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Transient discontinuities in ductile shear zones

R. H. SIBSON
Department of Geology, Imperial College, London SW7 2BP, England

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Abstract—Earthquake fault ruptures sometimes extend to deep crustal levels and beyond, where moderate- to high-grade metamorphic conditions must prevail in mylonitic shear zones. Evidence for such transient loss of continuity in mylonite belts tends to be obliterated by continued aseismic shearing and accompanying metamorphic processes, but in parts of the Outer Hebrides Thrust zone, NW Scotland, textures suggest that pseudotachylyte friction-melt has been produced intermittently by seismic slip on discrete planes within an otherwise ductilely deforming shear zone. All stages can be recognised in the progressive smearing-out of originally cross cutting, random-fabric pseudotachylyte veins, which end up as bands of ultramylonite in near-concordance with the mylonitic foliation.

Though generally leaving little trace, transient discontinuities are probably not uncommon in deep mylonite belts. It follows that strain integration across apparently ductile shear zones, on the assumption of continuity, may severely underestimate the total shear displacement.

DEPTH DISTRIBUTION OF CRUSTAL SEISMICITY

ALONG large continental transforms such as the San Andreas Fault, most seismic activity cuts out at a depth of around 10–15 km (Eaton *et al.* 1970). This accords well with a simple model for a major fault zone in which the transition with increasing depth to a greenschist metamorphic environment is accompanied by a change from frictional, discontinuous faulting in the upper crust to continuous, ductile shearing in quasi-plastic mylonite belts below (Sibson 1977a). However, even away from sites of active subduction, earthquakes do occur from time to time in the deep continental crust and may contribute significantly to regional displacements at this level. From seismic moment estimates, the largest of these events involve slip of the order of a metre or so with rupture areas extending up to a thousand square kilometres or more (e.g. Abe 1975, Fukao & Furumoto 1975).

The loci of deep crustal earthquakes are presumably planar zones of weakness in the basement such as deep-level shear belts, perhaps inherited from earlier orogenic phases, which intermittently respond by brittle shear failure to regional deviatoric stress. At such depths one may expect that the metamorphic processes accompanying continued aseismic shearing, involving recrystallisatiion, neomineralisation and the transfer of aqueous fluids (Beach 1976), will generally obliterate traces left by the transient passage of earthquake ruptures. Here, however, textural evidence for intermittent seismic slip in an otherwise ductilely deforming mylonite belt is presented from one area within the Outer Hebrides Thrust zone in NW Scotland.

THRUST DEFORMATION AT SEAFORTH HEAD, ISLE OF LEWIS

The Outer Hebrides Thrust, of probable late Caledonian age, is a broad zone of variable thrust deformation with a sheet-dip of around 25°ESE, which disrupts the Lewisian Gneiss Complex of the Outer Isles, and margins their eastern seaboard for almost 190 km (Jehu & Craig 1934, Francis & Sibson 1973, Sibson 1977a, b). In the Seaforth Head region on the Isle of Lewis, the host rocks to the thrust zone are of high amphibolite grade, consisting mainly of quartzo-feldspathic gneisses with some hornblende and/or biotite, the *grey gneisses* of Dearnley (1962). Patches of rather coarse, pink granitic gneiss occur locally and immediately below the thrust base, large bodies of fairly massive amphibolite [typical assemblage: (quartz) – plagioclase – hornblende – diopside – garnet] are common and may have had some influence on the localisation of thrust deformation.

In the forefront of the thrust zone, which in this region extends some 13 km eastwards to the Minch coast, these host rocks have been variably mylonitised and otherwise deformed within a broad shear belt about 1 km in width, which dips eastward at low angles. The areas of most severe deformation, from which the rocks described below have been collected, are well exposed on the flanks of the hills Malasgair (Grid Ref: NB301167) and Feirihisval (NB301146), lying respectively north and south of Loch Sgibacleit. Fault rock nomenclature follows that put forward by Sibson (1977a).

