THE PETROLOGY OF THE HARTLEY DISTRICT. III.

THE CONTACT METAMORPHISM OF THE UPPER DEVONIAN (LAMBIAN) SERIES.

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(Plate i; three Text-figures.)

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Introduction and Previous Records.

The contact altered sediments of the Hartley district belong to the Lambian Stage (Brown, 1931) of the Upper Devonian Series. There are various records of the contact effects produced by the Hartley–Bathurst bathylith, but a number of these describe altered rocks that belong to a different sedimentary series. C. S. Wilkinson (1877) reported on the occurrence of wollastonite, epidote and garnet in rocks from Kirk's Farm on the Fish River, near Oberon; and as far as the present writer is aware these are altered Lambian sediments. The earliest record of the Hartley hornfelses themselves is to be found in a note by G. W. Card (1896) in which he describes a series of specimens forwarded to him by Curran, Ball and Rienits (1896). In his report to the Metamorphic Committee of Section C at the Hobart Meeting of the Australasian Association for the Advancement of Science (1928), W. R. Browne gives a later reference to the Hartley hornfelses, and they are again mentioned in the Sydney Handbook of the Australian and New Zealand Association for the Advancement of Science (1932). No detailed work, however, has been done on this aureole, and it is hoped that the present paper will contribute to our knowledge of this large and interesting bathylith.

Herein is given a detailed account of the metamorphism of the Lambian series, which consists of arenaceous, argillaceous and areno-calcareous sediments with intercalated lavas of acid and intermediate character.

Sequence and Structure.

It has been found convenient to divide the Lambian Stage, as developed at Hartley, into an upper and a lower series. The upper consists essentially of quartzites and is unfossiliferous. The lower includes all those types that are associated with the fossiliferous quartzites.

The upper series is found capping the spurs of the entrenched Cox's River and its tributaries. It is directly overlain by the Kamílaroi Upper Marine, and is usually deeply weathered. There appears to be little variation in the rock type, but this may be due to weathering which tends to produce uniformity. Highly jointed quartzites with intercalated "purple-hornfelses" comprise the upper series.

The lower series outcrops along the river and in the beds of the tributary creeks, and good unweathered sections may hence be obtained. Massive quartzites, crowded with *Spirifer disjunctus*, and interbedded with bands of "purple-hornfels" of varying width, are by far the most prominent beds in this series. Grits passing in places into conglomerates, calcareous cherty rocks and argillaceous types are developed to a lesser extent. Sills of altered porphyrite occur on several different horizons, and it is believed that the felsites outcropping on Cox's River, on Pine Ridge Creek, and on Moyne Farm, represent a flow at the base of the lower series. As most of the hornfelses with which this paper deals were collected from the lower series, it is pertinent to describe this series in a little further detail.

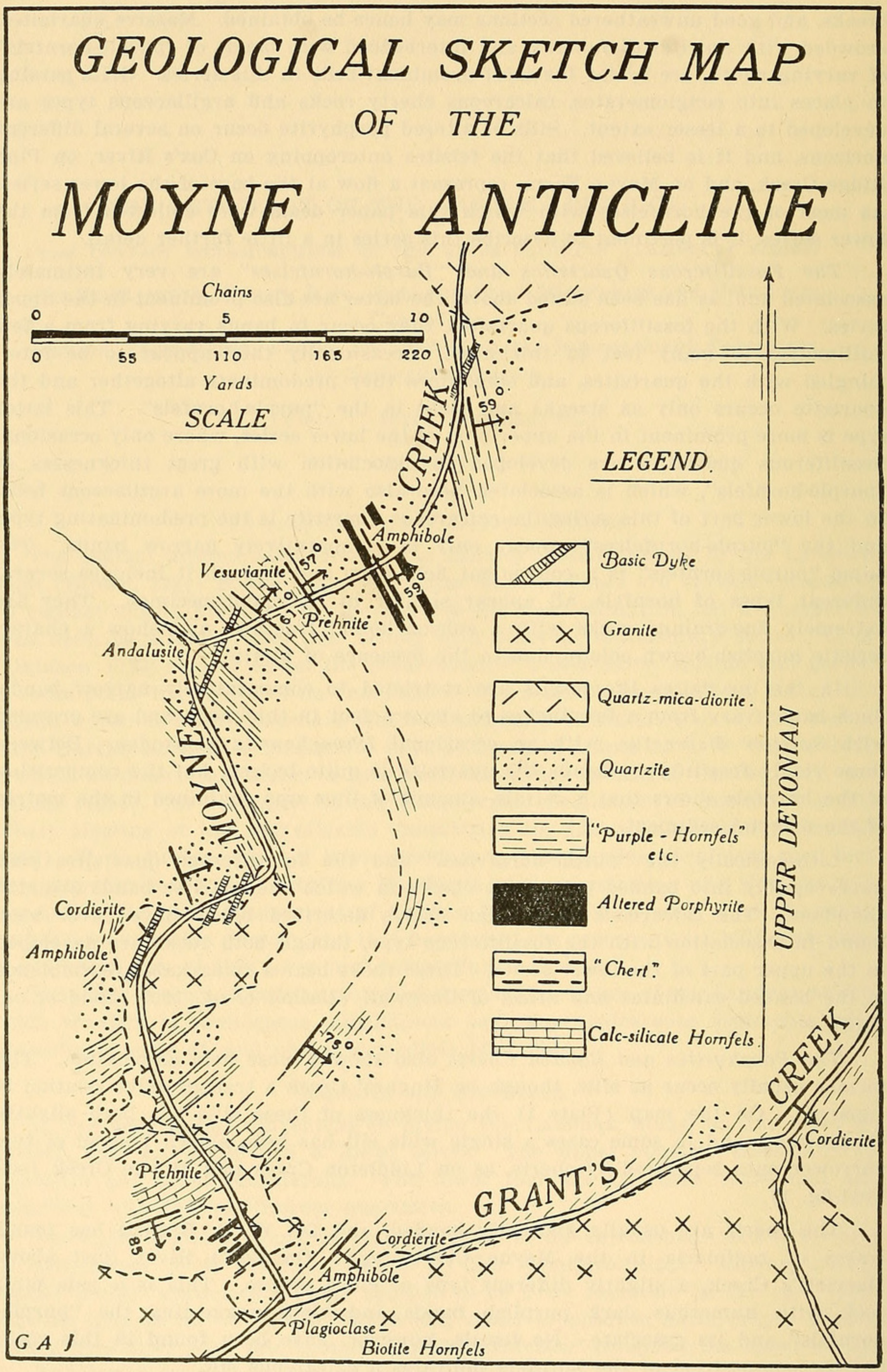
The Fossiliferous Quartzites and "Purple-hornfelses" are very intimately associated and, as has been stated above, the latter are also prominent in the upper series. With the fossiliferous quartzites, they occur in bands varying from a few millimetres to many feet in thickness. Occasionally they appear to be intermingled with the quartzites, and sometimes they predominate altogether and the quartzite occurs only as streaks and blebs in the "purple-hornfels". This latter type is more prominent in the upper part of the lower series, where only occasional fossiliferous quartzites are developed in association with great thicknesses of "purple-hornfels", which is associated here also with the more argillaceous beds. In the lower part of this series the calcareous quartzite is the predominating type, and the "purple-hornfelses" appear only in comparatively narrow bands. The name "purple-hornfels" is a convenient field term and, though it includes several different types of hornfels, all appear similar in the hand-specimen. They are extremely fine-grained rocks with a subconchoidal fracture, and show a characteristic purplish-brown colour, due to the presence of biotite.

