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DEFORMED GARNETS IN A MYLONITIC ROCK FROM THE GRENVILLE FRONT AND THEIR TECTONIC SIGNIFICANCE

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ABSTRACT. A study of garnet porphyroclasts in a specimen of quartzo-feldspathic mylonitic rock from the transitional zone between the Southern and Grenville provinces of the Canadian Shield (the Grenville front) near Sudbury, Ontario, is described. An X-ray method was employed that may prove useful for comparing the deformation of single crystals under natural and experimental conditions.

The garnets form oblate spheroids with an axis of symmetry normal to the mylonitic foliation. Deformation of the porphyroclasts appears to have been tectonically controlled. The crystals have no crystallographic preferred orientation, but where bend axes in the structure can be detected on Laue photographs, they consistently lie in the mylonitic foliation nearly normal to a prominent regional lineation (elongation of quartz and porphyroclastic feldspar grains).

Consideration is given to the significance of the study in the interpretation of minor structures along the Grenville front and in similar tectonic situations such as the Moine thrust belt along the western margin of the Scottish Caledonides.

INTRODUCTION

In recent years considerable advances have been made in our understanding of the mechanisms by which crystals deform under stress (Carter, Christie, and Griggs, 1964; Christie, Griggs, and Carter, 1964; Raleigh, 1965). These advances have come from experimental work, however, and a number of problems arise in attempting to extend such studies to naturally deformed crystals. Late stage recrystallization has often obscured the effects that earlier deformation may have had on crystals in metamorphic tectonites. Also, glide systems are determined in experimental studies by means of rotated lamellar structures (for example, twin lamellae in calcite; Turner, Griggs, and Heard, 1954) and by slip bands on polished specimen boundaries (Christie, Griggs, and Carter, 1964; Raleigh, 1965). In naturally deformed materials lamellae are not always visible, however, and slip bands are not, of course, available for measurement.

The purpose of this paper is to describe an X-ray study of naturally deformed garnet. Application of the Laue method to the study of naturally deformed crystals is not new (see, for example, Bailey, Bell, and Peng, 1958). However, so far as the authors are aware, this method has not been used previously in an attempt to relate distortion of the structure of certain crystals to the fabric of the tectonite in which they occur.

The specimen containing the crystals studied was collected from an outcrop in the (largely mylonitic) zone of structural and metamorphic transition between the Southern and Grenville provinces of the Canadian Shield, the Grenville front, near Coniston, Ontario, and about 7 miles southeast of Sudbury (figs. 1 and 2). The outcrop (loc. A, fig. 2) is actually on the extreme western margin of the Grenville province as mapped by

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Grant and others (1962). The marginal zone of the Grenville province, here at least, has escaped complete post-tectonic recrystallization.

On the scale of a map of the Canadian Shield, the Grenville front is a line or a narrow zone (fig. 1). Many theories have been put forward to explain its origin. Most commonly it is considered to be:

1. A metamorphic transition (for example, southeast of Sudbury at Coniston, Ontario—Grant and others, 1962; Stockwell, 1964).
2. A fault (for example, northeast of Lake Timagami—Johnston, 1954).
3. A combination of a metamorphic transition and a fault (for example, Lake Timagami—Grant, 1964a).

The hypotheses involving faulting generally invoke either strike-slip movement (Brooks, ms) or else reverse faulting with the southeastern (Grenville) side upthrown.

The presence of mylonitic rocks[1] along the Grenville front has previously been recognized, for example at Lake Ossokmanuan (fig. 1) in

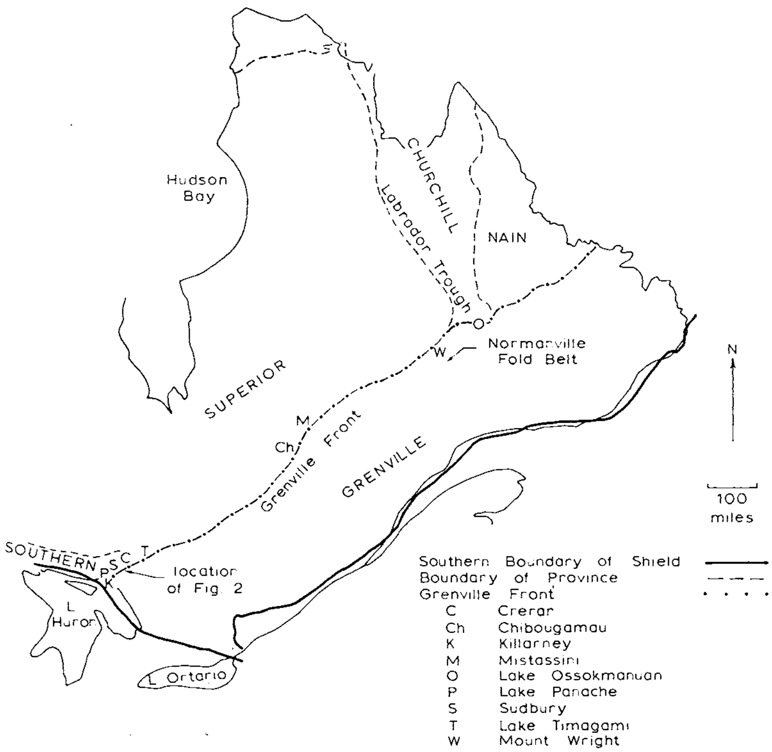


Fig. 1. Generalized map of the eastern Canadian Shield.

[1] The term "mylonitic rock" is used in this paper to avoid the common misuse of the term "mylonite" (Christie, 1960). All the rocks described as "mylonitic" are fine grained and well laminated. However, they show varying degrees of recrystallization.

Labrador (Wynne-Edwards, 1961). However, neither the extent to which these mylonitic rocks are developed along the front nor their age and significance have been fully appreciated. At every locality along the front visited by one of us (I.W.D.D.) from Lake Huron to the Labrador trough (near Killarney, Coniston, Crerar, and Lake Timagami in Ontario; near Mount Wright in Quebec and Wabush in Labrador) northeast-southwest striking mylonitic rocks occur, and a well developed lineation (elongation of quartz and porphyroclastic feldspar grains) plunges southeast into the Grenville province down the dip of the mylonitic foliation. These rocks will be discussed in another communication. At present, however, it is of interest to note that mylonitic rocks occur even where the front has been interpreted as a metamorphic transition (for example, at Coniston, Grant and others, 1962; Dalziel, Brown, and Warren, 1967, and in preparation). Where the front is obviously faulted at Crerar, Ontario (Fairbairn, 1939), brecciated mylonitic rocks have been found—that is, "clean cut" faulting is apparently a later phenomenon that tends to obscure the mylonitic zone.

STRUCTURAL HISTORY OF THE GRENVILLE FRONT NEAR CONISTON, ONTARIO

While it is outside the scope of this paper to discuss the structural and metamorphic history of the region in any detail, it is important to point out the geometry and relationships of the structural elements along the Grenville front near Coniston.

