The Garnets and streaky rocks of the English Lake District.

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THERE exists in the Lake District a peculiar type of metamorphism of which no analogue has, as far as the writer is aware, been described elsewhere, with the exception, perhaps, of South America. It is indicated chiefly by the presence of garnets and 'streaks', the former being found indifferently in every variety of igneous rock of the district, the latter being mainly confined to the rhyolites or quartz-keratophyres. The most similar known to the writer is at Oyacachi in Ecuador, whence vom Rath [1] has described flow-brecciated soda-rhyolites which sometimes contain red garnets. He also refers to rocks which may be 'streaky'.

The presence of garnets in the Lake District volcanic rocks has long been known. Otley [2] recorded several localities. J. C. Ward [3] frequently referred to them, and regarded them as undoubtedly metamorphic. Sorby,[4] however, considered them original, but, later, W. M. Hutchings [5] suggested a secondary origin for minute garnets which he found in the Lake District slates. Dr. Marr [6] supported Sorby's view. But in the discussion on a posthumous (and unfinished) paper by E. E. Walker,[7] who, though not very definitely, suggested originality, Mr. Harker expressed the opinion that the garnets were of metamorphic derivation. The 'streaks' were noted by Ward,[8] who supposed them to be relics of

[1] G. vom Rath, Zeits. Deutsch. Geol. Gesell., 1875, vol. xxvii, pp. 341–342.

[2] J. Otley, 'A concise description of the English Lakes.' 6th edit., 1837.

[3] J. C. Ward, Quart. Journ. Geol. Soc., 1875, vol. xxxi, p. 599.

[4] H. C. Sorby, ibid., 1880, vol. xxxvi, Proc., p. 75.

[5] W. M. Hutchings, Geol. Mag., 1892, p. 154; see also Quart. Journ. Geol. Soc., 1904, vol. lx, p. 105.

[6] J. E. Marr, Proc. Geol. Assoc., 1900, vol. xvi, p. 476.

[7] E. E. Walker, Quart. Journ. Geol. Soc., 1904, vol. lx, p. 70, discussion on p. 105.

[8] J. C. Ward, loc. cit., pp. 411–413.

bedding. He noticed the resemblance of the rocks to the Welsh felstones, and concluded that they were altered felsitic ashes. Dr. Marr seems first to have noticed the close association between the streaky and the garnetiferous rocks, and to have separated them off as a definite group. Walker, in the incomplete paper already referred to, came to the conclusion that there was a streaky garnetiferous series of contemporaneous igneous rocks; and Dr. Marr[1] in 1906, accepting this view, named it the Sty Head Group.

The investigation of these rocks by the writer has chiefly been carried out in the neighbourhood of Haweswater, though they have also been examined near the Duddon River and about Borrowdale; and, with the kind assistance of Mr. A. Harker, use has been made of the fine set of specimens collected by Walker and preserved in the Sedgwick Museum at Cambridge. In a paper recently read before the Geologists' Association[2] it was shown that the Sty Head Group had no real existence in the Haweswater area, but that it is made up of infolds of the rhyolitic lavas at the top of the Borrowdales with portions of neighbouring andesite and tuff; and less detailed observations about Borrowdale, Seathwaite, and Thirlmere tend to the same conclusion for other parts of the Lake District.

The distribution of the garnets is curiously capricious. Over considerable areas of the Borrowdale Volcanics they are quite unknown. For example, the district between Cawdale and Ullswater, the Duddon Estuary (where, however, one garnet, 1·5 mm. in diameter, was found in a pumice-tuff of the Harrath horizon near Arnaby), the south-eastern section between Grasmere and Shap, and Eycott Hill. In other places, as about Rosthwaite and on Kidsty Pike, they are fairly plentiful in several types of rock. They are known in soda-rhyolites and andesites, both effusive and intrusive, hypersthene-basalts, andesitic slates, rhyolitic pumice-tuff, coarse rhyolite-variolite tuff, quartz-porphyry, granophyre, mica-porphyrite, and granite. In all these rocks the garnets are usually associated with pyrites, the presence of which is a good indication of the probable occurrence of garnets. Stratigraphically, they have been observed in every horizon of the Borrowdale Series except the Mottled Tuffs;[3] and also in andesites between the Mottled Tuffs and the Middle

[1] J. E. Marr, Quart. Journ. Geol. Soc., 1906, vol. lxii, Presidential address.

