On the occurrence of metamorphic minerals in calcareous rocks in the Bodmin and Camelford areas, Cornwall.[1]

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CORNWALL has long been famous for the occurrence of certain minerals, found in the neighbourhood of the great granitic intrusions, that are rare in, or absent from, the aureoles of metamorphism surrounding the granites of many other regions. It is now generally recognized that these minerals have been produced by the action of certain heated gases on the rocks they penetrate along cracks and fissures; but the exact age of this type of alteration is not so well known. It is often held to be contemporaneous with the thermo-metamorphism produced by the granite, and rocks containing these minerals are included in the description of the 'contact rocks' surrounding the granite. This view, however, is not correct; while the gases and the granite clearly have a common deep-seated source, the greater part of the gaseous intrusions are not only later than the granite, but later also than many of the elvans that actually cut the granite and have chilled margins. Further, the finest illustrations of this type of alteration do not occur close to the granite, but at a distance, in the best case, of at least two miles from its margin, where the ordinary killas shows no trace of 'contact-action'. Lastly, this action often profoundly modifies the already 'contact-altered' rocks, and specially fine illustrations of this phenomenon have been met with by Mr. W. A. E. Ussher in the South Brent area, near the Dartmoor granite.

Recent investigations have also shown that the species of minerals produced is far more rigidly dependent on the nature of the material penetrated by these gases than is generally supposed: thus over a considerable area a vast number of small patches of banded killas have been tourmalinized, almost every particle of material other than quartz being absorbed in the formation of tourmaline. So far as is known, no

[1] Communicated by permission of the Director of H.M. Geological Survey.

other mineral than this has been found developed in a true shale by this pneumatolytic action. In impure calcareous rocks, similarly altered, tourmaline is very rare, though if a band of interbedded shale occur, this mineral is not uncommon in it. In these calcareous rocks other special minerals have been produced by this gas-action, not only in great quantity, but also in considerable variety of species, and it is to these that attention is drawn in the first part of this paper.

Impure calcareous rocks occur in the neighbourhood of the granites in many localities and at several geological horizons; sometimes they show practically little but normal 'contact alteration' (thermo-metamorphism), in other cases the special effects of gas-action (pneumatolysis) are specially well marked. The calc-flintas, or impure banded calcareous rocks of the Meadfoot series of the Lower Devonian, have been selected as showing pneumatolysis and little 'contact-action' along their outcrop on the north side of the St. Austell granite. Similar rocks in the Upper Devonian have been taken as an illustration of normal 'contact-action' accompanied by a minimum of 'pneumatolitic action'; these latter rocks occur on the north side of the Bodmin Moor granite, in the Camelford area.

Bodmin area.

The calc-flintas of the Meadfoot series were first met with in a quarry on the west bank of the stream, about a quarter of a mile west of the hamlet of Tregullan, which lies about a mile and a half south of Bodmin. From this quarry the calcareous rocks have been traced westward for some ten miles, and in the course of their outcrop, owing to their extreme hardness, they often rise like a great wall above the softer killas to the north. At intervals all along this outcrop axinite can be met with, developed along small cracks and fissures, and at three points it has been proved by quarrying to be specially abundant. In the quarry just referred to, near Tregullan, the calcareous rock lies next an altered greenstone, and near their junction the former contains abundant axinite.

Associated with this axinite is a green pyroxene of markedly prismatic habit, as well as garnet and other minerals not easily identified by the unaided eye. These minerals are rare in the adjacent greenstone, the minute cracks in this being for the most part filled with small needles of actinolite, which if analysed would probably prove to contain a certain amount of some special gaseous element.

The second locality is an old quarry to the north-west of Lanivet,

and, though this quarry has long since been abandoned, some large loose blocks suggest that these minerals may be here more abundant than at any other point along the outcrop.

The third locality is in the steep banks of the stream near Tremore, some four miles south-west of Bodmin. Here two quarries have been opened for road-metal, one on each side of the stream; the first and largest belongs to the County Council, and from its height and size it gives a fine section of the rocks. The second, on the west side of the stream, though smaller, is the more interesting, as it is in this that blocks mainly composed of axinite have been obtained that at times weigh several hundredweight.

