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P, *M* and *G* tectonites: a classification based on origin of mineral preferred orientations

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Abstract—The mechanisms responsible for mineral preferred orientations can be used as the basis for a classification of tectonites. *P* tectonites develop mineral preferred orientations by plastic deformation, *M* tectonites by mechanical reorientation of inequidimensional grains and *G* tectonites by various growth processes. Intermediate tectonite types can be defined with the aid of a triangular diagram. Examples discussed include marble and quartzite (*P*-types), slates (*M*- or *MG*-types), certain hornblende or feldspar-rich schists (*G*-types), granite-derived gneisses and mylonites (*PM*-types), and common schists (*MG*- or *PMG*-types). The classification is designed to promote a holistic approach to fabric studies. In addition, the *PMG* triangle provides a framework for tracking the sequential fabric development of tectonites.

INTRODUCTION

THE fabrics of metamorphic rocks that have undergone some degree of strain are characterized by mineral preferred orientations, and the most conspicuous of these (of the micas, for example) are at the heart of metamorphic rock terminology, providing names like slate and schist. In purely descriptive terms, mineral preferred orientations can be categorized according to whether there is a preferred orientation of the crystal lattice (LPO) or the crystal shape (SPO), or both. In terms of genesis, metamorphic rock fabrics can be categorized into three main groups which embrace both LPO and SPO types (e.g. Wenk 1978, p. 50). For the purposes of this paper I propose to name these three categories as follows:

(1) *P*-types: fabrics produced by plastic deformation;

(2) *M*-types: fabrics produced by the mechanical alignment of inequidimensional grains;

(3) *G*-types: fabrics produced directly as the result of grain formation and growth, including diffusion-aided anisotropic crystallization in a stress field, and recrystallization.

The whole area of fabric studies has become very active in recent years, and great strides have been made in the experimental deformation of minerals and in modelling the effects of strain and various combinations of slip mechanism on expected mineral preferred orientations. Quartz, calcite and olivine have been the subject of most attention. For calcite, the works of Turner, Griggs and associates (Turner *et al.* 1954, Griggs *et al.* 1960) represent the culmination of experimental work to elucidate glide mechanisms. Experimental plastic deformation of quartz was not achieved until the 1960s (Carter *et al.* 1964), and the results of such work have now been incorporated in studies modelling quartz fabrics (e.g. Lister & Hobbs 1980, Etchecopar & Vasseur 1987). For olivine, the work of Carter & Ave'Lallemant (1970) elucidated the variations in glide mechanism at different temperatures, and more recently Etchecopar & Vasseur (1987) have modelled the results of olivine deformation.

A HOLISTIC APPROACH TO FABRIC STUDIES

The works cited above deal mainly with single crystal studies or model one-mineral rocks, and indeed the three rocks dunite, quartzite and marble, provide the best examples of pure *P*-type fabrics in nature, often little modified by any other mineral orienting mechanism. However, the commoner metamorphic rocks consist of a number of intimately associated minerals, and fabric development is more complex. For example, the deformation and orienting mechanisms that characterize quartz in a quartzite are not always effective when quartz is mixed with other minerals. Thus, Starkey & Cutforth (1978) demonstrate a linear correlation between degree of lattice preferred orientation and quartz content in quartz-bearing tectonites: as the quartz content approaches zero, so the *c*-axes patterns become random. The same effect is noted by Walniuk & Morris (1985). Such studies are relatively few in number, and even in these examples it is only the quartz fabric that is described in any detail. Completely integrated fabric analyses of all associated minerals in multimineralic metamorphic rocks are not at all common.

The purpose of this paper is to argue for an integrated or, to use a better term (see note later), *holistic* approach to fabric studies. Questions which need to be asked include: How are deformation and orienting mechanisms modified when one mineral is associated with another? Are the orienting mechanisms for the rock as a whole different from what may have been expected from a study of the individual constituent minerals? Can the interpretation of the fabric of one mineral shed new light on the fabrics of intimately associated minerals?