In the quartzites the fossils are restricted to comparatively narrow bands. Such bands vary from a few inches to about a foot in thickness, and are crowded with *Spirifer disjunctus*, with an occasional *Rhynchonella pleurodon*. Between these richly fossiliferous bands the quartzite is quite barren, but the composition of the hornfels shows that a certain amount of lime was contained in the matrix of the original sediment.

Lithologically the "purple-hornfelses" and the fossiliferous quartzites pass imperceptibly into banded calcareous cherts in which the *Spirifer* bands are still abundant. The calcareous radiolarian cherts described below have never been found in association with the fossiliferous type, though both rocks are developed in the upper part of the lower series. These rocks bear a remarkable resemblance to the banded calcflintas and killas of Cornwall (Ussher *et al.*, 1909; Reid *et al.*, 1910).

The Porphyrites and Banded Cherts also show a close field association. The former usually occur as sills, though on Hughes' Creek a transgressive relation is apparent. On the map (Plate i) the thickness of these sills has been slightly exaggerated, and in some cases a single wide sill has been shown instead of two narrower ones separated by cherts, as on Liddleton Creek and Moyne Creek (see Text-fig. 1).

The cherts are usually distinctly banded, and Dr. W. R. Browne has found traces of radiolaria in the Moyne Creek type. On Cox's River, just above Marriott's Creek, a slightly different type of chert occurs. This is a pale pink rock with numerous dark purplish bands and blebs suggesting the "purple-hornfels" and its associate. No fossils, however, have been found in this rock, but the composition of the hornfels indicates a calcareous silt.


GEOLOGICAL SKETCH MAP
OF THE
MOYNE ANTICLINE
Chains
0 5 10
0 55 110 165 220
Yards
SCALE
LEGEND.
Basic Dyke
Granite
Quartz-mica-diorite.
Quartzite
"Purple - Hornfels" etc.
Altered Porphyrite
"Chert"
Calc-silicate Hornfels
UPPER DEVONIAN
MOYNE
CREEK
GRANT'S
CREEK
Amphibole
Vesuvianite
Prehnite
Andalusite
Cordierite
Amphibole
Prehnite
Cordierite
Amphibole
Plagioclase - Biotite Hornfels
Cordierite
57°
61°
59°
59°
75°
85°
G A J

Text-fig. 1.

With regard to the structure of the Devonian beds, it has already been stated (Joplin, 1933) that they occupy a broad syncline between the northern and southern outcrops of granite. The major fold, which trends approximately east and west and pitches to the east, is turned over abruptly into sharp anticlines at the granite contacts. The basic stocks of the plutonic complex (Joplin, 1931, 1933) are injected into the trough of the syncline, and there is reason to believe that they are associated with fault zones.

The exact nature of the felsites on Cox's River and on Pine Ridge Creek is doubtful. They may represent pre-granite intrusions of an irregular nature, which have been subsequently contact-altered by the granite; or, what seems more likely, they may represent a basal flow which has been duplicated by faulting.

Reference to Plate i will show that the sequence of the beds indicates a repetition which is suggestive of a north-south fault along the western boundary of the eastern felsite. Actually there are indications of brecciation both in the felsite and in the adjacent calcareous beds along this margin, and the felsites are very highly jointed. Minor faults have been observed on the north-eastern margin of the felsite; and the displacement of the anticlinal axis is again suggestive of a north-south fault with a throw to the west.

It is difficult to correlate the Moyne Creek section without postulating another fault of considerable magnitude. The close association of the porphyrites and cherts on Moyne Creek and Liddleton Creek suggests a datum horizon. The occurrence of a small patch of felsite on Moyne Farm is another difficulty that might be explained by faulting.

It is not improbable that complex faulting would occur along a contact where there have been successive periods of injection. Only detailed mapping and contouring of this fairly rugged area will show the extent of such faulting and, as far as the present study is concerned, there is little to be gained from a piece of work that would involve such an expenditure of time. Nevertheless, the writer has pointed out (1933) that the nature of the Cox's River Intrusion is suggestive of faulting in that area, and it seems not impossible that both the basic stocks have been associated with fault zones. Moreover, if no faulting be postulated, there would be an unbroken succession of Lambian strata over a distance of about four miles from east to west, and as the dip is usually at a high angle, this would give an abnormal thickness. On the other hand, if faults be assumed to be present west of the river and west of Moyne Creek, an approximate estimate gives a thickness of about 2,000 feet, which is in accord with more recent observations at Rydal.

On Plate i certain of the arrows indicating dips do not show the amount of dip. Where the amount of dip is indicated, measurements have been made with a clinometer rule, and where such is not shown, general compass directions have been taken along the strike of the bed.

Correlation with the Type Section at Mt. Lambie, Rydal.

In 1896 G. W. Card pointed out that the Hartley sediments "may be regarded as the eastern extension of the Mt. Lambie Beds". In the Rydal district, as at Hartley, *Spirifer disjunctus* occurs abundantly in restricted bands in a massive quartzite. On Mt. Lambie these beds are apparently unmetamorphosed and this prompted the writer to look for the bands corresponding to the Hartley "purple-hornfelses". They were found to be represented by soft reddish-purple shaly rocks which readily weather away, and appear quite insignificant among the resistant quartzites. That the "purple-hornfelses", in their unaltered condition, correspond to the so-called "red shales" is further supported by the presence of an occasional pebble of "red shale" in the Kamilaroi conglomerate at Hartley. It is possible that these soft red rocks represent either fine-grained periodically extruded tuffs, or fine silts brought down by floods. A microscope examination of the Rydal rock shows small angular fragments of quartz and lends support to the former view. This material, whatever be its origin, has possibly been responsible for the sudden periodic killing off of the Spirifers, which evidently formed massive shell banks along the shallow coast.

At Rydal the Spirifer beds pass up into grits, "red shales", buff shales and quartzites and, if the so-called "red shales" may be taken as the equivalents of the "purple-hornfelses", the sequence at Rydal closely corresponds to that at Hartley.

To the west of Mt. Lambie, below the Spirifer beds, there is an igneous rock, which may correspond to the basal felsite at Hartley.

As far as the present writer is aware, there are no porphyrites in the Rydal district, and only one bed of calcareous chert is known. This occurs near the top of the series just to the west of Rydal railway station. It is probable that the sills and their associated cherts are developed quite locally at Hartley.

At Rydal the general direction of strike is north and south, whilst at Hartley (10 miles distant from Rydal) the axes of the folds trend approximately east and west. It is possible that the intrusive masses of granite to the north and south of Cox's River at Hartley have acted as the jaws of a vice in which the sediments have been squeezed into their present position.

Width of the Contact Aureole.

There are three difficulties in the way of measuring the width of the contact aureole, and of zoning the progressive changes as the igneous boundary is approached: (1) Owing to the close proximity of the overlying Kamilaroi strata, no unaltered Devonian rocks are exposed, and there is thus no standard of comparison; (2) the contacts of the basic stocks and of the granite are so close that if a bed be traced out of the aureole of one intrusion it immediately enters that of another; (3) apophyses some distance from the apparent boundary, as well as large inclusions of sediments in the igneous rocks, suggest that the roof of the bathylith has not been completely removed; there is reason to believe, therefore, that the gradient of the intrusions is fairly shallow, and thus linear distances measured from the apparent contact are obviously incorrect. For reasons stated above, therefore, very little information may be gained by tracing a single bed along its strike, but in the next section it will be shown that some idea of the intensity of metamorphism, and of the width of the inner zone of hornfelses, may be gained by an examination of a series of specimens of the same rock type from different parts of the area.

