On quartz-kyanite-rocks in Unst, Shetland Islands, and their bearing on metamorphic differentiation.

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AMONG the many beautiful rocks of Unst, the most northerly of the Shetlands, is one composed of rosettes of pale blue kyanite set in a base of glassy quartz. This rock was mentioned by Heddle,[1] but has never been described, nor have its genetic relationships been considered. During the mapping of Unst for the Geological Survey, opportunity was afforded of examining the field-relations of these quartz-kyanite-rocks and of collecting adequate material for study. I am indebted to Sir John Flett, F.R.S., Director of the Survey, for permission to present this account. These rocks have a considerable intrinsic interest; in addition, their investigation is closely concerned with certain general problems in metamorphism, especially those connected with metamorphic differentiation. The present paper is therefore divided into two portions, the first dealing with the description and origin of the Unst rocks, and the second with more general aspects.

I. *Quartz-kyanite-rocks of Unst.*

The Country-rocks.—The north-eastern part of Unst is composed of chloritoid-kyanite-schists. These form the hills of Housi Field, Sothers Fields, Ward of Norwick, and Saxa Vord; from the last, the highest hill in the island, they take their name.[2] The Saxa Vord Group is well exposed in sea-cliffs which, though often hundreds of feet high, are for the most part readily accessible, and inland exposures are fairly numerous. The lithological composition and variations of the group are therefore quite well known, a circumstance of importance in what follows.

[1] M. F. Heddle, The county geognosy and mineralogy of Scotland. Min. Mag., 1879, vol. 2, p. 19; and The mineralogy of Scotland, 1901, vol. 2, p. 60.
[2] Summ. Prog. Geol. Surv. Great Britain for 1930, 1931, part 1, pp. 65, 66, 68.

By far the dominant rock-type is a greenish-grey schist. In slice (fig. 1) these schists, as developed on Saxa Vord itself, are found to be composed of kyanite, chloritoid, muscovite, quartz, and iron-ore, with chlorite in some examples and relics of staurolite and garnet in most. Kyanite builds prismatic crystals; swarms of small crystals are often seen in knots of micaceous material. Chloritoid occurs as

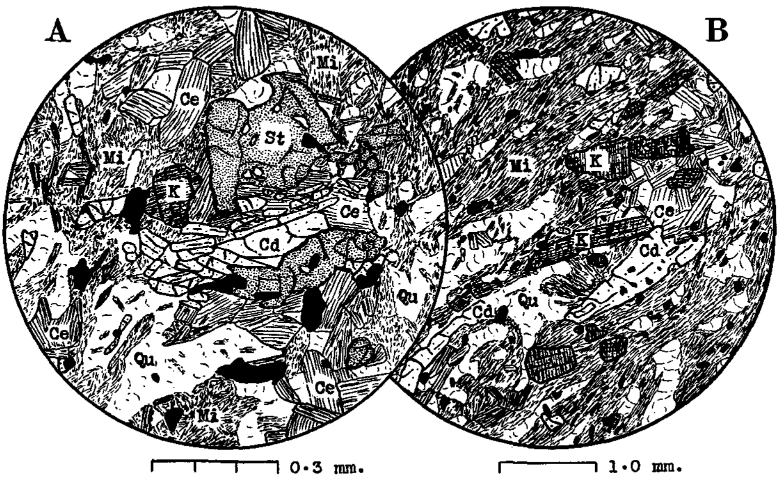

FIG. 1. Argillaceous rocks of the Saxa Vord Group.
A. Summit of Saxa Vord. B. Ritten Hamar, North Coast, Unst.
Cd = chloritoid, Ce = chlorite, K = kyanite, Mi = muscovite,
Qu = quartz, St = staurolite, solid black = iron-ore.