The dominant component of the sedimentary material here present is a hard flinty or horny rock, which occurs in thin bands of incessantly varying tint, though generally pale-coloured. The tint varies from white to pale yellow, buff, pinkish, and occasionally pale green; the texture varies from flinty, or horny, to very finely granular. The dominant type is essentially an admixture of very fine siliceous material with a varying percentage of lime (a calcareous sand), and the changes of tint and texture are essentially due to the varying proportion between the two components. Scattered through the whole mass are partings of brittle killas in which the siliceous mud contained no lime. This latter material, beyond being hardened, shows no sign of 'contact-action' by the granite; but the calcareous rocks do, certain lime-silicates occurring in the body of the rocks that are clearly due to contact-action. There is little sign of gas-action in the interbedded killas, but in a few cases this has proved to contain a great number of minute crystals of tourmaline.

The dip of the calcareous bands being very high, the beds have in many cases been forced open parallel to the stratification, and along the fissures thus formed the axinite and other minerals have been abundantly developed, of which a list and description are given later. This gas-action is here not confined to the calcareous rocks; for these are traversed by an elvan within which a considerable amount of bluish fluor-spar has been developed. Finally, a copper-lode occurs on the south edge of the larger quarry, and in the refuse of an old pit sunk in it, fluor-spar may be obtained in considerable quantity, while a peculiar form of chlorite is specially abundant.

Camelford area.

The impure calcareous bands in the Upper Devonian have a fairly extensive outcrop on the north side of the Bodmin Moor granite in the

Camelford area. These rocks have a more complex composition than those last described, and a greater diversity of minerals has been produced by the 'contact-action' of the granite. The minerals so produced can be studied in two quarries close to a small stream about a mile east-north-east of Camelford. The rocks in these quarries are also traversed by cracks and joints, within which certain minerals have been developed in such a manner as to suggest that they are of pneumatolitic origin; but Mr. Thomas's examination has shown that they are characteristic of thermo-metamorphism. The fact that the cracks were partly filled with calcite seems to have afforded special facilities for the development of crystallized minerals. When, later, the calcite was dissolved, the crystals, in particular those of idocrase, were left partially isolated, in a manner simulating the mode of occurrence of the axinite in the rocks previously described.

The minerals produced by gas-action and not developed by ordinary thermo-metamorphism are as follows:—

1. Axinite.
2. Prismatic, green pyroxene.
3. Fluor-spar.
4. Tourmaline.
5. Zinc-blende.
6. Bright-yellow garnet.
7. Talc, as found in the veins (the 'green peach' of the tin-miners).

Those developed by normal thermo-metamorphism are:—

1. Idocrase.
2. Garnet.
3. Pale and pale-green pyroxene.
4. Epidote.
5. Actinolite.

The last two minerals also occur associated with axinite in such a manner as to suggest that they may contain a small amount of some special element, such as boron, fluorine, &c. Their optical properties remain, however, the same as those of the normal types. It is hoped to isolate and analyse the actinolite and epidote from the pneumatolytic veins, to ascertain if such elements are present.

We will now pass on to a description, by Mr. Thomas, of the various mineral species which have been met with at the three localities mentioned above.

Tregullan quarry, Bodmin.

The most interesting specimens consist of an aggregate of badly-formed axinite crystals, patches of greenish pyroxene, actinolite, and epidote, with masses of crystallized calcite surrounded by, and including, a pale-yellow garnet.

The *axinite* builds crystals up to ¼ inch in greatest dimension, and of a dark brownish-purple colour; it seldom shows good outline except when it projects into patches of calcite or quartz, for in the body of the rock the crystals interfere with each other. When well formed it has a habit almost identical with those crystals from Tremore quarry, but, unlike most of the axinite from that locality, is not quite so tabular parallel to the face $r\ \{1\bar{1}1\}$.

The *pyroxene* is a monoclinic variety referable to *hedenbergite*. It occurs in minute crystals of marked prismatic habit, elongated parallel to the edge *ab*. The crystals are bounded by well-developed $a\ \{100\}$ and $b\ \{010\}$ faces modified by narrow prism-planes $m\ \{110\}$; they give rectangular cross-sections with feebly truncated corners and diagonal cleavage-traces. They are terminated by somewhat indefinite planes, probably referable to $c\ \{001\}$ and $u\ \{111\}$.