The first of these difficulties may be overcome to some extent by a comparison with unaltered rocks at Rydal.

In the petrographical sections, distances from the apparent contact are always stated, but it must be borne in mind that these are not necessarily correct, and that the actual contact may be much closer. The section dealing with incipient metamorphism indicates some of the anomalies that arise, if this be disregarded.

In a general way, it may be stated that the contact is widest in the arenaceous, areno-calcareous and calcareous chert beds, and less wide in those that contain an appreciable amount of shaly material. Thus it is shown that calc-silicates, such as diopside, amphiboles and epidote, may develop as well-formed minerals, when associated more argillaceous rocks show only an incipient development of biotite.

As it seems very evident that distances cannot be measured from the true contact, it is useless to give figures for the width of the inner zone of hornfelses.

Incipient Metamorphism.

It has been shown above that difficulties attend the study of this phenomenon, and the present section deals with a description of unmetamorphosed specimens from Rydal, and of scattered rocks at the greatest possible distance from the contact at Hartley. The main rock types that have given rise to the hornfelses in the Hartley district are: (i) "red shales", (ii) fossiliferous quartzites, (iii) calcareous cherts, (iv) sandstones and grits, (v) normal shales.

(i) Two of the so-called "red-shales" from Rydal have been examined, and are found to consist of small angular chips of quartz and a little alkaline felspar set in a matrix of chlorite with a small quantity of white mica. Greenish biotite, magnetite, sphene, zircon and tourmaline are accessories. The chlorite is much stained by haematite, which gives the rock its red colour.

In the Hartley region a rock in Deep Ravine, at a distance of 660 yards from the apparent contact, shows some evidence of metamorphism. It is exactly similar to the "purple-hornfelses" in the hand-specimen, but under the microscope a slightly clastic structure is apparent and the rock consists of quartz and alkaline felspar grains surrounded by a matrix of tiny flakes of greenish-brown mica and a little chlorite. This rock is something of an anomaly, and the contact is possibly closer than is apparent. The typical reddish-brown authigenic biotite has been noted at a distance of about 450 yards from the contact, and incipient brown biotite enters at 580 yards.

(ii) Fossiliferous quartzites from Mt. Lambie and from Solitary Creek, Rydal, have been examined, and in both cases calcite is conspicuously absent. Occasionally groups of calcite crystals have been noted in the field, and it appears that the carbonates have been removed by leaching. Though unaffected by contact metamorphism, the Rydal quartzites show evidence of silicification, which is possibly due to cementation (Van Hise, 1904), and it would appear that the lime had been removed during this process. In the hornfelsed type, where lime is fixed in the form of a silicate, it may be preserved. Both quartzites consist of quartz and a little alkaline felspar in a matrix of chlorite. Accessories are white mica, sphene, magnetite and haematite. It is believed that the fossiliferous quartzites at Hartley originally had a composition rather similar to this, and that calcite was present in the matrix as well.

At Hartley the fossiliferous quartzites do not occur at a greater distance than 580 yards from the contact, and at this distance the effects of thermal metamorphism are apparent. Hand-specimens show well preserved fossils and "nests" of secondary calcite crystals.

Under the microscope the rocks still show their clastic structure, but the fine-grained groundmass is entirely recrystallized and consists of quartz, basic plagioclase, diopside, amphibole and sphene. Small patches of calcite are also present, and though they appear to have been recrystallized, the temperature has not been sufficiently high for the formation of wollastonite. Wollastonite occurs abundantly at the actual contact in several localities and has never been found at a greater distance than 350 yards from the apparent contact. In most of these cases wollastonite may be seen replacing the actual fossil, and recognizable Spirifers, partly changed to wollastonite, have been collected within a few inches of the contact. Shells pseudomorphed by aggregates of diopside, sometimes containing a little epidote or amphibole, have been noted at 580 yards, and the associated "purple–hornfels" bands show a development of incipient biotite.

(iii) One example of calcareous chert has been collected in the Rydal district, and it is quite unaffected by thermal metamorphism. It is a very fine-grained rock consisting mainly of quartz with a matrix of chlorite and a little calcite. Magnetite, biotite and a little plagioclase are also present, and zircon occurs as an accessory. No specimen of this rock has been found outside the inner zone of hornfelses at Hartley.

(iv) A rock occurring on top of the ridge between Deep Ravine and Bonnie Blink Creek lies at a distance of about 850 yards from the granite, but in the hand-specimen it is a fairly typical quartzite.

Under the microscope, however, there is a distinctly clastic structure apparent. Large (0·4 mm.) somewhat rounded grains of quartz and alkaline felspar are surrounded by a matrix of sericite and a little chlorite, and minute flakes of incipient biotite are just discernible. Magnetite and zircon are accessories.

(v) No unaltered or partly altered normal shales are known.

From these scanty observations it would appear that the width of the contact varied in the different beds and that the calcarous rocks responded to the thermal effects before the more argillaceous types.

In the more porous sandstone hornfelses incipient biotite is noted at 850 yards, but in the more compact "red-shales" it does not make its appearance until within 580 yards of the contact.

Petrography of the Hornfelses of the Inner Zone.

(i) *Andalusite-cordierite-biotite Hornfelses.*

Three examples of this class have been recorded from different parts of the aureole. They are fine-grained, dense, dark grey rocks. One, near the road crossing on the southern branch of Grant's Creek, at a distance of 880 yards from the granite and 660 yards from the diorite, shows a faint spotting, which under the microscope is seen to be due to aggregates of quartz grains associated with andalusite and flakes of muscovite.

A rock from Moyne Creek, at a distance of 130 yards from the granite and 300 yards from the diorite, is fairly typical of this class. Its structure is grano-blastic with an average grainsize of about 0·15 mm. The constituent minerals are quartz, andalusite, altered cordierite, biotite, orthoclase, magnetite and a little muscovite, chlorite and tourmaline. Rutile and sphene have been noted as accessories in rocks of this class.

The andalusite occurs in small stumpy prisms (averaging 0·1 mm.), which often show a strongly pleochroic rose-pink core. There is a slight marginal alteration to sericite. The cordierite is entirely altered into a green micaceous substance, and occurs in large aggregates of ill-formed stumpy prisms, or more commonly as xenoblasts. Small flakes of biotite are associated with these pseudo-morphs and probably represent inclusions in the original cordierite. Deep-brown biotite ($\alpha' = 1{\cdot}592$, $\gamma' = 1{\cdot}637$) occurs in poikiloblastic flakes measuring up to 0·3 mm., and, though more frequently associated with the cordierite areas, is present to a lesser extent in the andalusite-quartz and andalusite-quartz-orthoclase areas.

A partial analysis of this rock is shown in Column I below:

	I.	II.	
SiO_2	67·00	62·80	
Al_2O_3	16·34	19·74	
Fe_2O_3	0·75	0·00	
FeO	4·34	1·98	
MgO	1·16	1·34	
CaO	0·66	0·87	
Na_2O	2·14	1·22	
K_2O	5·44	6·56	
H_2O+	2·38	0·27	Loss on Ignition, 2·71
H_2O-		0·86	
C	—	1·58	
TiO_2	0·03	1·36	
P_2O_5	abs.	0·60	
MnO	pnd.	0·02	
S	nd.	0·52	
	100·24	99·72	
Less O=S		0·23	
		99·49	

I. Andalusite-cordierite Hornfels, Moyne Creek, Por. 124, Parish of Hartley. Anal. G. A. Joplin.

II. Andalusite-cordierite Hornfels (Class 1), Gunildrud, Contact of Soda-Granite, Christiania. Anal. M. Dittrich. V. M. Goldschmidt, Die Kontaktmetamorphose im Kristianiagebiet. *Videnskap. Skrift.* I. Math.-Nat. Kl., No. 1, p. 148, 1911.