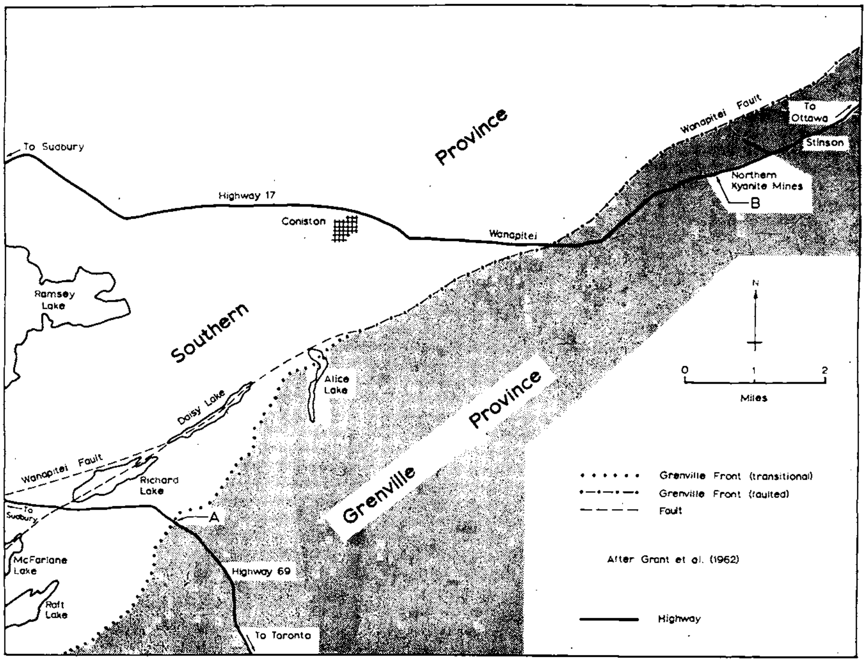


Fig. 2. Sketch map showing the geologic setting of the localities mentioned in the text.

The specimen studied was collected from a locality (loc. A, fig. 2) a few yards north of Highway 69 (Sudbury-Toronto) and about 75 yards southeast of the Grenville front as mapped by Grant and others (1962). However, in reality the front here (as pointed out by Grant and others) is a zone of structural and metamorphic transition between the Southern and Grenville provinces. The structural geometry and relationships described are typical of the northwestern margin of the Grenville province in this immediate area.

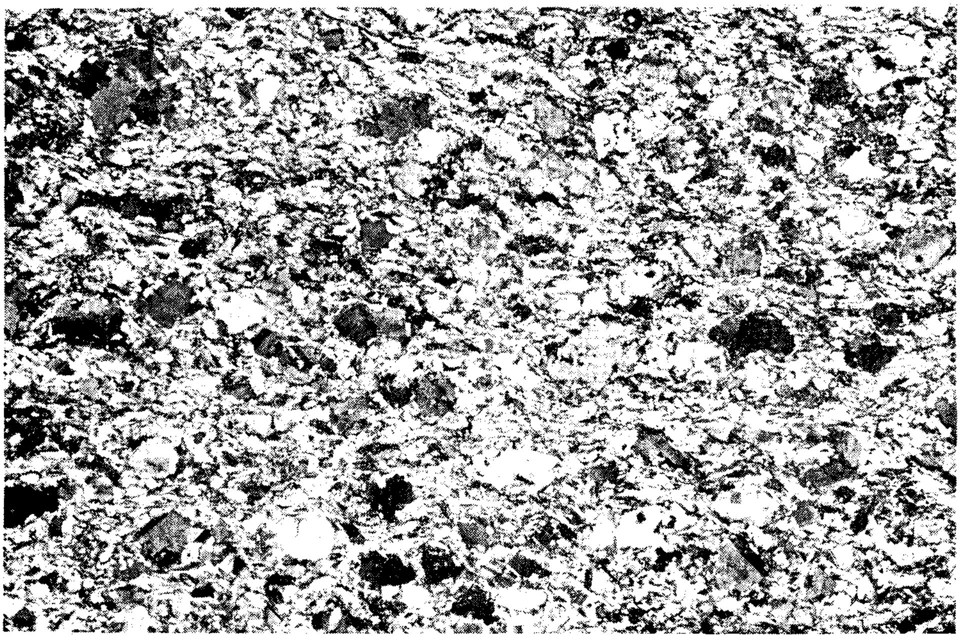
The mylonitic foliation and associated lineation in the transition zone are geometrically related to the earliest recognizable folds—a set of intrafolial isoclinal folds developed only on a mesoscopic scale. The foliation is axial planar to these folds (figs. 3 and 5), and the lineation is parallel to their axes. The mylonitic foliation, the lineation, and the isoclinal folds are all deformed by at least two later sets of more open folds which need not be of further concern here. Regional migmatization and hence presumably high almandine-amphibolite facies conditions (Winkler, 1965, p. 149) were attained prior to the main movements of the first (isoclinal) folding (Dalziel, Brown, and Warren, 1967).

The orientation of the early structures in the outcrop from which the specimen was collected is shown in figure 3. The isoclinal minor folds plunge southeast at 40 to 58° down the dip of their own axial planes (that is, they are reclined folds) and of the mylonitic foliation. While their axes are parallel to the lineation at any one point, both vary in attitude in a single outcrop (fig. 3).

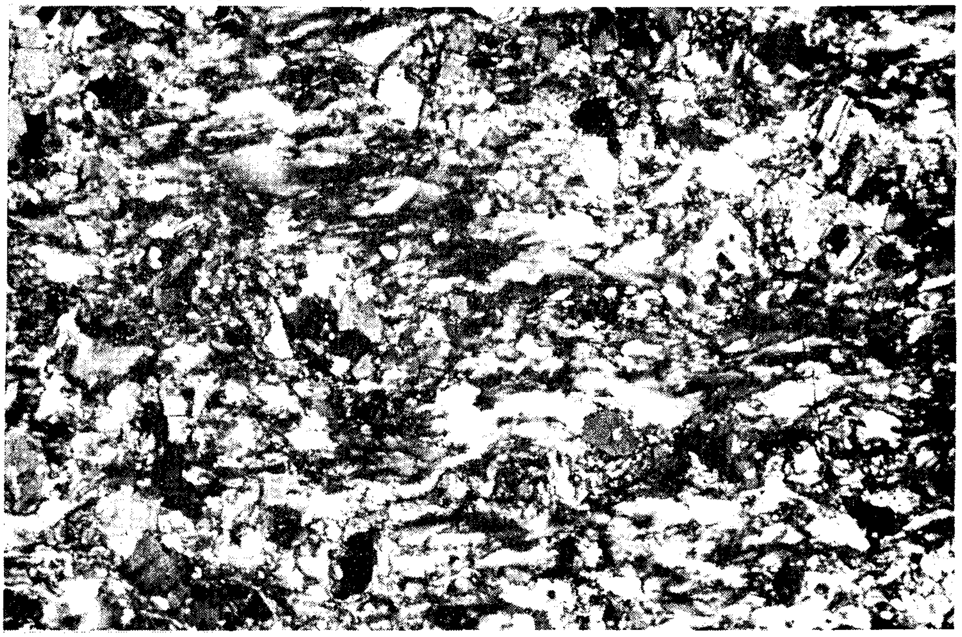
This picture will be familiar to students of thrust belt tectonics. The structural geometry at Coniston is similar to that of the Moine thrust belt along the western margin of the Caledonian mobile belt in Scotland (for example, Johnson, 1957; Christie, 1963; Barber, 1965), also the Jotun thrust belt in Norway (Flinn, 1961). This need not imply *per se* that the Grenville front must be a major thrust fault. There is still doubt, for example, whether the major displacement along the Moine thrust zone accompanied the formation of the early formed mylonites or else was due to late-stage clean cut thrusting (Barber, 1965; Johnson in discussion of Barber, 1965), and there is as yet no evidence for such thrusting on more than a local scale (Grant, 1964a) along the Grenville front. Moreover, Christie (1963, 1967) has recently advanced the hypothesis that movement along the Moine thrust zone (which has a very low regional dip compared with the Grenville front) may have been parallel to the strike of the zone. Hence, an understanding of the nature of the widely developed down-dip lineation in the mylonitic rocks is obviously vital in any interpretation of the nature of the Grenville front. The tectonic significance of lineations of this type has been a highly controversial topic for many years (Anderson, 1948; Kvale, 1953; Johnson, 1965; Christie, 1965). This is because the lineations lie in what would appear to be the logical "transport" directions for the thrust sheets, yet their parallelism to the axes of the (monoclinic) isoclinal folds has raised serious objec-

