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Metasomatism associated with the greenstone-hornfelses of Kenidjack and Botallack, Cornwall.

(With Plates VI and VII.)

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IN a paper entitled 'Hornfelses from Kenidjack, Cornwall'[1] the nature and origin of the rock types characterized by anthophyllite and cummingtonite occurring in the aureole of the Land's End granite were discussed.

Since these rocks were investigated in 1928 the writer has extended his study of them both in the field and in the laboratory, with the result that further light on the origin of these rock types has been obtained. It is the purpose of these notes to examine in more detail the evidence which is considered to add to their understanding. In the Kenidjack paper the petrography of the rocks was described at some length and in the present paper petrographic data will be given only in so far as they supplement the previous account, which may be consulted for a detailed statement.

The contact altered greenstones.

The greenstones at Kenidjack are known only in their contact altered state. In the Kenidjack paper their mineralogical composition was described but hitherto no chemical data on these rocks have

[1] C. E. Tilley and J. S. Flett, Summ. Progr. Geol. Surv. Great Britain, 1930, for 1929, pt. 2, pp. 24–41, hereafter referred to as the Kenidjack paper. [M.A. 4–402.]

been presented. The account now given supplies this deficiency. The rocks are essentially hornblende-plagioclase types. Prior to contact metamorphism they had been subject to shearing and dynamic metamorphism so that banded types are prevalent among them. This fact had been realized long ago by Allport[1] in his description of these rocks in 1876, and has been emphasized both in the account in the Survey Memoir and in the Kenidjack paper. Though there is considerable variation in the relative proportions of the component minerals, the mineralogy is comparatively simple, the variety being dominated by the relative proportions of green hornblende and plagioclase. It is true that hornfelses occur among them containing grossular, epidote, diopside, and axinite, yet these types are comparatively uncommon in the coastal region between Kenidjack and Botallack dealt with in this paper.

TABLE I. *Analyses of hornfelses and cummingtonite.*

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO_2	40·25	49·10	58·15	48·87	47·07	33·58	52·60	51·15	53·55	53·12
TiO_2	2·65	1·20	1·85	2·71	2·12	2·96	1·85	2·20	0·40	0·21
Al_2O_3	17·22	10·54	12·95	16·71	20·20	11·79	20·64	16·42	8·40	2·78
Cr_2O_3	—	—	—	0·01	0·02	—	—	—	—	—
Fe_2O_3	1·88	0·87	trace	0·13	trace	11·27	0·20	4·42	0·74	0·25
FeO	11·16	10·27	10·76	12·85	12·73	17·50	7·66	11·91	26·75	22·46
MnO	0·24	0·17	0·12	—	0·11	0·21	trace	trace	0·25	0·27
MgO	7·78	10·72	6·44	9·60	10·09	15·55	5·02	3·92	2·37	15·46
CaO	14·82	14·00	7·05	5·42	2·14	0·89	2·45	1·50	1·20	2·26
Na_2O	1·20	1·22	1·02	1·61	1·48	0·60	2·28	3·57	0·26	—
K_2O	0·97	0·10	0·14	0·27	1·97	0·32	4·73	2·83	2·94	—
H_2O+	0·90	0·90	0·60	0·99	1·50	4·60	1·80	1·60	2·15	3·33
H_2O-	0·20	0·10	0·50	0·07	0·16	0·13	0·40	0·30	0·65	—
P_2O_5	0·65	0·78	0·49	0·50	0·12	0·36	0·40	0·04	0·06	—
CO_2	nil	nil	nil	0·07	—	nil	nil	nil	nil	—
	99·92	99·97	100·07	99·81	100·21	99·78	100·03	99·86	99·72	100·14
Sp. gr.	3·203	3·031	2·982	2·966	2·907	3·041	2·819	2·916	3·019	—

No. 5, also FeS_2 0·47, Li_2O 0·03. No. 6, also Cl 0·02, F nil.

1. Greenstone-hornfels, Carn Kenidjack. Analyst, W. H. Herdsman. Green hornblende, small amounts of colourless augite, plagioclase (replaced by white mica), ilmenite, sphene, and apatite.

2. Greenstone-hornfels, Zawn a Bal. Analyst, W. H. Herdsman. Bands of green hornblende, alternating with plagioclase bands containing accessory ilmenite, sphene, and apatite.

3. Cummingtonite-plagioclase-hornfels, North Zawn quarry. Analyst, W. H. Herdsman. Plagioclase (Ab_1An_1) with some anthophyllite, quartz, cordierite, biotite, ilmenite, and apatite.

[1] S. Allport, Quart. Journ. Geol. Soc. London, 1876, vol. 32, p. 407.

4. Cummingtonite-anthophyllite-cordierite-plagioclase-hornfels, coast between North Zawn and Wheal Edward Zawn, Kenidjack (with ilmenite and biotite). Analyst, B. E. Dixon, Summ. Progr. Geol. Surv., 1930, for 1929, pt. 2, p. 32.

5. Anthophyllite-cordierite-hornfels, Carn Kenidjack (with biotite, plagioclase, ilmenite, and some cummingtonite). Analyst, B. E. Dixon, Summ. Progr. Geol. Surv., 1930, for 1929, pt. 2, p. 28.

6. Anthophyllite-cordierite-(clinochlore)-spinel-diaspore-hornfels, Inner quarry, Kenidjack (with magnetite, ilmenite, apatite, and biotite). Analyst, R. Sutcliffe, Summ. Progr. Geol. Surv., 1930, for 1929, pt. 2, p. 33.

7. Cordierite-biotite-hornfels, Zawn a Bal, Botallack. Analyst, W. H. Herdsman. Cordierite, biotite, quartz, oligoclase-albite, ilmenite, rutile, apatite, muscovite.

8. Cordierite-biotite-hornfels, Zawn a Bal, Botallack. Analyst, W. H. Herdsman. Cordierite, biotite, quartz, albite-oligoclase, ilmenite, magnetite, apatite.

9. Grunerite-biotite-hornfels, Zawn a Bal, Botallack. Analyst, W. H. Herdsman. Grunerite, biotite, quartz.

10. Cummingtonite from cummingtonite-biotite-cordierite-hornfels, Rifle Ranges, Kenidjack. Analyst, R. Sutcliffe. Water below 105° C. not separately determined. Sign and elongation positive, optic axial plane parallel to (010). Extinction $\gamma : c = 19°$, refractive indices α 1·643, γ 1·670. Analysis corresponds to $(OH)_{3\cdot2}(Ca,Fe,Mg,Mn,Ti)_{6\cdot5}(Si,Al)_8O_{22}$. Summ. Progr. Geol. Surv., 1930, for 1929, pt. 2, p. 31.

To determine the range of chemical composition amongst these greenstones, two varieties have been chosen for analysis. In the one, the dominant mineral is green hornblende; in the other, hornblende and plagioclase form alternating bands. These two types may be taken as representing the prevalent varieties among the greenstones of the area. A hornblende-rich type from Carn Kenidjack chosen for analysis gave the result under 1, table I. Green hornblende is the dominant mineral forming more than 80% of the rock. The mineral is optically negative, $\gamma : c = 19°$, and has β 1·678. The remaining constituents are granules of colourless augite, ilmenite, sphene, and small amounts of plagioclase now partly replaced by white mica (γ 1·586). The analysis makes it clear that this hornblende must be a highly aluminous type. A hornblende with high Al_2O_3 (16·75%) has already been recorded by J. A. Phillips[1] from the greenstones of the Botallack cliffs.