The latter question derives from a recent study of a New Zealand Haast Schist (Shelley 1989), summarized here. The lower greenschist facies schist is characterized by segregation into sheet silicates plus feldspar, and quartz plus feldspar layers. An initial examination of the quartz and feldspar suggests two quite different processes for producing their respective preferred orientations. The quartz, for example, shows clear evidence of plastic deformation, an LPO consistent with this and a strong SPO, whereas the feldspar displays euhedral terminations and simple albite twins indicating anisotropic growth to be the cause of its strong SPO and distinct LPO (plastic deformation would have rotated the albite twin composition planes away from (010), and this is not observed). However, the quartz and feldspar textures and fabrics, viewed together, suggest a consanguineous relationship and a common origin. There is, for example, no evidence that plastically deformed quartz has been wrapped around non-ductile feldspar. Evidence for the feldspar growth fabric is sufficiently compelling to demand reconsideration of the effects of plastic deformation on the quartz. Such a re-evaluation shows that the quartz preferred orientation can in fact be interpreted as a growth fabric modified by relatively minor effects of plastic deformation. It is unlikely that this interpretation would have been arrived at had the plagioclase fabrics not been closely examined, and the example illustrates how first conclusions may be modified as a result of the holistic approach.

To encourage this approach further, I propose below a classification for deformed rocks, based on the origin of fabric types, and one that requires the fabrics of all minerals in a rock to be assessed.

First, a note on the word holistic. Derived from holism, a word coined by J. C. Smuts in 1926, it has usefully filled a niche in the English language to cover the situation where an analysis of the whole provides information, an interpretation, or some insight, not immediately evident from an analysis of the parts. In this way, holistic means a little more than 'integrated'. A holistic study does not preclude an analysis of the parts, but it does require an extra level of analysis applied to the whole.

TECTONITES AND THE *PMG* TRIANGLE

For the purposes of the proposed classification, the term 'tectonite' is the most suitable for a metamorphic rock with a mineral fabric developed during deformation. This is in accord with general modern usage which follows Turner & Weiss (1963) who used the term tectonite as a synonym for metamorphic tectonite. Fabrics can be categorized by origin as *P*-, *M*- or *G*-types (as defined in the Introduction), and *P*, *M* and *G* tectonites (each characterized by the one fabric type) can be plotted at the corners of a triangular diagram (Fig. 1). The rest of the triangle can be subdivided into intermediate *PM, MG, PG* and *PMG* tectonite fields, according to the relative proportions of minerals of contrasting fabric origin in a particular tectonite (Fig. 1).

EXAMPLES OF *P, M* AND *G* FABRIC TYPES

P-*types*

The essentially monomineralic rocks quartzite, marble and dunite, provide good examples of *P*-type fabrics, and these rocks often plot as *P* tectonites on the triangle (Fig. 2). In *P*-type fabrics, grain shapes (ribbons of quartz, etc.) may give some indications of the character of the strain, and the LPO will reflect the particular glide systems operating. Often the SPO and LPO reflect only the later stages of deformation, and at moderate or high temperatures, static or dynamic recrystallization may obscure the SPO and modify the LPO produced by plastic deformation. If the modifying effects become significant, then the fabric type moves towards the *PG* field; this and other effects of recrystallization are discussed further later.

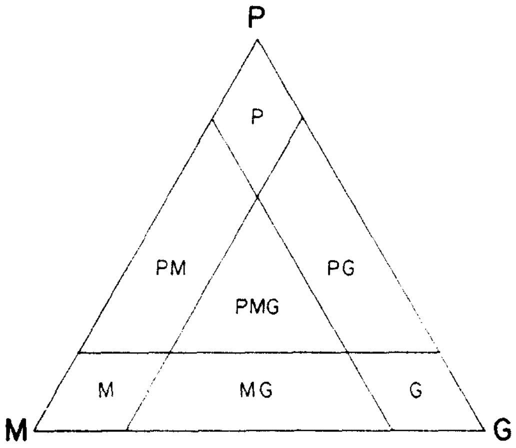

Fig. 1. *PMG* triangle which defines the fields of the seven tectonite types discussed in the text.

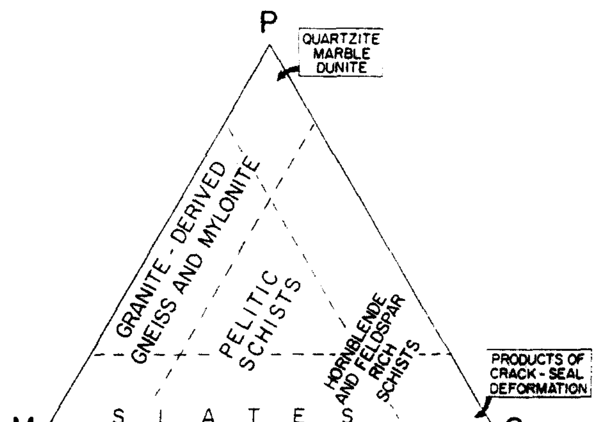

Fig. 2. Various common metamorphic rocks plotted on a *PMG* triangle, as discussed in the text.