PLATE I

Photomicrographs of mylonitic rocks from the



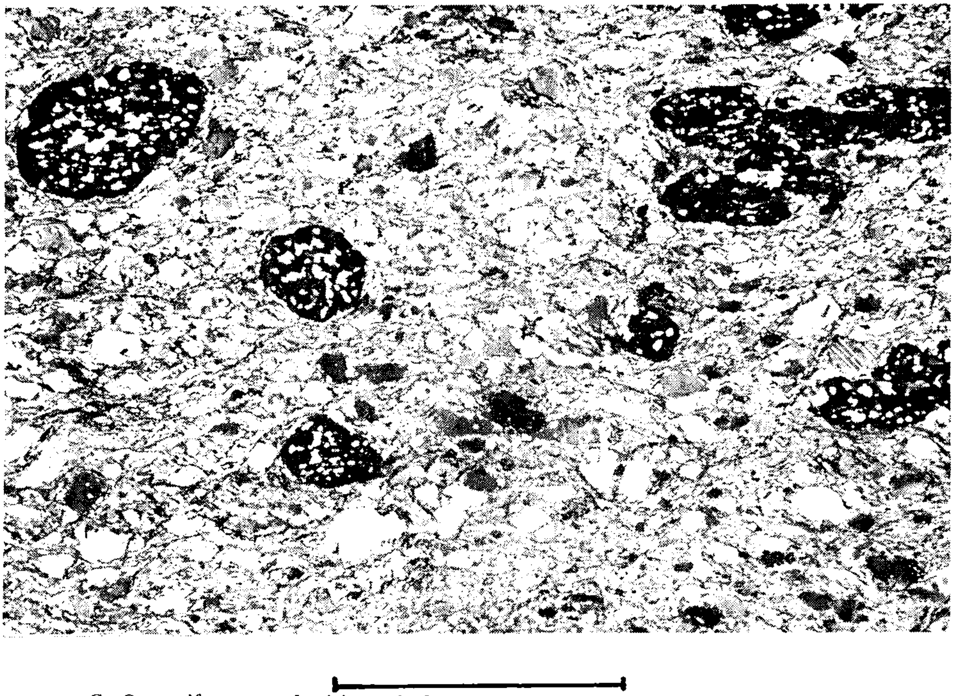
A. Mylonitic rock viewed perpendicular to the foliation and normal to the lineation (bar represents 2 mm).



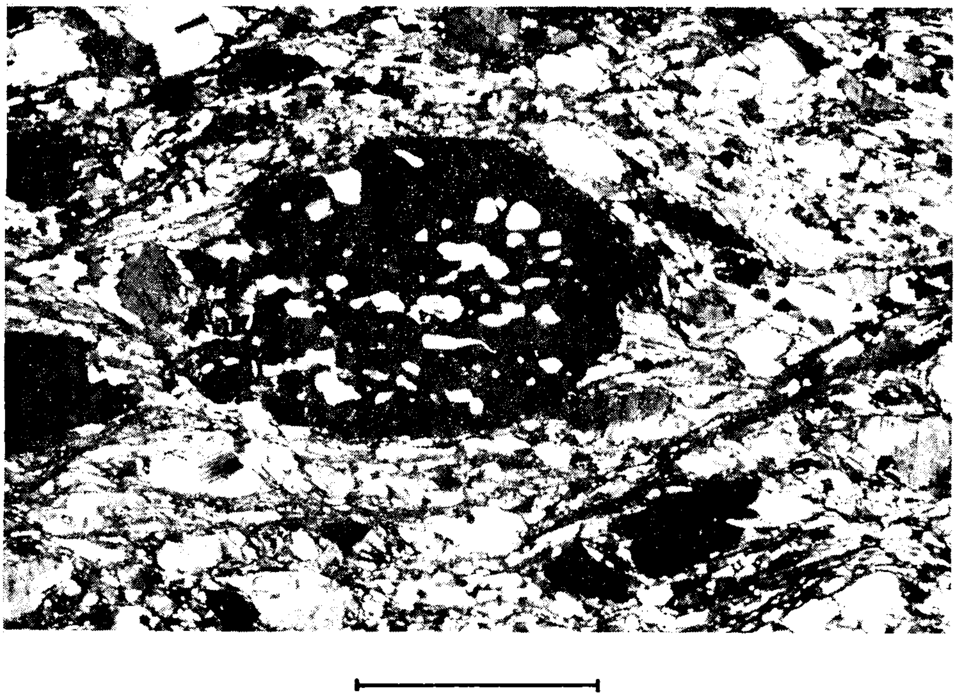
B. The same rock in the plane of the foliation; note the elongation of quartz grains to form the lineation (bar represents 1 mm).

PLATE 1

Grenville front near Coniston, Ontario (crossed nicols).



C. Garnetiferous mylonitic rock from locality A; section perpendicular to foliation and normal to lineation (bar represents 8 mm).



D. Garnet porphyroclast from the same thin section (bar represents 2 mm).

tion to their interpretation as *a* ("transport") lineations, for example on grounds of symmetry.

Our study of the deformation of garnets in the lineated mylonitic rocks immediately adjacent to the front south of Coniston is pertinent to this problem.

THE GARNETIFEROUS MYLONITIC ROCKS

The mylonitic rocks along the Grenville front near Coniston are variable in composition (although dominantly quartzo-feldspathic). They are all fine grained and finely laminated, but they show varying degrees of recrystallization. Photomicrographs of typical examples are shown in plate 1.

It is apparent that individual quartz grains are intensely flattened in the foliation. The feldspar grains are also flattened but to a lesser degree. They stand out in thin section as porphyroclasts, while individual quartz crystals curve around them. Both quartz and feldspar grains are elongated within the mylonitic foliation so as to form the pronounced lineation (pl. 1-B). The quartz crystals, however, show much greater elongation without fracture; individual feldspar porphyroclasts are fragmented. Amphibole and garnet porphyroclasts also occur.