The second rock (analysis 2, table I) comes from the promontory on the north side of Zawn a Bal. In this, bands rich in green hornblende alternate with bands composed of plagioclase and ilmenite (fig. 1). Granular sphene in part replaces the ilmenite. The hornblende is optically negative, $\gamma : c = 19°$, and has β 1·650. The plagio-

[1] J. A. Phillips, Quart. Journ. Geol. Soc. London, 1876, vol. 32, p. 167.

clase bands contain a minutely granular plagioclase of composition Ab_1An_3, β 1·569, with streams of ilmenite partly replaced by sphene, together with minute granules of apatite. The modal composition of the rock is green hornblende 64, plagioclase 30·5, ilmenite, magnetite, and sphene 3·5, apatite 2%. In contrast with the hornblende of the first rock the hornblende of this greenstone-hornfels must be practically free from alumina, as the rock itself contains only 10·54% Al_2O_3. The low silica percentage of the Carn Kenidjack greenstone-hornfels is accounted for by the replacement of silicon by aluminium in the constitution of its dominant amphibole.

In table II the analyses of these two hornfelses are set down together with comparative analyses. The principal distinguishing feature of the analyses is the high lime percentage and low soda figures. Comparable figures can be found amongst existing analyses of basic igneous rocks but it seems probable that these greenstones may have suffered some enrichment in lime during the shearing (and segregation) to which they have been subject prior to contact metamorphism.

TABLE II. *Analyses of type varieties of greenstone, with comparative analyses.*

	1.	1*a*.	2.	2*a*.	2*b*.	2*c*.	3.
SiO_2 ...	40·25	42·08	49·10	48·72	49·75	48·70	44·67
TiO_2 ...	2·65	2·26	1·20	1·04	4·60	2·41	1·92
Al_2O_3 ...	17·22	16·04	10·54	11·75	12·18	12·61	13·88
Fe_2O_3 ...	1·88	5·93	0·87	1·44	0·03	3·26	1·37
FeO ...	11·16	8·75	10·27	6·63	9·88	5·65	10·72
MnO ...	0·24	0·32	0·17	0·45	0·48	0·03	0·20
MgO ...	7·78	6·95	10·72	10·92	9·54	8·49	9·25
CaO ...	14·82	12·66	14·00	16·45	11·79	13·38	14·41
Na_2O ...	1·20	1·88	1·22	0·96	1·19	2·46	1·21
K_2O ...	0·97	0·93	0·10	0·10	0·11	0·63	0·54
H_2O+ ...	0·90	2·76	0·90	1·28 }	0·35 (H₂O+ and H₂O−)	0·90	0·90
H_2O- ...	0·20	—	0·10	0·06 }		0·10	0·15
P_2O_5 ...	0·65	0·34	0·78	0·30	0·06	0·36	0·72
CO_2 ...	nil	—	nil	nil	—	0·97	nil
	99·92	100·90	99·97	100·40	99·96	99·95	99·94

1. Greenstone-hornfels, Carn Kenidjack.

1*a*. Basalt, Mindello, Cape Verde Islands. (H. S. Washington's Tables, 1917, p. 656.)

2. Greenstone-hornfels, Zawn a Bal, Botallack.

2*a*. Gabbro, Kalgoorlie, Western Australia. (H. S. Washington's Tables, 1917, p. 704.) Also FeS_2 0·24, V_2O_3 0·06.

2*b*. Hornblende-schist, Yarikita Hill, British Guiana. (J. B. Harrison, Publ. Imp. Bureau Soil Science, Harpenden, 1934, p. 31.)

2*c*. Greenstone (lava), Mesket formation, NE. of Lake Seimajaure, Swedish Lapland. O. Kulling, Geol. För. Förh., 1933, vol. 55, p. 326.

3. Greenstone-hornfels, mean of analyses 1 and 2.

Reference has already been made to the shearing the greenstones had suffered prior to thermal alteration. Original structures are rarely to be met with, but an exception is provided in the cliff section on the south-west side of Kenidjack cliff where pillow structures are to be recognized (pl. VII, fig. 4). Here good exposures of pillow lavas are to be found over a small area. The pillows range in size upwards from a foot in diameter to two feet or more. They have in places siliceous material forming the interspaces between the pillows. The material of the pillows has suffered radical changes in composition. Granules and streams of ilmenite persist, but hornblende may be largely absent. In one type hornblende is confined to nests $\frac{1}{2}$–$\frac{3}{4}$ mm. in diameter set in a base of biotite and plagioclase; and in some pillows hornblende has completely disappeared, the pillow being made up of nests of secondary quartz, muscovite with some chlorite after biotite, set in a groundmass composed almost wholly of biotite with a little plagioclase. The nests stand out as excrescences on weathered surfaces. It is clear that the original lavas have suffered extensive metasomatic change with loss of lime and enrichment in potash.

FIG. 1. Greenstone-hornfels, Zawn a Bal. Green hornblende, plagioclase, and streams of ilmenite.

The material in the interspaces between the pillows is usually quartzose—built up of quartz with some green hornblende, or quartz with biotite, muscovite, and oligoclase. Some interstitial material is composed wholly of green hornblende (γ 1·655, $\gamma : c = 19°$).

In the Kenidjack paper the intimate association of the anthophyllite- and cummingtonite-bearing rock types with the typical greenstones was stressed, and evidence was presented for the view that these rock types were derived from the greenstones. The results of further study all go to show that this view of their origin is the only one which is in harmony with the field evidence and the laboratory examination. The greenstones were believed to have suffered in part intense weathering whereby lime was leached out of the weathered products and these on contact metamorphism gave rise to the variety of rock types bearing anthophyllite, cummingtonite, and cordierite.

There can be no doubt that these hornfelses have been derived from the greenstones by an essential leaching of lime from them, but the writer's more extended field and laboratory study has led him to modify his previous view as to the time when this removal of lime took place. In brief, it is now believed the greenstones have suffered this loss of lime during the period of contact alteration as a result of the passage of solutions eventually derived from the granitic magma, solutions which eventually gave rise to the rich tin and copper deposits which characterize the Botallack area. Before, however, the character of this replacement is discussed in detail the mineralogical and chemical changes which can be traced through the various mineral assemblages from the greenstones will be briefly reviewed.

It has already been remarked that banded greenstone-hornfels are the characteristic contact rocks with which the anthophyllite and cummingtonite rocks are associated. It is particularly in the preservation of this banding and of the essential textural features that the chemically contrasted rock types resemble one another.

The essential mineralogical changes which can be traced through from the greenstones are the five following:

1. *Incoming of biotite.*—Here a light-brown coloured biotite appears amongst the green hornblende fibres partly replacing them, but this mineral also appears in the plagioclase bands. In other respects the texture of the greenstone-hornfels is unchanged.

