Strain-insensitive foliations in polymineralic rocks[1]

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Means recently introduced the concept of strain-insensitive foliation. For strain-insensitive foliation to form in monomineralic aggregates, foliation-forming processes must be balanced by foliation-destroying processes, e.g., grain rotation and dynamic recrystallization. In polyphase aggregates a further process is required to disperse monomineralic polycrystalline aggregates of the rock-forming phases in order to eliminate the strain sensitivity of the resultant foliation.

Dispersal of silicate phases in amphibolite and granulite facies mylonitic bands suggests that destruction of monomineralic polycrystalline aggregates may be a diffusion process, driven by a reduction of grain boundary energy of the aggregate where diffusion coefficients are high and kinetic barriers to diffusion are low. Such conditions may pertain in high-temperature shear zones and can result in steady-state foliations.

Le concept de foliation, insensible à la déformation finie, a été esquissé par Means. Pour que se forme une telle foliation dans un agrégat monominéralique, il faut que les processus de développement de la foliation soient compensés par ces processus qui tendent à la détruire, tels la rotation de grains ou la recrystallisation dynamique. Dans un agrégat polyminéralique il faut, en plus, un mechanism capable de disperser des agrégats polycrystallins monominéraliques des phases volumétriquement importantes afin d'éliminer la sensibilité à la déformation finie de la foliation qui en résulte.

La dispersion des phases silicatées dans des bandes mylonitiques des faciès des amphibolites et des granulites révèle que la destruction des agrégats polycristallins monominéraliques correspondrait à un processus de diffusion, résultant d'une réduction de l'énergie des joints de grain de l'agrégat où les coefficients de diffusion sont élevés et les barrières cinétiques de diffusion sont faibles. De telles conditions peuvent prévaloir dans les zones de cisaillement de haute température et peuvent engendrer des foliations "steady state."

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Introduction

Allowing for the discussion of the relationship of the microstructurally diverse types of foliations to the principal directions ($X \geq Y \geq Z$) of the finite strain ellipsoid (Wood 1974; Williams 1976, 1977; Williams *et al.* 1977; Hobbs *et al.* 1976, 1982), the relationship of strain-sensitive foliation to the boundaries of ductile shear zones is generally established (e.g., Ramsay and Graham 1970; Coward 1976; Ramsay 1980). Williams (1976, 1977) has shown that the precise angular relationship of the foliation to the finite strain ellipsoid during progressive strain depends in part on the relative roles of the several contributing foliation-forming mechanisms and in part on the material structure of the foliation. Means (1981), on the other hand, suggested that the strain sensitivity of a foliation during steady-state flow will decrease as the rate of foliation-destroying processes (grain rotation and dynamic recrystallization) approaches that of the foliation-forming processes (rotation, crystallization, recrystallization, and mass transfer in the sense of White and Knipe 1978; Gray 1977, 1978, 1979; Le Corre 1979; Knipe 1981). In the ideal case, such a structure would be a steady-state foliation.

According to Means (1981), a given grain will flatten during deformation and represent a foliation-forming element. With further strain, rotation and dynamic recrystallization produce several strain-free equant grains, which are not foliation-forming elements, that is, until they in turn are strained. Notwithstanding Means' (1981) justifiable caution, such foliations have been illustrated in monomineralic aggregates by Eisbacher (1970), Brunel (1980), and Garcia-Celma (1982).

However, in the case of a polyphase aggregate deforming by steady-state flow, the newly recrystallized aggregate of a given mineral phase remains a discrete strain-sensitive foliation-forming element, which will rotate with increasing strain. In order for a strain-insensitive foliation to form in a polyphase aggregate, an additional process must operate that rapidly eliminates polycrystalline single-phase aggregates. Although Means (1981) did discuss strain-insensitive foliations in polymineralic rocks, he invoked local violations of the steady-state flow (boudinage, localized shearing, local dilation) in order to destroy strain-sensitive foliation elements such as layers and lenses. Means' discussion, however, implying, as it does, local variation in strain sensitivity and a fortuitous relationship (1:1) between the periodicity of the variation and the layer thickness, is not general enough to be widely applicable.

This contribution, using examples of high-temperature mylonitic rocks, will suggest that, in a more general case of strain-insensitive foliation, this additional process is diffusion, driven by a reduction in the grain boundary energy of the deforming polyphase aggregate.