It appears that the main difference between these rocks lies in the greater abundance of andalusite and orthoclase in the Christiania hornfels, and the excess of quartz, biotite and magnetite in the Hartley rock.

In the field this rock is closely associated with a rather mottled, lighter grey hornfels. Under the microscope these are essentially the same, but the latter contains in addition an abundance of white mica and tourmaline. The biotite is also somewhat altered to chlorite. A very similar type of hornfels occurs on Cox's River below the mouth of Marriott's Creek at a distance of 400 yards from the diorite.

A very much altered rock is met with on Bonnie Blink Creek, and it is possible that it may belong to this class. In the hand-specimen it is a banded grey hornfels with rows of black rectangular spots which consist entirely of sericite and muscovite. Remnants of cordierite have been recognized, and it is possible that the dark spots were originally andalusite.

(ii) *Andalusite-biotite-orthoclase Hornfels.*

A rather unique type has been collected as a boulder in Bonnie Blink Creek. It is light purplish-grey rock containing abundant pinkish-white spots which measure about 6 mm. and stand out in relief on weathered surfaces. These spots are prismatic crystals of andalusite which show a good deal of sericitization.

The fine-grained groundmass consists of orthoclase, very abundant reddish-brown authigenic biotite ($\alpha' = 1{\cdot}595$, $\gamma' = 1{\cdot}635$), muscovite and a little quartz. Accessory minerals are greenish zircon, magnetite, tourmaline and sericite. The zircons commonly occur as inclusions in the andalusite.

(iii) *Cordierite-quartz Hornfelses.*

C. E. Tilley (1924) has divided these hornfelses into (*a*) Biotite-rich and (*b*) Biotite-free types. At Hartley no hornfels of the type absolutely free from biotite has been recorded, but a number contain such a small amount of this mineral that they stand out in marked contrast to the Biotite-rich division, and it is proposed to consider them separately as Biotite-poor types.

(*a*) *Biotite-rich Types.*—These hornfelses are developed abundantly on Cox's River and Bonnie Blink Creek, and one example has been collected from the contact on Yorkey's Creek. Except for the total absence of plagioclase these rocks are similar to the cordierite-plagioclase assemblage described below. The constituent minerals are cordierite, quartz, biotite, orthoclase, magnetite and a little white mica. Accessory minerals are zircon and apatite, and a little sphene has been noted in a few examples. As in the more calcareous type described below, cordierite may occur as oval porphyroblasts giving the rock a spotted appearance, or it may form small xenoblasts in an even-grained granoblastic rock.

A typical example of the even-grained type occurs on the spur between the river and the junction of Liddleton and Bonnie Blink Creeks. It is a rather coarse-grained, resinous, greyish-brown rock, which, on weathered surfaces, shows a distinct banding. Under the microscope several types of banding may be recognized—differences in grainsize, alternations of biotite-rich and biotite-poor types, cordierite-rich seams and selectively altered cordierite seams.

In most of these rocks cordierite is very abundant, and several good examples of twinning have been noted. In longitudinal section multiple twinning is apparent and in cross section the mineral breaks up into sectors. The cordierite is frequently altered both to aggregates of white mica and to yellow, isotropic pinite. In some of the cordierite-rich seams this mineral is clouded by minute inclusions of iron ore. These evidently represent iron-rich chlorite seams in the original sediment.

(*b*) *Biotite-poor Types.*—It is stated above that these hornfelses occur inter-bedded with a biotite-rich assemblage near Cox's River. Another example occurs on Moyne Creek. Except for a marked decrease in biotite, a concomitant increase in orthoclase and magnetite and the total absence of white mica, these rocks are very similar to the above and need no further description.

The table below is an analysis of a cordierite-quartz hornfels containing a small amount of biotite; it is regarded as fairly typical of this class of hornfels. It is a medium-grained granoblastic rock consisting of cordierite, quartz, orthoclase, magnetite, and a little biotite ($\alpha' = 1{\cdot}587$, $\beta' = 1{\cdot}630$, $\gamma' = 1{\cdot}633$) and white mica.

The analysis used by C. E. Tilley (1924) in his discussion on this class of hornfels has been included to show that the resulting mineral assemblage is independent of the amount of quartz in the original rock. It is evident that the Hartley rock was a sandstone with an iron-chlorite matrix, whilst the rock in Column II represents an original chlorite-rich shale. As pointed out by Prof. Tilley, the mineral assemblage in these hornfelses depends upon the RO/R_2O_3 ratio.

(iv) *Cordierite-plagioclase Hornfelses.*

A number of examples of this type are recorded from the contacts on Moyne and Grant's Creeks and, with but two exceptions, they occur within 5 yards of the igneous boundary. One rock of this type is found on Grant's Creek at a distance of 220 yards from the diorite and apparently 400 yards from the granite, but the fact that it is invaded by veins of tourmaline-aplite suggests an underground extension of the granite. Another example is recorded from near the head of Horse Hole Gully at a distance of 700 yards from the diorite.

	I.	II.
SiO_2	84·23	59·83
Al_2O_3	7·13	17·47
Fe_2O_3	2·06	4·09
FeO	1·61	3·93
MgO	0·64	3·70
CaO	0·78	0·49
Na_2O	1·20	1·08
K_2O	1·53	4·42
H_2O	0·57	3·80
TiO_2	tr.	0·93
MnO	tr.	—
P_2O_5	abs.	0·18
SO_3	—	0·13
	99·75	100·05

I. Cordierite-quartz-biotite Hornfels, from granite contact on hillside above junction of Liddleton and Bonnie Blink Creeks, Por. 27, Parish of Lowther. Anal. G. A. Joplin.

II. Cordierite-quartz-biotite Hornfels, Abbenstein (Harz), described by O. H. Erdmannsdörffer (*Jahrb. Preuss. Geol. Landesanst.*, Vol. xxx, 1909, p. 357). Quoted by C. E. Tilley (*Quart. Journ. Geol. Soc.*, 1924, p. 37).

These rocks fall into three groups—a spotted type, a massive resinous dark grey hornfels, and a type very rich in biotite with indications of a parallel structure.

The rock on Grant's Creek, Por. 124, Par. of Hartley, is a typical spotted hornfels. It is a dense, dark purplish-grey rock crowded with resinous, black oval spots about 2 mm. in length. On weathered surfaces pitting is conspicuous.

Under the microscope the hornfels is seen to consist of numerous oval porphyroblasts of cordierite set in a fine granoblastic groundmass of biotite, quartz, plagioclase and orthoclase. Accessory minerals are magnetite, tourmaline and zircon. The cordierite is extremely fresh, and is crowded with inclusions of pale greenish-brown biotite, quartz and plagioclase. The biotite inclusions are by far the most abundant, and are of a paler colour than the biotite of the groundmass. In the groundmass flakes of biotite are particularly abundant as a fringe around the porphyroblasts, and this is probably due to the throwing out of inclusions during advancing metamorphism. The biotite of the groundmass occurs in numerous, strongly pleochroic, reddish-brown flakes ($\alpha' = 1{\cdot}587$, $\beta' = 1{\cdot}627$, $\gamma' = 1{\cdot}633$). The colour, pleochroism and refractive indices indicate a high iron content. Plagioclase is sometimes twinned and appears to be andesine.