2. *Appearance of spinel and diaspore.*—A rarer type of change is the appearance of pleonaste with or without diaspore in the plagioclase areas or near their contact with the green hornblende areas. A palimpsest feature not uncommonly met with is the preservation of the characteristic ilmenite streams passing unresorbed through the spinel areas. Diaspore is often associated with the spinel and is then frequently accompanied by almost colourless clinochlore forming a fringe to the diaspore grains as if the conditions permitting the formation of diaspore were favourable to the formation of clinochlore. Corundum has not been met with in these hornfelses, nor does it appear ever to have been present. Examples of greenstone-hornfelses carrying spinel and diaspore with associated clinochlore have been figured in the Kenidjack paper (pl. II, figs. 5 and 6).

3. *Appearance of cummingtonite and anthophyllite.*—The intimate relation of the ferromagnesian amphibole types with the true greenstones is shown by the transition of these rock types one into the other. The commonest rock type showing this transitional relationship is a cummingtonite-plagioclase type. These cummingtonite-

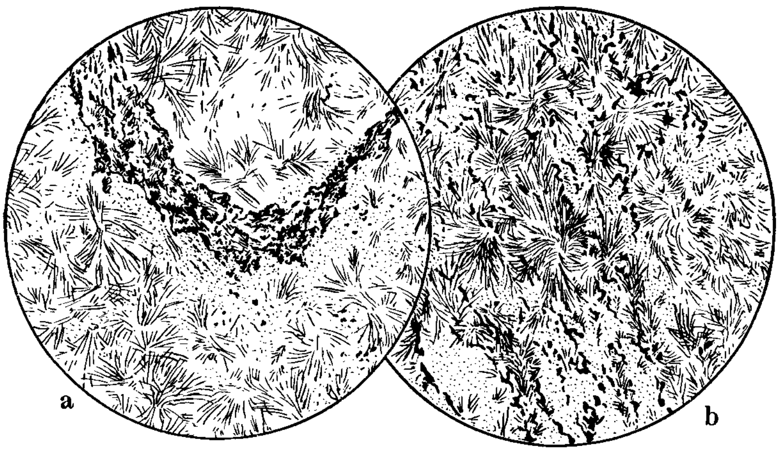

FIG. 2*a*. Banded anthophyllite-cordierite-plagioclase-hornfels rich in quartz, Carn Kenidjack. Anthophyllite with some cummingtonite, quartz (clear areas), plagioclase, and bands of plagioclase and cordierite enclosing abundant ilmenite.

FIG. 2*b*. Cummingtonite-plagioclase-hornfels, North Zawn quarry. Cummingtonite, plagioclase, and streams of ilmenite; some interstitial cordierite and quartz.

plagioclase-hornfelses (with or without biotite) present the same textures as those of the greenstones proper (fig. 2 *b*). The cummingtonite and plagioclase bands of the former represent in essentials the green hornblende and plagioclase bands of the latter. The streams of ilmenite and minute granules of apatite so characteristic of the normal greenstones are preserved intact in the cummingtonite-hornfels. The cummingtonite and plagioclase may be accompanied by biotite, and quartz often appears among the plagioclase grains. Anthophyllite may appear together with the cummingtonite, but it usually becomes prominent only when cordierite is developed (fig. 2 *a*).

4. *Appearance of cordierite.*—The incoming of cordierite brings us to the dominant types of chemically altered hornfelses which can be traced back to a greenstone parentage. The petrography of these rocks has been given in some detail in the Kenidjack paper. The

cordierite development belongs characteristically to the plagioclase areas, and it appears that by replacement of plagioclase, cordierite increases in amount in these rocks (figs. 3 *a* and 3 *b*). In this change the streams of ilmenite and granules of apatite persist as a relict feature, appearing as they often do enclosed in large twinned cor-

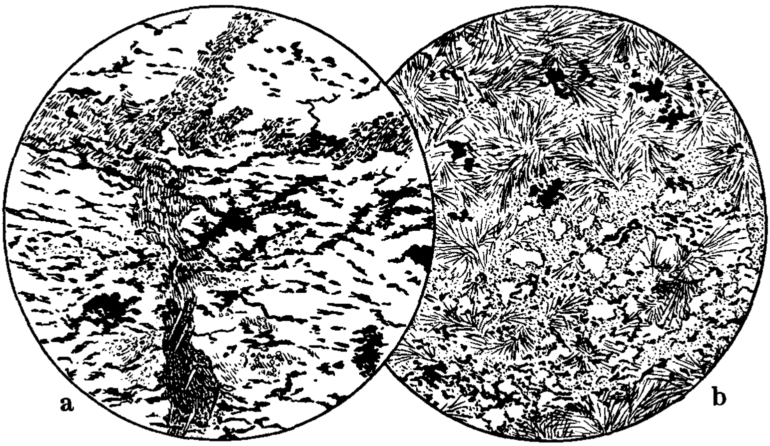

FIG. 3*a*. Anthophyllite-cordierite-hornfels, Carn Kenidjack. Cordierite forms the colourless groundwork in the form of coarse-grained crystals through which pass streams of ilmenite. These are separated by threads of biotite with a crystal of anthophyllite at the bottom of the figure.

FIG. 3*b*. Anthophyllite-cordierite-plagioclase-hornfels, Carn Kenidjack. Anthophyllite, cummingtonite, cordierite, plagioclase, and ilmenite. The clear areas are cordierite extinguishing as a unit.

dierite crystals of the anthophyllite-rocks. A fine example of this texture is figured in the Kenidjack paper (pl. I, fig. 6).

It is to be noted that the development of cordierite corresponds to a stage when all green hornblende has disappeared from the rock.[1] There is clearly a tendency, when much plagioclase is still present, for the dominant amphibole to be cummingtonite, the orthorhombic anthophyllite being more typically associated with the cordierite-

[1] A. L. Hall and G. A. F. Molengraaff (Verh. Akad. Wetenschappen, Amsterdam, 1925, vol. 24, no. 3, pp. 128–131) have recorded the association cordierite-actinolitic hornblende in amygdules and in the body of a basic igneous rock—the basal amygdaloid of the Vredefort area. Some doubt may be expressed on this reported co-existence of cordierite and hornblende, and it may be questioned whether a cordierite-cummingtonite or anthophyllite association is not indicated. A further genetic study of this unusual occurrence would be of interest.

bearing rock types. Where the chemical changes have been such as to lead to a deficiency of silica, the cordierite is accompanied not infrequently by spinel with or without diaspore.

5. *Eventual disappearance of amphibole.*—In the previous study the anthophyllite-cordierite-rocks were regarded as the extreme variants from the greenstone proper. The present study has shown, however, that more particularly at Botallack rock types are developed which must be regarded as further variants derivative of the greenstones.

These rocks are essentially cordierite-biotite-hornfels in which no amphibole is developed. Their finest exposures are to be met with on the promontory between Zawn a Bal and De Narrow Zawn south of The Crowns, Botallack. The rocks are characteristically dark to reddish-brown in hand-specimens, due to the development of abundant fine-grained iron-ore and biotite.

They are closely associated with the greenstones and anthophyllite-rocks, passing into them both across and parallel to the prevalent banding. These rocks weather with rough excrescences formed of cordierite or quartz and plagioclase. Many of them as seen at Zawn a Bal are extensively veined by quartz. In this feature they stand often in strong contrast to the associated greenstones which are usually free from such anastomosing quartz veins.