unoriented laths of normal characters. The ground-web consists of quartz grains and tiny colourless mica plates, these latter giving the schistosity directions. Iron-ore occurs as large subhedral grains. Staurolite forms irregular porphyroblasts sieved with quartz and ore pellets; with it chloritoid and rarely kyanite are associated in a fashion suggesting that they have arisen by destruction of the staurolite. Garnet is rare in the slices of these argillaceous schists, but in certain more quartzose types it is fairly common in spongy masses passing over into chlorite. Chlorite is absent in many of the chloritoid-kyanite-schists, but in certain examples it is abundant, appearing then to replace the chloritoid; such chloritic rocks show a lenticular sheared structure. It is suggested, therefore, that the metamorphic history of the Saxa Vord Group is complex; a development of staurolite and garnet has been followed by a phase of destruction of these minerals to give a chloritoid-kyanite assemblage and this is followed by conditions causing the formation of chlorite from the chloritoid.

The Quartz-kyanite-rocks.—The quartz-kyanite-rocks that are the subject of this paper occur as vein-like bodies in the kyanite-chloritoid-schist. Such veins may be observed at several localities, as, for example, in the Dale Burn where it is crossed by the road to the gun emplacement on Saxa Vord, in the saddle between Sothers Fields and Ward of Norwick, and in the upper part of the Burn of Skaw. Most of these veins are seen to lie along the schistosity planes, but transgressive veins have been noted. The veins observed in place have a maximum width of a foot or so, but blocks of exactly similar material reach an enormous size; some are estimated to contain at least thirty cubic yards. Hundreds of these blocks are scattered over the eastern slopes of Housi Field and Sothers Fields, the more prominent receiving names, such as the White Stane of Housi Field, the White Haggle, and so on. The quartz-kyanite-rocks thus form vein-like masses, often exceeding several yards in thickness, in the Saxa Vord kyanite-chloritoid-schists.

Two main varieties of these masses may be distinguished. In the first type, they are simple, uniform in composition, and vein-like. In the second, they form complexes with the country-rock, this occurring as flakes or irregular masses enclosed within the quartz-kyanite-rocks. At the margins of these irregular bodies, the country-rock is intimately mixed with patches of quartz-kyanite-rock. No hard and fast line can be drawn between the two types of masses and no genetic significance can be attached to this distinction.

The components of these rocks are quartz as almost glassy grains of large size, and kyanite as rosettes of pale blue crystals that reach a maximum length of two inches. Under the microscope the quartz grains are seen to have somewhat sutured margins and often show undulose extinction. In crushed fragments the kyanite exhibits normal characters. A few small flakes of muscovite are found in some specimens.

The arrangement of the kyanite in the masses and the positions of the country-rock cheeks and flakes are shown in figs. 2 and 3. The kyanite rosettes are confined to the margins of the veins or are based upon included pieces of country-rock.

Rocks immediately associated with the Quartz-kyanite-rocks.—The rocks intimately associated with the quartz-kyanite-rocks either as included flakes, selvages to the veins, or as parts of the vein-complexes differ from the normal schist of the Saxa Vord Group in several particulars. They are coarser, much richer in kyanite, and usually wholly free from quartz (fig. 4). Their main component is kyanite; in some examples the rocks are entirely kyanite except for a few tiny patches of chlorite, sericite, and iron-ore. The kyanite here forms large interlaced or subradiate blades between which occur

