On the preferred crystallographic orientation of garnet in some metamorphic rocks

By Derek Powell, Ph.D.

Department of Geology, Bedford College, University of London

[Taken as read 9 June 1966]

Summary. A study of inclusions within garnet porphyroblasts demonstrates that planar inclusion bands and trails lie sub-parallel to one of the {110} planes of the host. The inclusions provide a relic of a rock fabric that existed before the growth of garnet. It is suggested that this fabric has determined the crystallographic orientation of garnet and may have arisen by the nucleation and epitaxial growth of garnet within or upon the mica lattice.

PREVIOUS work on the textural relationships of garnets found in metamorphic rocks has been concerned with discussions of their significance in terms of garnet growth (Rast and Sturt, 1957; Galwey and Jones, 1962) and in terms of the structural-metamorphic history of the containing rock (Flett, 1912; Read, 1949; Rast, 1958; Zwart, 1960; Rast, Sturt, and Harris, 1962; and Spry, 1963, are among the many contributions). The character of the included material in garnet crystals has figured as a basis for much of this work but its relationship to the host crystal structure has rarely been discussed. The observations upon which the earlier work has been based were made using normal optical methods and were thus essentially two-dimensional.

In this study an attempt has been made to examine garnets with inclusions in three dimensions, and thus to determine the exact distribution and shapes of the inclusions and their spatial relationships to the host crystal structure.

Detailed studies have been made of garnets from Moinian pelitic metasediments of the Loch Mama Pelitic Group of eastern Morar, Scotland (Powell, 1964) and of the Garnetiferous Group of western Morar (Richey and Kennedy, 1939). The conclusions derived from observations on these rocks are supported and extended by a study of other metamorphic rocks.

Methods. Garnets occurring in the Moine rocks have been studied in thin section (rock slice 0·03 mm thick), and in thick section (rock slice

0·25 to 0·5 mm thick). The examination of the thick sections on a two-axis Universal Stage mounted upon a stereoscopic non-polarizing microscope has allowed the measurement of the attitudes of various planar elements within and bounding the garnet crystals.

The Moinian garnets and their environment

The garnets and their host rocks. The host rocks are schistose, medium-grained pelites. They preserve a strong lineation, which is the result of both micro-folding of the micas and the presence of elongated masses of quartz and feldspar. In sections cut normal to the lineation and thus normal to the schistosity, the rocks have an 'eye' structure (Flinn, 1954, fig. 4), and the micas define a crude schistosity. There is no segregation of the mineral constituents into bands. In sections cut parallel to the lineation and normal to the schistosity the micas show strong, parallel, dimensional orientation and a tendency to segregate into discontinuous, parallel bands.

The garnets often form equidimensional porphyroblasts ranging from 1·5 to 6·0 mm in diameter. The micas adjacent to the garnets and thus the schistosity are deflected around the porphyroblasts.

Many of the garnets are idioblastic though garnets in which part of the crystal is idioblastic while other parts are xenoblastic are common. They are zoned, a feature that is shown markedly in the thick sections but only indistinctly in thin sections. All the garnets exhibit at least two zones, a wide inner zone and a thin outer zone (fig. 1); the outer surface of the outer zone normally forms the boundary of the crystal but occasionally an incomplete thin zone is seen outside the two zones mentioned.

The boundary between the inner and outer zones is marked in all crystals by a plane of inclusions consisting mainly of iron ore and unidentified opaque dust. The zone boundary surfaces are essentially planar though in detail curving irregularities are evident (figs. 1, 2, and 8a); their arrangement in three dimensions commonly mimics the external crystal form of the garnets. Occasionally faces present at the crystal surface are not reflected at the zone boundary surface, and vice versa.

The two zones are distinct in that the inner one is orange-red and contains numerous inclusions, whereas the outer zone is relatively inclusion free and pale purple-red; again the colour difference is much more apparent in thick sections. The garnets are isotropic. There are no differences in shape or internal characteristics between garnets viewed in sections cut at different angles to the schistosity and the lineation of the host rock. The idioblastic garnets are usually six-sided, occasionally eight-sided, and rarely four-sided. On weathered rock surfaces 60 of 100 crystals examined had recognizable rhombododecahedral crystal form; other crystal forms were not observed.

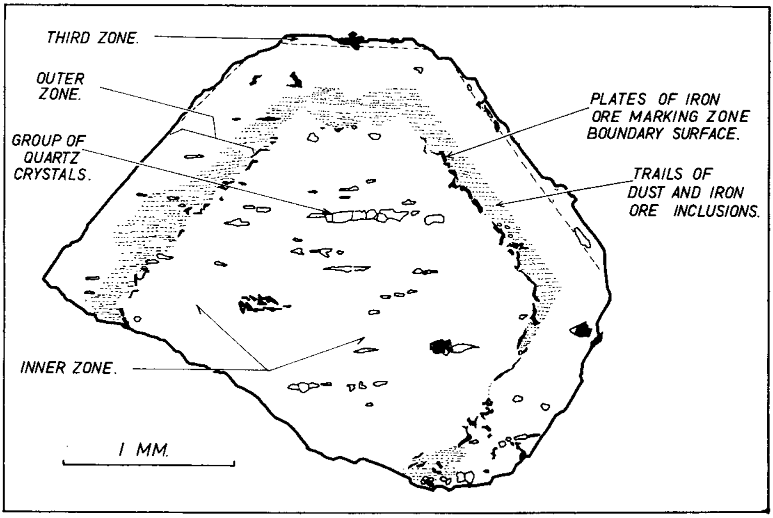

FIG. 1. Garnet with three well-developed faces exhibiting three zones and inclusion trails. Section 0·03 mm thick, from pelite, East Morar. Slide No. D.P.* 501, Moine. (Grid ref. NM 74258275.) *D.P., author's collection; L., Dept. of Geology, University of Liverpool, slide collection.