Under the microscope, the relation these rocks bear to the greenstones is clearly indicated by their banded character, the cordierite areas containing the characteristic streams of ilmenite with granules of apatite as in the less fundamentally altered types. The cordierite-rich lenses and bands alternate with other bands rich in red-brown biotite or into more quartzose and acid plagioclase (albite-oligoclase) bands carrying ilmenite. Many of them contain fine-grained magnetite in considerable amount, which clearly has been introduced.

These rock types appear bound to the anthophyllite-biotite-rich hornfelses by types in which anthophyllite is present in variable amount among the biotite-rich layers. Two of these hornfelses from Zawn a Bal have been analysed (table I, analyses nos. 7 and 8). One of these (no. 7) is a dark-red fine-grained rock, which on the weathered surface shows white streaks and knots as excrescences. On the fractured surface the presence of cordierite is indicated in the resinous-lustred elliptical areas up to ½ inch in length. Under the microscope, the minerals seen are cordierite of the resinous patches referred to containing streams of ilmenite, biotite, and granules of apatite. In these ilmenite streams there is a considerable amount of rutile which has arisen from the ilmenite by loss of iron. Between the cordierite areas are developed biotite-rich zones which in places also carry ilmenite streams, also quartz, and a fair amount of oligoclase-albite (fig. 4*b*). The white streaks consist largely of quartz accompanied by tufts of white mica. It is clear that much of the quartz in this rock has been introduced, as is evident from its predominance in the streaked patches.

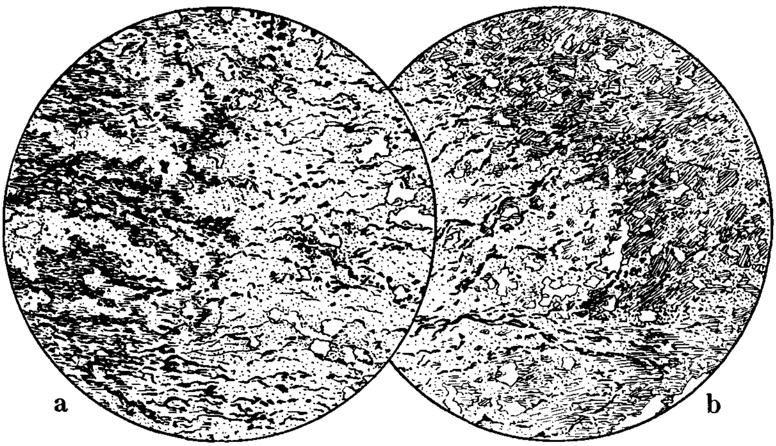

FIG. 4*a*. Cordierite-biotite-hornfels, Zawn a Bal. The right half of the figure consists of a large twinned crystal of cordierite enclosing ilmenite, magnetite, and quartz. The left half contains abundant biotite. The streams of ilmenite persist.

FIG. 4*b*. Cordierite-biotite-hornfels, Zawn a Bal. Streams of ilmenite traversing a cordierite crystal enclosing quartz and oligoclase-albite (left half of figure), right half rich in biotite.

The second rock (Z B 22) is dark-grey in hand-specimens with a knotted weathering (cordierite). Under the microscope, it is seen to be a banded type which has been clearly enriched in quartz and iron-ores (fig. 4*a*). The cordierite areas have the familiar ilmenite streams, but in addition have numerous idioblasts of magnetite. The biotite areas contain, in contrast to the previous rock, a yellow-brown biotite associated with finely granular quartz and albite-oligoclase. This rock also contains knots of quartz and acid plagioclase.

The amount of cordierite in rocks grouped under this heading is subject to considerable variation and appears dependent on the amount of silicification and introduction of potash. There are some types in which cordierite is in very small amount, its place being taken by quartz or by biotite. The significance of the replacement processes in relation to the development of these extreme variants will be referred to hereafter.

Occurrence of almandine at Botallack.

The well-crystallized icositetrahedra of garnet recorded from Botallack and often to be seen in British mineral collections have recently been analysed.[1] The garnets were originally found only in one place—at low-water mark on the promontory north of Zawn a Bal amongst the altered greenstones. The analysis of this garnet shows it to be an almandine-rich variety of composition $Fe_{91\cdot3}Mn_{1\cdot7}Mg_{2\cdot4}Ca_{4\cdot6}$. The crystals rest upon a highly biotitic layer of the altered rocks, and an analysis (table I, no. 9) has been made of the country-rock to which the garnets belong. The almandine contains enclosures of red-brown biotite and grunerite. The surrounding rock is banded, containing, immediately adjacent to the garnet, layers rich in biotite and quartz. Passing out from the contact with the garnets the biotite passes from a yellow-brown to a green-brown variety, the associated mineral being quartz. This band is succeeded by another composed almost wholly of grunerite with some green biotite and quartz (fig. 5).

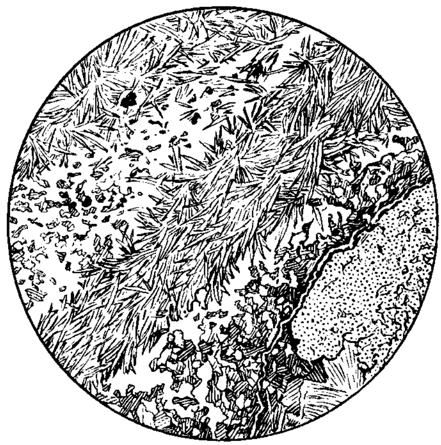

FIG. 5. Grunerite-biotite-quartz-hornfels, Zawn a Bal. Almandine bordered by a felt of biotite, the remainder of the figure grunerite in bands with quartz and biotite.

In hand-specimens the grunerite is greenish-brown, but in thin section almost colourless: α and β colourless, γ light greenish-yellow. It is commonly multiple twinned on (100), $\gamma : c = 12°$, optic axial angle high, negative, γ 1·715. It is clear from these properties that the monoclinic amphibole must be close to grunerite in composition.

[1] A. R. Alderman, Min. Mag., 1935, vol. 24, p. 42.

The garnet-free material analysed comprises the two layers, biotite-quartz and grunerite-biotite-quartz, and the high percentage of ferrous oxide (26·75 %) and low magnesia (2·37 %) confirm the gruneritic character of the amphibole.

In all specimens examined garnet occurs in intimate association with biotite but it may also be found adjacent to grunerite bands. There can be no doubt that this occurrence of garnet is connected with the strong metasomatism that has affected the country-rock. The original material has been a metamorphosed greenstone which has suffered intense impregnation with potash, iron oxide, and silica. Among the garnetiferous specimens in the mineral collection at Cambridge there are other types from this locality where the garnet is embedded in a groundmass composed almost wholly of biotite, frequently chloritized, or where the garnet occurs in a biotite-rich zone of a biotite-cordierite-plagioclase-spinel aggregate.

In a previous paper[1] I have referred to the rarity of almandine in normal contact metamorphism, the common red garnet in lime-poor rocks under these conditions being characteristically a spessartine-bearing variety. But at Botallack manganous oxide is but sparingly present. While this occurrence does not affect the conclusion that manganiferous garnets are to be expected in the normal contact alteration in a lime-poor environment, it does make clear that almandine can arise in thermal aureoles without the adjunct of stress or high hydrostatic pressure. No appeal to these agents can be made for the Land's End aureole. In the paper referred to (p. 50) it was stated: 'It is as yet impossible to estimate what contributory part, if any, the presence of abundant water during metamorphism—as the principal garnet-bearing aureoles reveal—plays in producing a concentration of an orthosilicate molecule as garnet.' In this connexion it may be added that the Land's End aureole is of the wet and probably low-temperature type alluded to, as is evident from the mineral paragenesis both in the sediments and the metasomatic greenstones, and in particular from the absence of potash-felspar which is so characteristic a feature of dry aureoles like Oslo and Comrie.