At locality A there is a zone of relatively coarse grained mylonitic rock that contains garnet. Electron microprobe analysis (kindly carried

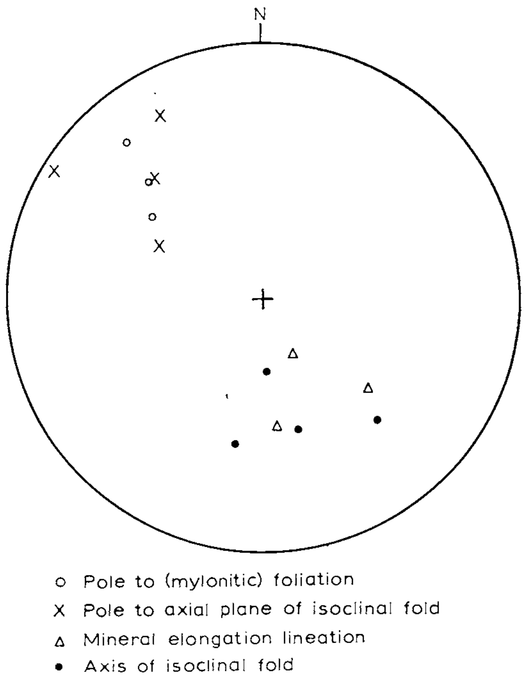


Fig. 3. Stereoplot (equal area net, lower hemisphere) of structural data from locality A, figure 2.

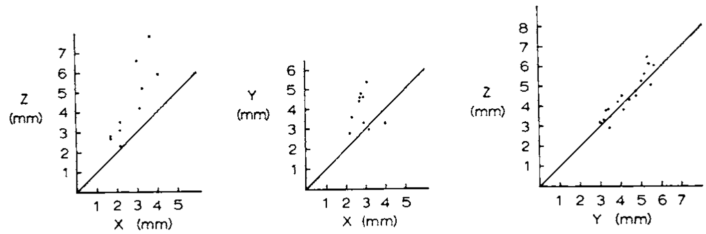


Fig. 4. Plots showing dimensions of garnets visible in three mutually perpendicular planes. X is the direction normal to the foliation, Y is perpendicular to the lineation in the foliation, and Z is parallel to the lineation. The line on each graph represents a 1:1 ratio.

out for the authors by Dr. Bernard Evans) and unit cell dimensions both indicate a composition close to that of pure almandine. The quartz grains in this rock appear to be slightly more recrystallized than is usual.

Measurements (fig. 4) made with vernier calipers on crystals visible in three mutually perpendicular planes (parallel to foliation, normal to lineation, and perpendicular to foliation but including the lineation) show that the garnets are dimensionally slightly flattened in the foliation but show no marked linear preferred orientation despite the presence in the outcrop of the down-dip lineation due to the elongation of quartz and feldspar grains. Thus, the garnets form roughly oblate spheroids with the axis of symmetry normal to the mylonitic foliation. In thin section it can be seen that this foliation is deflected around the garnets that contain numerous quartz inclusions (pl. 1-C and 1-D).

In most of the mylonitic rocks from the Grenville front studied to date the *c*-axes of the ground mass quartz form a microfabric that has a symmetry approaching orthorhombic (figs. 5 and 6); the plane of the mylonitic foliation being a plane of symmetry. The microfabric of the quartz inclusions in the garnet clearly has a lower symmetry (fig. 6).

An obvious conflict arises here between the near orthorhombic symmetry of the quartz microfabrics and of combined mylonitic foliation and lineation, and the monoclinic symmetry of the isoclinal folds—again reminiscent of the situation in the mylonites along the Moine thrust belt (Christie, 1963; Gangopadhyay and Johnson, 1961).

The shape of the crystals and deflection of the mylonitic foliation around them suggest that the garnets in the mylonitic rock from Coniston crystallized prior to the formation of the mylonitic banding; or at least (following Christie, 1963) prior to a flattening episode immediately subsequent to the mylonitization and formation of the isoclinal folds. The imperfect orthorhombic symmetry of the quartz microfabric of the mylonitic rocks (figs. 5 and 6) supports such an interpretation, the mylonitic foliation being a symmetry plane of the microfabric.

On this evidence alone it might be possible (if unlikely) for the shape of the garnets to be the result of later mimetic growth within certain layers and not of post-crystalline deformation. However, if the garnet growth had been mimetic one would expect the quartz internal to garnet to have the same microfabric as the ground mass quartz.

X-RAY STUDY OF GARNETS

Theory.—Laue X-ray diffraction photographs of stationary crystals are especially sensitive to crystal imperfections that produce a change of shape either of the entire crystal or of certain volumes or directions within the crystal. The effects show up on the film as distortions of the shapes of the Laue spots or by the appearance of extra spots and streaks on the film. These same imperfections may or may not be revealed by