Geological setting

Specimens described here come from the Ontario Gneiss Segment (Wynne-Edwards 1972) of the western Grenville Province, Canada. Regional studies (Davidson and Morgan 1981; Davidson *et al.* 1982) have shown that the western part of the Ontario Gneiss Segment (Fig. 1) is composed of several structural units (domains and subdomains) that were juxtaposed during major north and northwestward ductile overthrusting during the Grenville Orogeny. These workers showed that the boundaries of these structural units are high-strain zones.

Fieldwork related to the present study was carried out at the junction of three of the structural units (Fig. 1), the detailed results of which will appear elsewhere (Hanmer 1984). Within the high-strain zones are a variety of coarse- to fine-grained granitoid and amphibolitic gneisses, as well as other lithologies. Locally within these gneisses, thin, fine-grained layers (1-5 mm thick) lie parallel to the gneissic banding, to mylonitic

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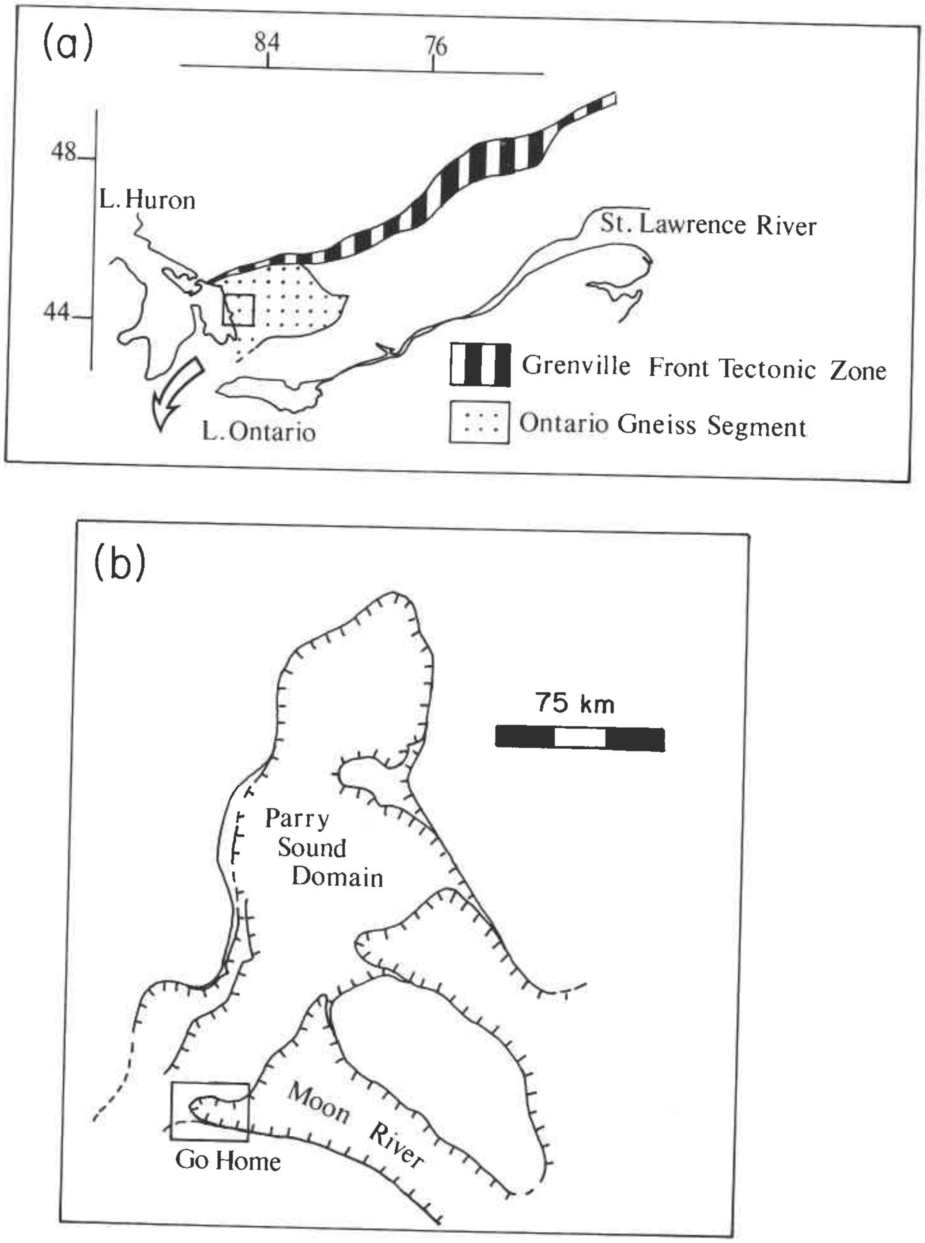