Origin of the hornfelses.

A summary of the principal types of hornfelses which are derivatives of the greenstones is given below.

[1] C. E. Tilley, Min. Mag., 1926, vol. 21, p. 47.

Hornblende-plagioclase-rocks (typical greenstone-hornfelses)
Hornblende-biotite-plagioclase-rocks
Cummingtonite-plagioclase ± biotite-rocks
Cummingtonite-anthophyllite-plagioclase-cordierite ± biotite
Anthophyllite-cordierite-biotite ± plagioclase
Biotite-cordierite-plagioclase-quartz ± anthophyllite

} with spinel-diaspore-bearing varieties.

The evidence of field and microscopic study leading to the conclusion that all these rock types have a genetic relationship having already been given, it remains to consider again the manner in which the fundamental changes in chemical and mineralogical composition have been brought about.

The conception that the chemical changes were brought about under the influence of intensive weathering of the greenstones followed by further changes during shearing movements is a tempting one, and was that adopted in the Kenidjack paper. After a renewed study, the writer has concluded that appeal must be made to agencies other than those of chemical weathering. The processes of weathering in action at the present day, and affecting basic igneous rocks of the composition of the Cornish greenstones, so far as they have been studied, have not yielded residuals with a closely similar chemical composition. One of the chief characteristic features of the analyses of weathered basaltic rocks is the low content of magnesia they show.

Lime, magnesia, and soda are indeed the most soluble constituents and decrease gradually and regularly with increasing residual character. This is brought out very clearly in the data set out by Merrill[1] and confirmed by more recent studies. The Kenidjack rocks show the pronounced loss in lime expected, but it is in their content of magnesia that they stand in direct contrast to weathering residuals of basic igneous rocks.

Analyses like those of the cummingtonite- and anthophyllite-rocks are not matched among available residual weathering products.[2]

[1] G. P. Merrill, Rocks, rock weathering and soils. 1906.

[2] The analysis of the weathered product of the Rowley Regis dolerite given by H. Warth (Geol. Mag., 1905, p. 21) is in some ways exceptional. The analyses of the fresh rock (I) and the weathered top (II) are given as follows:

	SiO_2.	TiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	H_2O.	P_2O_5.
I.	49·3	0·4	17·4	2·7	8·3	4.7	8·7	4·0	1·8	2·9	0·2
II.	47·0	1·8	18·5	14·6	—	5·2	1·5	0·3	2·5	7·2	0·7

Here the chief contrast between the fresh and weathered basalt is the loss of CaO and Na_2O, enrichment in K_2O, and gain in water. MgO has suffered little change. The unusual character of this analysis merits further investigation of the weathering products of the Rowley Regis dolerite.

The important chemical changes normally effected by the weathering of basaltic rocks are graphically compared with those that have operated on the basaltic greenstones of Kenidjack in fig. 6.

The view already expressed at the beginning of this paper that the chemical changes took place under the influence of solutions emanating from the granite can now be considered in more detail.

In the vicinity of Zawn a Bal, particularly on the promontory between this Zawn and De Narrow Zawn, all the rock types referred to in the foregoing account are well displayed. The metamorphosed greenstones are seen to pass by gradation into the rock types described. This gradual passage takes place not only across but laterally along the prominent banding. Hornblende-plagioclase-rocks pass thus into cummingtonite-plagioclase-biotite assemblages and into cordierite-rich types with or without anthophyllite. In various localities these transitions are especially marked in the vicinity of small zawns and fractures which have served as channels for solutions. The larger zawns mark the sites of tin or copper lodes, the vein material of which has been selectively removed by weathering agencies yielding narrow steep clefts in the cliff face.

It is considered, therefore, that hot solutions eventually emanating from a granite source have passed through the greenstones and produced an effective removal of lime with the production of anthophyllite and related types of hornfelses. The process is in reality one of contact metasomatism. It is believed that while the chief substance removed has been lime, the process has not been one of simple abstraction, but of replacement in which the constituents removed have been replaced by other material. As already noted, there has been a clear introduction of potash resulting in the formation of much biotite in some of these rocks. In comparing the analyses of the various rocks believed to be related to one another we cannot, however, use the basis of comparison instituted by Merrill, i.e. assume some constituent to remain constant. For this assumption there is no justification. A more reasonable assumption is that the chemical changes have operated without volume change. The preservation of the essential textural features of the greenstones and the absence of drusy structures is in harmony with this assumption. The analyses have therefore been recalculated in terms of equal volumes.

In table III are given in the columns numbered 3–9, the gains and losses in grams per 100 c.c. of rock, the basis of comparison being the average of the two greenstone analyses 1 and 2. The mineralogy of the greenstones has been shown to be simple but with considerable variation in the proportions of hornblende and plagioclase. Of the two analyses, one represented a rock rich in hornblende, while the

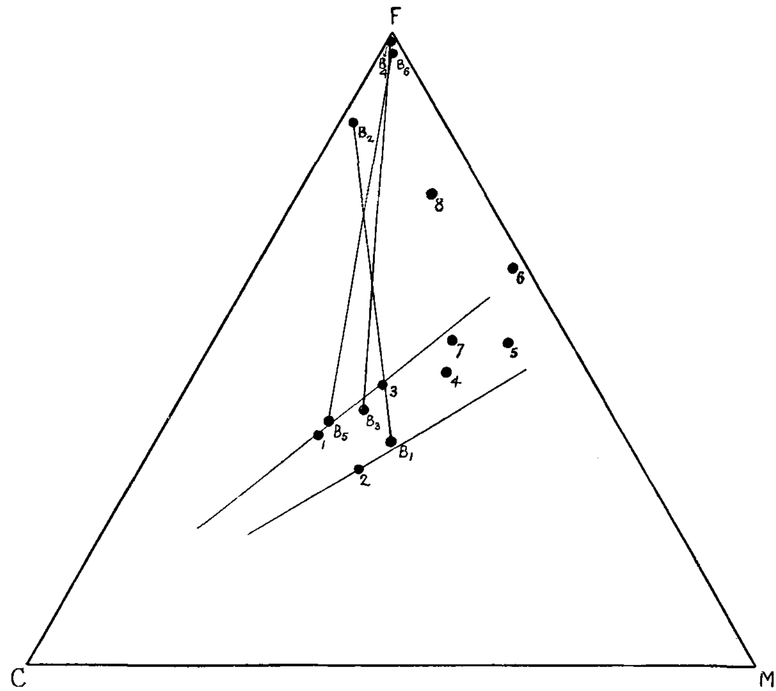

FIG. 6. Plot of analyses of the greenstones and anthophyllite-rocks of Kenidjack and Botallack, compared with analyses of basalts and their weathered products.