The maximum extinction in the prism-zone is approximately 42°, and the birefringence 0·023. In general characters it seems to agree fairly well with the pyroxene obtained by Mr. D. A. MacAlister and described by Dr. J. S. Flett[1] from the axinite-bearing rocks of Crugoes near St. Columb Major, but is practically identical in habit, optical properties, and associations, with that mentioned by Professor K. Busz[2] from certain limestones altered by the Dartmoor granite-mass. As pointed out by him it is one of the earliest calc-silicates to form, for it penetrates the garnet, axinite, and calcite with which it is associated.

The *garnets* are all pale coloured varieties, and range in colour from bright wine-yellow or canary-yellow to brownish-green.

The bright yellow garnets occur in minute rhombic-dodecahedra and seldom reach more than a millimetre in diameter. They have exceedingly bright faces of the form $\{110\}$ and no modification of this form could be detected. The crystals surround, and occur in, patches of recrystallized calcite from which presumably they have been formed, and the calcite surrounding many included garnets is optically continuous. Under the microscope the garnet crystals are seen to be strongly zoned,

[1] Geology of Newquay (sheet 346). Mem. Geol. Surv., 1906, p. 27.
[2] K. Busz, Neues Jahrb. Min., 1899, Beil.-Bd. xiii, p. 128.

each zone varying somewhat in colour and also in birefringence, for it is a characteristic of these garnets when free from large inclusions to be anisotropic.

The birefringence of certain parts of the outer zones is often as high as that of axinite, for which $\gamma - \alpha = 0{\cdot}009$, but the central part is most often isotropic or nearly so. Sections through the centre at right angles to a trigonal axis show six distinct triangular sectors, the base of each triangle being the trace of a dodecahedral face, and its sides the traces of dyad axes. The birefringent layers are arranged parallel to the trace of the dodecahedron, and have their smaller axes of elasticity approximately parallel to the same line. These layers are differently orientated in adjoining triangles and present an orientation suggesting a rotation of 180° about a dyad axis. Extinctions range up to $+15°$ with the trace of the dodecahedron in one triangle, and $-15°$ in the two adjacent.

The small crystals are usually free from inclusions, but some of the larger are composed of a variety of minerals cemented together by small patches of bright yellow, isotropic garnet. These are bounded by the usual dodecahedral faces, but it is calculated that the included material often makes at least half their bulk. The included minerals are axinite, quartz, fluor-spar, actinolite, and pyroxene, showing that the garnets were probably one of the last metamorphic minerals to form.

A pale coloured yellowish-green garnet has also been met with in crystalline aggregates. The individuals consist of well-formed dodecahedra of the form {110}. They are fairly rich in manganese, and have strong anomalous double refraction, but are probably less manganiferous than those associated with idocrase at Tyland quarry, Camelford.

In composition the bright yellow garnet[1] seems to be related to the andradites, while the darker coloured varieties are intermediate between grossular and spessartine.

A bright yellow garnet similar to that of Tregullan has been known from Cornwall for some time, but so far as we are aware not described. As long ago as 1822 J. Carne[2] mentioned the occurrence of this mineral in association with axinite and other species in the Roscommon cliff near St. Just, and he also records the fact that it is

[1] A qualitative analysis of the garnetiferous portion of the Tregullan calc-flintas showed the presence of the rare earths, but it was found impossible to prove to which mineral they belonged. It was at first thought that they might be present in the epidote in the form of orthite, but it is quite likely that they may be contained in the bright yellow garnet.

[2] J. Carne, Proc. Geol. Soc. Cornwall, 1822, vol. ii, p. 309.

embedded in calcite near Lewellin. The deeper coloured varieties, which are generally more common, have been described by Busz[1] and Solly.[2]

Tourmaline is extremely rare in the more calcareous metamorphosed rocks, but a few minute, deep brownish-black needles have been noticed in one specimen. It is associated in this instance with the axinite, and yellow garnet and arranged in radiating groups of fine needles.

Actinolite. A microscopic, bright green variety with moderately strong pleochroism occurs in long prisms, usually enclosed in some other mineral (p. 120).

Haematite has been met with in minute plates and larger crystalline masses in the axinite-pyroxene-rock of Tregullan. It has the usual black metallic lustre, red streak, and is blood-red by transmitted light in thin sections. From its mode of occurrence it appears to occupy what were originally cavities in the rock, and it probably results from the metamorphosis of some ferrous compound, such as the carbonate, which most likely existed in the original calcareous deposit.

Zinc-blende is associated with the calcite patches in small quantity. It is brown in colour, has no definite outline, but shows the cleavages distinctly. A little iron-pyrites and fluor-spar are also present.