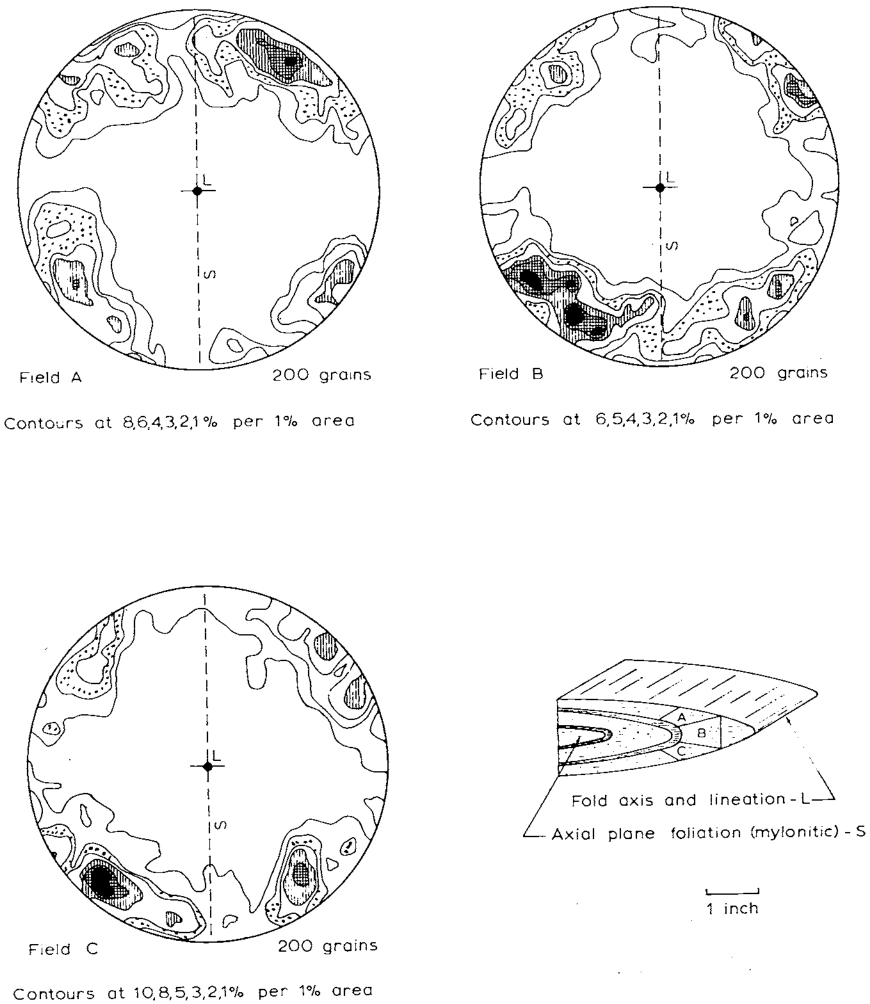
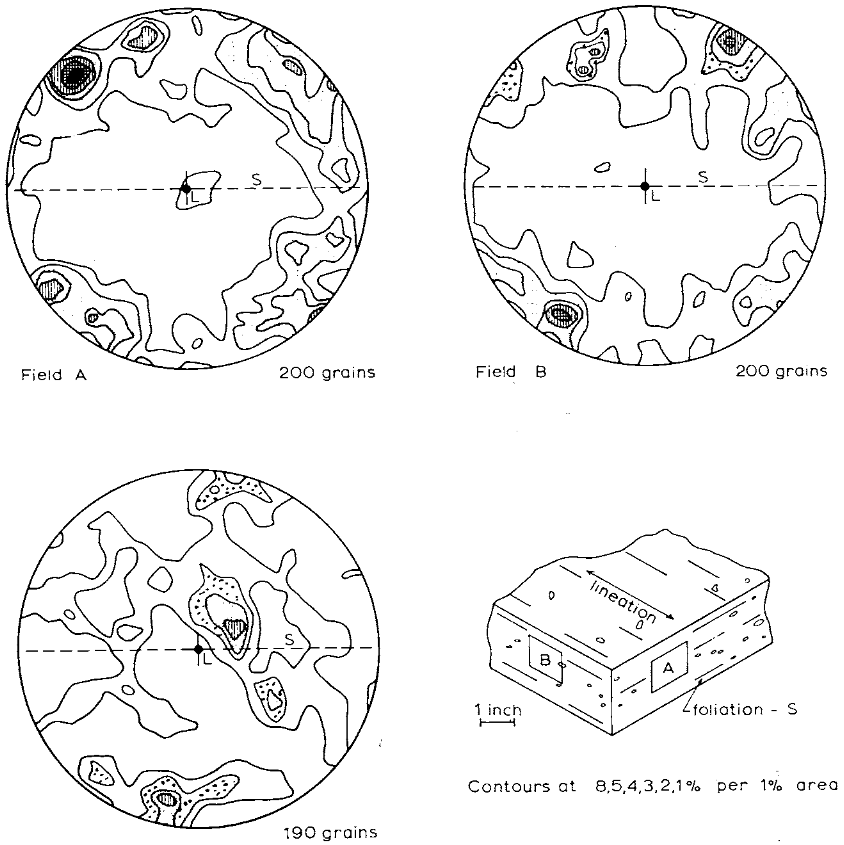


Fig. 5. Microfabric diagrams (equal area net, lower hemisphere) of quartz *c*-axes from fields near the hinge of an isoclinal fold in a specimen of mylonitic rock collected close to locality A.



Inclusions in a garnet crystal (Field B)

Fig. 6. Microfabric diagrams (equal area net, lower hemisphere, all rotated to the plane normal to the lineation) of quartz *c*-axes from two fields in the garnetiferous mylonitic rock from locality A.

other single crystal X-ray methods in which the crystal must be oscillated or rotated during the exposure.

The spots on a Laue photograph of a relatively perfect crystal are generally uniformly sharp. They are usually round or elliptical, irrespective of the orientation of the crystal in the X-ray beam, although grain shape will affect the shape of the spots to some extent (Lonsdale, 1945). The Laue patterns of deformed crystals, however, show reflections that are usually elongate, twisted, and often subdivided into striations. It was by use of this technique that Bailey, Bell, and Peng (1958) demonstrated the plastic deformation of quartz in nature—long inferred from undulatory extinction.

If the crystal is distorted by simple bending, the Laue spots closest to the center of a transmission film are elongate toward the center. This effect is known as asterism and can be demonstrated experimentally for many compounds by "before-and-after" Laue photographs. The axis of bending can be determined by a series of photographs taken with the crystal in different orientations. If the crystal is twisted in a spiral fashion, the Laue spots are twisted also so that reflections in the same zone have different inclinations to the zone axis (spiralling effect).

It is often noted as the amount of asterism increases that the intensity within the elongate reflections may no longer be distributed uniformly but instead may be subdivided into a number of alternately light and dark striations or sub-segments. In the case of metals this can be shown to take place if the metal, after bending, is annealed below its recrystallization temperature. It is believed that the dislocations, which are distributed at random in the bent crystal, is changed into an array of blocks or polygons of fairly perfect structure separated from adjacent blocks by walls of dislocations. This effect is known as polygonization (Cahn, 1951; Barrett, 1952). It represents a lower energy state for the crystal because of the creation of strain-free polygons, a reduction in the total number of dislocations, and a more orderly arrangement of the remaining dislocations.

Distortion of the garnet crystal structure.—Laue photographs (taken using unfiltered cobalt radiation) of the garnets in the specimen of mylonitic rock have been compared with those of other garnets that formed at a later stage in the structural and metamorphic history of the Grenville province. The latter crystals were obtained from a kyanite gneiss band 9 miles northeast of the first locality (loc. B, fig. 2). The gneiss is not mylonitic, and the garnets are equidimensional, overgrowing kyanite closely associated in time with the second fold episode recognizable in this part of the Grenville province (Dalziel and others, in preparation). The Laue photographs of these younger garnets (pl. 2-A) have well defined spots showing no sign of asterism or splitting, and the crystal structure has not, therefore, been bent substantially.

However, Laue photographs of the dimensionally flattened garnets in the mylonitic rocks (pl. 2-B, C; pl. 3-A) show marked asterism and splitting of the spots indicating considerable distortion of the crystal structure and a degree of polygonization. Hence, these garnets have been tectonically deformed.

Geometry of the distortion.—Having established that the garnets in the mylonitic rock are in fact deformed, the next step is to determine the nature of this deformation and whether or not it can be geometrically related to the structure of the crystal and/or to the fabric of the tectonite.

In order to carry out this study, unusually thick sections were prepared from slabs cut in a number of different orientations from the hand specimen. The sections were left uncovered, and on the surface of the sections the orientation of the down-dip lineation and/or the intersection of the plane of the mylonitic foliation were marked. The garnet crystals were then removed from the thin section with a razor blade, broken up, and fragments of suitable size were mounted on glass fibers for X-ray study. Orientations were marked on the thin sections using a very thin "Rapidograph" pen; it was possible to select broken garnet fragments in which the edge of such a line could be clearly seen. Thus, the orientation of any fragment was known, relative to the specimen (and hence to the lineation and mylonitic foliation), by the cut surface and the line marked on this surface. For each of these fragments (9, all from different crystals) Laue photographs were taken with the cut surface oriented both normal and parallel to the X-ray beam; in the latter case photographs were taken with the beam parallel, normal, and at 30° to the direction of the ink line.