[2] J. F. N. Green, Proc. Geol. Assoc., 1915, vol. xxvi, pp. 195-223.

[3] For these horizons, see J. F. N. Green, 'The Older Palaeozoic succession of the Duddon Estuary.' [London (Dulau & Co.), 1913.]

Tuffs; between the Middle Tuffs and the Harrath Tuffs; and between the Harrath Tuffs and the Rhyolites.

This sporadic distribution is equally well marked on a smaller scale. On Kidsty Pike the Rhyolites and Upper Andesites are garnetiferous; tracing the same horizons to Measand Beck, Haweswater, they are found to contain none. On a still less scale the discontinuity is even more striking. The same band of rock—the same flow-line even—is found to be full of garnets at one point, and a few yards away to contain none whatever. Hand specimens may be selected, one end of which is crowded with garnets, while the other shows none.

The same patchiness characterizes the 'streaks', though the changes are not so rapid. Streaky rhyolites frequently pass into ordinary varieties, both laterally and vertically.

It is hardly possible that the rhyolites, augite-andesites, basalts, and quartz-porphyries of the Lake District could all have developed almandines in this capricious manner by crystallization from the original magma; and it is therefore necessary to look for subsequent alteration for their causation.

It will be convenient to begin the discussion of the mode of alteration by a description of the garnets. They are often of irregular form when minute, but if larger than a millimetre in diameter are commonly good rhombic-dodecahedra, sometimes with small faces of the icositetrahedron added. Crystals 5 mm. in diameter are frequent and they have been noted twice that size. All have the deep claret-red colour of almandine, and the uniformity in depth of coloration points to some uniformity in composition.

No quantitative analysis appears to be on record. By the kindness of Mr. G. T. Holloway, to whom I am greatly indebted, such an analysis is now available. The garnets used come from a basic andesite forming the upper part of the Upper Andesites in Riggindale, on the slopes of Kidsty Pike.[1] It would appear from this analysis that the garnets are fairly pure almandine. Mr. Holloway writes:—

'The sample consisted of two lots of garnets which had been almost completely separated from the matrix. One lot weighed 20 grams and was composed of whole and broken, transparent to opaque red garnets resembling ordinary almandine, and from about ¼ inch to about 1/20 inch in size. The other lot weighed 7 grams and consisted of similar material, but smaller and

[1] The exact spot is in the middle of a bare rock-face, easily identifiable by sloping flow-lines, at a point 400 yards north of the folds.

less free from waste matter. The garnets were from about 1/20 inch to about 1/30 inch in diameter.

In each lot, the waste consisted mainly of films or adherent pieces of greyish-green rock matter. No titaniferous iron-ore was found. The garnets were slightly magnetic, i. e. were attracted only by a powerful electro-magnet.

An analysis on picked garnets (free from waste matter) from the coarser lot, gave the following results on the material dried at about 105° C.:—

Silica	35·90
Ferric oxide	6·12
Ferrous oxide	27·48
Alumina	20·20
Manganese oxide	3·84
Lime	1·42
Magnesia...	3·28
Titanic acid	1·53
Alkalis, &c., and loss	0·23
	100·00

The alumina result is the lowest of three determinations. As is usual in alumina determinations, it is probably slightly high, so that the figure given for alkalis, &c., is likely to be slightly lower than is correct.'