Metamorphic environment during thrusting

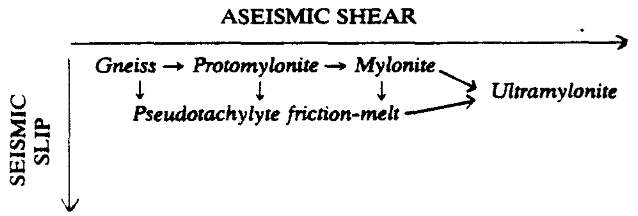
In comparison with other mylonite belts in the thrust zone, that at Seaforth Head is anomalous in both its width and the lack of retrogression within it. Elsewhere, rocks within most of the mylonite belts are hydrated to phyllonites, having undergone almost total retrogression to lower greenschist assemblages (Sibson 1977a). At Seaforth Head, however, evidence for retrogression is slight. Hornblende, biotite and garnet, while undergoing some mechanical degradation, have apparently remained chemically stable and, at least locally, the last two of these minerals have undergone recrystallisation.

At this stage, it is not clear whether at Seaforth Head we are looking at a deeper portion (15 km + ?) of the thrust zone than is exposed elsewhere, or whether lack of fluid access has inhibited retrogression and strain-softening, kept stress levels relatively high, and led to the development of an unusually broad shear zone in which temperatures have been locally raised by shear heating. It has also been suggested [D. Fettes, J. Mendum & D. Smith (IGS, Edinburgh) pers. comm.] that at Seaforth Head, the primary mylonitic foliation at least may be inherited from an older Laxfordian (*ca.* 1800 Ma) phase of deep crustal shear zone development. Against this, it has to be pointed out that quartz stretching lineations in the *L–S* mylonitic fabric are consistent with the ESE–WNW direction of translation observed elsewhere in the thrust zone (Sibson 1977b).

Whichever of these explanations is correct, the conclusions reached below concerning textural development in the high deformation portions of the shear zone, remain unaffected.

Deformation processes and textures

In those regions of the shear belt where deformation is at its most intense, there is a complex mixture of brittle faulting and high-strain ductile mylonitisation. Texture-forming processes are outlined in the synoptic diagram below.



Variations in the intensity of mylonitisation indicate considerable strain heterogeneity on a small scale which is often promoted by the presence of lensoid bodies of relatively competent metabasite. Locally, progressive mylonitisation has produced bands of intensely foliated ultramylonite almost devoid of porphyroclasts. The well-ordered fabrics of such mylonite series rocks may generally be associated with quasi-plastic, steady-state shearing at aseismic rates (Sibson 1977a).

However, the mylonitic fabric is also invaded by networks of exceedingly fine-grained, close-jointed black veins, lying both concordant and discordant to the foliation (Fig. 1). Many of them display the fault/injection-vein habit characteristic of pseudotachylyte friction-melt, the product of seismic slip on discrete planes (Sibson 1975). It appears that most of the brittle shear fractures on which the melt was generated developed subparallel to the mylonitic foliation which clearly acted as a preferential plane of failure, with injection veins ramifying across the foliation.

Examination of thin-sections shows, however, that while some of the vein material possesses the textural characteristics of pseudotachylyte (random-fabric quartz and feldspar porphyroclasts, with fine microlitic chill textures developed in the groundmass of the thicker veins), most show signs of subsequent deformation with the development of shape fabrics of varying intensity (Figs. 2 a–h). Even while the veins remain strongly discordant to the surrounding foliation, their internal textures become ultramylonitic with porphyroclasts deformed into alignment with a recrystallised groundmass rich in phyllosilicates. With increasing shear strain, originally cross-cutting veins are smeared out into near-concordance with the host foliation (Figs. 2 f & g), eventually becoming indistinguishable from ultramylonite bands resulting from progressive mylonitisation. The product is a banded mylonite–ultramylonite which in turn may be disrupted by further pseudotachylyte-generating slip events (Fig. 2h).

Nucleation of earthquake ruptures

The source of the intermittent earthquake ruptures responsible for pseudotachylyte generation remains problematic. Assuming a depth equivalent to the metamorphic grade under normal geothermal gradients, say 15–20 km, and low intergranular fluid pressures [indicated by the lack of hydration reactions and thought to be a prerequisite for pseudotachylyte formation (Sibson 1977c)], then unrealistically large differential stresses ($> 10^9$Pa = 10 kbar) would be required to overcome frictional constraints and initiate thrust ruptures within the mylonites (Sibson 1974). One possibility is that the shear fractures nucleated in an upper frictional regime within the fault zone and propagated dynamically downwards through the mylonites. The level of required stresses would also be reduced if sufficient shear heating had occurred for the mylonites to have developed at a significantly shallower depth.