More detailed studies were made of two of the fragments. Photographs were taken at 30° intervals in the plane of the foliation, in the plane normal to the foliation and including the lineation, and in the plane normal to the lineation. Photographs of these fragments were also taken at 5° intervals in the plane of foliation up to an angle of 30° from the lineation.

Theoretically (Berg, 1934; see also Bailey, Bell, and Peng, 1958), when a crystal is bent about an axis perpendicular to the incident X-ray beam, the front reflections will be elongated radially most along the glide direction and least along the axis of bending. However, bending around the X-ray beam as an axis will cause the front reflections to be extended in a tangential direction with respect to the center of the film (compare pl. 3-A and B). The elongation is smaller than that produced by bending about an axis normal to the beam.

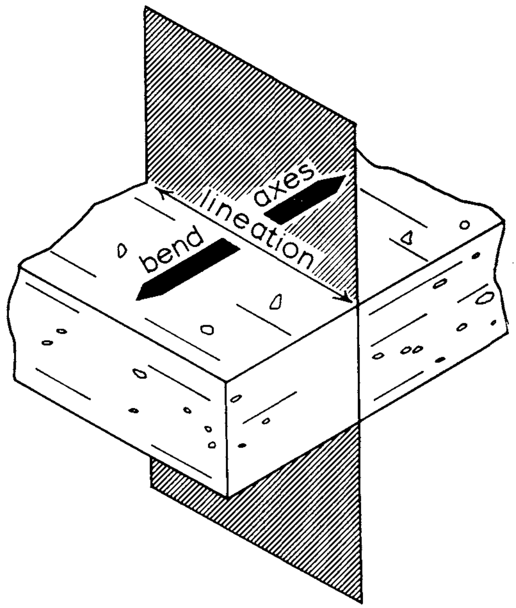
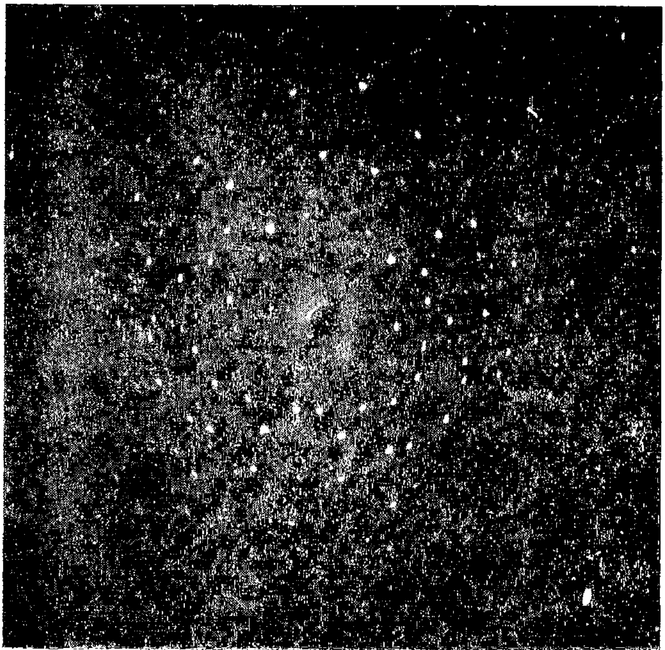
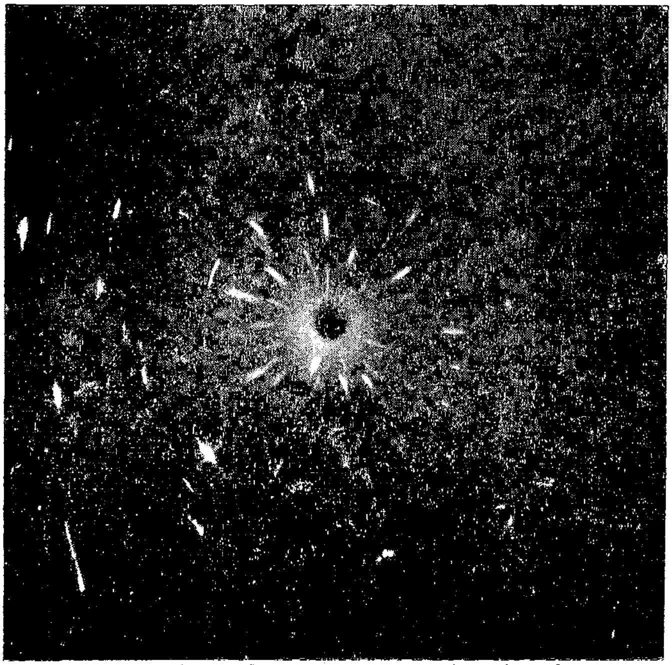


Fig. 7. Schematic illustration showing relationship of bend axes in the structure of the garnets to mesoscopic fabric elements.

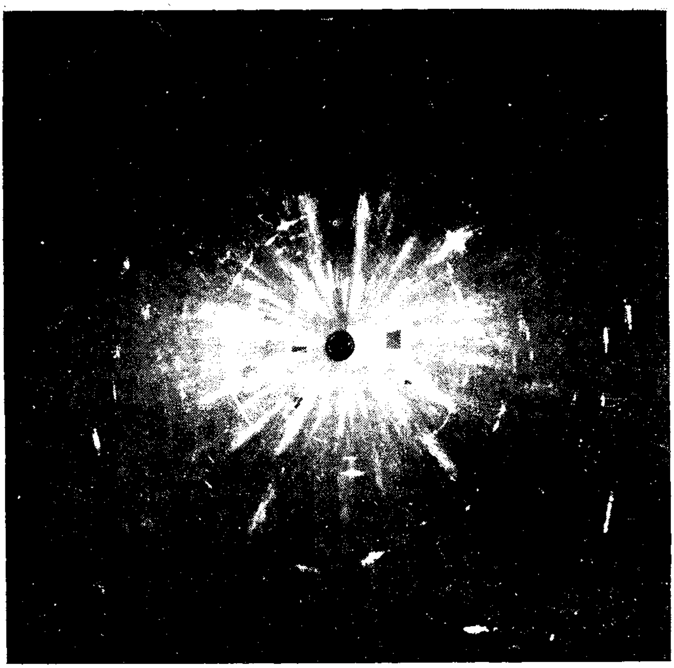
PLATE 2



A. Laue photograph of an undeformed garnet from kyanite gneiss at locality B; note slight variations in shape of spots.



B. Laue photograph of a deformed garnet porphyroclast from mylonitic rock at locality A; note marked asterism and splitting of spots.



C. Laue photograph of another deformed garnet showing extreme asterism.

The Laue patterns produced by the deformed garnets do not all show distortion of the shape of the spots distinctive enough to enable directions of bend axes or gliding to be determined. However, all patterns characteristic of bend axes with a small amount of tangential elongation of the spots (pl. 3-B) were obtained with the X-ray beam in the foliation and nearly normal to the lineation (fig. 7.) Of nine garnets studied, distinctive bend axes were recognized in six cases. The remaining three showed no clear bend axes, but one of these was not photographed with the beam in the foliation and normal to the lineation.