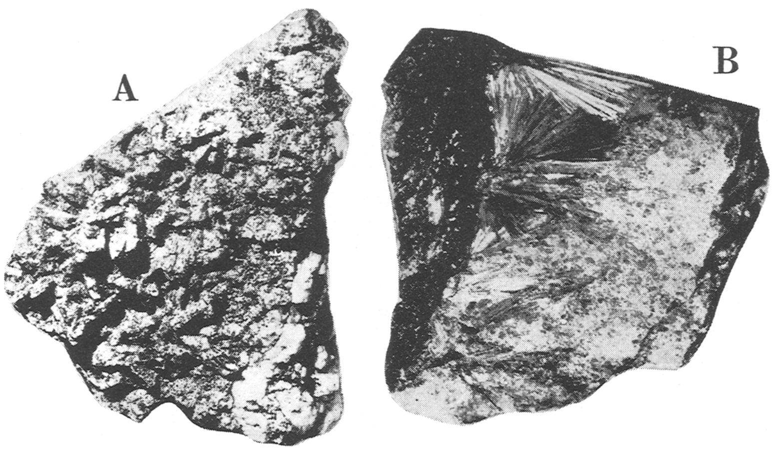

FIG. 2. Quartz-kyanite-rocks, Unst.
A. Kyanite crystals, average length ½ inch, on the selvage to a quartz mass seen at lower right-hand corner.
B. Kyanite rosettes, greatest length 1¼ inch, projecting into quartz (on right), and based upon quartz-free country-rock (on left).

the subordinate components. A common type of rock associated with the quartz-kyanite-rocks is formed of large blades of kyanite set in a base of large chlorite sheaves, or of tiny ripidolitic chlorite. Allied to these are rocks in which is present in addition a small amount of muscovite as flakes. Chloritoid enters into some of these rocks but is always subordinate in amount to the kyanite. Black iron-ore is abundant in most examples, most often as clots or veins in the chlorite; more rarely it forms grains enclosed within the kyanite. Quartz is usually absent; in a few examples it forms patches of grains into which project kyanite blades, such patches forming, in effect, minute quartz-kyanite-rocks.

The difference in mineral composition between the normal country-rock and that associated with the quartz-kyanite-rocks is brought out by the results of micrometric measurements of typical rocks of both groups given in the table (p. 322).

In estimating the silica and alumina percentages of these rocks, the compositions of the minerals present have been somewhat arbitrarily chosen as follows:—for kyanite and muscovite, the theoretical

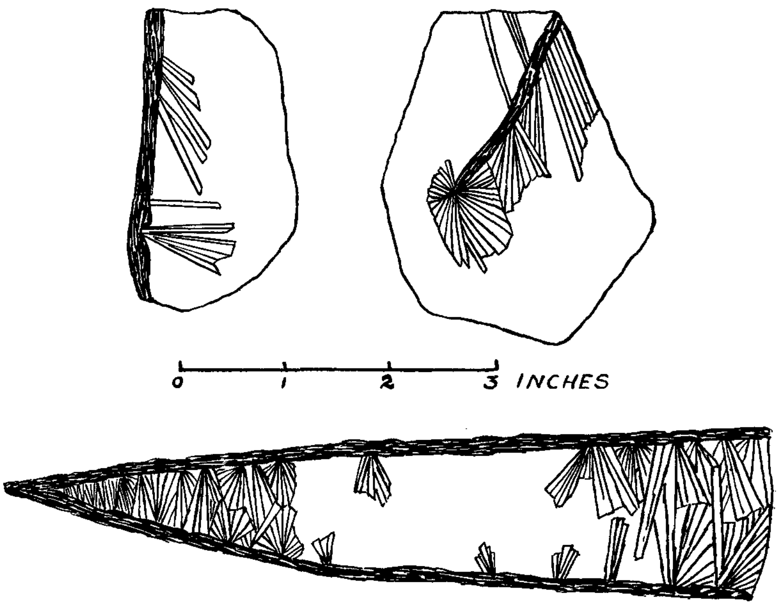

FIG. 3. Diagrammatic representation of the quartz-kyanite-rocks, showing kyanite rosettes, projecting into quartz, and based on selvages and flakes of quartz-free country-rock.

compositions; for chloritoid, Heddle's analysis[1] of the Vannlip Hillswick, Shetland, material; for staurolite, Rammelsberg's analysis[2] of St. Gotthard material; and for chlorite, von Hamm's analysis[3] of Zermatt material.

These estimates of silica and alumina can therefore be only approximately correct, but it is considered that the agreement among each group is sufficiently good to justify the view that the average

[1] M. F. Heddle, The mineralogy of Scotland, 1901, vol. 2, p. 123; and C. Hintze, Handbuch der Mineralogie, Leipzig, 1897, &c., Bd. 2, analysis XX, p. 677.