1–8 ... Analyses 1–8 of table I.
B_1—B_2 ... Basalt and its weathered product, Oberkassel (Zeits. Deutsch. Geol. Gesell., 1904, vol. 56, p. 1819).
B_3-B_4, B_5—B_6 ... Basalt lavas and their weathered products (Amer. Journ. Sci., 1929, ser. 5, vol. 17, p. 314).
C = [CaO]; F = [$FeO+Fe_2O_3$]; M = [MgO].

second was a banded type with 30% plagioclase. The average of these two analyses is chosen for comparative purposes. It is of course not possible to be confident that the actual analysed rocks which are compared come from a rock of identical composition;

TABLE III. Gains and losses of constituents per 100 c.c. of rock, analyses 3–9 compared with the mean of analyses 1 and 2 (table I).

	3.	4.	5.	6.	7.	8.	9.
SiO_2	*+34·2*	+ 5·7	− 2·4	*−37·2*	+ 9·0	+ 9·9	*+22·4*
TiO_2	− 0·5	+ 2·1	+ 0·2	+ 3·0	− 0·8	+ 0·4	− 4·8
Al_2O_3 ...	− 4·6	+ 6·3	*+15·4*	− 7·4	*+14·9*	+ 4·6	*−17.9*
Fe_2O_3 ...	− 4·3	− 3·9	− 4·3	*+30·0*	− 3·7	+ 8·6	− 2·0
FeO	− 1·3	+ 4·7	+ 3·6	*+19·8*	*−11·8*	+ 1·3	*+47·3*
MgO	− 9·6	− 0·4	+ 0·5	*+18·5*	*−14·7*	*−17·4*	*−21·7*
CaO	*−23·9*	*−28·8*	*−38·7*	*−42·2*	*−38·0*	*−40·5*	*−41·3*
Na_2O ...	− 0·7	+ 1·0	+ 0·5	− 1·9	+ 2·4	+ *6·6*	− 3·0
K_2O	− 1·3	− 0·9	+ 4·0	− 0·7	*+11·6*	+ *6·6*	+ *7·2*
&c.	− 1·0	− 1·5	+ 0·7	+10·0	+ 1·2	− 0·5	+ 3·3
Totals ...	−13·0	−15·7	−20·5	− 8·1	−29·9	−20·4	−10·5

nevertheless the range of chemical composition of the original greenstones is not so great that some valid comparisons cannot be drawn. When the figures tabulated in table III are inspected, the features that can be considered significant are as follows:

1. Lime is the chief oxide that has been removed, falling from 14 % in the greenstones successively to under 1 % in the anthophyllite-cordierite-spinel-diaspore-hornfels.

2. Silica has clearly been added in some examples, in 3, 7, 8, and 9. This addition of silica is supported also by the microscopic characters of the rocks indicated. In the cummingtonite-plagioclase-hornfels (table I, analysis 3, table III, no. 3) quartz is present among the plagioclase bands (Ab_1An_1) and also forms in narrow venules. The cordierite-biotite-hornfelses (nos. 7 and 8) contain clear quartz in nests amongst the biotite and cordierite areas, which form excrescences on the weathered surface. It has already been remarked that this variety of hornfels in the field is frequently crossed by numerous veins of introduced quartz, whereas the surrounding greenstones are usually free from these veins. The grunerite-biotite-quartz-hornfels has clearly also suffered an introduction of silica, and plagioclase is scarcely represented in its constitution. On the other hand, one rock—the cordierite-anthophyllite-spinel-diaspore-rock—is a basic type which has lost silica.

3. Iron oxides. The most striking example of accession of iron oxide is the grunerite hornfels (no. 9) containing 26·75 % FeO. It is this rock which is the home of the analysed almandine garnet. Accession of iron oxide is also unmistakable in no. 6, revealed in abundant spinel and magnetite, and in the cordierite-biotite-hornfels

(no. 8), which contains abnormal amounts of ferric oxide in the form of magnetite.

4. Magnesia. The only rock where addition of magnesia can be confidently postulated is the anthophyllite-cordierite-spinel-diaspore-hornfels with a content of 15·55 % MgO. This rock appears to have suffered loss of lime and silica and received notable gains in iron oxides and magnesia. The biotite-cordierite-hornfels and the grunerite-biotite-hornfels, on the other hand, have lost magnesia.

5. Alkalis. The biotite-rich hornfelses (nos. 7, 8, and 9) reveal a clear addition of potash and no. 8 an addition of soda. This deduction is supported by their richness in biotite and the presence of considerable albite-oligoclase in no. 8 associated with quartz forming nests of introduced material. Of the other oxides, alumina must be considered removed in the grunerite-hornfels (Al_2O_3 8·40 %) and has possibly been added in nos. 5 and 7. The small changes in the alumina of the remaining rocks cannot be considered significant.

The examination of tables I and III makes it evident that the metasomatism effected has been a consistent removal of lime partly compensated by additions of silica, iron oxides, and alkalis, more particularly potash, but that these gains are not revealed throughout the series (fig. 7). Replacement has resulted in the development of rock types of less density.

Among the common end-products of metasomatism of the greenstones is a biotite-cordierite-hornfels, which mineralogically is closely similar to the mineral assemblage of contact altered normal shales. Like the anthophyllite-cordierite-rocks, however, the biotite-cordierite-hornfelses show certain chemical peculiarities, viz. richness in iron oxides and magnesia, inherited from their parent rock. The chemical characters of these rocks compared to those of normal shales, slates, and mica-schists is indicated in fig. 8. Mineralogically, the metasomatism is expressed in replacement of green hornblende areas by cummingtonite and anthophyllite, and the plagioclase gives place eventually to cordierite. It is clear, however, that we cannot explain the process by any simple equation which represents it as an exchange of ferrous oxide and magnesia for lime.

The removal of lime from green hornblende leaves Mg, Fe, Si, and Al in excess of that required for cummingtonite, or alternatively an excess of Si and Al. The incoming of the magnesia-iron-amphiboles and the disappearance of green hornblende probably involves a complex change in which the removal of lime from the rock is accompanied by internal migration of magnesia and iron oxide as well as alumina. The green hornblende of these greenstones, as has been shown, must have contained in many cases high percentages of alumina which is unrepresented in the new cummingtonite formed. The cummingtonite analysed (table I, no. 10) contains only 2·78% Al_2O_3. Among

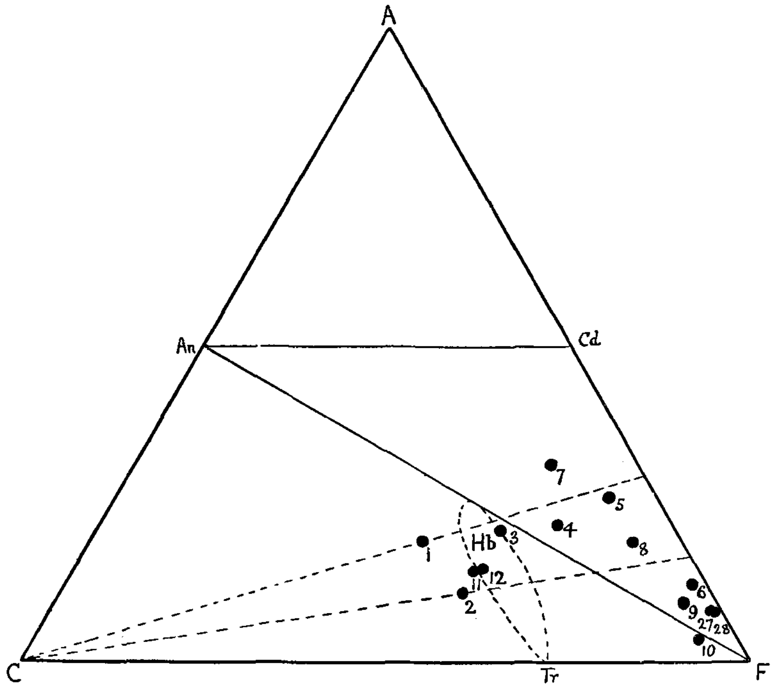

FIG. 7. Plot of analyses of greenstones, anthophyllite- and cummingtonite-rocks of Kenidjack and Botallack.