The inclusions. All the garnets contain numerous inclusions of quartz, iron ore, and opaque dust. The inclusions can be divided into two groups:

The first consists of iron ore and opaque dust, which are distributed in a way indicating that their arrangement is due directly to chemical or physical influences of the surrounding garnet. Within the inner zones of the garnets, opaque dust and iron ore are often concentrated in wedge-shaped sectors that extend from the inner zone edges inwards towards the centre of the garnet. They appear, therefore, to be aligned parallel to internal dodecahedral planes of the host crystal (fig. 2). Such a distribution has been described by Karpinsky (1887, quoted by Harker, 1932), Gliszynski (1940), Schaacke (1949), Rast and Sturt (1957), and Grigor'ev (1965, p. 99). Iron ore inclusions lying along the zone boundary plane are always flattened in the plane of the boundary surface. They have, therefore, either been bodily rotated by the crystallizing garnet

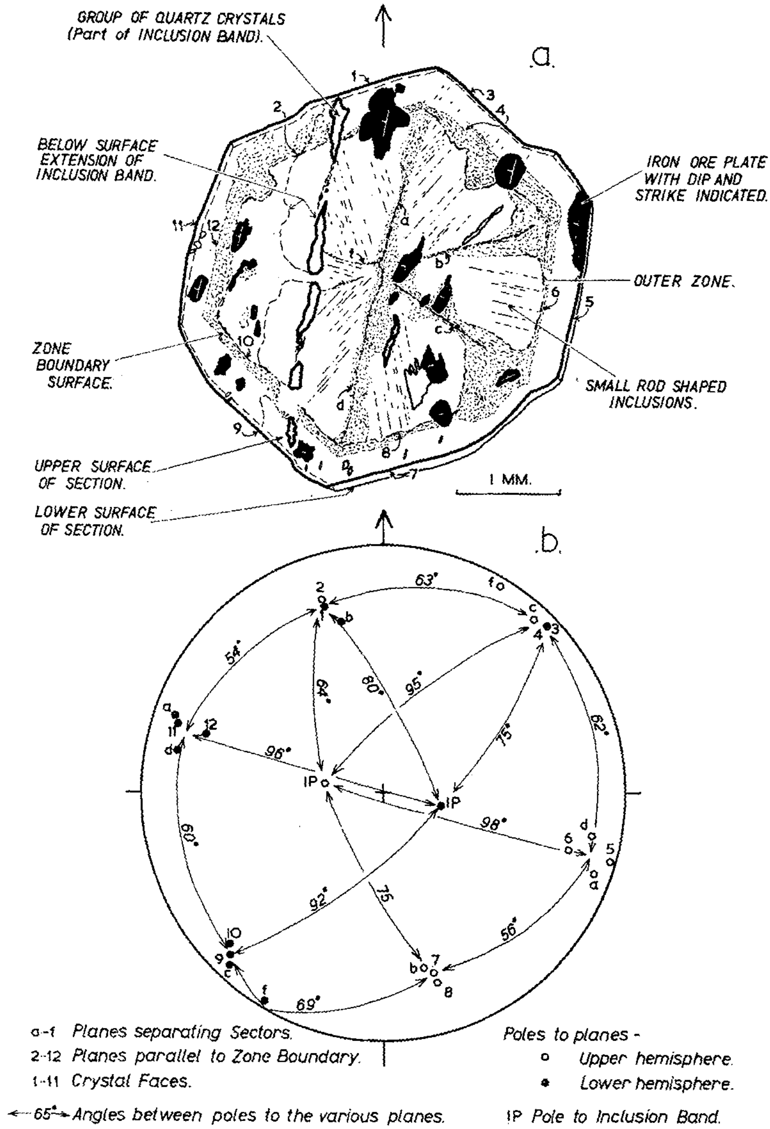

FIG. 2. *a.* Idioblastic garnet illustrating the appearance of zones and inclusions in thick section. Section 0·25 mm thick. Black inclusions, opaque ore; unornamented, quartz; stippled, opaque dust. Slide No. D.P. 502 Al, pelite, East Morar, Moine. (Grid ref. NM 74208370.) *b.* Stereographic projection (equal area), combined upper and lower hemisphere plot, of the planar elements in the garnet illustrated in *a.* The {110} form of the garnet is evident and the inclusion band lies almost parallel to one of the {110} planes of the host.

or exsolved in this position (fig. 1). Opaque dust is concentrated adjacent to the zone boundary surface within the outer zone of the garnets. It forms a thin, sometimes discontinuous band whose outer margin frequently parallels the crystal faces developed by the garnet (figs. 1 and 2*a*).

Very small rod-shaped inclusions of unknown composition often lie normal to the crystal faces and are thus sectorially arranged (fig. 2*a*). These inclusions probably owe their orientation to the growth processes of the garnet (Rast and Sturt, 1957).

The second group of inclusions consists of quartz and iron ore and is characterized by the distribution of the inclusions as discrete, usually flat, planar bands that cross the garnets (figs. 1 and 2*a*). Several such parallel bands may be present in one crystal; they are generally seen within the inner zones of the garnets, where they are composed of both isolated inclusions of quartz and iron-ore and groups of quartz crystals (fig. 2*a*). Some garnets contain scattered inclusions of quartz and ore, which form parallel trails through the crystal. Both trails and bands are often present in the same garnet. The inclusions fall into two size groups: small inclusions of quartz and iron-ore from 0·01 to 0·5 mm in diameter, and large inclusions of quartz, iron-ore, and occasionally plagioclase from 0·25 to 0·75 mm in diameter.