FIG. 1. (*a*) Generalized map of western Grenville Province. After Wynne-Edwards (1972). (*b*) Detail of (*a*) showing structural units, bounding high-strain zones (dip indicated by tick), and location of study area. After Davidson *et al.* (1982).

layers, and to local shear zone boundaries when these are visible. They may be widely spaced and up to several metres long, or closely (1 cm) spaced and anastomosing. They correspond to small-scale shear zones and to Higgins' (1971) grain-size based definition of mylonite. They will be referred to as mylonitic bands.

Microstructure

The following microstructural modifications are observed passing from the medium- to coarse-grained host gneiss into the mylonitic bands.

(1) The grain size decreases from several millimetres to 50 μm (Fig. 2*a*) and there is a marked decrease in the range of grain-size distribution. Within the coarse grains of the host gneiss, all silicate phases show abundant optical subgrain and new grain development. Plagioclase clearly recrystallizes by subgrain rotation (Hanmer 1982). Internally strained new grains and subgrains suggest dynamic recrystallization. In the mylonitic bands equant, often polygonal, feldspar with 120° triple junctions represents the ultimate product of dynamic recrystallization accompanied or followed by normal grain growth.

(2) The irregular distribution of coarse grains and aggregates of quartz, biotite, and hornblende in the host gneiss is replaced by a regular distribution of small, single grains of each phase, dispersed quasi-homogeneously and regularly through the mylonitic bands (Fig. 2 *b* and *c*). Although some coarse relics of old host grains may persist (Fig. 2*e*), very few polycrystalline, monomineralic aggregates occur. With respect to biotite, such aggregates are restricted to marginal selvedges (Fig. 2*b*) and to oblique internal stringers (Fig. 2 *a* and *d*).

(3) The orientation of dispersed, isolated biotite laths in the mylonitic bands is typically oblique to the band boundaries (Fig. 2*b*). Where polycrystalline swaths of biotite do occur,

