the limiting inequality for frictional sliding under conditions of zero pore-fluid pressure is:

$$(\sigma_1 - \sigma_3) \geqslant (R' - 1) \rho g z \tag{16}$$

where

$$R' = \left(\sqrt{(1 + \mu^2)} - \mu \right)^{-2} \tag{17}$$
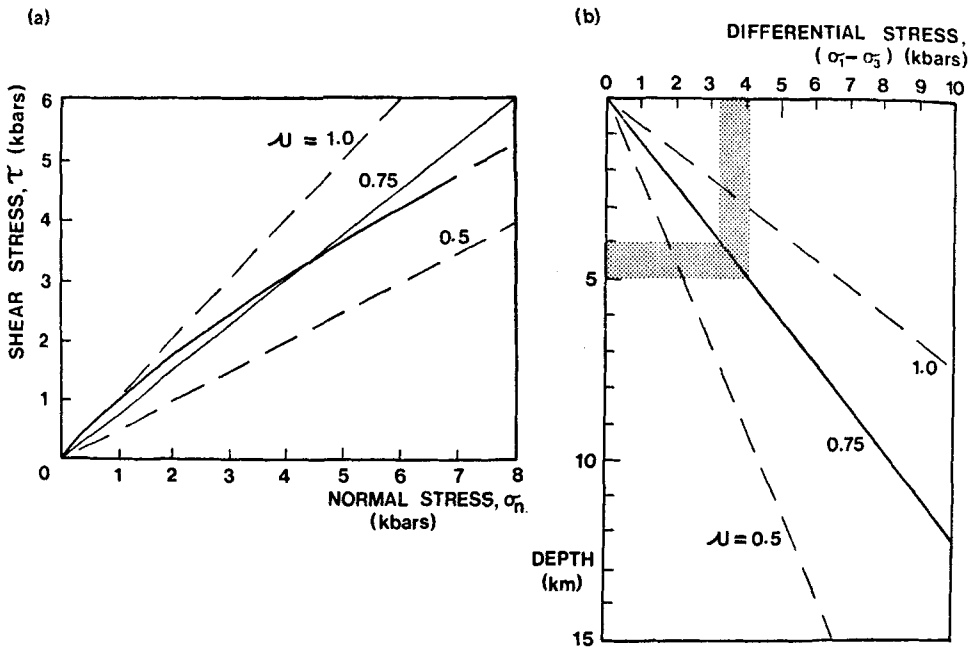
J

(a)

(b)

Fig. 9. (a) Byerlee's (1968) general curve for rock friction with the straight line approximation $\tau/\sigma_n = \mu = 0\cdot75$. (b) Minimum differential stress $(\sigma_1 - \sigma_3)$ required to initiate sliding on a dry 'Andersonian' thrust fault, versus depth (z) for $0\cdot5 < \mu < 1\cdot0$.

Provided the present sheet-dip of 25° for the thrust zone has not changed greatly since the time of thrust activity, the assumption that the Outer Hebrides Thrust can be treated as an 'Andersonian' thrust is probably valid. Using (16) and (17), the minimum differential stress required to initiate dry frictional sliding has been plotted against depth for $\mu = 0\cdot75$ (and also for $\mu = 0\cdot5$ and $1\cdot0$, these values being respectively the likely lower and upper bounds for the static friction of silicate rocks (Dieterich 1974)) (Fig. 9(b)). The estimated differential stresses of 3·2 kbar or more are clearly consistent with dry thrust faulting at a depth of around 4–5 km, near the middle of the possible depth range. Note, though, that the addition of a term for cohesive strength in the failure criterion (15) would increase still further the minimum differential stress required for failure. It is also of interest that these estimates of differential stress approach the previously mentioned preferential failure strength of 4·2 kbar, which Borg & Handin (1966) determined from triaxial testing of intact biotite gneiss. However, these were fast strain-rate tests, carried out at higher temperatures and confining pressures than those postulated for the thrust zone, so their relevance is questionable. A further point of interest is that during movement on a pseudotachylyte-generating fault, slip may be brought to an abrupt halt by rapidly increasing friction if at some stage melt is suddenly lost from the fault plane into tension cracks. Such a process, essentially similar to the 'wet stick-slip' mechanism proposed by Sibson (1973), could give rise to widely varying stress drops for similar initial stress conditions.