The rock exhibits a slight parallelism due to the arrangement of the biotite flakes and of the longer axes of the porphyroblasts. This appears to be the original direction of bedding.

The tourmaline has no doubt been introduced by the tourmaline-aplite that invades the hornfels. In this rock muscovite is absent.

The analysis of this rock is given in Column I below, where it is compared with analyses of similar assemblages cited by Goldschmidt (1911). Except for a slightly greater abundance of silica and lime, and a little less magnesia, the

Hartley rock is intermediate in composition between these hornfelses. A strict comparison made on the basis of specific gravity might indicate closer affinities.

	I.	II.	III.
SiO_2	61·50	58·83	56·88
Al_2O_3	19·84	17·54	20·68
Fe_2O_3	1·39	0·00	2·66
FeO	5·20	8·42	4·54
MgO	2·67	3·40	3·15
CaO	2·91	2·24	1·29
Na_2O	1·11	1·35	0·91
K_2O	4·39	4·35	7·49
H_2O+	1·28	1·96	2·36
H_2O-	0·04	0·13	
TiO_2	0·42	0·59	—
MnO	tr.	0·09	—
P_2O_5	abs.	0·46	—
C (?)	—	0·50	—
	100·75	99·86	100·12

I. Cordierite-plagioclase Hornfels, Grant's Creek, Por. 124, Parish of Hartley. Anal. G. A. Joplin.

II. Cordierite-plagioclase Hornfels (Class 3), Kolaas, contact of the nordmarkite, Christiania. Anal. M. Dittrich. V. M. Goldschmidt, Die Kontaktmetamorphose im Kristianiagebiet. *Videnskap. Skrift.* I. Math.-Nat. Kl., No. 1, 1911, p. 156.

III. Cordierite-plagioclase Hornfels, Monte Doja, Adamello. Pelikan (*Tscher. Min. Pet. Mitt.*, 12, 1891, p. 156). Quoted by Goldschmidt. *Ibid.*, p. 157.

An example of the massive, resinous type of hornfels occurs on Grant's Creek just above its junction with Moyne Creek at about 1 yard from the contact. It is a granoblastic rock with slightly coarser grainsize (0·6 mm.), and contains the same mineral assemblage as above. The biotite is less abundant, and is of a more reddish colour with R.I. $\alpha' = 1{\cdot}588$, $\beta' = 1{\cdot}635$, $\gamma' = 1{\cdot}637$. Cordierite is represented by masses of secondary mica.

The biotite-rich members of this class occur at the mouth of Moyne Creek and are banded with biotite-plagioclase and biotite-amphibole-plagioclase assemblages. The biotite may be arranged in criss-cross fashion, but is more often parallel to the original bedding.

(v) *Plagioclase-biotite-quartz and Biotite-quartz Hornfelses.*

These types are perhaps the most widely distributed in the Hartley aureole and represent the largest bulk of the "purple-hornfelses".

A hornfels of this type occurs in the upper series at the top of the spur to the west of Grant's Creek, Por. 118, Parish of Hartley, at a distance of 200 yards from the granite. Under the microscope it is seen to consist of a fine mosaic of quartz, biotite, plagioclase and orthoclase, with tourmaline in large irregular aggregates. There are very small veins of igneous material associated.

A typical example of this hornfels, containing a small amount of plagioclase, has been analysed (see Column I below). It occurs on Bonnie Blink Creek at a distance of 440 yards from the granite. It is a fine granoblastic rock consisting of quartz, biotite ($\alpha' = 1{\cdot}585$, $\gamma' = 1{\cdot}633$), orthoclase, plagioclase, ilmenite and accessory zircon.

	I.	II.	III.
SiO_2	82·27	79·28	47·93
Al_2O_3	9·32	6·60	20·34
Fe_2O_3	abs.	0·51	4·35
FeO	2·65	2·32	8·63
MgO	1·09	1·96	5·58
CaO	1·80	3·95	1·64
Na_2O	0·83	3·27	4·70
K_2O	1·27	0·96	4·88
H_2O	0·72	0·72	0·72
TiO_2	0·47	0·40	0·76
MnO	nd.	0·25	0·13
P_2O_5	abs.	0·11	—
CO_2	—	0·09	—
	100·42	100·42	99·66

I. Biotite-plagioclase Hornfels ("Purple-hornfels"), Bonnie Blink Creek, Little Hartley. Anal. G. A. Joplin.

II. Felspathic Hornstone of the Calc-flinta Series, Tregullan, 1½ m. SSW. of Bodmin, Cornwall (Slide E5458). Anal. E. G. Radley. W. A. Ussher *et al.*, *Mem. Geol. Surv. Eng. and Wales*, Sheet 347, 1909, p. 101.

III. Biotite-plagioclase Hornfels (Class 3), Christiania. Anal. M. Dittrich. V. M. Goldschmidt, *l.c.*, 1911, p. 37.

The Cornish hornfels occurs associated with calc-flintas, as does the one from Hartley. The Hartley rock appears to be less rich in plagioclase, but biotite and orthoclase are possibly more abundant. The Christiania hornfels has been included for contrast. This again emphasizes the fact that a similar mineral assemblage may arise in a shale or in a siliceous rock with a shaly matrix. There are other rocks of a very similar appearance in which plagioclase cannot be identified, and it is believed that these represent lime-poor assemblages related to those described above.

It will be shown later that with an increase of lime and magnesia these rocks pass into amphibole-bearing types from which they cannot be distinguished in the hand-specimen.

One example of the biotite-plagioclase assemblage occurs at the mouth of Moyne Creek, where it is interbedded with cordierite-plagioclase-biotite and amphibole-plagioclase-biotite types. All three types are much coarser in grain-size than the "purple-hornfelses", which they closely resemble in mineral constitution, and their origin will be discussed later. They are often veined with igneous material.

(vi) *Amphibole-plagioclase-biotite Hornfelses.*

These rocks have been collected from within a few yards of the granite near the mouth of Moyne Creek, and from among the "cherts" on the northern limb of the Moyne anticline at a distance of 140 yards from the diorite.

The rock occurring at the mouth of the creek has been referred to above; it has a fairly coarse grainsize, is very rich in biotite, and exhibits a parallel structure similar to the associated assemblages which have already been described. The other example is typically a "purple-hornfels" in the hand-specimen. Under the microscope the coarser grained rock is seen to consist of biotite, plagioclase, amphibole, orthoclase, quartz, sphene and a little magnetite and/or ilmenite, tourmaline and pyrites.

The amphibole forms highly poikiloblastic plates (0·5 mm.) which are arranged in linear fashion, and evidently represent calcareous seams in the original sediment. The amphibole is green, markedly pleochroic, with an extinction angle of about 22°, and R.I. $\alpha' = 1{\cdot}637$, $\gamma' = 1{\cdot}658$. It is optically negative, and is thus a common hornblende near pargasite. The biotite shows a parallel arrangement which is in the same direction as the strings of amphibole xenoblasts. It is a strongly pleochroic reddish-brown type with R.I. $\alpha' = 1{\cdot}580$, $\gamma' = 1{\cdot}633$. The plagioclase is frequently twinned and occurs in small xenoblasts (0·1 mm.). It is andesine ($Ab_{63}An_{37}$) with R.I. $\alpha' = 1{\cdot}550$, $\gamma' = 1{\cdot}555$.