To account for the production of these garnets, it is natural first to suggest contact-alteration. The evidence is, however, opposed to such a view. When ordinary non-calcareous sediments undergo purely thermal alteration, garnet seems always to require a higher temperature than either the production of biotite or the re-crystallization of felspar. This is particularly evident in the enormous zones described by Mr. Barrow in the Highlands of Scotland. In igneous rocks the same rule may hold, except perhaps in the case of lavas quite fresh when heated, but the evidence is not so full. Only one garnet is recorded in the lavas near the Shap granite, and that in a vesicle. The Eskdale granite aureole appears only to contain them in the neighbourhood of garnetiferous rocks not otherwise metamorphosed. They are not recorded among the varied igneous rocks thermally altered in Skye. In the chief garnetiferous areas of the Lake District there is no intrusive mass to which the thermal production of garnets could reasonably be assigned; and the mineral is not accompanied by new biotite, re-crystallized felspar, or by the compact hornblende so common round the Eskdale granite. There cannot, then, have been any considerable rise of temperature.

Turning to dynamic action, lime-garnet is known as an element of 'saussurite', which has been ascribed to great pressure. But there is no evidence for strong dynamic action in the district. Crush-conglomerates and mylonites have not been met with (the supposed crush-rocks near

Haweswater are simply the basal or crustal flow-breccias of lavas);[1] garnetiferous intrusives are often hardly affected by cleavage; and where any crushing has taken place the garnets are themselves affected, a highly birefringent material of a sericitic appearance being produced. If isostatic pressure is invoked, it is difficult to understand how a pressure sufficient to produce large garnets could be so capriciously distributed. Further, dynamic alteration does not account for garnets with high iron content in rhyolites.

Garnets, however, are known, though rarely, which must have been formed at comparatively low temperature with the aid of circulating solutions, gaseous or liquid. The well-known occurrence of garnet and topaz in lithophyses of rhyolite at Nathrop, Colorado, is of this character.[2] C. H. Smyth[3] has recorded partial replacement of scapolite by garnet; Cornu[4] and Jeremejew[5] pseudomorphs of garnet after idocrase; Sustschinsky[6] after fassaite; Pelikan[7] after augite; Cathrein[8] after gehlenite. Garnet is also known replacing limestone.[9]

In none of these is the operation of a considerable degree of heat absolutely excluded, but it is otherwise with the description by Brögger of 'Umhüllungs- und Ausfüllungspseudomorphosen' of garnet and natrolite after sodalite.[10] An occurrence very similar to that just mentioned, but indicating even more clearly the comparatively low temperature of formation, has been described by Kretschmer[11] from the contact-zone of Gobitschau near Sternberg in Moravia. The garnets here are partly like almandine and partly like grossularia, and occur superimposed on natrolite as the latest product of hydrothermal activity.

Some positive evidence for the production of garnet by circulating solutions has been noted in the eastern Lake District, but the strongest witness is to be found among the series of specimens collected by the late E. E. Walker and deposited in the Sedgwick Museum at Cambridge.