[2] C. Hintze, loc. cit., analysis VIII, p. 429.

[3] C. Hintze, loc. cit., analysis XLVI, p. 729.

figures give the correct order of the differences between the two groups. An analysis of a chloritoid-staurolite-schist from the summit of Saxa Vord, made by Mr. B. E. Dixon of H. M. Geological Survey, in connexion with the present writer's Survey work in Unst, shows silica 50·88 % and alumina 31·89 %. The differences between these figures and the average values for the Saxa Vord rocks given in the table below are most likely due to the arbitrary selection of the compositions of the minerals employed in the calculations, and to the difficulty of estimating correctly the quartz in the fine quartz-muscovite aggregate. It is of course possible that the compositions of the phases in the two groups are different, but such a variation cannot be sufficient to invalidate the general conclusion that the rocks intimately associated with the quartz-kyanite-rocks are much poorer in silica and richer in alumina than the normal argillaceous country-rocks of the Saxa Vord Group. These differences are held, as immediately explained, to be of genetic significance.

	Quartz.	Kyanite.	Chloritoid.	Chlorite.	Staurolite.	Muscovite.	Iron-ore.	SiO_2.	Al_2O_3.
Argillaceous rocks of the Saxa Vord Group.	17·0	1·9	9·4	18·4	15·3	30·7	7·3	44·6	27·2
	16·4	11·0	8·1	9·3	—	47·8	7·7	47·2	29·8
	13·7	2·8	5·6	—	6·2	65·6	6·1	47·6	32·6
	12·5	8·2	1·8	2·5	4·2	67·4	3·4	48·3	34·2
	11·2	5·6	5·2	1·9	—	73·6	2·5	48·5	34·2
							Average	47·2	31·6
Rocks associated with the quartz-kyanite-rocks.	—	73·1	—	20·5	—	—	6·4	34·0	48·6
	—	77·0	—	15·1	—	—	7·9	33·6	50·4
	—	66·5	10·7	—	—	—	22·8	27·2	46·3
	—	44·4	25·4	—	—	28·0	2·1	35·2	49·3
	—	72·6	—	9·3	—	18·1	—	38·1	54·0
	—	69·9	—	5·3	—	23·2	1·5	38·2	53·6
							Average	34·4	50·3

Origin of the Quartz-kyanite-rocks.—In many localities the quartz-kyanite-rocks have a habit like that of true veins. Their origin from igneous or external sources may be considered. It may be suggested that they are quartz veins of igneous origin that have either brought the components of kyanite in with them, or have taken up kyanite material from the vein walls. The habit of the kyanite shows that this mineral is not xenocrystic in the surrounding quartz, and it must be admitted that the quartz and kyanite are of contemporaneous formation. The known conditions of formation of kyanite in nature render it extremely unlikely that any solution such as an introduced magmatic entity was ever in existence, for it is difficult to conceive the action of stress upon introduced fluid bodies of the requisite size. Further, minerals of known end-stage pyrogenic origin, other than quartz, are absent from the quartz-