1–10	...	Analyses 1–10 of table I.
11	...	Average plateau basalt (Proc. Amer. Acad. Arts and Sci., 1925, vol. 60, p. 73).
12	...	Hornblende-schist, Meneage, Cornwall (Geol. Lizard and Meneage, Mem. Geol. Surv., 1912, p. 48).
27–28	...	Anthophyllite analyses, Orijärvi region (Bull. Comm. Géol. Finlande, 1915, no. 44, p. 59).

$A = [Al_2O_3-(K_2O+Na_2O)]$; $C = [CaO]$; $F = [FeO+MgO]$.

An = anorthite; Cd = cordierite; Hb = field of hornblendes; Tr. = tremolite.

analysed members of the cummingtonite-grunerite series there seem to be no representatives rich in sesquioxides, such as are found among the anthophyllite-gedrite series.

The formation of cordierite in place of plagioclase, appearing only when all green hornblende has disappeared, is to be regarded as a replacement of lime by magnesia and ferrous oxide derived in part from the hornblende→cummingtonite (anthophyllite) conversion. Such internal migration is made evident by residual plagioclase

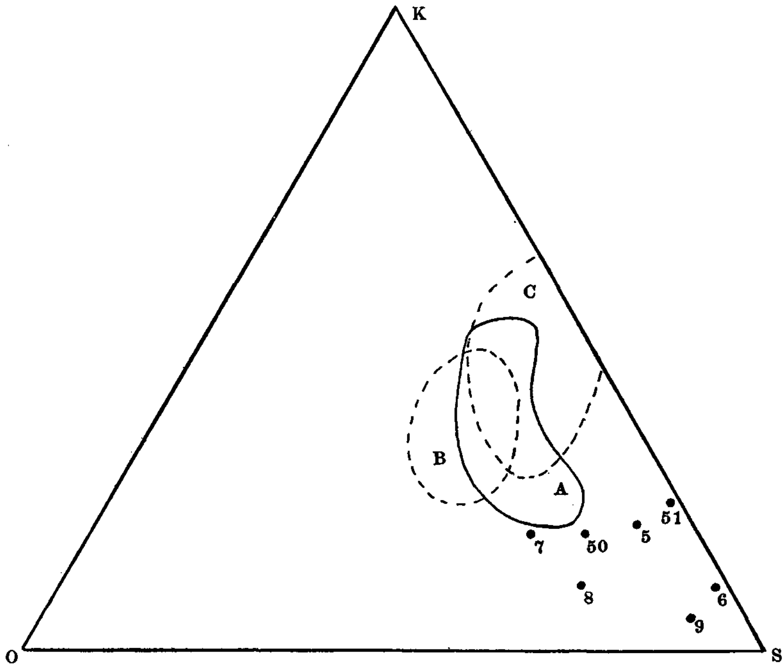

Fig. 8. Plot of analyses of the anthophyllite-cordierite-rocks, &c., of Kenidjack and Botallack in relation to the concentration fields of slates (A), mica-schists (B), and chloritoid-schists (C).

5–9 ... Analyses 5–9 of table I.

50–51 ... Analyses of similar rocks from the Orijärvi region (Bull. Comm. Géol. Finlande, 1915, no. 44, pp. 65–66).

O = [K_2O+Na_2O]; K = [$Al_2O_3-(K_2O+Na_2O+CaO)$]; S = [$FeO+MgO$].

in the cordierite areas which still retain the ilmenite streams of the original greenstones, and the formation of narrow veins of cummingtonite traversing the hornfelses.

Introduction of potash from without is responsible for biotite which characterizes many of these hornfelses, sometimes in abundance. The mica takes the place of cordierite or eventually of the amphiboles. Pseudomorphs of biotite after cummingtonite can be recognized, and the replacement of plagioclase areas by felts of biotite containing plagioclase residuals make clear the metasomatic exchange which has operated in these hornfelses.

In the development of spinel and diaspore together with clinochlore in some of the early stages of alteration of the greenstones the same process is effective.

Comparison with rocks of other areas.

Among published data probably no closer comparison could be made of the Kenidjack rocks than with those of the Amulet mines, Quebec, and the cordierite-gedritites of the Bamle formation, southern Norway.

1. Amulet mines, Dufresnoy township, Quebec.[1]—The chief rocks of the Amulet mines are Keewatin rhyolites and dacites. Particularly along the boundaries of these two lava groups sulphide ore-bodies (pyrite, pyrrhotine, chalcopyrite, and zinc-blende) have been introduced and these are surrounded by areas of mineralization within the lavas. The dacites in the mineralized zones suffer fundamental changes in composition with the production of cordierite-bearing types including the rock styled *dalmatianite*. The authors of the Survey Memoir (1931) in describing these alterations state that dacite, constituted of biotite 3–4, quartz 2–3, green hornblende 40, and oligoclase 50–55 %, is first converted to a rock made up of biotite 40, quartz 15, recrystallized actinolite 5–10, and oligoclase 35–40 %. In a later stage of alteration they are converted to a spotted rock made up of quartz, chlorite, 'colorless hornblende' with a very small extinction-angle, the spots consisting of sericitic aggregates including within themselves numerous quartz grains. The sericitic aggregates are tentatively referred to altered cordierite. A final stage is recorded from the mine in which the matrix is wholly chlorite with some 'hornblende', and the spots are recognized as cordierite. Some of these altered rocks have been studied and analysed by Dr. T. L. Walker, who has given a description of the chief types. Dr. Walker has kindly forwarded to the writer specimens of the rocks analysed together with a specimen of typical dalmatianite. This is a white spotted rock with large spots of cordierite showing sieve

[1] H. C. Cooke, Summ. Report Geol. Surv. Canada, 1925, part C, p. 41; T. L. Walker, Univ. of Toronto Studies, Geol. Series, 1930, no. 29, p. 9 [M.A. 4-401]; H. C. Cooke, W. F. James, and J. B. Mawdsley, Mem. Geol. Surv. Canada, 1931, no. 166, pp. 206–218.

texture with numerous quartz and biotite enclosures and occasionally small grains of green spinel set in the cordierite. The matrix between the spots is composed principally of biotite with some quartz.