Another rock of this type, also from Moyne Creek, is a little more calcareous and contains a nodule consisting almost entirely of large (3 mm.) sub-idioblastic crystals of amphibole, with refractive indices $\alpha' = 1{\cdot}616$, $\beta' = 1{\cdot}625$, $\gamma' = 1{\cdot}635$, and an extinction of about 15°. Thus, according to Winchell (1933), the mineral belongs to the tremolite-pargasite series, and has a composition $Tr_{35}Pr_{65}$.

(vii) *Amphibole-diopside-plagioclase-biotite Hornfelses.*

Only a few examples of this type have been recorded from the aureole. They occur on Moyne Creek, Bonnie Blink Creek, and on the river just above the mouth of Marriott's Creek.

Except for the entrance of a little granular diopside these rocks are essentially the same as the fine-grained types referred to above, and, like them, they occur among the so-called "cherts".

(viii) *Amphibole-diopside-plagioclase Hornfelses.*

These are usually fine-grained rocks constituting some of the lighter bands in the calcareous cherts.

One coarse-grained example occurs on Moyne Creek at the contact of a large granite apophysis. It is a mottled light and dark greenish-grey rock which, under the microscope, is seen to consist of large (0·75 mm.) highly poikiloblastic sheets of amphibole and smaller granules of diopside in a groundmass of plagioclase, quartz and orthoclase, with accessory sphene, zircon and magnetite. A little epidote and clinozoisite and a few flakes of biotite are also present. Scattered hexagonal pseudomorphs consisting mainly of chlorite and clinozoisite possibly represent cross-sections of biotite. The amphibole has an extinction of 20°, and the refractive indices ($\alpha' = 1{\cdot}635$, $\gamma' = 1{\cdot}655$) and optically positive character indicate pargasite near common hornblende. Large pleochroic haloes are frequent around inclusions of zircon.

A coarser more quartzose member of this class occurs on the hillside north-west of the junction of Liddleton and Bonnie Blink Creeks. It contains abundant hollow crystals of pyrites, which are filled with sphene bordered by clinozoisite. A biotite-bearing assemblage is associated.

A rock on Moyne Creek shows this assemblage alternating with seams very rich in magnetite and containing a little biotite.

(ix) *Diopside-plagioclase Hornfelses.*

Banding is very common in rocks of this type. It may be caused by alternations with biotite-plagioclase or amphibole-bearing assemblages, by differences in texture and/or by seams consisting almost entirely of pyroxene.

Some of the bands are extremely narrow, and in one slide 1½ inches across as many as twelve such alternations have been counted. The pyroxene in some of these banded rocks is of a deep green colour and may contain up to 60% of the hedenbergite molecule ($\alpha' = 1{\cdot}710$, $\gamma' = 1{\cdot}732$). The sharp banding, however, does not admit of an addition of iron from the magma, and this pyroxene possibly arose from layers rich in ferriferous chlorite and calcite, or from mixtures of these minerals with iron ores. Banding in these rocks appears to be indicative of slight fluctuations in sedimentation.

Spotted rocks containing small ellipsoidal aggregates of diopside and plagioclase, or groups of larger crystals of diopside, are also common in this class. A fine-grained massive type consisting almost entirely of diopside also frequently occurs. Dr. A. Harker (1904, 1932) records cherty diopside-rocks from Skye, where they occur as narrow bands in dolomitic limestones.

All the rocks belonging to this class are chert-like in the hand-specimen, and have a high specific gravity owing to their large content of diopside. They are light-coloured—white, pale pink, grey or, most frequently, pale green. They are extremely like the calc-flintas of the south-west of England.

A typical example from Delaney's Creek at a distance of 130 yards from the contact may here be described. Under the microscope it is seen to be a fine-grained granoblastic rock with some coarser patches. The constituent minerals are diopside, plagioclase, orthoclase, quartz, sphene, and a little iron-ore. The diopside is very abundant and forms small granules and sub-idioblastic prisms distributed throughout the rock. In the coarser patches the crystals are larger and are always sub-idioblastic. According to Winchell (1933), the composition is $Di_{59}He_{41}$ ($\alpha' = 1{\cdot}695$, $\gamma' = 1{\cdot}712$) and $Z \wedge C = 41°$. The plagioclase occurs in extremely minute grains associated with orthoclase. Small light-coloured oval patches are numerous and, under strong magnification, are found to consist of diablastic intergrowths of plagioclase and orthoclase. The plagioclase is untwinned and the refractive index is well above that of quartz, but the exact composition cannot be determined. In one of the banded types of slightly coarser grainsize, it has been determined as $Ab_{40}An_{60}$ ($\alpha' = 1{\cdot}559$, $\beta' = 1{\cdot}564$, $\gamma' = 1{\cdot}568$).

Under this class might be mentioned a rather unique assemblage consisting of plagioclase, sphene and quartz. The rock in which this type occurs was found as a boulder in the river just below the mouth of Campbell's Creek. It is a banded rock of the calcareous chert type. It consists mainly of fine "purple-hornfels" with a white calcareous band an inch in width. In the centre of this band there is a seam consisting only of pale green diopside ($Di_{74}He_{26}$; $\alpha' = 1{\cdot}684$, $\gamma' = 1{\cdot}710$) and on both sides of this the sphene-plagioclase assemblage occurs. It would appear that magnesia had been withdrawn from the outer part of the calcareous band and deposited in the central seam, a change which probably took place before metamorphism (see p. 47). In the absence of magnesia the available lime has combined with titania and silica to give sphene. The titania may have been derived from either detrital rutile or ilmenite.

(x) *Plagioclase-diopside-epidote Hornfels.*

Only one example of this class is recorded from the Hartley aureole. It occurs interbedded with a vesuvianite assemblage and an unstable wollastonite-plagioclase assemblage on the northern limb of the Moyne anticline.

In this rock there seems little doubt that the epidote has arisen as a mineral of primary metamorphic crystallization, and not as a product of metasomatism. The constituent minerals are plagioclase, diopside, epidote, sphene and a little quartz and iron-ore. Orthoclase has not been detected with certainty. The plagioclase forms large poikiloblastic plates or granoblastic aggregates up to 3 mm. across, and encloses granules of epidote and diopside. The composition is basic labradorite. Diopside sometimes forms sub-idioblastic crystals 0·4 mm. across, but is more often developed as small xenoblasts intimately intergrown with epidote to form a granular mosaic. In places epidote shows alteration into clinozoisite and haematite. There is a slight textural banding.

(xi) *Plagioclase-diopside-wollastonite Hornfelses.*

This is essentially an unstable assemblage, but is by no means uncommon in at least two other aureoles—Deeside (Hutchison, 1933) and Carlingford (Osborne, 1932). A number of wollastonite-diopside rocks containing a very small quantity of plagioclase and scapolite have been collected from many parts of the contact, but there are two examples containing a slightly greater amount of plagioclase, and these will be described here.

One occurs at the diorite contact on Cox's River just below the mouth of Deep Ravine and, except for the presence of a little andesine, is similar to other rocks with which it is interbedded. It is a cherty green hornfels with bands of radiating wollastonite, which are parallel to the stratification. Under the microscope the green cherty layers are found to be made up of a fine aggregate (0·1 mm.) of quartz, diopside, orthoclase, andesine, wollastonite and sphene.