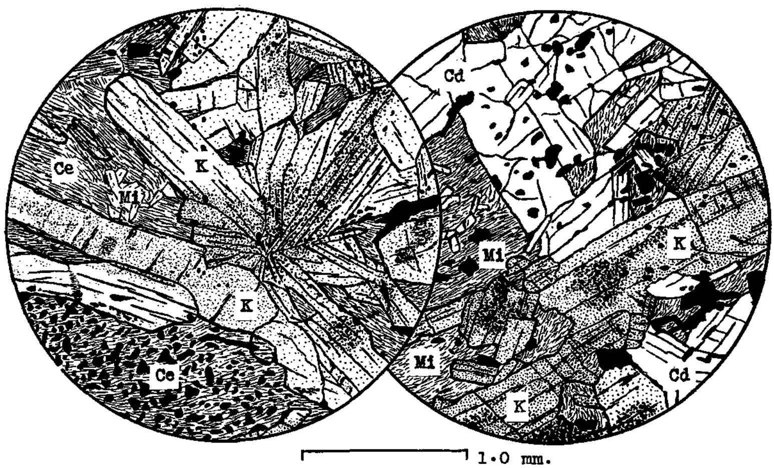

FIG. 4. Alumina-rich rocks intimately associated with the Unst quartz-kyanite-rocks. Housi Field, Unst. Cd = chloritoid, Ce = chlorite, K = kyanite, Mi = muscovite, solid black = iron-ore.

kyanite masses, and no evidence of igneous activity is forthcoming from this area of the Saxa Vord Group. It is concluded, therefore, that these quartz-kyanite veins are not of igneous origin, a conclusion which is greatly strengthened by certain general considerations given later.

The second origin that may be suggested is that these quartz-kyanite-rocks and the associated alumina-rich selvages have original sedimentary compositions which have been unaltered during metamorphism. Against this view may be urged the habit of the quartz-kyanite-rocks, their complexes with the associated rocks, and the abnormal composition of the assemblage considered as sediments.

The origin of these rocks advanced by the writer is a metamorphic one, namely, that they have been formed by a process of endogenous secretion during the period of metamorphism. That this is the most reasonable interpretation is indicated by a comparison of the normal argillaceous member of the Saxa Vord Group and the rocks intimately associated with the quartz-kyanite-rocks. We find the remarkable fact that the country-rock immediately adjacent to the quartz-kyanite-rocks is much richer in alumina than the normal country-rock of the district, or, put another way, shows an impoverishment in silica. The material of the quartz-kyanite veins represents the difference in composition between the normal country-rock and that associated with the veins.

The process considered to have operated is somewhat as follows. The fairly homogeneous country-rocks on being metamorphosed were converted into the usual quartz-bearing schists of the Saxa Vord Group. In certain localities, however, there took place concentrations of silica which had been excreted from the surrounding rocks, leaving these poorer in silica. Thus quartz bodies were formed in quartz-poor rocks. This separation is not quite clean, for from the silica-poor cheeks of the quartz masses and from the included flakes of silica-poor rocks, there were formed *pari passu* with the quartz those large rosettes of kyanite which render these rocks so striking. That there was ever in existence a body of quartz-kyanite 'magma' comparable in size with the quartz-kyanite-rocks as now found is extremely unlikely; these rocks grew by the gradual addition of quartz to already deposited quartz, so that only a small amount of solvent was in action at any one time. This solvent was most likely water which may well have been derived from the rock undergoing metamorphism.

It is concluded, therefore, that these quartz-kyanite-rocks were formed by a process of endogenous secretion during metamorphism, and that their complementary portion is indicated by the silica-poor country-rock immediately adjacent to them.

II. *Some General Remarks on Metamorphic Differentiation.*

Opinion on the possibility and scope of movement of material during metamorphism is extremely varied. On the one hand, there is the view that such movements are small and special. Harker[1] says 'Diffusion of dissolved material . . . is . . . restricted within very narrow limits' and again, 'phenomena indicative of segregation,

[1] A. Harker, Presidential address, Quart. Journ. Geol. Soc. London, 1919, vol. 74, p. lxx.

such as garnet-lenticles and streaks of quartz sillimanitisé, are found only in the highest temperature-grade of metamorphism'. At the other extreme stands Holmquist,[1] who would interpret migmatitic and vein-complexes as due to endogenous segregation during regional metamorphism; the presence of an igneous rock here merely intensifies the process.