The three analysed rocks are rich in cordierite. One is a cordierite-biotite-quartz-hornfels with a fair proportion of oligoclase; the second is an anthophyllite-(with cummingtonite)-cordierite-quartz-biotite-hornfels; while the third, a more basic type, has a groundmass rich in chlorite with brown biotite and contains clear spots of twinned cordierite with sheafed aggregates of anthophyllite. Numerous scattered idioblasts of green spinel occur both in the matrix and in the cordierite. The rock types produced at the Amulet mines are clearly from these descriptions closely allied to the rocks of Kenidjack. The field data in the Survey reports—the close association of the spotted and altered rocks with the ore-bodies—make it abundantly clear that they owe their development from the dacites (and rhyolites) to the passage of solutions associated with the copper ore-bodies. At Kenidjack the parent rocks and the metasomatic products were typically more basic.

2. Kragerø region.—In a recent memoir Brögger[1] has described in the Kragerø district of southern Norway, cordierite-gedritites which appear everywhere to be connected with amphibolites or amphibolitic schists. The gedrite-bearing rocks also include gedrite-plagioclase types (Skåtø type) of the Bamle formation, and these are linked by transitional varieties with the cordierite-bearing members. They are interpreted by Brögger 'as a special facies of the amphibolites or perhaps as rocks originated by the metamorphosis of amphibolites (eventually by the carrying away of certain amounts of CaO and alkalis)'. These rocks in their association with basic igneous rocks clearly have a similar chemical environment to those of Kenidjack, but beyond the conclusion already stated above Brögger gives no detailed discussion of their precise mode of origin.

During the last twenty-five years, anthophyllite-cordierite-rocks, rather similar to the Kenidjack type, have been recognized in numerous localities of Sweden and Finland (Grängesberg, Falun, Riddarhyttan, Orijärvi, &c.), more particularly by the work of Johansson, Eskola, and Geijer.[2]

[1] W. C. Brögger, Vid.-Selsk. Skrifter, I. Math. Naturv. Kl. 1934, no. 1, p. 225.

[2] H. E. Johansson, Geol. För. Förh., 1910, vol. 32, p. 239; P. Eskola, Bull. Comm. Géol. Finlande, 1914, no 40; P. Geijer, Årsbok Sveriges Geol. Unders., 1916, vol. 10, no. 1, and Kungl. Kommerskoll. beskriv. mineralfyndig., 1923, no. 1.

The studies of Eskola and Geijer have led these authors to conclude that anthophyllite-cordierite-rocks in the Fennoscandian pre-Cambrian have arisen by metasomatic processes affecting more particularly siliceous leptites. The introduced materials include particularly magnesia and iron oxides, and the process has often been referred to under the term magnesia-metasomatism. The writer must confess that he originally felt somewhat sceptical of the reality of the magnesia-metasomatism suggested by Eskola and Geijer for the genesis of these rocks, more particularly as at Orijärvi there were abundant basic intrusions—amphibolites—often associated with them. He therefore takes this opportunity of adding that he has recently had the privilege of visiting the Orijärvi area under the guidance of Professor Eskola and has been convinced that many of the anthophyllite-cordierite-rocks show a metasomatic relation to siliceous leptites. The gradual transitions that can be followed at Orijärvi between the leptites and the cordierite-anthophyllite-rocks, and the intimate association of the 'ore quartzites' with the sulphide ore-bodies, make clear the operation of metasomatic solutions carrying in magnesia and iron oxides.

The Kenidjack rocks can thus be brought into line with the similar rocks of Sweden and Finland with this important difference, that in the former case the parent rocks were essentially basic and the metasomatic processes involved a widespread removal of lime, accession of silica, alkalis, particularly potash, and an *internal* magnesia-metasomatism as contrasted with an accession of magnesia characterizing the Orijärvi and Falun regions.

EXPLANATION OF PLATES VI AND VII.

Greenstone-hornfelses of Kenidjack and Botallack, Cornwall.

PLATE VI, FIG. 1. Zawn a Bal promontory. Greenstones below passing upwards through cummingtonite-biotite-hornfelses into cordierite-anthophyllite-rocks (ball rock).

— FIG. 2. North face of Zawn a Bal, Botallack, showing greenstones on the left below with anthophyllite-cordierite-rocks (veined) above. Below on the right bands of cummingtonite-hornfelses.

PLATE VII, FIG. 3. Zawn a Bal. Striped greenstones passing to cummingtonite-biotite-plagioclase-hornfelses and cordierite-bearing types.

— FIG. 4. Pillow lavas, south-west side of Kenidjack cliff.

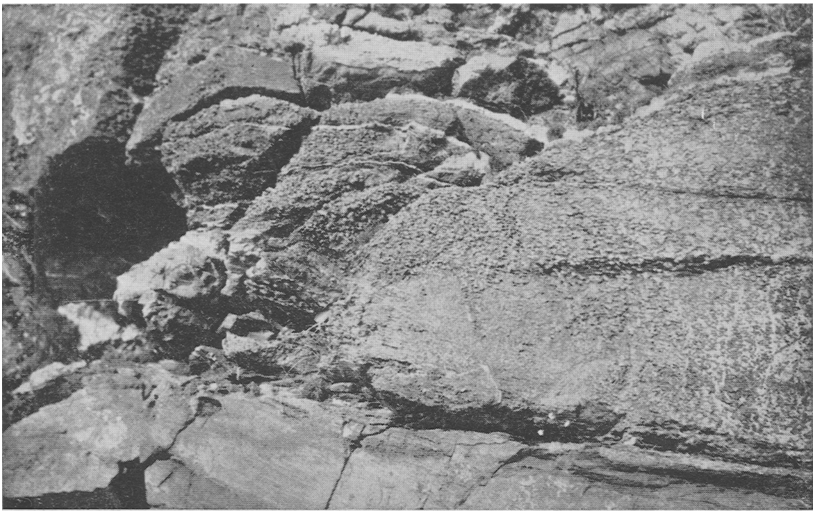

Fig. 1

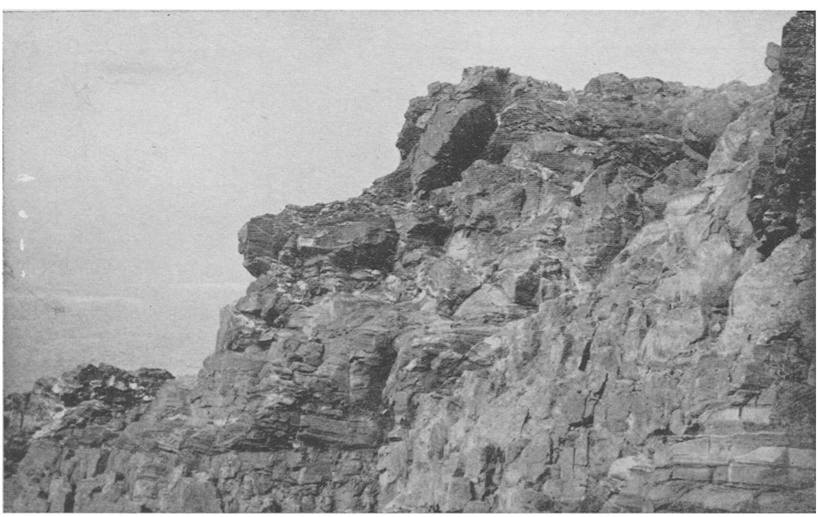

Fig. 2.

C. E. TILLEY: GREENSTONE-HORNFELSES, CORNWALL

Fig. 3.

Fig. 4.

C. E. TILLEY: GREENSTONE-HORNFELSES, CORNWALL