Epidote, in prisms and acicular forms, occurs in some quantity intimately associated with the pyroxene described above; it is similar in every respect to that met with at Tyland quarry.

Tremore, Bodmin.

The rocks of this locality which yield the best specimens were evidently more calcareous than those of Tregullan, for such minerals as the pyroxene and epidote are much less abundant. The calc-flintas in the larger Tremore quarry are cut by a copper-vein which has yielded a few minerals not recognized in the calc-flintas themselves.

Axinite. The axinite-rock of this locality consists chiefly of aggregates of small crystals loosely cemented by quartz and calcite. The mineral builds small, blade-like crystals of pale-plum to cinnamon-brown colour with deeply striated faces. A few crystals which were measured gave the following angles and forms:—

[1] K. Busz, loc. cit., 1899, p. 125.

[2] R. H. Solly, Min. Mag., 1886, vol. vi, p. 202.

	Measured.	Calculated.
$Mr = (1\bar{1}0):(1\bar{1}1)$ . .	45° 15′	45° 15′
$rm = (1\bar{1}1):(110)$ . .	64° 23′	64° 22′
$Ms = (1\bar{1}0):(201)$ . .	33° 24′	33° 18′
$Mx = (1\bar{1}0):(111)$ . .	49° 4′	49° 25′
$My = (1\bar{1}0):(021)$ . .	79° 25′	79° 12′

The most common forms are $M\{1\bar{1}0\}$, $r\{1\bar{1}1\}$, and $m\{110\}$. The form $r\{1\bar{1}1\}$ is developed at the expense of the others and is deeply striated parallel to the edge $(1\bar{1}1)(1\bar{1}0)$. The crystals are tabular parallel to the form $r\{1\bar{1}1\}$. Crystals of slightly deeper colour and thicker build have been met with which have the forms $M\{1\bar{1}0\}$, $s\{201\}$, $x\{111\}$, and $y\{021\}$ more or less equally developed. The form $e\{\bar{1}11\}$ is also present on some of these crystals.

Extinctions on $r(1\bar{1}1)$ measured to the edge rM give $8\frac{1}{2}°$; and the pleochroism is pale-plum parallel to the edge rM and colourless to a faint shade of yellow at right angles. This pleochroism, although fairly strong, is not so intense as that shown by axinites from the uranium mine at Grampound Road and several other Cornish localities.

Amphibole. Many of the best axinite crystals occur embedded in a pale green silky *asbestos*, a mineral often found in association with axinite-rocks, as described[1] from other localities in Cornwall, Devonshire, and the United States.

In the axinite-rock, especially in the more massive varieties, patches of a green, vitreous mineral were noticed running up to about three-quarters of an inch in diameter and pierced by axinite crystals. Under the microscope this vitreous mineral proved to be quartz which was penetrated by numberless extremely slender crystals of a pale green actinolite, which gives the colour to the whole mass. The pleochroism of the amphibole is slight, and the extinction $\mathbf{c}\wedge\dot{c} = 18°$ approximately. The maximum absorption is parallel to $\mathbf{c}$, and the zone of elongation has a positive sign. Similar needles are enclosed in crystallized calcite to which also they impart the same green colour.

The most interesting amphibole is that which occurs in the drusy cavities of the axinite-rock; it consists of minute, extremely slender needles of a dark brown to black colour, forming a woolly mass and recalling strongly the breislakite[2] of Vesuvius and the Capo di Bove near Rome.

[1] R. H. Solly, loc. cit., 1886, pp. 210–211.

[2] E. Weinschenk, Zeits. Kryst. Min., 1903, vol. xxxvii, p. 442.

In view of Weinschenk's description of this species, however, the resemblance between it and the mineral from the axinite-rock is only superficial. The individual needles, which have a submetallic lustre, reach two centimetres in length. They are striated parallel to the long axis and are bounded by the faces $m\{110\}$ without any recognizable terminations. The zone of elongation has a positive sign, and the extinction $\mathfrak{c}\wedge\acute{c}=18°$ approximately. The maximum absorption in the prism-zone is for light vibrating parallel to $\mathfrak{c}$, which is yellowish-green, and at right angles to $\mathfrak{c}$ yellowish.