The small inclusions of quartz are often elongated and where they form groups of crystals the group shape is that of a flattened lens (figs. 1 and 2*a*). Iron-ore occurs as rods, plates, and roughly equidimensional grains. The larger inclusions of quartz almost always occur as elongated grain groups within the inner zones of the garnets; component crystals are usually equidimensional and quartz–quartz triple junctions are common. Such inclusions may be replacive towards the garnet (Rast, 1965, p. 94). The large iron-ore crystals are plate-like or irregular in shape. Elongation or flattening of these inclusions is almost always in the plane containing the inclusion bands or trails.

Spatial relationships between inclusion bands and trails and host. A common feature in all sections is the parallelism or near parallelism of the trace of the inclusion bands and trails to one or more of the traces of the host crystal faces (figs. 1 and 2*a*). 33 garnets with recognizable crystal form have been studied and in the majority this relationship is apparent. In eight crystals the trace of the inclusion bands and trails lies normal or nearly normal to opposite crystal faces.

In order to determine the three-dimensional relationship between the plane containing the inclusion bands or trails and the host crystallographic form, the attitudes of the various planar elements in the crystals were measured in thick sections and plotted on stereographic projections (for example, fig. 2*b*).

The histogram (fig. 3), showing peaks around 60° and 120°, confirms that the garnet crystal form is rhombododecahedral. The occurrence of angles other than 60°, 90°, and 120° is probably the result of errors in measurement due to inherent inaccuracies in the method, or the occurrence of slightly deformed crystals, or both. The occurrence of angles

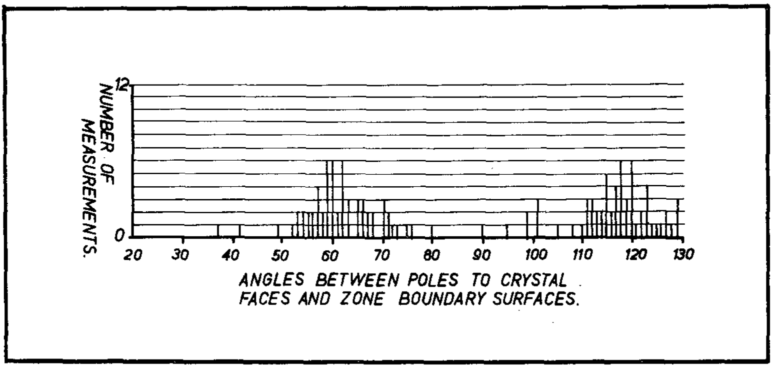

FIG. 3. Histogram illustrating the angular relationships between crystal faces in 10 Moine garnets from East Morar.

of 70° to 75° and 54° may suggest the development of icositetrahedral faces but it is important to note that angles of near 30° and 48°, which would confirm their development, are absent.

Stereographic projections of four garnet crystals are shown in fig. 4; the planes of inclusion bands and trails are also shown and lie very close to one of the dodecahedral planes of the host crystal. This is true of all the garnets measured where a rhombododecahedral form can be established. Even in garnets where the crystal form cannot be certainly established the plane containing the inclusion bands and trails almost always lies parallel to either an external crystal face or the boundary plane between the inner and outer zones.

In order to represent and assess this parallelism more precisely data from eleven garnets have been plotted together and compared with an ideal garnet crystal projection. The garnets chosen were those in which the bounding faces or the zone boundary planes or both showed least deviation from the ideal rhombododecahedron. Fig. 5*a* shows the poles to the inclusion bands and trails grouped together; they show a