However, it is worth pointing out a field relationship which suggests a further, intriguing explanation. Within the mylonites, the pseudotachylyte-generating ruptures are often concentrated close to the margins of lensoid bodies of metabasite, which commonly range from 10 to 100 m in dimension and apart from their borders, remain virtually undeformed. It seems possible that they have functioned as stress risers, locally nucleating earthquake ruptures. Figure 3 illustrates schematically the perturbing effect on the strain and strain-rate fields of a single such metabasite lens in a ductile shear zone otherwise undergoing uniform simple shear. To maintain strain continuity, locally intensified shear strain (γ) and rates of shear strain ($\dot{\gamma}$) must develop adjacent to the bodies. The resulting stress amplification will be a function of the aspect ratio of the metabasite body and the rheological flow laws operating. Whether such failure would be an entirely brittle process or would involve some form of creep runaway to overcome friction (e.g. Orowan 1960, Griggs & Baker 1969) remains unresolved.

DISCUSSION

With deep crustal shear zones it is common practice to assume a deformation history involving strain con-

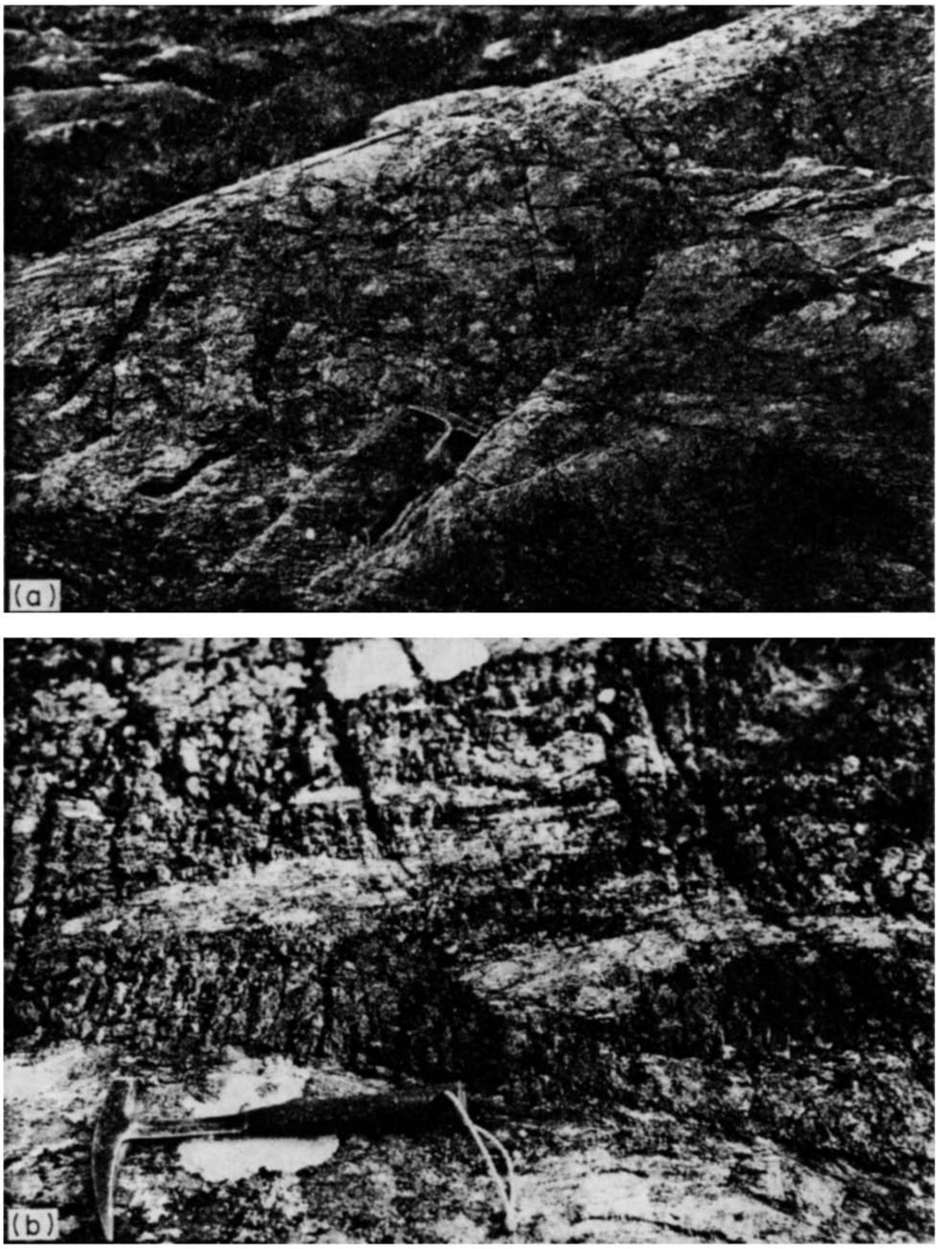


Fig. 1. (a) Fault/injection vein complex of pseudotachylyte cutting mylonitised grey gneiss, Malasgair. (b) Pseudotachylyte vein network, deformed and flattened into the mylonitic foliation, north flank of Feirihisval.