1 See J. F. N. Green, Proc. Geol. Assoc., 1915, vol. xxvi, plate 17, fig. A.

2 Whitman Cross, Amer. Journ. Sci., 1886, ser. 3, vol. xxxi, p. 432.

3 C. H. Smyth, Amer. Journ. Sci., 1897, ser. 4, vol. iv, p. 312.

4 F. Cornu, Min. Petr. Mitt., 1905, vol. xxiv, p. 336.

5 P. W. Jeremejew, Abstract in Zeits. Kryst. Min., 1899, vol. xxxi, p. 505.

6 P. Sustschinsky, Zeits. Kryst. Min., 1903, vol. xxxvii, p. 68.

7 A. Pelikan, Sitz.-Ber. Deutsch. Natur.-Med. Ver. f. Böhmen, 'Lotos', 1899, vol. xlvii (N. F. xix), p. 342.

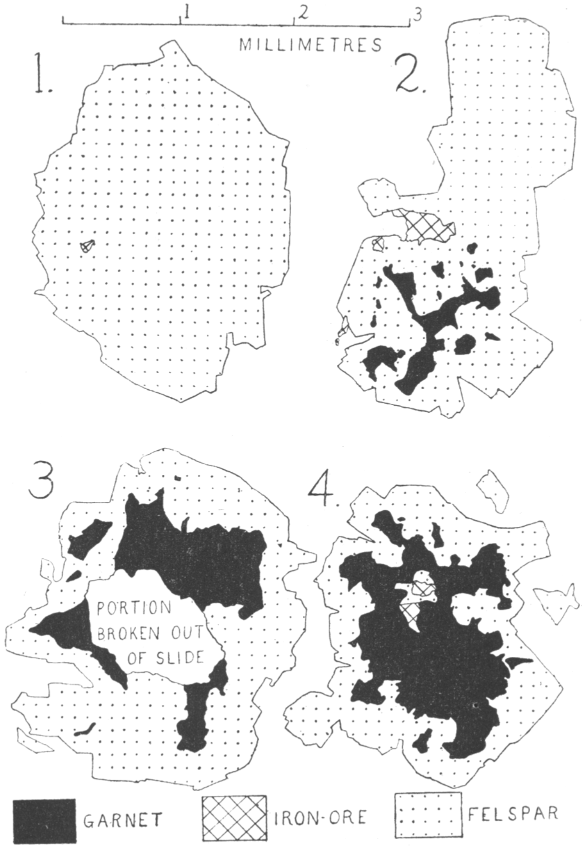
8 A. Cathrein, Min. Petr. Mitt., 1887, vol. viii, p. 412.

9 W. Lindgren, quoting S. F. Emmons, Trans. Amer. Inst. Min. Eng., 1901, vol. xxx (for 1900), p. 611.

10 W. C. Brögger, Zeits. Kryst. Min., 1890, vol. xvi, p. 165.

11 F. Kretschmer, Centralblatt Min., 1907, p. 299.

The smaller isolated bits of garnet are often found inside felspars, either porphyritic or in tuffs. The next stage is illustrated by such a specimen as that in fig. 2, where the garnet has replaced the centres



Felspar aggregates in Lake District rocks.

FIG. 1.—Arthur's Pike, Ullswater. FIG. 2.—Eagle Crag, Langstrath (3824).
FIG. 3.—Base Brown, Seathwaite (3819). FIG. 4.—Esk Hause (3834).
[The numbers are those of slides in the Sedgwick Museum collection.]
Decomposition products of felspar and garnet are included with those minerals in the drawings.

only of the individual crystals of a felspar aggregate. The latter is clearly an early stage in the formation of one of the numerous 'felspar-rings' described by Walker. But these rings show no resemblance of any kind to the kelyphite fringes or to the reaction borders[1] found round certain garnets elsewhere; on the contrary, they differ in no respect from the glomeroporphyritic felspars of the rest of the rock, which are often notably rounded in form, as in fig. 1, taken from a specimen collected some miles from the nearest recorded garnets; and the manner in which the garnet has worked its way along the centres of the components of the aggregate (no doubt owing to the higher basicity and consequent higher solubility of these centres) indicates that it is corroding pre-existing felspar, not the reverse. A further stage is illustrated by fig. 3, and also by Plate XIV, fig. 4, in Walker's paper.[2] The ring-like character of the unaltered felspar is seen in such a case as fig. 4, which also shows a portion of unreplaced felspar near the centre.

If on reaching the confines of the felspar, the alteration has any difficulty in attacking the surrounding matrix, a pseudomorph should result. This accounts for the case figured in Walker's Plate XIII, fig. 2. Here the rock is an acid granophyre with numerous phenocrysts of quartz and felspar set in a delicate micropegmatite matrix. The garnet appears to have had some difficulty in pushing into this matrix and accordingly garnet and isotropic 'viridite' have formed a pseudomorph after orthoclase, the outlines of which are well preserved.

But in the case of the lavas, the garnet seems to have had no difficulty in spreading into the groundmass, the composition of which probably differs little from that of felspar with a small admixture of magnetite. In such circumstances good crystal faces are usually exhibited by the part within the groundmass; and this may be due to the comparatively homogeneous character of this groundmass when compared to the felspar phenocrysts, which, besides the differences in physical properties in varying directions due to crystalline structure, show basicity decreasing from the centre, and twinning on several plans. All the larger garnets, however, whatever may be the material bounding them, and many of the smaller, show a tendency to good crystalline form. This tendency to perfect crystalline form is very striking in hand specimens from the eastern Lake District; as the garnets break out from the surrounding rock in beautiful rhombic-dodecahedra.