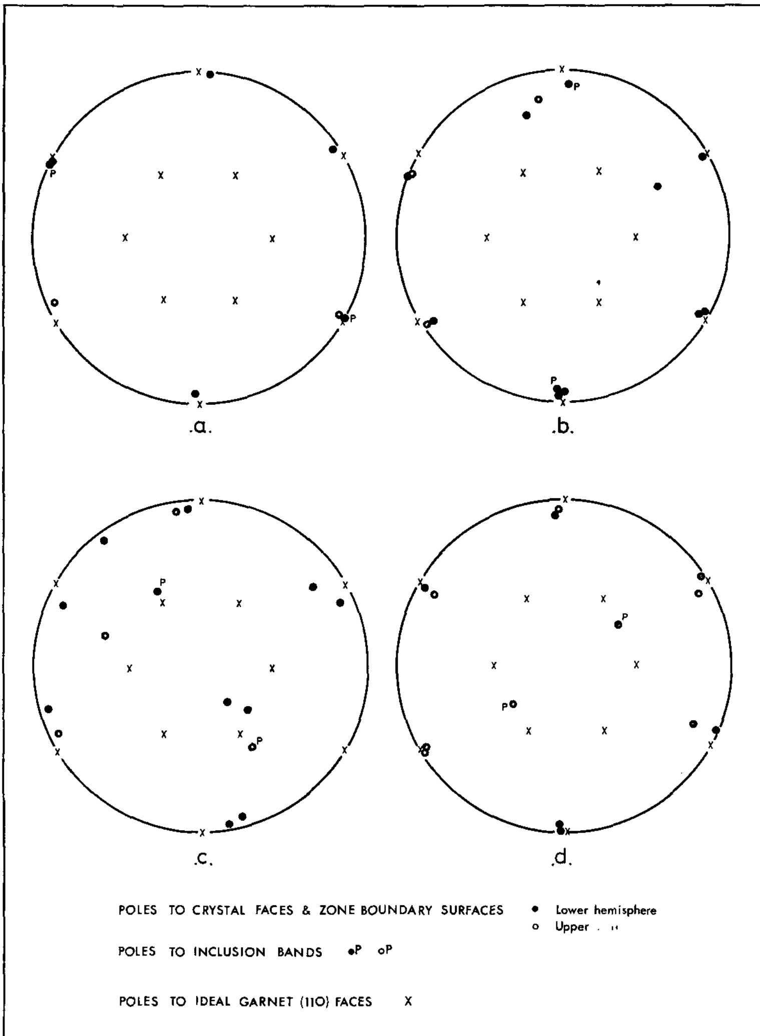

FIG. 4. Combined upper and lower hemisphere equal-area stereographic projections of data from four Moine garnets to illustrate crystal form and the relationships of the inclusion bands to the crystal form. The distribution of poles to the various planar elements in each garnet is compared with an ideal projection of garnet {110}, centred on one of the triad symmetry axes. *a.* Slide No. D.P. 502 A, East Morar, Moine. Garnet No. 3 (Grid ref. NM 74208370.) *b.* Slide No. D.P. 502 A, East Morar, Moine. Garnet No. 1. *c.* Slide No. D.P. 4F B, East Morar, Moine. Garnet No. 4. (Grid. ref. NM 74258375.) *d.* Slide No. D.P. 502 A, East Morar, Moine. Garnet No. 2.

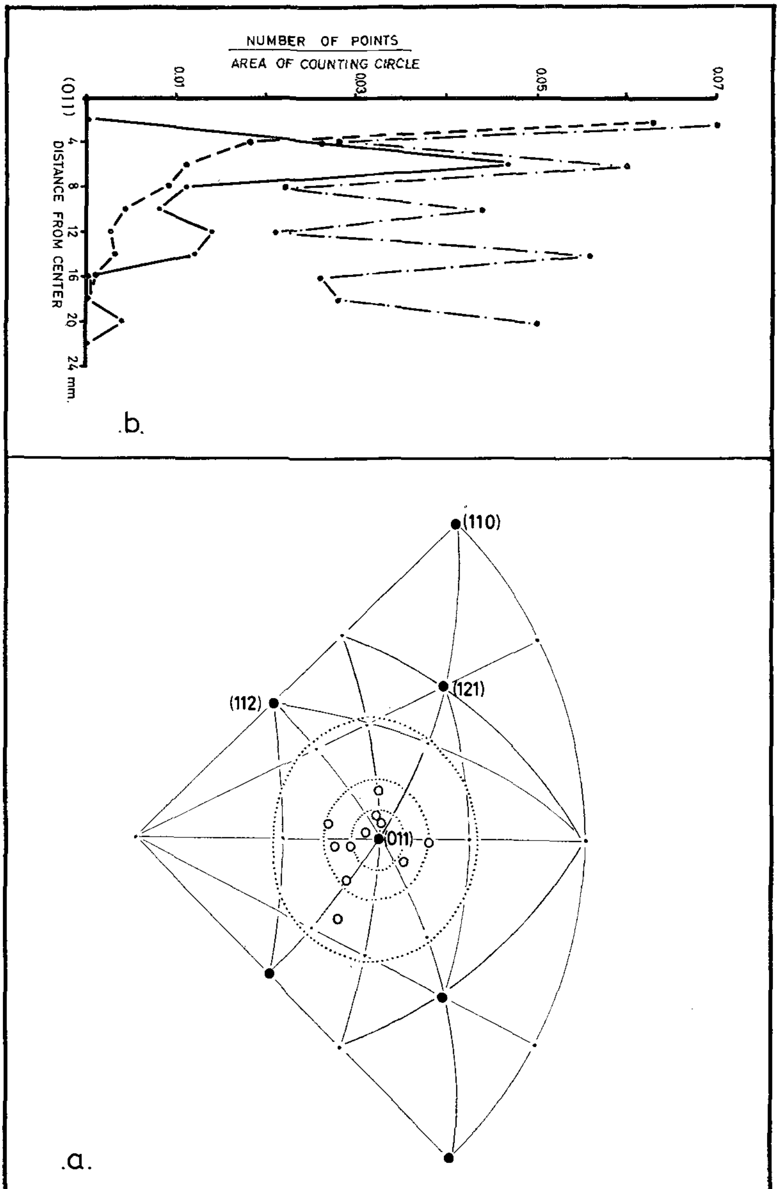

FIG. 5*a*. One quadrant of an upper hemisphere equal-area stereographic projection of poles to inclusion bands in 11 Moine garnets compared with an ideal projection of garnet {110} and {211}, centred on the *c* crystallographic axis. The dotted ellipses indicate 5°, 10°, and 20° cones about the pole to (011). *b*. Graph determining the statistical centre of the poles to inclusion bands shown in *a*; – – – – – – model distribution of poles concentrated with (011) as the statistical centre; — · — · —, model random distribution of poles about (011). The solid line curve indicates that the statistical centre of the poles to inclusion bands shown in *a* lies at a small angle from (011).

marked concentration around the pole to (011) of the perfect garnet crystal; a relationship that is confirmed by the graph, fig. 5*b*.

The significance of the preferred orientation. The inclusion bands and trails are restricted to the garnet crystals and, unlike the examples drawn from the Dalradian material (fig. 7*a*, *e*, and *f*), they are not continuous with planar structures in the surrounding rock. It is therefore impossible in the Moinian examples to establish directly that these inclusions represent a relic of a planar structure that existed before the growth of garnet. The frequent arrangement of inclusion bands and trails in parallel bands that cut through the sectors mentioned above does, however, suggest that the garnet has overgrown previous compositional banding.