The deep colour of these needles when viewed by reflected light is due to bunches of black oxide of manganese deposited upon them, but when treated with dilute hydrochloric acid they appear pale green and are then indistinguishable from actinolite. In this state they resemble the byssolite of Traversella. There is no doubt that the brown woolly amphibole occurring in the druses of the axinite-rock was originally contained by some other mineral, probably calcite or quartz; and fragments of the actinolite-bearing calcite mentioned above when treated with dilute hydrochloric acid yielded aggregates which differed from it only in the absence of the clusters of manganese oxide. It is, therefore, probable that these woolly aggregates owe their present characters to the solution of the calcite or quartz in which they were originally embedded and the deposition of manganese oxide on the freed needles.

The other minerals met with at Tremore, including yellow garnet and pyroxene, are identical with those already described from Tregullan; but from the copper-vein in the large quarry we recognize a deep purple fluor-spar, well-crystallized talc, zinc-blende, and masses of chlorite in the form of 'peach'. The copper-ore is massive chalcopyrite. The talc has a well-marked cleavage; the cleavage-fragments show the emergence of a negative bisectrix normal to the flake and an axial angle of 10°–20° in air.

Tyland quarry, Camelford.

The minerals from this locality belong almost exclusively to those usually regarded as due to true contact-metamorphism, but at the same time small quantities of axinite, fluor-spar, and allied minerals of pneumatolytic character are present.

Garnet. The garnet of Tyland quarry occurs massive in the more calcareous bands of the calc-flintas and well crystallized on certain joint-faces. It has a cinnamon-brown to brownish-yellow colour, and occurs with idocrase and quartz. The form is that of the simple rhombic-

dodecahedron {110} modified by very narrow planes of {211}. The faces {110} are deeply striated parallel to their shorter diagonal.

These garnets are often hollow and are built up around other minerals. A qualitative analysis showed the presence of calcium, iron, manganese, a little magnesium, and no chromium, indicating that the mineral should probably be referred to the grossulars or spessartines. Optically, these garnets are strongly birefringent, the double-refracting layers being arranged in a similar manner to those of the yellow garnet described from Tregullan.

Idocrase occurs in colourless to pale yellowish-green or yellowish-brown prisms, deeply striated parallel to the vertical axis, and usually terminated by the basal plane alone. The prisms are rectangular, being bounded by the form m {110}; no modifications in this zone were noticed, but very narrow pyramids, probably p {111}, were observed to truncate the edge between the prism and the basal plane. Modifications of the quoins occasionally occur. The crystals average three to five millimetres in length and are seldom more than one millimetre in width. Occasionally, however, they reach a centimetre in length. In some instances they have been noticed implanted on the garnets described above, after the manner of those of Péguères in the Pyrenees.[1]

Optically, they show the usual low birefringence in the prism-zone, and cross-sections show a bisectrix. The mineral is most often biaxial with an angle between the axes in air varying from 0° to 10°.

This mineral is one of the best known products resulting from the metamorphism of calcareous rocks, but so far as we are aware has not previously been recorded from Cornwall.

Epidote. Well-crystallized epidote occurs associated with the garnet-idocrase-masses both in the rock and on the joint-faces. On the joints it builds extremely long (up to 4 cm.) prismatic crystals, elongated parallel to the axis of symmetry, of a pale greenish-brown to greenish-purple colour. They are bounded by the a {100} and c {001} faces, giving generally rhombic cross-sections, whilst occasionally hexagonal cross-sections may be observed, due to the presence of r {10$\bar{1}$} in addition. Light vibrating parallel to $\mathfrak{b}$ is plum-coloured and at right angles to this yellowish-green. This pleochroism, together with the other optical properties, suggests an epidote with a percentage of ferric oxide of about 7 to 8, somewhat similar to the epidote from Inverness-shire, but slightly richer in iron. The pleochroism is, however, almost identical with that of the Inverness-shire mineral.[2]

[1] A. Lacroix, 'Minéralogie de la France.' 1893, vol. i, p. 163.

[2] H. H. Thomas, Min. Mag., 1906, vol. xiv, p. 112.

Chlorite. A chlorite of a dark green colour occurs well-crystallized in association with the garnets, &c. It has a perfect cleavage parallel to the base and shows the emergence of a negative bisectrix normal to the flakes. The angle between the optic axes is extremely small, and occasionally the mineral seems to be uniaxial. It is probably related to the penninites.

In the less calcareous bands a pyroxene occurs and is apparently similar to that already described. Axinite with the usual characters occurs in small quantities, but in this case seems to be moulded on the garnet.