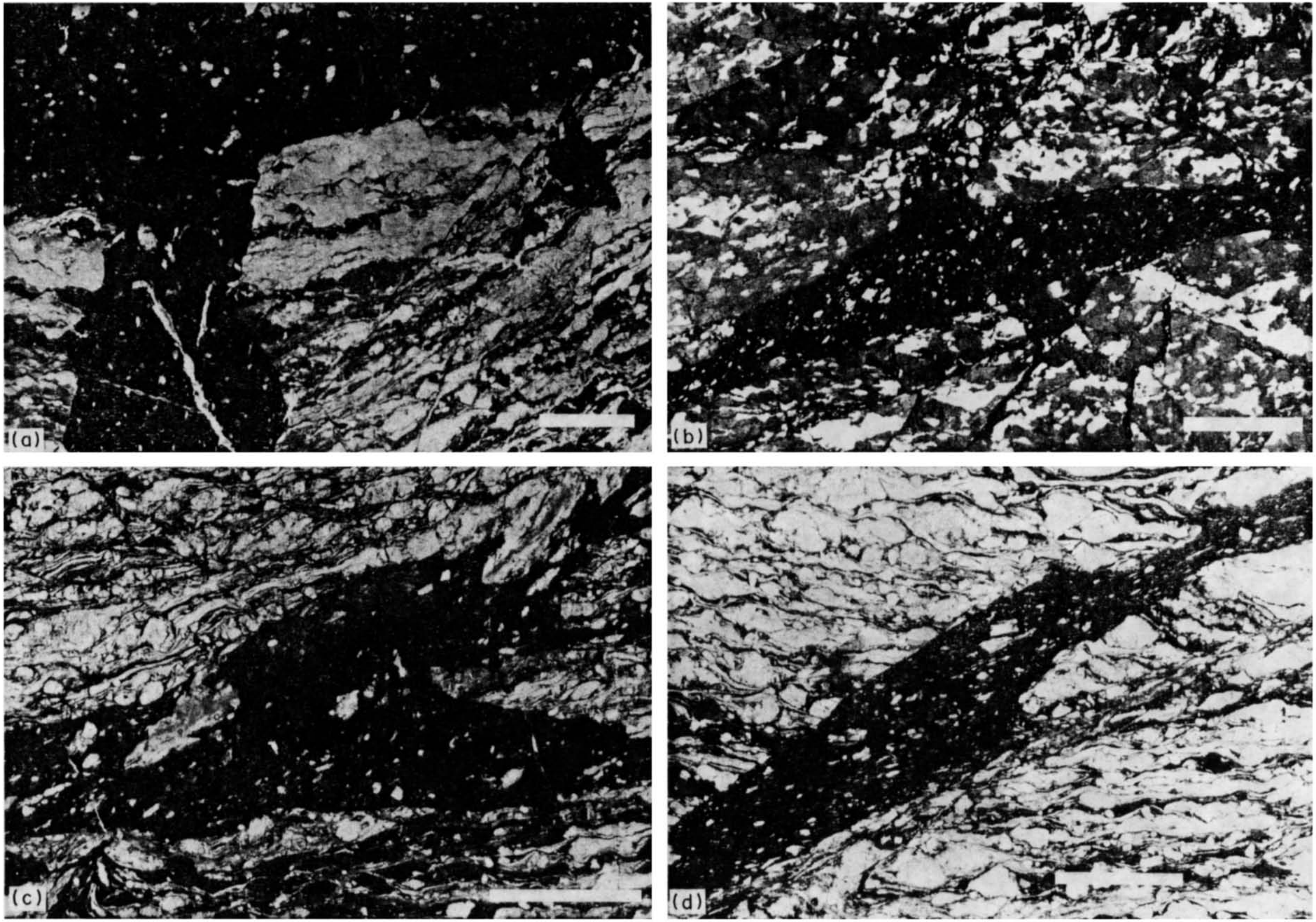


Fig. 2(a) – (d). For caption see p. 169.