If the inclusion bands and trails contained by the Moinian garnets represent an earlier rock fabric it follows that the garnets are crystallographically oriented relative to this fabric. The crystals grew so that a dodecahedral plane lay approximately parallel to the planar structure within the original rock. There is, however, no parallelism between the inclusion bands and trails from one crystal to another in the same rock. Any earlier systematic relationships have been disrupted by deformation.

In view of the sometimes marked preferred dimensional orientation of many of the inclusions making up the bands and trails it is probable that the pre-garnet rock fabric was quite strongly planar and that the micaceous minerals present, which have since been digested by the growth of garnet, were oriented sub-parallel to the inclusion planes. Garnet may have nucleated within or upon these mica crystals.

Comparison of garnet and mica crystal lattices. Frondel (1940) studied inclusions of euhedral garnet crystals within muscovite in a pegmatite. He found that the (110) of garnet very frequently lay parallel to the (001) of mica with an angle between the (001) of garnet and the (100) of muscovite of 0°, 30°, 60°, or 90°. In view of this and the author's results geometric comparisons have been made between the lattices of garnet and mica in order to ascertain the possible effects on the lattice orientation of garnet, presuming its epitaxial growth within or upon mica.

Fig. 6*a* and *b* illustrate the similarity between the arrangement of K atoms in mica and the Al atoms in garnet on particular crystallographic planes. The arrangement of O atoms in layers adjacent to the K layer in mica (fig. 6*a*) is such that the layer could possibly accommodate Al atoms arranged in a pattern very similar to that shown by Al on the (110) of garnet (fig. 6*c*). If garnet nuclei can arise by the introduction of Al atoms into the mica structure in this way it is possible to predict that the garnet nuclei and thus subsequent garnet lattices would show preferred crystallographic orientation such that the angle between

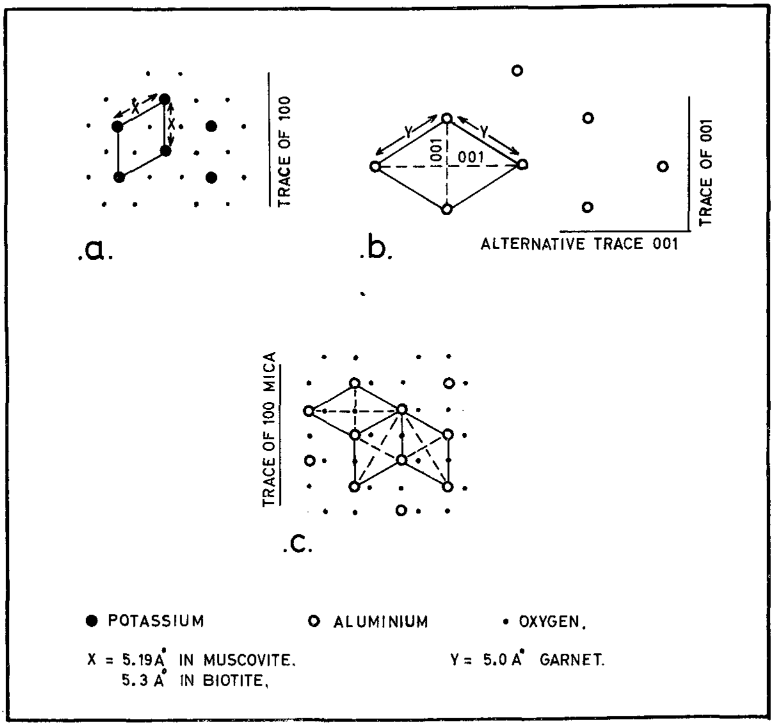

Fig. 6*a*. Pattern of K atoms and O atoms adjacent to the K layer, on 001 planes in mica. *b*. Pattern of Al atoms on dodecahedral planes in garnet. *c*. Suggested positions of fit of Al atoms with a spatial distribution as in *b* above, onto the O layer above or below the K layer in mica. The angles between the trace of the (001) of garnet and the (100) of mica, assuming a contact plane parallel to the (001) of mica and a dodecahedral plane of garnet, would be 0°, 30°, 60°, or 90°. Octahedral co-ordination of Al could possibly arise by the addition of further O atoms above the Al layer.

the trace of the (100) of mica and the trace of the (001) of garnet is 0°, 30°, 60°, or 90°.

Frondel attributed the phenomena he found to a 'skating' action of garnet when precipitated out of solution onto the cleavage surface of a growing muscovite book, the skating being in response to the surface

