The rôle of kyanite in the 'hornfels zone' of the Carn Chuinneag granite (*Ross-shire*).

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THE metamorphism surrounding the granite of Carn Chuinneag in eastern Ross-shire [1] provides the classical example of polymetamorphism in which a regional metamorphism is superimposed on a normal thermal metamorphism.

Prior to the regional alteration a pelitic facies of the Moine sediments suffered metamorphism of a purely thermal type in the vicinity of the granite. At a subsequent date the whole region was involved in fold movements with the production of crystalline schists. In this deformation the belt of rocks surrounding the granite yielded in such a way that belts of the hornfels zone moved *en masse* and are preserved amidst rocks which are now typical crystalline schists, and all stages of transition between genuine hornfelses and typical mica-schists can be traced in the field.

The hornfels zone is particularly well preserved in the vicinity of Kildermorie Lodge and south-east of Glencalvie Lodge. The character of these hornfelses has been described in detail in the Survey Memoir. Though highly metamorphosed they show the original lamination and consist of alternating bands of siliceous and argillaceous composition. One of the most striking mineralogical features of the pelitic members is the presence of abundant garnet. Where they are least affected by the second metamorphism the hornfelses are constituted of quartz, orthoclase (variable), biotite, muscovite (variable), and garnet, to which may be added acid plagioclase (oligoclase and albite), iron-ores, and graphite.

The widespread occurrence of garnet in the hornfels zone merits further inquiry into its nature. The garnet from a typical hornfels was therefore isolated and a determination of ferrous and manganous oxide made. The results, FeO 32·40 %, MnO 0·72 % (almandine 74·7,

[1] Mem. Geol. Surv. Scotland, 1912, Explanation of sheet 93.

spessartine 1·7), make clear that the mineral is essentially an almandine. The occurrence therefore belongs to the rare type in which a thermal aureole carries an almandine- rather than a spessartine-rich type of garnet.

Amongst the thermal products recorded by the Survey officers none is more striking than the chiastolite of the hornfelses of Carn Loch nan Amhaichean. In these hornfelses outlines of original chiastolite crystals occur, but all chiastolite substance has disappeared, the core of the pseudomorphs being filled with divergent fibres of kyanite, whilst the periphery is occupied by sericite (fig. 1).

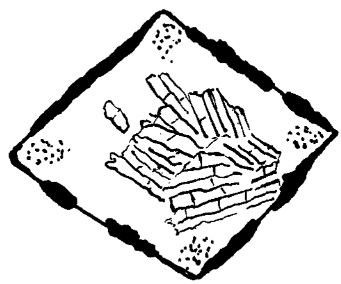

FIG. 1. Kyanite fibres surrounded by sericite forming a pseudomorph after chiastolite. × 120 diameters.

It seems clear that chiastolite has been a not infrequent constituent of the hornfelses, but is represented now only by the pseudomorphs just referred to, or by ovoid areas of sericite where the rocks have suffered visible deformation.

A suite of rocks collected from the hornfels zone north of Kildermorie Lodge has revealed a further more extensive development of kyanite in these hornfelses. From an examination of a series of rocks within the zone kyanite can now be recorded in the following associations:

1. Replacing chiastolite crystals.
2. Replacing cordierite, being then accompanied by biotite.
3. As swarms of fine needles associated with biotite in the more argillaceous bands.
4. As a constituent in coarser-grained crystals of quartz-kyanite venules cutting the banding of the hornfelses.
5. In quartzose areas immediately adjacent to garnet porphyroblasts.

The first method of development has been discussed in detail in the Survey Memoir. No original cordierite has been with certainty recognized in the aureole, but pseudomorphs have been recognized. It seems probable, however, from the petrographical character of the aureole rocks—the abundance of chiastolite—that it was once an important constituent. The typical xenoblastic character and sieve texture of hornfels cordierite render its recognition—when replaced by other minerals—less certain than is the case with idioblastic chiastolite pseudomorphs.