The direction of maximum radial elongation of the spots, and hence of maximum bend gliding, proved difficult to determine with any degree of accuracy. This could be due to the operation of more than one glide system but is probably due mainly to the difficulty in comparing the amount of asterism. Where it could be determined, it was found to lie within a cone of apical angle 35° or 40° coaxial with the lineation.

Crystallographic orientation of the garnets.—Experimental studies have shown that under most conditions a strong crystallographic control is exercised on the glide systems that operate in a crystal undergoing deformation. Bailey, Bell, and Peng (1958) were also able to establish a crystallographic control of deformation in their X-ray study of quartz. In order to determine whether a similar control had operated during the deformation of the garnet porphyroclasts, 10 crystals were mounted on a precession camera. The direction of the lineation was marked on each fragment.

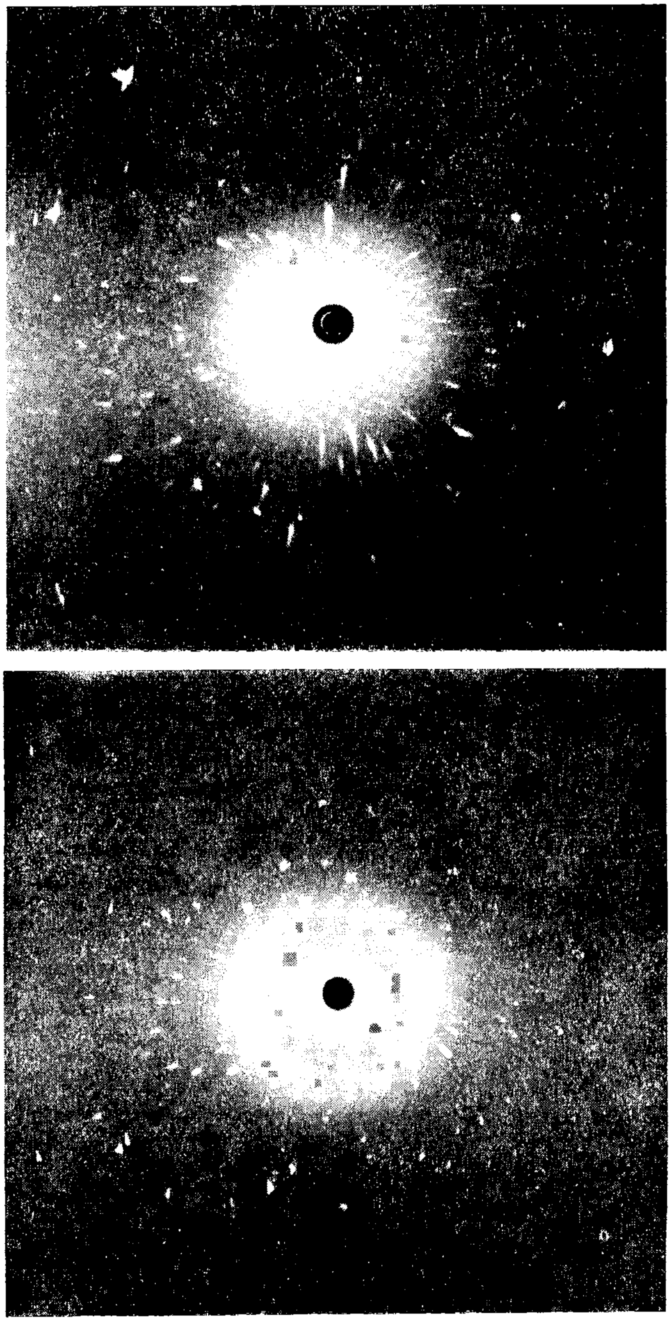


PLATE 3

Laue photographs of another deformed garnet (no. 8). A was taken with the beam parallel to the lineation, and B with the beam in the foliation but normal to the lineation. Note difference in shape of spots.

The orientation of the foliation and lineation are shown relative to the crystallographic axes in figure 8. It is apparent that the garnets show no marked crystallographic preferred orientation. Four of the crystals oriented on the precession camera (nos. 3, 6, 8, and 11) had previously been studied using the Laue method, and the orientation of their bend axes is also shown on the stereoplot. The other two crystals showing well-defined bend axes were obtained from thin sections cut in attitudes unsuitable for re-orientation on the precession camera.

The lineation direction is close to one of the 4-fold axes of garnets 6 and 8. The bend axes are relatively close to one of the 4-fold axes in garnets 6 and 11, near a 2-fold axis in garnet 8, and nearly equidistant from 2-fold, 3-fold, and 4-fold axes in garnet 3. Dr. Neville Carter has pointed out (personal commun.) that if body-centered garnet behaves like body-centered metals it would have 48 potential slip systems. The garnet structure is sufficiently complex (160 atoms per unit cell) that most of these potential systems probably are unfavorable energetically. The data in figure 8 do not rule out deformation by a slip mechanism on crystallographically favorable planes in the structure. But the relationship of the bend axes to the mesoscopic fabric of the rock indicates that tectonic control has dominated to the extent that, if slip has taken place, then it has had to occur along several different crystallographic planes, or combinations of planes, in the several garnet grains studied.

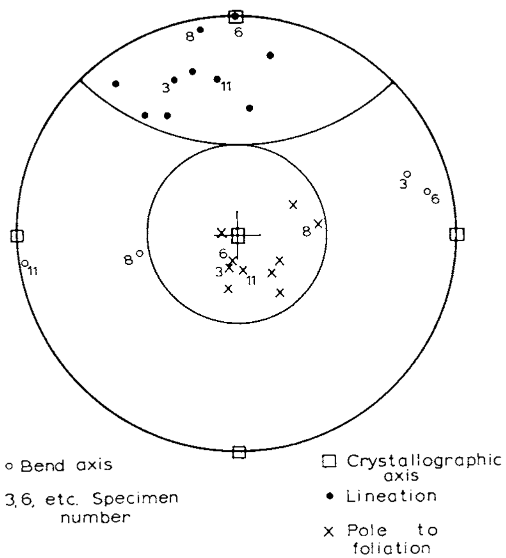


Fig. 8. Stereoplot (Wulff net, lower hemisphere) showing relationship of crystallographic axes in ten garnets to the mesoscopic fabric elements. Bend axes were distinguished for four of the crystals, and their orientation is also shown; the remaining six crystals were not studied using the Laue method. Small circles are drawn at 45° to crystallographic axes.

DISCUSSION

The structural and metamorphic history of the Grenville front. From the X-ray evidence it is clear that the garnet crystals are porphyroclasts that have been tectonically deformed. It is also clear that there is a close geometric relationship between the following:

- isoclinal folds
- mylonitic foliation (axial planar to isoclines)
- lineation (elongation of flattened grains forming the foliation and essentially parallel to the isoclinal fold axes)
- nearly orthorhombic quartz microfabric (foliation is a symmetry plane)
- symmetry of the garnet shape (axial, axis of symmetry normal to foliation)
- distortion of garnet structure (bend axes are nearly normal to lineation in foliation).