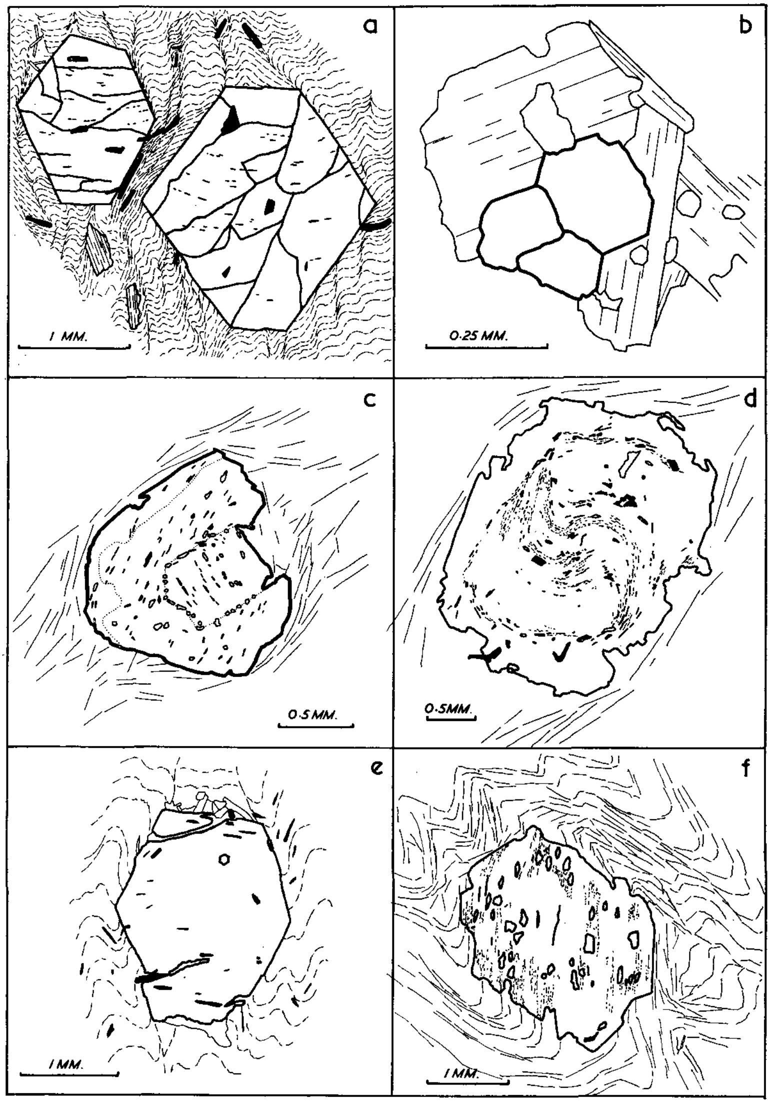

FIG. 7. Garnets from other metamorphic rocks in thin section. *a*. Idioblastic garnets with inclusions of opaque ore (black), showing preferred orientation in a fine grained, muscovite-rich pelite. Dalradian, Slide No. L. 15380, Dunkeld, Scotland. The relic fabric apparently lies sub-parallel to a dodecahedral face of garnet in both crystals. Note the continuity, in places, between the included fabric and trails of opaque ore crystals in the matrix. Post-garnet folding has largely destroyed the earlier fabric in the matrix. *b*. Cluster of partly euhedral garnets (heavy outline),

energy fields of the two crystals. The orientation found by the author may be explicable in terms of the epitaxial growth of garnet in or on mica and may provide an alternative to Frondel's suggestion (see also Rast, 1965, p. 79).

Garnets in other metamorphic rocks

Several thin sections of garnetiferous rocks from the Dalradian Series of Scotland have been examined. They show relationships between inclusions and host crystal form similar to those described above. Figs. 7 and 8 demonstrate the parallelism between the traces of inclusion bands and trails and the trace of the (110) of garnet. In some sections the inclusions can be seen to be relics of lithological banding that was probably bedding (fig. 9). In other sections deformation has wholly or partly disrupted the continuity between the relic included fabric and the same fabric in the matrix (fig. 7*c* and *e*).

Many of the garnets contain S-shaped inclusion trails. Fig. 7*d* indicates that even where movement probably coincided with garnet growth the orientation of the garnet lattice was controlled by the pre-existing fabric; the innermost inclusions (the middle of the S) in fig. 7*d* form bands and trails that appear to be parallel to the diagonal of the almost square garnet section, that is, parallel to (110). In fig. 8 the central part of the S shows a crystallographic relationship to the inner zone of the garnet; the outer zone does not have good crystal faces except on its south-eastern margin.

Fig. 7*c* illustrates a garnet in which the orientation of the inclusion trails changes abruptly from zone to zone. Within the inner zone the

---

associated with biotite (dashed), in a metamorphosed ignimbrite. Slide No. L. 2614, Hong Kong. Garnet: garnet junctions are curved and meet at triple points; garnet: quartz junctions (to the south-west), are irregular; garnet: biotite junctions are crystallographic towards both garnet and mica. *c.* Partly idioblastic garnet with inclusions of opaque ore (black), and quartz (no ornament). Dalradian pelite, Slide No. L. 21326, Schiehallion, Scotland. For explanation see text. *d.* Almost square section of garnet from Dalradian pelite, Slide No. L. 21307, Schiehallion, Scotland. The garnet has two growth zones separated by planes of concentrated inclusions; quartz, no ornament; opaque ore, black. For explanation see text. *e.* Idioblastic garnet with inclusions of opaque ore, tourmaline, and chlorite. The former indicate a relic fabric. Dalradian pelite, Slide No. L. 15372, Amulree, Perthshire, Scotland. The section illustrates similar features to those of *a* in this figure. *f.* Idioblastic garnet with inclusions of quartz (no ornament), opaque ore (black), and graphite dust (dots). The included fabric is here continuous with the fabric of the matrix. The parallelism of the inclusion trails with two of the dodecahedral faces is evident. Post-garnet growth deformation has folded the matrix. Slide No. L. 8980, Dalradian, Dunkeld.