M-*types*

The concept that rotation of inequidimensional mineral grains during a deformation can produce a preferred orientation was clearly enunciated by Sorby (1853). The idea is still widely advocated for sheet silicates in slates (Wood & Oertel 1980) for which a quantitative measure of strain can be made according to the ideas of March (1932). In some slates, selective pressure solution of quartz, particularly along steep limbs of microcrenulations, leads to seams of sheet silicates with a high degree of preferred orientation (Gray 1979). In such slates, mechanical reorientation is partly due to volume loss because of the solution of quartz. Volume loss due to water escape during strain has a similar effect, and Maxwell (1962) argued that sheet silicates become oriented as a direct result of water flow through muddy rocks. Shelley (1975) described grain-size sorting due to water flow in association with cleavage formation in the Ordovician slates of New Zealand, and Jones & Addis (1986) argued that particulate deformation is more widespread than generally recognized.

Cataclasis may be an important deformation mechanism in some rocks. In general it can produce *M*-type fabrics only if the mineral grains in question are inequidimensional.

In superplasticity, most strain is achieved by grain-boundary sliding, though this must be accompanied by plastic deformation or diffusional mass transfer processes to accommodate necessary grain shape changes. Superplasticity may occur in natural rocks if dynamic recrystallization produces an ultra-fine grain size, and in general the onset of superplasticity is marked by a rapid decline in the strength of a preexisting LPO (Behrmann 1985). However, Gapais & White (1982) found that elongate subgrains of quartz, produced during such a dynamic recrystallization, may be bounded by prism and rhomb planes, and they proposed that rotation during grain-boundary sliding produced *M*-type fabrics with quartz *c*-axes close to the extension or shear direction.

G-*types*

Perhaps the most obvious examples of *G*-type fabrics are those produced during fracturing and precipitation of minerals from solution in the resulting spaces, a process termed 'crack–seal' deformation by Ramsay (1980). The new mineral growths may have an LPO due to growth competition and anisotropies (Cox & Etheridge 1983), as well as a strong SPO with grain lengths parallel to the opening directions. In some cases, the new growth simply enhances an existing preferred orientation in the host rock.

Many schists are characterized by new mineral growth, often as segregation layers, as well as a general recrystallization, and one might expect *G*-type fabrics to be typical. This expectation is not reflected in the literature, though in my view growth fabrics are more important than is generally recognized. An example from the New Zealand Haast Schists (Shelley 1989) is summarized above. In that example, feldspar, quartz and the sheet silicates are in about equal proportions in the rock, and most fabric elements can be ascribed to diffusion-aided anisotropic growth, probably resulting from a stress-driven combination of solution transfer and crack–seal mechanisms, as advocated, for example, by Sawyer & Robin (1986).

Until recently there had been a general lack of information on feldspar preferred orientations in schists, although this situation is now partly rectified. In the greenschist facies (Shelley 1986, 1989), a growth origin of feldspar fabrics is most consistent with the common observation that feldspar is not ductile at low temperatures. However, at higher grades of metamorphism, Olsen & Kohlstedt (1985) and Shaocheng & Mainprice (1988) give evidence for the plastic deformation of feldspar and the production of *P*-type feldspar fabrics.

Many workers have suggested that a sheet silicate preferred orientation may result from various growth mechanisms (Vernon 1976, Ishii 1988). It may be generated by growth of new mica at a high angle to earlier kinked grains, nucleated by the most strongly rotated parts of the original grains (Bell 1978), or, to quote Etheridge *et al.* (1974) "by the interaction of anisotropic growth with either anisotropic fluid movements or rock structure, or with orientation dependent pressure solution". The usual problem is to assess whether crystallization or recrystallization has mimetically adopted an orientation produced by an earlier mechanical alignment.

A mineral which may generally develop preferred orientations by growth is hornblende. There is a dearth of thorough modern descriptions, and the common observation of very elongate euhedral or subhedral hornblendes almost perfectly aligned and closely spaced in linear hornblende schists requires explanation. Although there is some evidence for plastic deformation of hornblende, especially at high temperatures (Rooney *et al.* 1975), it is generally thought to be one of the strongest of minerals (Wenk 1985). Acknowledging this, Nicolas & Poirier (1976) suggest hornblende preferred orientations develop by growth during strain. Since feldspar is similarly non-ductile at low temperatures, the fabrics of low-grade hornblende–feldspar schists are probably the result of stress-driven solution and growth.