In time, too, they appear to be closely related at least to the extent that there is no definite basis for separating them; all predate the second fold episode. As previously mentioned, Christie (1963) has interpreted the orthorhombic microfabric of the mylonites along the Moine thrust belt as being indicative of flattening (non-translative) movements immediately following a rotational (translative) movement episode expressed by the isoclinal folding (and pre-dating the later, north-south folds). However, as Johnson (1967) has pointed out, if a flattening component in the folding process was responsible for the orthorhombic microfabric, then there is no need to appeal to two distinct periods of deformation.

Can the garnet porphyroclasts, then, be considered as deformation ellipsoids representative of the behavior of their parent rock as a whole? Flinn (1965) has discussed the problem of single crystals as deformation ellipsoids at some length and in so doing has pointed out a number of other factors that may have been responsible for a preferred dimensional orientation in crystals (mimetic growth, preferential growth along planes or directions of closest atomic packing). However, the equidimensional shape of undeformed garnets, the fact that those under consideration are known to have been deformed, and the close relationship between the external shape of the garnet crystals in the mylonitic rock and the symmetry of the mesoscopic fabric, all indicate that the shape of the garnet porphyroclasts is the result of deformation. Hence the garnets, which were presumably equidimensional prior to deformation, represent deformation ellipsoids if no grain boundary migration has occurred (Flinn, 1965, p. 63).

According to Barrett (1952, p. 361; see also Flinn, 1965, p. 54 and 58) five glide systems have to operate simultaneously for the change in shape of individual grains to conform to that of the deformation ellipsoid for the rock as a whole; otherwise dimensional and/or rotational restrictions will be placed on the deformation of the lattice. However, if a restriction is placed on the type of deformation by the stress field (for example if $k = k' = 0$, 1, or ∞)[2] fewer glide systems need be active

[2] k and k' are deformation paths of Flinn (1962, 1965).

at the one time (see Flinn, 1965, p. 58). On this basis the high symmetry of garnet means that it is more likely to behave as a deformation ellipsoid than any non-cubic mineral. However, the rocks involved here consist mainly of quartz and feldspar, so it would seem advisable to consider all three minerals.

The essentially oblate shape of the garnets studied (a few of them do show a slight tendency to be elongated in the foliation parallel to the lineation, see fig. 4) indicates that a major flattening component was involved and that $0<k<1$ (Flinn 1962). However, since this material was studied, Mr. J. M. Brown of the University of Wisconsin has collected other garnets in mylonitic rocks from the vicinity, some of which display orthorhombic symmetry of shape with a more marked elongation parallel to the down-dip lineation. This indicates a higher value of k. In some localities the lineation (elongation of quartz and feldspar grains) is dominant, and in others the mylonitic foliation (flattening of quartz and feldspar) is present with little sign of a lineation. In fact, where the oblate garnets occur the lineation is less pronounced than in most of the mylonitic rocks. Thus, as in the Moine thrust belt (Johnson, 1967, p. 247) the value of k appears to vary between 0 and ∞.

While the lineation cannot be regarded as a classical *a* ("transport") lineation, it does apparently reflect the direction of maximum extension in the stress field. Quartz has behaved in a more ductile manner, but many feldspar porphyroclasts have open fractures roughly normal to the lineation (partly cleavage controlled), and some of the garnets with an orthorhombic symmetry of shape collected by Brown are also split open by extension cracks normal to their longest axis (that is, normal to the lineation).

In order to account solely for the prominent foliation and lineation that characterize all the localities along the Grenville front visited to date, it is not necessary to envisage major displacement of the rocks of the Grenville province relative to those of the isotopically older provinces to the northwest. Rather may the foliation and lineation have resulted from the constriction of the marginal zone of the highly mobile Grenville province against the relatively rigid provinces to the north and west. Johnson (1967) has pointed out that, unless volume reduction is involved, the flattened mylonite zone must be displaced relative to the "undeformed surrounding rocks". In the present context it is not possible to regard the interior of the Grenville province as being "undeformed" at the time of formation of the mylonites; the general structural style along the Grenville front grades into that of the interior of the province. However, the marginal zone must have undergone more severe flattening, and hence elongation parallel to the lineation, than the interior. The problem posed by the isoclinal folds is a complex one and cannot be discussed in detail here. However, although their axes always plunge down the dip of the mylonitic foliation parallel to the lineation, some of them do occur as extremely flattened domes and basins observed in outcrop as "eyefolds". This indicates that they may have been rotated into parallelism with the lineation (direction of maximum elongation or Z axis of the deformation ellipsoid) as the deformation proceeded.

Mechanism of garnet deformation.—It is well known that deformation of metals leads to bending of the crystal structure with slip in certain planes and hence to asterism of spots in Laue photographs (Barrett, 1952; Guinier, 1952). Later annealing of strongly deformed crystals at relatively high temperatures without recrystallization (Cahn, 1951) leads to the formation of sub-grains with slightly different orientations (polygonization), which is revealed on Laue photographs of the material as splitting of the spots already showing asterism (pl. 2-B, C). Annealing above a critical temperature results in recrystallization, the formation of new and perfect grains at the expense of the sub-grains formed by polygonization. Sub-grains may also form by creep where deformation and annealing occur simultaneously (Guinier, 1952). This is important, because under geological conditions of low strain rate and (frequently) relatively high temperatures, the latter process is more realistic. Certainly the deformation of garnet in the mylonitic rocks near Coniston must have taken place under relatively high temperature/low strain rate conditions.

Experimental studies of mineral deformation have shown that bending and/or kink-banding of the grains due to inhomogeneous slip along the glide plane (Raleigh, 1965, p. 740) may occur even at small strains. The axes of bending and kink-banding lie in the glide plane at right angles to the glide direction, and it seems likely that the "bend axes" detected in the crystal structure of the garnet porphyroclasts represent such axes of external rotation. The splitting of the Laue spots indicates that a degree of polygonization has occurred. The sub-grains produced by this process are also elongated at right angles to the glide direction; Bailey, Bell, and Peng (1958) have reproduced the splitting of Laue spots resulting from polygonization by exposing the same crystal successively in slightly different orientations in an X-ray beam using the same film.

Under the conditions of the deformation along the Grenville front at Coniston, low strain rate presumably and high almandine amphibolite facies, the orientation of bend axes in the deformed garnets appears to have been more closely controlled by tectonics than crystallography. Again, this may be a factor of conditions of deformation, including the stress field. Critical shear stress may only have been exceeded to permit slip on atomic planes along directions contained in the XZ plane of the regional deformation ellipsoid, resulting in bending about an axis normal to this plane, that is, normal to the lineation in the foliation (fig. 7).

Glide directions would be expected to lie in the plane normal to the bend axes, and from the maximum elongation of the Laue spots they appear to do so. Failure to define a glide direction within this plane may indicate the operation of multiple glide systems and/or partial rotation of glide directions toward the regional extension direction (see Flinn, 1965).

The Laue method may provide a powerful tool in the comparison of deformation mechanisms in naturally and experimentally deformed crystals, particularly isotropic crystals such as garnet. It is hoped to compare the Laue patterns obtained from naturally and experimentally deformed crystals in the near future.

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