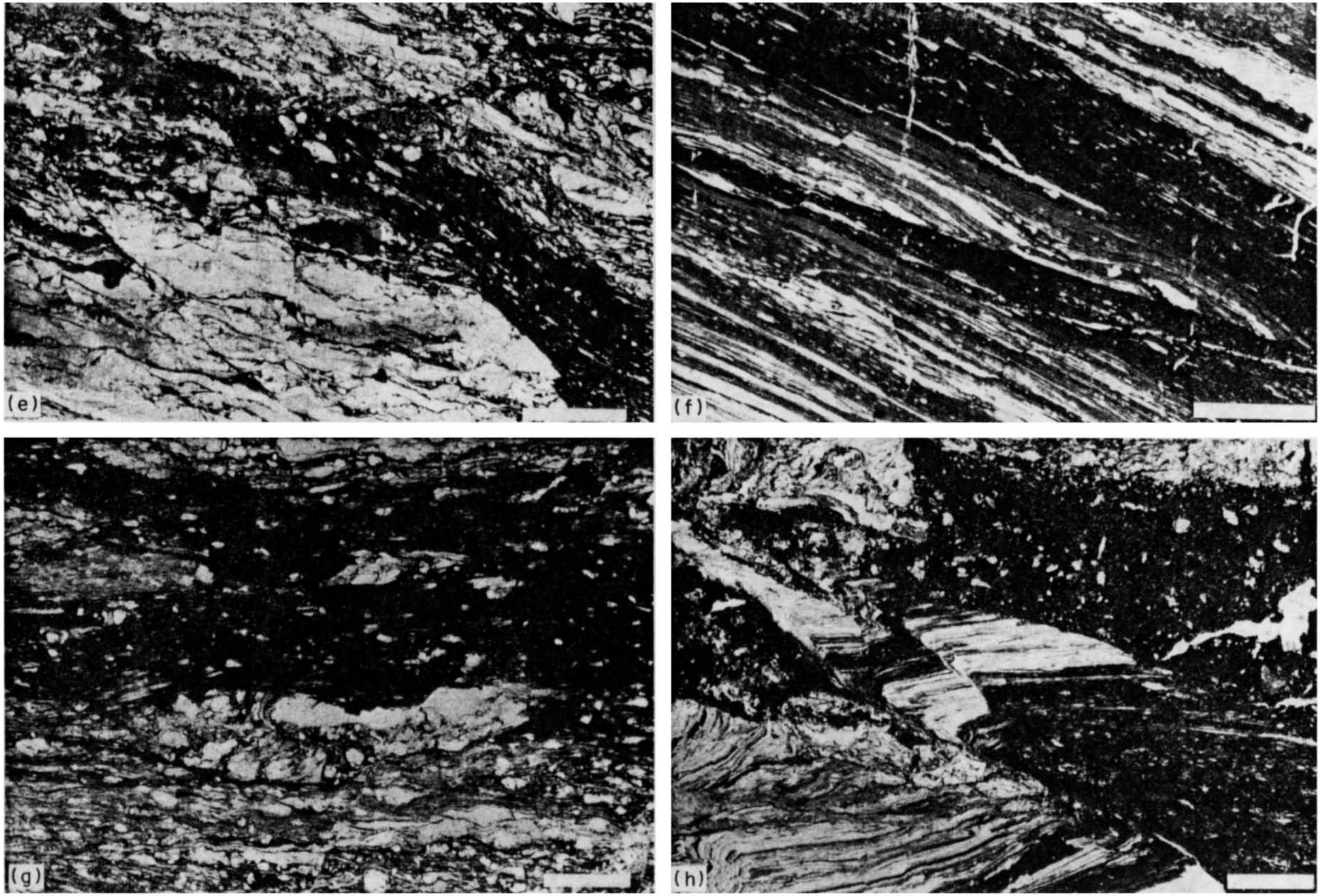


Fig. 2. Deformation of pseudotachylyte veining (Plane polars, white scale bar represents 4 mm). (a) Pseudotachylyte with random-fabric porphyroclasts in a fault/injection vein relationship disrupting mylonitised grey gneiss. A microlitic groundmass is visible at higher magnification. (b) Pseudotachylyte veining with incipient alignment of porphyroclasts, cutting hornblende-rich protomylonite. (c) Shape fabric developing in deformed veining still discordant to the mylonitic foliation. (d) Locally intense shape fabric in cross-cutting vein. (e) Strong shape fabric in slightly discordant vein. (f) Bands of ultramylonite barely discordant to the host foliation. (g) Details of concordant band of ultramylonite. (h) Fresh invasion of pseudotachylyte, accompanying faulting, disrupting banded mylonite-ultramylonite.

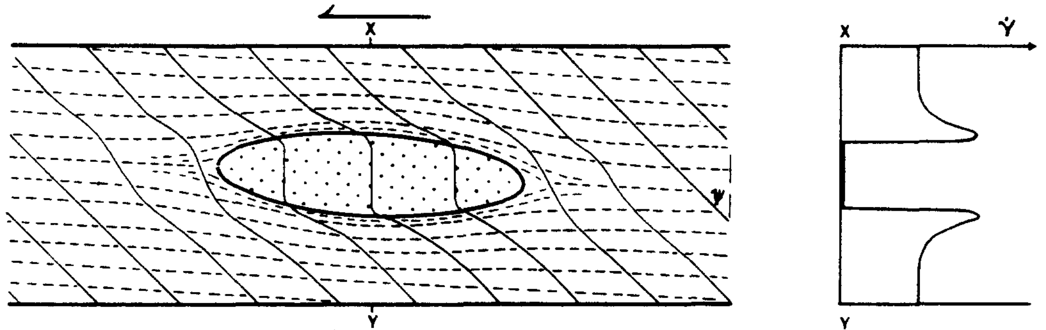


Fig. 3. Distortion of strain and strain-rate fields induced by a metabasite lens in a ductile shear zone otherwise undergoing uniform simple shear. Slope of marker lines, ψ, reflects the intensity of shear strain, $\gamma = \tan\psi$, over a given time interval, and thus the rate of shear straining, $\dot{\gamma}$.

tinuity, and to estimate displacement by integrating shear strain across the zones in the manner outlined by Ramsay & Graham (1970) (e.g. Coward 1976). If the process of intermittent seismic slip on discontinuities within an otherwise ductilely deforming shear zone, as demonstrated here, is widespread, such methods may severely underestimate the total shear displacement. In most cases, evidence for such transient loss of continuity will be difficult to recognise. Within the more common hydrated mylonite belts, the products of seismic slip will probably not be pseudotachylyte (Sibson 1977c), and more extensive recrystallisation and neomineralisation will tend to obliterate cataclastic traces left by propagating earthquake ruptures.

Though clearly a difficult task, it is nonetheless highly desirable that every effort should be made to establish the ratio of seismic slip to aseismic shear at all crustal levels, for comparison with the results of seismic moment summation along major active fault zones (e.g. Davies & Brune 1971, North 1974, Hanks *et al.* 1975).

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