Finally, an example of *G*-type quartz fabrics is given by Gapais & Barbarin (1986) in which quartz grains grew (either by primary grain growth or by 'migration recrystallization') with *c*-axes close to the extension direction at high temperatures during the syntectonic deformation of a granite. There is a transition between this behaviour and the plastic deformation of the quartz at lower temperatures.

PROBLEMS IN DETERMINING FABRIC TYPES

Because the proposed classification is in terms of fabric genesis, not description, and because the interpretation of fabrics may be contentious, plotting tectonites in the triangle will not always be easy. The possibility of reinterpretation will seldom be ruled out. However, the classification should serve as a framework for discussion and an incentive for interpretative work involving total rock fabrics.

It is not necessarily a straightforward matter to decide the best fabric-type designation, even when an interpretation has been made. For example, consider the case where euhedral, strongly inequidimensional grains are mechanically rotated and continue to grow during rotation. Does this produce a *G*-, *M*- or *MG*-type fabric? If one can decide that the growth process in itself would not produce a preferred orientation, then designation as an *M*-type seems most appropriate. Yet continued growth as the grains progressively become oriented would undoubtedly enhance the strength of the preferred orientation, and though difficult to quantify, probably warrants designation in the *MG* field.

The effects of recrystallization on LPO and SPO are complex, and much of the relevant literature has been summarized in Wenk (1985) and Urai *et al.* (1986). In general, the main elements of *P*-type preferred orientations are retained, particularly during dynamic recrystallization, and if recrystallization merely reduces the strength of the SPO and LPO, but does not create a preferred orientation itself, the fabric should retain the *P*-type designation. An interesting example of the interaction of recrystallization and plastic deformation of quartz in a mylonite is given by Lister & Snoke (1984). They show that the normal rotation of elongating grains towards the shear plane in a mylonite was repeatedly interrupted by recrystallization to equidimensional grains. This had the effect of resetting the SPO in primitive orientations oblique to the *C*-surfaces. However, the recrystallization did not in itself produce any preferred orientation, and the Lister & Snoke example is a pure *P*-type fabric. In other situations, recrystallization does produce preferred orientations. Thus Knipe & Law (1987) show that a quartz LPO was changed due to the selective removal of some grains during grain-boundary migration recrystallization, and Urai *et al.* (1986) show that 'ribbons' may form during recrystallization by the coalescence of grains with similar lattice orientations. Both *P*- and *G*-type factors are involved here. Similarly, post-tectonic annealing may change preferred orientations, so that Bouchez *et al.* (1984) ascribe a quartz SPO to post-tectonic grain-boundary migration recrystallization, a process which did not, however, destroy the LPO produced by plastic deformation.

Although it may be difficult to quantify the effectiveness of competing orienting mechanisms, the mechanisms themselves do fit well into either *P*, *M* or *G* categories. An exception is the case of an SPO created by pressure solution, common for quartz and feldspar in slates and low-grade schists. In diffusive mass transfer processes, growth is a corollary of pressure solution, and on this ground I suggest fabrics resulting from pressure solution be designated *G*-type. If inequidimensional grains so produced are later mechanically reoriented, the fabric becomes an *M*-type.

Application of the proposed classification is clearly not without its problems. However, the classification does not create the problems. It merely draws attention to them, and in this way provides a useful service.

TECTONITES OF MIXED FABRIC TYPE

Tectonites of mixed fabric type are common because the various minerals in rock often have different responses to deformation. The following is a brief outline of some of the more common combinations and how they can be classified.

Granite-derived gneisses and mylonites

This group of rocks has been the subject of close attention during the development of ideas on *C*- and *S*-planes and quartz fabrics in shear zones (Berthé *et al.* 1979). Commonly three minerals are present: igneous-shaped feldspar which is brittle; quartz which is plastic and forms ribbons; mica which is smeared out along the shear planes. These rocks are PM tectonites (Fig. 2) which result from a combination of plastic deformation of quartz and mica, and the mechanical reorientation of feldspar and mica. The contribution of new mineral growth is generally of minor importance, and often restricted to fibrous growth of quartz and chlorite in shadow zones around and within feldspar porphyroclasts.

Slates

Some slates are *M* tectonites, as described above, but others contain substantial contributions to the fabric from new mineral growth. This may be in pressure shadows around rigid grains (Durney 1976, Beutner & Diegel 1985), or from the more general crystallization of new sheet silicates, particularly in situations where earlier grains are crenulated (Etheridge & Hobbs 1974, Bell 1978). In addition, grains of quartz and feldspar may become elongate as a result of pressure solution. The contribution of plastic deformation is generally small, and most slates can be expected to have fabrics lying within the *M* and *MG* fields (Fig. 2).