9. General discussion

A case has been presented to show that the pseudotachylyte associated with the Outer Hebrides Thrust is necessarily the product of frictional fusion brought about by

high-stress seismic faulting in crystalline quartzo-feldspathic crust devoid of inter-granular fluid. Most probably, the faulting took place at depths of around 4–5 km. These results are in accord with the views of several previous workers who have suggested, either from field evidence (see reviews by Higgins (1971) or Spry (1969, p. 238)), or from theoretical analyses of frictional heating effects (Jeffreys 1942; McKenzie & Brune 1972), that melting can occur on fault planes during seismic faulting. Recently, Friedman, Logan & Rigert (1974) have shown experimentally that thin patches of glass form on pre-cut surfaces in sandstone as the result of frictional sliding at quite low confining pressures and temperatures. Difficulties have arisen, however, in attempts to reconcile the theoretical considerations which suggest that melting on fault planes should be a fairly common phenomenon, with the rather scarce occurrence of pseudotachylyte in fault zones. Philpotts (1964), supported by Higgins (1971), has argued that a necessary condition for the generation of pseudotachylyte by rapid faulting is the pre-heating of the host rock to as much as 400 °C, perhaps by nearby igneous intrusions. There is no field evidence to support this contention in the Outer Hebrides; indeed such high temperatures might be expected to inhibit extremely brittle faulting by inducing a degree of intracrystalline plasticity. The most favoured depth estimate for pseudotachylyte faulting in the Outer Hebrides (4–5 km) leads one to infer host rock temperatures of about 150 °C. As previously argued (Sibson 1973), the key factor which determines whether or not melting occurs on fault planes at depth during seismic slip, is probably the absence or presence of an intergranular fluid.

It is tempting to draw an analogy between the pseudotachylyte faulting west of the main thrust zone, apparently resulting from the brittle failure of near-intact rock, and the random microcracking which as been shown (Scholz 1968) to precede ultimate brittle failure and the formation of a dominant fault plane in a rock specimen under load. Inhomogeneities in the gneissic complex, such as large lenses of metabasite and major fold structures, may fulfil the same function on a large scale as do grain boundaries and cracks in a test specimen, giving rise to stress concentrations and localized faulting which eventually clusters around the site of a major failure plane just prior to its formation.

Within the thrust zone proper, the main crush zones, which range up to 40 m in thickness, are largely made up of ultracataclastic (exceedingly fine-grained, cohesive rock powder), with only a minor fraction of intensely disrupted pseudotachylyte veining. It would appear, therefore, that the dry conditions needed for pseudotachylyte generation only obtained when the thrust zone first developed. As the result of increasing permeability, water percolated into the developing crush zones (perhaps from the deep crust), and inhibited further generation of pseudotachylyte. The increase in fluid pressure reduced the frictional constraints on faulting by lowering the effective normal stress across the crush zones, thereby contributing to the 'displacement weakening' necessary for the localization of a major fault zone.

If one were to look for modern seismic events similar to those which generated pseudotachylyte in the Outer Hebrides some 400 My ago, the intra-plate earthquakes described by Sykes & Sbar (1973) appear as obvious candidates. Fault plane solutions for these events typically indicate horizontal compression, with thrusting as the dominant mechanism. Their peculiar characteristic, however, is the very high propor-tion of energy they radiate in the high frequency end of the seismic spectrum, which is thought to indicate a particularly brittle, high-stress mode of faulting.

10. A note on the use of pseudotachylyte as a palaeoseismic indicator

It is by no means contended that all pseudotachylyte must, of necessity, have been generated by seismic faulting; there is evidence that some occurrences are intimately

linked with large crypto-explosion structures thought to result from meteorite impact (Spry 1969, p. 239). Indeed, the type pseudotachylyte described by Shand (1916) does not show the clear relationship to shear fractures seen in the Outer Hebrides, and is clearly related to the Vredefort Dome Complex, which has been cited as an impact structure (Dietz 1961; Wilshire 1971).

However, where pseudotachylyte is associated with shear fractures which can be traced in linear belts across country, it may be used as an indicator of palaeo-seismic activity, albeit of a rather special kind. While pseudotachylyte may well have been generated under dry conditions in crystalline crust at the time of inception of many fault zones, its general scarcity is explicable in that progressive development of the zones with accession of water, will have inhibited the further generation of pseudotachylyte, and in most cases obliterated the early-formed products of faulting.

It is to be hoped that advanced textural studies, both by optical means and transmission electron microscope, will eventually enable the recognition of those cataclastic rock-types which are necessarily the product of seismic faulting in other than dry conditions. Such a technique might be of considerable help in the recognition of fossil plate boundaries.

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