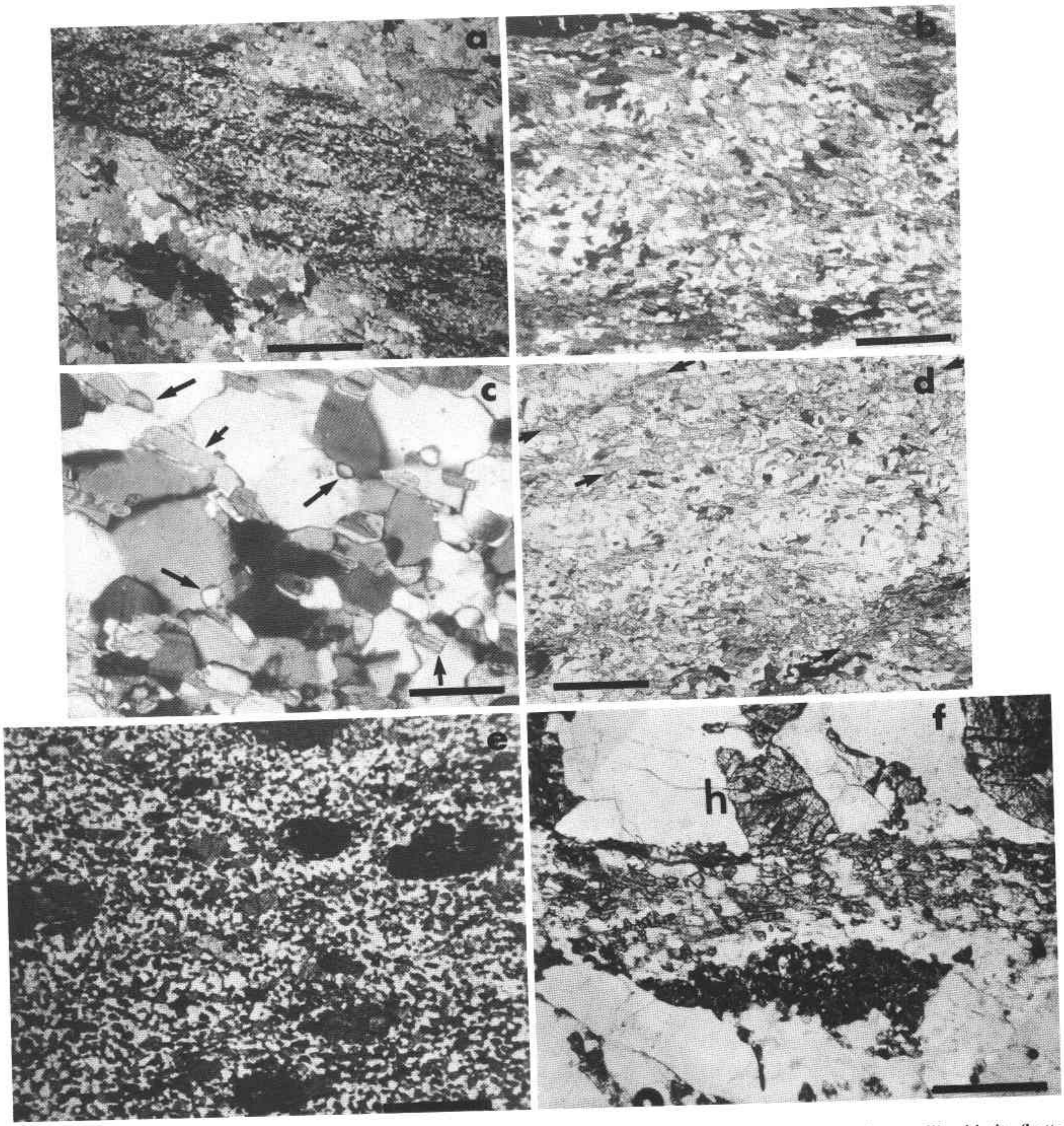

FIG. 2. (a) Mylonitic band trends top left to bottom right. Note coarse grain size and irregular distribution of polycrystalline biotite (bottom left). Fine grain size and regular phase distribution in mylonitic band. Note internal polycrystalline biotite stringers (horizontal) oblique to mylonitic band. Scale bar 3 mm. (b) Detail of mylonitic band. Dispersed, regularly distributed biotite laths and polygonal feldspar grains. Biotites trend at approximately 40° to mylonitic band boundaries but curve progressively into concordant polycrystalline biotite swaths (top and bottom) within which biotite laths lie closer to the band boundary. Scale bar 500 μm. (c) Detail of mylonitic band. Round, monocrystalline quartz drops (long arrows) plus biotite laths (short arrows) dispersed along grain boundary network of polygonal feldspar matrix. Mylonitic band boundary orientation horizontal. Note obliquity of biotite foliation. Scale bar 200 μm. (d) Detail of mylonitic band. Monomineralic polycrystalline biotite stringers (arrows) oblique to mylonitic band boundaries (horizontal). Note alignment of biotite in stringers, especially at bottom right. Scale bar 500 μm. (e) Large relic hornblende grains (dark) and relic clinopyroxene (centre) in homogeneous matrix of regularly dispersed hornblende and plagioclase in mylonitic band in amphibolite gneiss. Scale bar 500 μm. (f) Orthopyroxene (h), regularly dispersed as new grains (high relief) within mylonitic band. Dispersed biotite laths here parallel to band boundaries (cf. b), suggestive of relatively higher strain rate. Scale bar 200 μm. (All photos in $X-Z$ plane of finite strain ellipsoid.)

the biotite laths are aligned parallel to the band boundaries (Fig. 2*b*). The only exceptions to this rule are the thin, polycrystalline biotite stringers within the mylonitic bands that lie obliquely to the band boundaries (Fig. 2 *a* and *d*). Whereas the dispersed biotites make angles with the band boundaries of approximately 40°, the stringers occurring in the same band make angles with the boundaries of about 30°, but of opposite inclination.

(4) The behaviour of orthopyroxene is identical to that of quartz and hornblende in the mylonitic bands. Figure 2*f* shows small new grains of orthopyroxene dispersed through the mylonitic band. This indicates that some of the mylonitic bands formed under $P-T-X$ conditions of the granulite facies.

Discussion

Within the mylonitic bands, biotite is visibly a foliation-forming element, whereas quartz, feldspar, hornblende, and orthopyroxene are elements of the isotropic matrix. All of these phases, however, show the same grain-size reduction and dispersal across the mylonitic band boundaries. This suggests that a cause common to the above effects is to be found within the mylonitic bands.