The second example occurs on Moyne Creek, where it is associated with a plagioclase-diopside-epidote assemblage. This rock is also banded. Some of the bands consist almost entirely of andesine with a little wollastonite and diopside. These are intercalated with bands much richer in wollastonite, and which also contain diopside, scapolite, quartz, orthoclase and sphene.

As the Cox's River rock contains andradite as well, and because the scapolite of the Moyne Creek type is considered to be secondary, both these rocks will be referred to below under the heading of metasomatism.

(xii) *Diopside-grossular-wollastonite Hornfels.*

Only one example of this hornfels has been recorded. It was collected from the granite contact near the head of Liddleton Creek, and is here associated with wollastonite-diopside assemblages which show extensive metasomatism. In the hand-specimen this rock is green and chert-like, with large masses of radiating, silky wollastonite associated with brown garnet. On the weathered surfaces the wollastonite shows alteration into a white chalky substance described on p. 31. Under the microscope large plates of wollastonite, often measuring more than 6 mm., are seen to be surrounded by or partly wrapped by xenoblasts of garnet up to 5 mm. across. Both these minerals contain inclusions of, and are set in a granular mosaic (about 0·1 mm.) of, diopside, epidote, orthoclase, quartz and accessory sphene. In some cases the orthoclase forms large plates, but it is possible that some of this is of igneous origin. The wollastonite may show twin lamellae, and cracks are often filled with calcite. The garnet is apparently of two different varieties—grossular and andradite. The grossular is pale yellow and xenoblastic and is obviously the primary and original mineral in this assemblage. The andradite is deep brownish-yellow and occurs in sub-idioblasts and xenoblasts intimately associated with the lighter coloured variety. Veins of the darker garnet cut through the rock and "blotching" is similar to that observed by G. D. Osborne (1932) at Carlingford. The grossular is sometimes anisotropic. Both garnets are poikiloblastic and exhibit a sieve-structure. They frequently form a granular intergrowth with epidote. Like the andradite, much of the epidote is possibly secondary, and this rock will be discussed later in dealing with metasomatism.

(xiii) *Vesuvianite-diopside Hornfels.*

Only one example of this hornfels has been met with in the Hartley aureole. It occurs as a well-marked band in the centre of the calcareous bed on the northern limb of the Moyne Creek anticline, and is there associated with a wollastonite-orthoclase-diopside assemblage. In the hand-specimen it is a fine-grained chert-like rock showing pale green, white and light brown bands. The rock is highly metasomatized, and it is rather difficult to recognize the original hornfels. It is possible that metasomatism closely followed the recrystallization of the sediment, and that normal thermal metamorphism passed into metasomatism as one continuous process.

As far as can be made out, the hornfels first consisted of a vesuvianite-diopside assemblage in which orthoclase was abundant. Garnet may have been present also. The vesuvianite forms large xenoblasts about 4 mm. across, and often encloses crystals (1 mm.) of altered orthoclase. Orthoclase also forms large independent xenoblasts with a sieve-structure and these, together with the vesuvianite xenoblasts, are set in a fine granular mosaic of diopside, orthoclase, quartz, prehnite, and a little epidote. Patches of anisotropic garnet also occur, and it is possible that this mineral, as well as the prehnite and epidote, belong to the period of metasomatism. The vesuvianite shows extensive alteration into prehnite and a fibrous mineral described below (p. 42).

This assemblage occurs in bands which alternate with a prehnite-apophyllite assemblage, and it is believed (see p. 40) that prior to metasomatism these latter seams were represented by a wollastonite-orthoclase-diopside hornfels.

(xiv) *Wollastonite-diopside Hornfelses.*

Examples of this type are recorded from the granite contact near the head of Liddleton Creek, from Bonnie Blink Creek just above the junction of Liddleton Creek, from Moyne Creek, and from the diorite contact on the river below Deep Ravine. As most of these rocks have suffered some form of metasomatism, they will be considered only very briefly here. They find a place in this section, however, for it is evident that many of the metasomatized hornfelses were originally of this type.

In the hand-specimen they are fine-grained, greenish, granular rocks very rich in quartz. Wollastonite varies in amount and sometimes may be so abundant as to make up most of the rock. When less plentiful it may occur in small radiating masses or in bands parallel to the original bedding. In the field it is evident that the brachiopod shells have been replaced by wollastonite which, on weathered surfaces, is now represented by a fibrous, white earthy mineral.

This mineral has not been identified. It is isotropic and has a very low refractive index (1·460). Under the microscope masses of radiating wollastonite measuring up to 5 mm. across are set in a fine (about 0·1 mm.) granoblastic groundmass of diopside, quartz, orthoclase, and sometimes a trace of plagioclase. Sphene and iron-ores are usually present as accessories. Alteration of the wollastonite into the unknown fibrous mineral seems to occur only on weathered surfaces, but in the body of the rock it commonly shows alteration into carbonates. Small andradite veins often thread through these hornfelses, but the occurrence of this mineral is referred to below. Scapolite is sometimes associated, but this, too, is regarded as a product of metasomatism.

A partial analysis has been made of a rock from Bonnie Blink Creek. This hornfels contains traces of scapolite and plagioclase.

SiO_2	73·16
Al_2O_3	4·33
F_2O_3	0·07
FeO	1·66
MgO	0·49
CaO	17·15
Na_2O	0·38
K_2O	2·07
H_2O	nd.
TiO_2	0·22
	99·53

Wollastonite-orthoclase-diopside Hornfels, Bonnie Blink Creek, Little Hartley. Anal. G. A. Joplin.

(xv) *Sandstone Hornfelses.*

These rocks are very abundant in the Hartley aureole, and occur at all parts of the contact on many different horizons. Many of them have suffered greisenization, and it is often difficult to distinguish between the greisenized sandstone hornfelses and the greisenized cordierite-quartz hornfelses where the cordierite has also been altered to white mica. Like the cordierite-quartz assemblages, the sandstone hornfelses may be divided into two groups according to their biotite content.

(*a*) *Biotite-rich Types.*—In the hand-specimen these rocks are essentially dark grey quartzites, and sometimes slight banding is apparent. A typical example occurs in a small creek, south of Delaney's Creek, in Por. 128, Parish of Hartley, at a distance of 180 yards from the contact. Under the microscope this shows a granoblastic structure (0·2 mm.) and consists of quartz, orthoclase, biotite, magnetite and a good deal of white mica. Chlorite and carbonates have also been noted, but, like much of the white mica, these are probably secondary.

(*b*) *Biotite-free Types.*—These rocks have been collected on Moyne Creek, on the ridge north-west of the mouth of Grant's Creek (Por. 118, Hartley), on the old road east of Yorkey's Creek, and on the spur between Spring Creek and Marriott's Creek.

The Moyne Creek rock occurs as a well-marked bed of massive, resinous, white quartzite above the calcareous horizon of the Moyne anticline (see Text-fig. 1). Under the microscope this rock is seen to be almost a pure quartzite consisting of interlocking grains of quartz about 3 mm. in diameter. Occasional patches of white mica and iron-ores also occur, and a little carbonate and chlorite have been noted. These latter possibly represent the alteration products of a ferro-magnesian mineral during metasomatism—they are associated with grains of magnetite. Two generations of white mica may be recognized. The first possibly represents a simple recrystallization of an original sericitic matrix, and the second, consisting of larger flakes of muscovite, may be attributed to metasomatism.