In his account of the metamorphic rocks of Adelie Land, F. L. Stillwell[2] had given in 1918 a general discussion of movement of material in metamorphism, and introduced the term 'metamorphic differentiation' to denote the migration and segregation of material under metamorphic conditions. Stillwell laid great importance on solid diffusion as a process in metamorphism, the action of solvents being, in his opinion, only of minor account. Few petrologists familiar with metamorphic rocks would, I believe, agree with this view. P. Eskola[3] has recently discussed the principles of metamorphic differentiation, and has advanced a classification of metamorphic changes of composition. This classification is as follows:—

(1) Differentiation within a rock mass, due to
  (*a*) the growth of crystals or aggregates of crystals (the concretion principle),
  (*b*) the concentration of the least soluble substances (the principle of enrichment in the stablest constituents), or
  (*c*) the extraction and redeposition of the most soluble substances (the solution principle).

(2) Transfer of substances into and from a rock mass, effecting
  (*a*) addition,
  (*b*) metasomatism, or
  (*c*) extraction of substances.

The Unst rocks just described illustrate very clearly class 1 of Eskola's classification.

It is the purpose of the present writer now to discuss one aspect of metamorphic differentiation, that concerned with the development of quartz masses in metamorphosed argillaceous rocks. The occurrence of innumerable stringers, irregular stripes and even vein-like bodies of quartz in pelitic rocks is familiar to everyone who has

[1] P. J. Holmquist, Typen und Nomenklatur der Adergesteine. Geol. För. Förh. Stockholm, 1921, vol. 43, p. 612.

[2] F. L. Stillwell, The metamorphic rocks of Adelie Land. Australian Antarctic Expedition, 1918, vol. 3, pt. 1, pp. 12, 62, 200.

[3] P. Eskola, On the principles of metamorphic differentiation. Compt. Rend. Soc. Géol. Finlande, 1932, no. 5, p. 68; Bull. Comm. Géol. Finlande, 1932, no. 97, p. 68.

dealt with the rocks of metamorphic regions. The pelitic rocks of the Dalradian Highlands of Scotland, for example, such as the garnetiferous mica-schist of Perthshire, the Cowhythe gneiss of Banffshire and many others, are filled with such quartz masses. What is in the writer's opinion a very good example of the secretion of quartz on metamorphism is seen on the shore of Lake Nasijarvi, near Tammerfors in Finland; the Bottnian pelitic sediments show a development of quartz strings as soon as they attain even a low grade of metamorphism; it seems more reasonable to regard these quartz masses as excreted from the phyllites than as of igneous origin. Edward Greenly's great 'Geology of Anglesey' (1919) contains many references to venous quartz in the schists of that island. Greenly sees no reason to believe that the quartz material was introduced from without, but regards it as a product of the metamorphism (op. cit., p. 69). Since in such veins the quartz is always in excess over any other mineral, he points out that the country-rock must have been more siliceous, taken as a whole, than it is to-day (op. cit., p. 48). Here is a very clear recognition of the main principles of metamorphic differentiation.

On account of this excretion of quartz on metamorphism, it follows that analyses of pelitic schists containing quartz stringers do not represent the compositions of the original sediments from which such rocks are derived, but give too low a proportion of silica. The rocks from Unst described in this paper furnish an extreme case of this impoverishment in silica with the production of rocks rich in alumina. The possibility of the operation of metamorphic differentiation of this kind must be kept in mind in the making of averages of the composition of pelitic schists, in comparing analyses of such rocks, and in the use of specific analyses of pelitic country-rocks for the discussion of such matters as transfer in injection-complexes and at cross-cutting or xenolithic contacts.

A short and incomplete survey of the accounts of quartz-veining in metamorphic rocks shows very clearly the correspondence between the mineral content of the quartz veins and that of the country-rocks, and supplies additional examples of marginal enrichment in certain components. This correspondence indicates that such quartz-veinings belong to the metamorphic epoch, and to my mind illustrate the principles of metamorphic differentiation. The examples now given are arranged in some kind of order of increasing grade of the country-rocks.