If, while growing, the garnet meets a phenocryst that is not easily decomposed, its growth will be arrested in that direction. Two of Walker's figures illustrate this point excellently. In Plate XIII, fig. 3, a garnet in the Armboth dyke shows good crystal faces except in the

[1] See T. H. Holland, Rec. Geol. Surv. India, 1896, vol. xxix, p. 21.
[2] E. E. Walker, loc. cit.

direction of two quartz phenocrysts, which are in contact with the garnet. The quartzes are the ordinary rudely rounded phenocrysts of the rock, and it is impossible to suppose with Walker that they are corroding the garnet. Still more striking is Plate XIII, fig. 1. The rock in this case is a porphyry with phenocrysts of felspar and biotite and glomeroporphyritic aggregates of felspar which enclose some of the biotite (and also apatite). The aggregate figured is partly replaced by garnet, and the progress of the change outwards from the centre has been arrested by the biotite crystals, which are consequently left at the bottom of 'embayments' in the contour of the garnet. (Compare the behaviour of the 'streaks' towards biotite.) Had the felspar and biotite been formed by alteration of the garnet, as Walker apparently believed, they would show some differences from the phenocrysts; but this is not the case.

Garnets, with peculiarities of distribution which recall those of the Lake District, occur near Bastogne in the Ardennes. The rocks show some contact-alteration, but the garnets have been ascribed by Miss Raisin,[1] following Professor Bonney,[2] to the action of hot springs. Another case of curiously sporadic distribution in slightly altered rocks is well known in the Isle of Man, and I have noted in one of the described Geological Survey slides (No. E2417) a garnet enclosing needles of blue schorl. This is suggestive, but the rocks are very different in character from those of the Lake District, and I hesitate to compare the two cases at present.

But there are two reasons against the suggested mode of formation which still require consideration. In the first place, the zoning and optical anomalies which have been considered diagnostic of pneumatolytic garnet are absent. It may, however, be observed (*a*) that such phenomena do not appear to have been described in almandines; and (*b*) that these Lake District pseudomorphs are hardly comparable with the garnets formed by pneumatolysis near large intrusions, such as those of the south-west of England.

Secondly, why have not similar cases been noted elsewhere? It is admitted that the Lake District rocks are of a highly exceptional type, and accordingly an exceptional causation may be postulated. It is suggested that this is to be found in hydrostatic pressure. Most garnets when fused break up into minerals of lower density, and it seems clear that high pressure is necessary for the production of the almandine

[1] C. A. Raisin, Quart. Journ. Geol. Soc., 1901, vol. lvii, p. 55.

[2] T. G. Bonney, Quart. Journ. Geol. Soc., 1890, vol. xlvi, p. 214.

molecule. Accordingly, the exceptional cause would be solfataric action under considerable pressure.

As early as 1875 J. C. Ward[1] referred the garnets in the tuffs (in which he included many rocks now known to be lavas) to the action of highly heated water connected with the formation of the Eskdale granite. Although the writer sees reason to regard the Eskdale granite as connected with the volcanic series,[2] the distribution of the garnets shows no particular relationship to that intrusion; though perhaps they have some preference for the neighbourhood of minor intrusions. The constant association of garnet and pyrites and the prevalence of pyrites in the garnetiferous districts suggest solfataric action.

Turning to the 'streaks', they are chiefly to be found in infolds of rhyolite. In the eastern area these consist of pale rocks, exhibiting in a manner which is irregular and discontinuous, but far more constant than the garnets, numerous dark parallel linear marks which, when best developed, contain macroscopic quartz or pyrites. These marks are sections of parallel lenses, the direction of which corresponds within the limits of observation with the bedding, and, in a general way, with the flow-surfaces.

The streaks are brought into relationship with the garnets, not only by their distribution, but by the occasional occurrence of the latter as a component of the former, which are in general obviously secondary infiltrations. In the following discussion I confine 'streaks' to such structures, and do not deal with the flow-structures[3] which have been included with them. Highly developed original flow-structures are found in parts of the Lake District, notably at the junction of rhyolite and andesite, where they often seem 'eutaxitic' in character. But these are not considered here.