Nevertheless, as remarked above, its former presence is revealed in pseudomorphs in rocks preserving a typical hornfels texture. These pseudomorphs are now composed of bundles of fine needles of kyanite set in a base of muscovite and biotite. The original cordi-

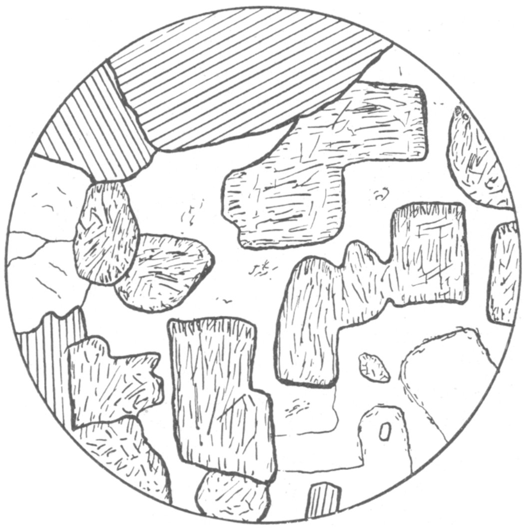

FIG. 2. Biotite-hornfels, Carn Chuinneag, showing biotite, quartz, acid plagioclase, and pseudomorphs of kyanite, biotite, and muscovite after cordierite. Kyanite is abundant in the pseudomorphs and forms fibres fringing the felspar grains. × 100 diameters.

erite crystals were subidioblastic and were associated with quartz, alkali-felspar, and biotite (fig. 2). The needles of kyanite do not exceed 0·05 mm. in length and are identified by isolation after treating the rock powder with cold hydrofluoric acid.

In addition to this manner of occurrence kyanite occurs as swarms of fine needles in bands associated with biotite and muscovite. They are thus specially confined to the argillaceous laminae of the original sediment. In some cases little remains to suggest how these kyanite swarms have arisen, but in others the arrangement is suggestive of replacement of xenoblastic cordierite.

A most striking case of the occurrence of kyanite in these rocks is the development of larger crystals of kyanite ($\frac{1}{2}$ mm. in length) associated with quartz—in some cases biotite—in venules which typically cut across the banding of the hornfelses (fig. 3). These quartz-kyanite veins are characteristic of the hornfelses which contain kyanite also in the groundmass of the rock in the form of fine needles. Crystals of kyanite of comparable size are elsewhere found only in the imme-

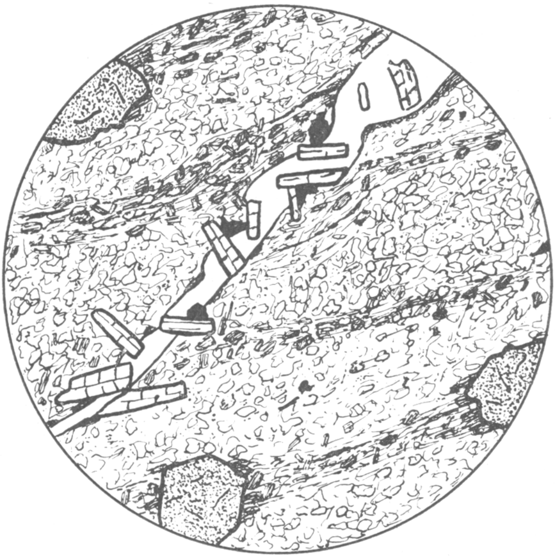

FIG. 3. Quartz-kyanite vein crossing the banding of a garnetiferous hornfels. Kyanite is also developed as fine needles associated with biotite in the argillaceous laminae which alternate with siliceous bands. × 30 diameters.

diate vicinity of garnet porphyroblasts, more particularly those which possess a quartzose environment.

All the rocks bearing kyanite in the associations already described belong to the hornfels zone proper. Texturally they preserve the straight bedding of the original sediment whence they were derived.