Hans Breddin[1] has described quartz veins occurring in the lowly-metamorphosed sediments of the Middle Rhine which contain the minerals of the country-rocks and no others; chlorite is found in chlorite-bearing rocks, calcite in carbonate-bearing rocks. The veins are confined to sheared belts and especially to areas of argillaceous rocks. In the chlorite-sericite-phyllites of the Muness group of Unst there are found very large and abundant quartz veins; these veins often show large chlorites at their margins.[2] In the Anglesey schists, E. Greenly[3] has noted the formation of quartz lenticles containing the minerals of the country-rocks, such as chlorite, albite, or carbonates, at many localities. Holmquist[4] has grouped such veins as these as low-temperature phenomena and holds that at higher temperatures there arise the quartz-felspar veins of the veined gneisses or injection-complexes.

Eskola[5] has described and figured an example of the concentration of staurolite at the margins of quartz veins in mica-schist from Karelia. This case seems exactly similar to the Unst kyanite concentration, and I would suggest that the process of formation is the same, namely, an impoverishment of the marginal zone in silica, rather than a migration of staurolite or kyanite components through the rock.

The occurrence of the aluminium silicates in veins or masses of quartz is instructive. In the Correen Hills, Aberdeenshire, Heddle[6] records andalusite 'in the flagstone quarries of the Correen Hills, rarely, in pink and grey crystals in the quartz veins which cut the slate, and associated with mica. . . . Commonly in greyish-blue crystals dispersed throughout the slate'. The country-rock of the district is the andalusite-schist that covers so great an area in north-east Scotland. With regard to kyanite there are the Unst occurrences described in this paper. To these may be added various

[1] H. Breddin, Die Milchquarzgänge des rheinischen Schiefergebirges, eine Nebenerscheinung der Druckschieferung. Geol. Rund., 1930, vol. 21, pp. 367–388.

[2] Summ. Prog. Geol. Surv. Great Britain for 1930, 1931, part 1, pp. 68–69.

[3] E. Greenly, The geology of Anglesey. Mem. Geol. Surv., 1919, vol. 1, pp. 46, 48, 68, 81.

[4] P. J. Holmquist, loc. cit., 1921, p. 627.

[5] P. Eskola, Conditions during the earliest geological times as indicated by the Archean rocks. Ann. Acad. Sci. Fennicae, Ser. A, 1932, vol. 36, no. 4, pp. 58–59.

[6] M. F. Heddle, The mineralogy of Scotland, 1901, vol. 2, p. 59.

records by Heddle[1] of kyanite-bearing quartz veins, nodules or 'concretions' in kyanite-bearing country-rocks. For sillimanite, the best examples are supplied by faserkiesel knots in sillimanite-gneisses. The present writer cannot support the view put forward by K. Hinterlechner[2] and L. Rüger[3] that faserkiesel nodules are metamorphosed clay-galls.

This brief survey shows the correspondence between the accessory minerals of the quartz veins and masses and those occurring in the country-rocks. Such a correspondence can hardly be accounted for if these quartz masses are unconnected with the metamorphic processes, which for the lower grades at least must be only very distantly related to igneous intrusion. The writer is not sufficiently well acquainted with the literature on ore-bearing quartz veins to be able from the data there assembled to test the views set out in this paper.

It seems likely, therefore, that some measure of metamorphic differentiation can take place in all grades of metamorphism. It is an interesting task for students of metamorphism to inquire into the scale of this differentiation, its modes of action, and especially into certain appearances of selectivity, both with regard to rocks and minerals, that are obvious in the field.

[1] M. F. Heddle, op. cit., pp. 61–62.

[2] K. Hinterlechner, Geologische Verhältnisse im Gebiete des Kartenblattes Deutschbrod. Jahrb. Geol. Reichsanst., Wien, 1907, vol. 57, p. 339.

[3] L. Rüger, Über 'Faserkieselknollen' (Sillimanitquarzite) aus den Biotitgneisen des Mt. Arbino (Tessin) und ihre Deutung als Gerölle. Centralbl. Min., Abt. B, 1931, pp. 488–492.