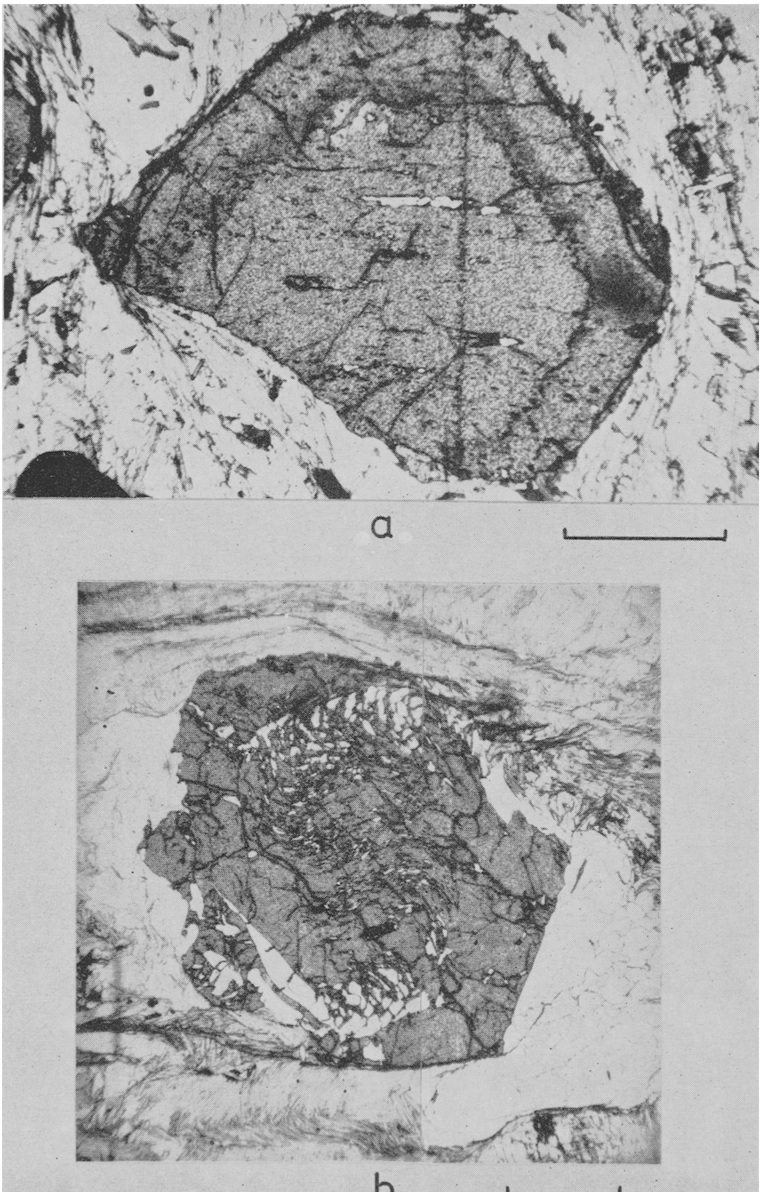

FIG. 8. *a*. Garnet in pelite showing three zones, inclusion bands, and inclusion trails. Slide No. D.P. 501, Moine. *b*. Partly idioblastic garnet with S-shaped inclusion trails. Slide No. D.P. A, Dalradian, Schiehallion, Scotland. For explanation see text. The scale bar represents 1 mm.

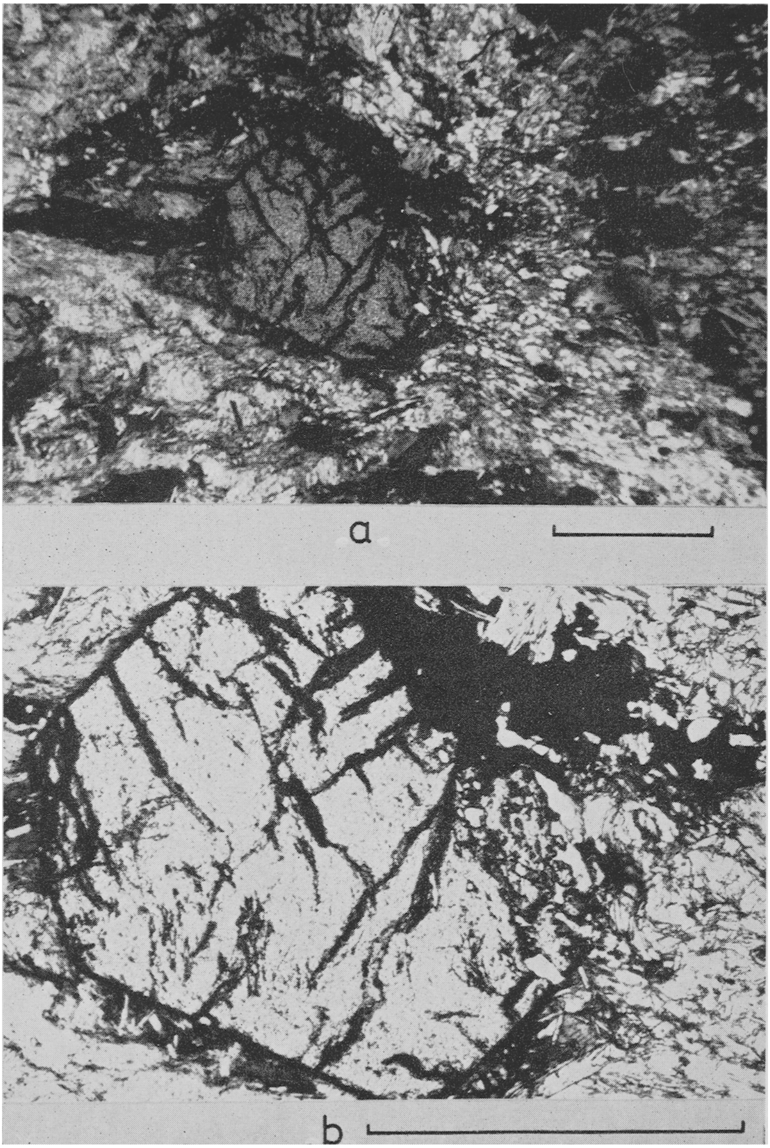

FIG. 9. *a*. Partly idioblastic garnet in folded pelite. Slide No. L. 15380, Dalradian, Dunkeld, Scotland, thin section. A light-coloured, quartzo-feldspathic band crosses the section from NW to SE to the immediate east of the garnet. The remaining matrix is predominantly micaceous. The band represents an early structure, probably bedding, which in the micaceous areas has largely been destroyed by deformation. A new E–W cleavage has resulted from the deformation. Note that the inclusion trails in the garnet lie subparallel to the light band and to a dodecahedral face of the garnet. *b*. The same, higher magnification. The scale bar represents 1 mm.

inclusion trails appear to lie parallel to (110) but those in the outer zone bear no such relationship. Movements taking place after the growth of the inner zone reorientated the planar fabric of the matrix; renewed garnet growth included this fabric but the crystallographic orientation of the outer zones was determined by the orientation of the inner zone, not the planar fabric of the matrix. Here garnet was growing on garnet and not in or on mica.