The transformations incident on the second metamorphism have been described in detail in the Survey Memoir, but it will be convenient to make reference to some of these changes in discussing the problem of the kyanite development. The production of abundant white mica at the expense of alkali-felspar, the development of a schistose texture with orientated mica plates, and a fine-scale folding of the laminae often with a resultant loss of the banding so prominent in the hornfels zone are the successive changes the hornfelses experience in their transition to mica-schists. Typical crystalline schists made up of quartz, muscovite, biotite, and garnet are thus produced. At an early stage in this conversion all traces of kyanite disappear, the mineral being presumably used up in the manufacture of muscovite. Kyanite is not recorded in the schists outside the hornfels zone.

Kyanite is found in the hornfels zone in rocks in which a minimum amount of sericitization has taken place, but it is also characteristic of those rocks in which muscovite development is considerable. In all cases the banding—where present originally—is well preserved. None of the rocks examined contain sillimanite, the fine needles appearing like sillimanite proving on isolation with hydrofluoric acid to be kyanite.

The manner of development of kyanite in the hornfelses having now been presented, the important problem of the genesis of this mineral remains for consideration. The principal points of interest lie (1) in the development of kyanite in rocks still preserving much of their original character as hornfelses, (2) the disappearance of kyanite when the hornfelses pass out into the schistose zone.

That kyanite cannot be considered a primary mineral of the hornfelses is, I think, clearly evident from its occurrence replacing chiastolite and cordierite. On the other hand, the imposition of regional metamorphism sufficient to induce noteworthy textural changes in the hornfelses leads to its disappearance. Outside the aureole the Moine sediments made over into crystalline schists do not appear to have reached the kyanite grade of metamorphism. Kyanite, in other words, has only a *temporary status in the regional* metamorphism.

The available evidence appears to warrant the belief that kyanite has arisen under the imposition of stress, in the first place under conditions which have been unaccompanied by visible deformation of the rock, for the textures of the hornfelses are frequently preserved, but the kyanite persists through the initial stages in the development of orientated flakes of sericite—one of the first signs of visible textural change. The development of the kyanite-biotite swarms is also in some cases one of a directional kind with a definite orientation oblique to the banding—indicative of crystallization under the imposition of stress.

The quartz-kyanite veins cutting the banding of the hornfelses represent a special case of metamorphic differentiation; probably quartz and kyanite represent material segregated from the groundmass of the rock. That migration of kyanite substance in addition to silica is involved seems to be demanded by the occurrence of kyanite in the veins opposite siliceous bands and not confined to the proximity of argillaceous layers where fine needles of kyanite are commonly present. The kyanites have, however, no constant orientation in the veins.

Can the kyanite be considered as developed under the incidence of stress while the aureole was still hot? If this were so the zone of sheared hornfelses developed between the granite and the hornfels zone might be expected to carry kyanite, but these rocks are transformed into crystalline schists without kyanite resembling those outside the aureole.

I believe the most reasonable explanation is to be found in the mineralogical constitution of the rocks upon which dynamic metamorphism was imposed. The kyanite production depended upon the prior presence of andalusite and cordierite, and kyanite itself represents but a temporary intermediate stage in the production of crystalline schists free from kyanite.

Kyanite remains one of the few minerals which still merit description as 'stress minerals'. Without denying the possibility that kyanite might be generated without the incidence of stress, yet it is to be noted that the development of this mineral at a definite stage in regions of progressive regional metamorphism appears to demand not only the appropriate conditions of temperature but also of shearing stress. If this were not so it is strange that kyanite has never been recorded as a product of simple thermal metamorphism.

As regards the occurrence of quartz-kyanite veins, which have sometimes been used in argument against the concept of kyanite as a stress mineral, it is to be remembered that in these cases the veins occur in typical stress rocks—crystalline schists which usually carry kyanite in the groundmass from which, no doubt, the kyanite of the veins is segregated. In the case already discussed, though the quartz-kyanite veins occur in 'hornfelses' these rocks themselves give clear evidence of the incidence of stress.

The occurrence of kyanite at Carn Chuinneag is thus not in conflict with the prevalent concept of this mineral as a stress mineral, though it presents the unusual feature of kyanite arising as a transient mineral phase in the manufacture of crystalline schists.