In order to indicate the arrangement of these curious markings, I take as an example a hand-specimen from the Naddle Beck infold near Haweswater. The area of one face is 62 square cm. On this are about sixty well-marked streaks, at an average distance apart of 4 mm., and with an average length estimated at between 2 and 3 cm. Under a hand-lens most of the streaks show merely a discoloration; but in eleven there is a visible fissure including red-brown powdery stuff. In seven of these pyrites can be detected, and there are two nests of pyrites not clearly connected with streaks.

[1] J. C. Ward, Quart. Journ. Geol. Soc., 1875, vol. xxxi, p. 599.
[2] J. F. N. Green, Quart. Journ. Geol. Soc., 1909, vol. lxv, p. 79.
[3] See E. E. Walker, loc. cit., Plate XIV, fig. 2.

The streaks in this and in many other rocks in the area originate primarily as fine cracks, which, while preserving one general direction, are extremely irregular on a small scale, often puckered in appearance, and throwing off short branches. They are marked by red opaque matter. In a more advanced stage these cracks become veinlets with quartz, chlorite, calcite and other carbonates, sericite, epidote, pyrites, sometimes garnet, and various indefinable materials, while the rock edging the crack or veinlet shows a development of products with a chloritic or serpentinous appearance. When the cracks cut a felspar phenocryst, or a flow line, absolutely no displacement can be seen to take place along the crack.

There is a complete absence of crushing along the cracks. But where 'streaky' rocks have been sheared, it is plain that the streaks are older than the squeezing. An instance is afforded by the Cawdale infold of rhyolite south-east of Sealhole, where movement perpendicular to the streaks has displaced, contorted, and dragged them out. They are also seen in places to be folded in exactly the same way as neighbouring bedded or fluidal rocks, notably above Low Barn, Haweswater, where the axes are about N.E.–S.W., pitching S.W. Specimens from this locality show irregular garnet in the streaks, which have been contorted.

The form and character of the cracks show that they are not produced by shearing, but by a process of internal readjustment in the rock itself. The structure may therefore be connected with the perlitic tendency of rhyolites.

Iddings[1] has described a case where, owing to differences in texture, there have been formed in rhyolite 'a multitude of nearly horizontal ones [cracks] which follow the planes of flow through all their complexities'.

In the eastern Lake District rocks, the cracks are shown by their general agreement with the direction of dip to have been originally horizontal, and in many cases closely resemble flow lines, especially when, as in rocks behind Low Whelter Farm, Haweswater, they wind round enclosed fragments. But they certainly cut flow lines not infrequently. This does not preclude the possibility that the general direction of flow may have had a controlling influence. In specimens from Seathwaite and Oxendale, as well as some from the eastern area, epidote streaks coincide strictly with the flow-lines, and appear to have originated in the manner suggested by Iddings.

[1] J. P. Iddings, Seventh Ann. Rep. U.S. Geol. Surv. for 1885-6, 1888, p. 260.

While perlitic structures are not uncommon in both acid and basic fragments enclosed in the tuffs, they are very rare in the flows of the Borrowdale Series. It seems possible that the cracks were due to contraction during cooling, and that the absence of perlitic curvature was determined by the presence during internal readjustment of hydrostatic pressure. The frequent addition of pyrites suggests that the subsequent infiltration took place during the solfataric period of volcanic episode. This infiltration replaces the groundmass and felspars of the rhyolites, but does not attack the biotite, as may be seen in a specimen from Dufton Pike in which the mica projects into the streaks.

It may be noted here that Rutley[1] has proposed solfataric action to explain a peculiar alteration in rhyolites from Dufton Pike in the Cross Fell area. He notes a mesh-like alteration of felspar (which I have myself seen in streaky rhyolites from several parts of the Lake District proper) and pseudomorphs that may be after garnet.

The conclusion is that the garnets, pyrites, and streaky alteration have been formed by circulating solutions under high hydrostatic pressure, probably during the solfataric stage of the Borrowdale volcanic episode.

[1] F. Rutley, Quart. Journ. Geol. Soc., 1901, vol. lvii, p. 31.