The subhedral garnets shown in fig. 7*b* occur in a contact metamorphosed ignimbrite in which large clusters of biotite crystals are common and are of metamorphic origin. It appears that the rock has suffered progressive metamorphic changes and that garnet crystallized later than biotite. Garnet is commonly associated with biotite in the way illustrated, and has probably nucleated within or upon the mica.

Pitcher and Read (1963, fig. 11) illustrate and describe idioblastic garnet that is pseudomorphed by micaceous minerals showing marked orientation parallel to the (110) of garnet. Here the process outlined above is apparently reversed, the garnet lattice influencing the orientation of the replacing mica lattices.

Concluding remarks

The development of preferred lattice orientation has been attributed in the main to the operation of non-hydrostatic stress or deformation (Strand, 1944; Kamb, 1959; Flinn, 1965). In the present case the lattice orientation may only be indirectly due to the existence of a stress field during the development of the host rocks; the planar fabric included within the garnets may represent an earlier cleavage. A somewhat analogous situation is known to occur in metals where preferred lattice orientation can develop by annealing recrystallization (Burke and Turnbull, 1952, p. 282; Flinn, 1965, p. 64). It appears, however, that such orientation in garnet can occur without the influence of deformation; the relic fabric may in some cases represent bedding and not a stress-derived structure.

Epitaxial growth phenomena are discussed in relation to non-silicate minerals by Seifert (1953), and to silicate minerals by Eitel (1964). Epitaxis has not been widely recognized in rocks. Chinner (1961) suggested that sillimanite nucleates and grows epitaxially within biotite but, as Rast (1965) has pointed out, the geometric relationships illustrated by Chinner are not universal. The present study may provide evidence for the existence in metamorphic rocks of epitaxial growth phenomena, which appear to be widespread.

Acknowledgements. The work presented was carried out in the Department of Geology, University of Liverpool, while the author was in receipt of an S.R.C. Fellowship. The author is grateful to Professor W. S. Pitcher for his encouragement, to Dr. N. Rast for his advice and for drawing attention to much of the Dalradian material, and to Dr. D. Flinn for his help with the crystallographic problems involved. He is grateful to Professor B. C. King and Dr. P. H. Banham for their criticism of the manuscript.

References

BURKE (J. E.) and TURNBULL (D.), 1952. Progress in Metal Physics, 3, p. 220.
CHINNER (G. A.), 1961. Journ. Pet., vol. 2, p. 312.
EITEL (W.), 1964. Silicate Science, vol. 1, p. 204. Academic Press, New York.
FLINN (D.), 1954. Quart. Journ. Geol. Soc. Lond., vol. 110, p. 177.
—— 1965. *In* Controls of Metamorphism, p. 46. Oliver and Boyd, Edinburgh.
FLETT (J. S.), 1912. *In* Memoir Geol. Surv. Great Britain, Scotland, Sheet 93.
FRONDEL (C.), 1940. Amer. Min., vol. 25, p. 69.
GALWEY (A. K.) and JONES (K. A.), 1962. Nature, vol. 193, p. 471.
GLISZYNSKI (S. VON), 1940. Zentr. Min., A, p. 181.
GRIGOR'EV (D. P.) [Григорьев (Д. П.)], 1965. Ontogeny of Minerals, translated from Russian, Israel Program for Scientific Translations, Jerusalem.
HARKER (A.), 1932. Metamorphism. Methuen, London.
KAMB (W. B.), 1959. Journ. Geol., vol. 71, p. 162.
PITCHER (W. S.) and READ (H. H.), 1963. *Ibid.*, p. 261.
POWELL (D.), 1964. Proc. Geol. Assoc. Lond., vol. 75, p. 223.
RAST (N.), 1958. Trans. Roy. Soc. Edin., vol. 63, p. 143.
—— 1965. *In* Controls of Metamorphism, p. 73. Oliver and Boyd, Edinburgh.
—— and STURT (B. A.), 1957. Nature, vol. 179, p. 215.
—— —— and HARRIS (A. L.), 1962. *Ibid.*, vol. 195, p. 274.
READ (H. H.), 1949. Quart. Journ. Geol. Soc. Lond., vol. 105, p. 101.
RICHEY (J. E.) and KENNEDY (W. Q.), 1939. Bull. Geol. Surv. Great Britain, vol. 2, p. 26.
SCHAACKE (I.), 1949. Neues Jahrb Min., Abt. A, Abh. vol. 80, p. 145.
SEIFERT (H.), 1953. *In* Structure and Properties of Solid Surfaces. Edit. Gomer and Smith, p. 318. University of Chicago Press.
SPRY (A.), 1963. Journ. Petrology, vol. 4, p. 211.
STRAND (T.), 1944. Norsk, geol. Tidsskr., vol. 24, p. 14.
ZWART (H. J.), 1960. Geol. en Mijn., vol. 39, p. 163.

[*Manuscript received 10 February 1966*]