Biotite forms three sets of planar structures. Morphologically the biotite swaths and the dispersed biotite foliation resemble the C and S planes of Berthé *et al.* (1979*a*). However, S planes are strain-sensitive structures that rotate with the finite strain ellipsoid with increasing strain. Accordingly, the mylonitic bands would represent very low-strain zones (shear strain of less than 0.2). However, a low-strain model does not account for the consistent deflection through approximately 40° of quartz, orthopyroxene, and feldspar monomineralic aggregates upon approaching the mylonitic zones from without. Nor does it account for the progressive rotation through approximately 40° of the internal foliation, marked by dispersed biotites, upon approaching the strain-sensitive biotite swaths both within and at the margins of the mylonitic zones. The dispersed biotites do not therefore mark S planes in the sense of Berthé *et al.* (1979*a*). Nor do they mark a second cleavage, since they curve into the biotite swaths and not vice versa.

An alternative hypothesis is that the dispersed biotites mark a strain-insensitive foliation tending to parallel the kinematic axes (maximum and intermediate stretches) of the deformation. This hypothesis is supported by the morphology, orientation, and sense of slip along the biotite stringers (determined from local foliation deflection) occurring in the same mylonitic bands. These are very similar to C or shear-band foliation planes (Berthé *et al.* 1979*b*; Platt and Vissers 1980; White *et al.* 1980), from which the sense of shear along the mylonitic bands may be deduced. The deduced apparent sense of shear is compatible with the hypothesis that the dispersed biotites in the same band are perpendicular to the instantaneous principal shortening direction of a deformation approximating to simple shear, in other words, a strain-insensitive foliation.

How then is the formation of monomineralic polycrystalline aggregates avoided in the mylonitic bands? Kerrich *et al.* (1980) suggested that mechanical dispersal of phases may occur by grain neighbour switching during superplastic flow. However, grain boundary sliding and rotation would drastically weaken the dispersed biotite foliation. Figure 2*b* shows that the foliation is well developed.

Flinn (1969) discussed a proposal by earlier workers that phase distribution in a polyphase aggregate would be such as to minimize interfacial or grain boundary energy of the aggregate. Sinnott (1958) stated that general, noncoincident boundaries between unlike phases have lower energies than boundaries between like phases. This implies that under kinetically favourable circumstances, a regular, nonrandom distribution of phases could occur through a polyphase aggregate, the location of a given grain of a given phase within the aggregate being governed by minimization of the grain boundary energy of the aggregate. This would enhance the occurrence of unlike boundaries. Flinn (1969) identified such distributions by careful analysis of granite and granulite. He suggested that two processes may account for his observations: (a) diffusion, nucleation, and grain growth; and (b) grain boundary migration alone. Both processes may be driven by a common surface driving force (Nicolas and Poirier 1976; Poirier and Guillopé 1979).

Kinetically favourable conditions for phase dispersion minimize kinetic barriers to diffusion and enhance diffusion coefficients. Such conditions imply fine grain size, high temperatures, and the presence of an aqueous gas phase (Elliot 1973). The first is demonstrably present in the mylonitic bands. The third may only play a minor role in the granulite facies bands. High temperatures are indicated by the presence of strongly bent plagioclases in the orthopyroxene-bearing gneisses. The polysynthetic twins of the plagioclase are bent through up to 120°. Within these grains, bending is accompanied by subgrain development, but recrystallization is absent. I take this to indicate extremely rapid recovery rates and in dry granulites to be suggestive of, as yet unspecified, high temperatures of the granulite facies $P-T-X$ field.

Similar textural dispositions (dispersed phases, oblique platy minerals) have also been observed in coarser grained gneisses. The spacing of included droplike quartz within the feldspars, however, suggests that these gneisses may once have been very much finer grained.

Conclusions

Strain-insensitive foliations appear to exist in natural rocks. In polyphase aggregates, polycrystalline aggregates of a single mineral phase can be eliminated by diffusive phase dispersion, driven by a reduction of the grain boundary energy of the polyphase aggregate. Such dispersion may be expected in mylonitic rocks in high-temperature shear zones. Some strain-insensitive foliations may be steady-state foliations (sensu stricto).

Strain-insensitive foliations are potentially a most useful kinematic indicator in high-temperature, high-strain zones.

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