Common schists

Quartzofeldspathic schists, such as the Haast Schists of New Zealand, may lie in the *G*, *MG* or *PMG* fields. Such schists are dominated by growth features, particularly segregation layering, and the fact that feldspar, which does not deform plastically in the greenschist facies, behaves as an integral part of the whole fabric (not like porphyroclasts in a mylonite) suggests that the fabrics of the other minerals were developed in a similar way to that of the feldspar, that is, by anisotropic growth.

An interesting question centres on the origin of feldspar fabrics in higher grade schists and gneisses. The LPO of feldspar is the same in the amphibolite facies (Olsen & Kohlstedt 1985, Shaocheng & Mainprice 1988) as in the greenschist facies (Shelley 1986, 1989), yet different orienting mechanisms are advocated, namely anisotropic growth at low grades, plastic deformation at high grades. Is this another example, familiar in the case of sheet silicates, of similar fabrics produced by different orienting mechanisms, or have the effects of plastic deformation at higher grades been overstated? The problem has been discussed by Olsen & Kohlstedt (1986) and Shelley (1986) who notes that it is a *non sequitur* to argue that evidence for slip necessarily means the associated preferred orientation results from slip.

The relative contributions of mechanical rotation and neocrystallization to sheet silicate fabrics in schists are notoriously difficult to assess. Plastic deformation often plays an important role in the development of quartz fabrics, though it may be a secondary effect, particularly where segregation veining is pronounced. Most pelitic schists are thus likely to be *PMG*-types.

DEALING WITH SEQUENCES OF EVENTS

Metamorphic rocks may have long histories with repeated episodes of strain. The classification should be used only for designating the origin of preferred orientations presently observed. Those may themselves involve a complex sequence of events, and that complexity will be reflected in the classification. Earlier strain or growth episodes that leave no significant preferred orientation relic should be discounted.

Nevertheless, the *PMG* triangle may prove to be a useful device for tracking and studying total rock fabric development through time. Metapelites, for example (Fig. 3), may possibly develop progressively through a slaty stage (*M* or *MG* tectonite) and highly segregated low-grade schists (*G* or *PMG* tectonites) to high-grade gneisses (with a trend towards the *P* tectonite field?). Are there, perhaps, a number of distinctive paths for the sequential fabric development of tectonites which can be plotted on a *PMG* triangle, and which depend on particular lithologies and pressure–temperature histories?

CONCLUSIONS

Tectonites can be classified on the basis of the mechanisms responsible for mineral preferred orientations. Three main categories of mechanism can be recognized, and these produce *P*-, *M*- and *G*-type fabrics depending on whether plastic deformation, mechanical reorientation of inequidimensional grains, or grain formation and growth was dominant. Various monomineralic rocks such as quartzite, marble and dunite are end-member *P* tectonites, and some slates are end-member *M* tectonites. *G* tectonites are less well recognized, but examples are rocks that have undergone extensive crack–seal deformation leading to vein formation at low temperatures, or mineral segregation parallel to foliation in schists. Many common schists are likely to be *MG* or *PMG* tectonites, whereas granite-derived gneisses and mylonites are *PM*-types. Sequences of fabric development can be plotted as paths on the *PMG* triangle.

This classification is designed to encourage a holistic approach to fabric studies so that the interrelationships of fabrics of all component minerals in a tectonite are examined. In particular, more attention needs to be paid to the orienting mechanism of non-ductile minerals like feldspar and hornblende in lower-grade tectonites. The fact that these minerals have strong preferred orientations, do not deform easily by slip, and may be intimately associated with minerals such as quartz and the sheet-silicates, may provide a valuable insight into the processes producing the associated ductile mineral fabrics.

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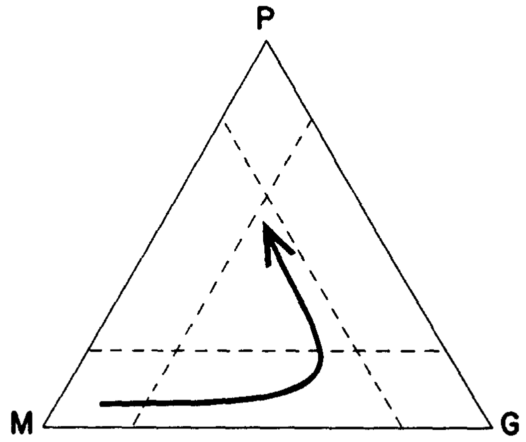

Fig. 3. *PMG* triangle showing the possible path of sequential fabric development in metapelitic rocks.

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