(xvi) *Altered Grits.*

Grits occur on Yorkey's Creek, Hughes' Creek and Delaney's Creek. In the hand-specimen they vary from fine siliceous conglomerates to coarse quartzites, and the colour of the matrix is usually purplish-brown. Under the microscope the rocks are distinctly clastic, and are made up chiefly of small, rounded grains of quartz and fine quartzite in a completely recrystallized matrix of quartz, reddish-brown biotite, orthoclase and magnetite. Sometimes a little plagioclase may be present in the matrix, so the hornfelsed grits may be considered as plagioclase-biotite-quartz or biotite-quartz assemblages.

A specimen from Hughes' Creek contains altered cordierite in the matrix, and the rock is very rich in white mica. This rock might be regarded as a greisenized cordierite-quartz hornfels.

The grit occurring on Yorkey's Creek passes into a conglomerate and has not been completely recrystallized.

METAMORPHISM OF THE INTERBEDDED IGNEOUS ROCKS.

There are two groups of igneous rocks within the Hartley aureole, (1) felsites, which appear to have been acid lavas at the base of the Lambian Series, and (2) porphyrites which occur as well-defined sills on several horizons.

(i) *Felsites.*

These are stony-pink, brownish-pink, or greenish-white rocks, which contain phenocrysts 3 mm. across. Muscovite may be seen in the hand-specimen, and some of the rocks have a rather chalky appearance and, when struck with a hammer, emit a hollow sound. The surface of these rocks shows a peculiar pitting. The hollows are sometimes an inch in diameter and about half an inch deep. Under the microscope there is no essential difference between the normal stony felsites and these apparently altered types. The phenocrysts consist of corroded quartz grains and tabular crystals of altered oligoclase. These are set in a fine mosaic of quartz and orthoclase, with accessory biotite and magnetite. Large flakes of muscovite, up to 5 mm. in length, replace the orthoclase and often enclose crystals of quartz. The plagioclase is altered both to kaolin and sericite.

A partial analysis of the rock gave the following results: SiO_2 75·39, CaO 0·23, Na_2O 2·32, K_2O 5·90. This indicates that the rock is a fairly normal potash felsite and that there has not been any appreciable addition of magmatic potash for the production of muscovite. The origin of this mineral is discussed below under metasomatism.

(ii) *Porphyrites.*

No unaltered representatives of this group of sills have been met, but the less altered types indicate that the rock was a porphyrite with slight variations in composition from place to place. Phenocrysts of both plagioclase and hornblende occur, but on Hughes' Creek the plagioclase phenocrysts predominate, and in other parts of the district the hornblende crystals are more abundant and measure up to half an inch in length. In some of the less altered types the groundmass has a pilotaxitic fabric and consists chiefly of plagioclase and a little hornblende. In the more acid types an intergranular fabric is developed and interstitial orthoclase and quartz occur between small stout crystals of plagioclase. Sometimes there is an indication of an original ophitic fabric. Biotite may or may not have been present in the orginal unaltered rock, and accessory minerals are apatite and iron-ores.

An initial rise of temperature is indicated by the separation of magnetite, small flakes of biotite, and granular sphene in the hornblende phenocrysts, and biotite becomes abundant in the groundmass, particularly in the neighbourhood of iron-ores (Harker, 1904; Skeats, 1910; Tilley, 1921; McGregor *et al.*, 1929). In some of the rocks plagioclase shows alteration into calcite at this stage, but this may be superimposed by metasomatism. At a later stage reddish-brown biotite entirely replaces hornblende in the groundmass, and the whole rock takes on a somewhat granular appearance. The plagioclase phenocrysts become spangled with tiny granules of zoisite, and hornblende phenocrysts are gradually becoming pseudomorphed by criss-cross flakes of biotite.

A rock from the head of Hughes' Creek represents a portion of the roof of the intrusion and rests directly on the diorite. This is completely recrystallized, and ferromagnesians are represented by masses of chlorite.

With a slightly higher grade of metamorphism crystalloblastic structures come into evidence. Whilst there is still a tendency for biotite to replace hornblende, the biotite of the groundmass takes on a highly poikiloblastic structure, and a good deal of the felspar of the groundmass becomes recrystallized. At the same time the phenocrysts lose their sharp outlines and become indented by the recrystallizing groundmass. A little white mica occurs in the felspar phenocrysts, but this may perhaps be attributed to metasomatism.

A type from Hughes' Creek shows inverted zoning in the plagioclase phenocrysts, and the outer calcic rim is clouded (for references to clouding of felspar, see Joplin, 1933). In this rock the groundmass forms a fine mosaic and the hornblende is not converted into biotite. Some of the hornblende phenocrysts, however, are entirely pseudomorphed by criss-cross flakes of brown mica, and masses of granular sphene surround iron-ores.

A few rocks exemplify conditions at which hornblende was stable, and there is no alteration to biotite. Crystalloblastic structures are developed, and clear grains of recrystallized felspar surround the phenocrysts. It is interesting to note that the hornblende in these rocks has much higher refractive indices ($\alpha' = 1{\cdot}640$, $\beta' = 1{\cdot}645$, $\gamma' = 1{\cdot}663$) than that which is developed in the metamorphosed sediments.

Another rock from Hughes' Creek at a distance of 88 yards from the granite and 660 yards from the diorite shows crystalloblastic structures and a little granular diopside. Some of the pyroxene occurs as independent grains, but some fringes hornblende, which has become pale and fibrous with the throwing out of iron-ores. The phenocrysts of plagioclase are highly zoned, and poikiloblastic and criss-cross structures are present. Column I below shows an analysis of this rock, which is a fairly typical porphyrite. Slight metasomatism is evidenced by a little pyrites, epidote and calcite.

	I.	II.
SiO_2	57·54	58·30
Al_2O_3	18·81	19·43
Fe_2O_3 ..	3·88	4·40
FeO	3·49	3·33
MgO	2·54	2·64
CaO	8·00	7·46
Na_2O	2·66	3·07
K_2O	0·88	0·88
H_2O+	0·70	0·37
H_2O-	0·09	—
TiO_2	0·53	0·49
P_2O_5	0·30	0·22
MnO	0·18	—
CO_2	0·79	—
$S(FeS_2)$.. ..	0·18	—
Cr_2O_3	abs.	
	100·57	100·57
Sp. Gr. ..	2·802	—

	I.	II.
Quartz ..	18·90	17·34
Orthoclase ..	5·56	5·00
Albite	23·06	26·20
Anorthite ..	33·08	35·03
Corundum ..	1·12	0·51
Hypersthene ..	8·81	8·18
Magnetite ..	5·57	6·50
Ilmenite ..	0·91	0·91
Apatite ..	0·67	0·67
Pyrites ..	0·36	—
Calcite	1·80	—

I. Metamorphosed Porphyrite (Bandose, (I) II.4.4.4″). S.E. Corn., Por. 218, Parish of Lowther, Little Hartley. Anal. G. A. Joplin.

II. Andesilabradorite (Bandose, (I)II.4″.4.4″). Carbet, Martinique, West Indies. Anal. A. Pisané. A. Lacroix, Mont Pélée, 1904, p. 573. In W.T., p. 411, No. 31.

Metasomatism.

Although the Hartley hornfelses are not intensely metasomatized, the phenomenon is fairly widespread, and evidence of it occurs at all parts of the contact. Several processes may be recognized, and it is proposed to deal here with these processes rather than with the individual assemblages that have been produced by them. In some cases there is evidence to show that metasomatism followed closely upon thermal metamorphism, and it is probable that there was an overlap. Nevertheless, thermal metamorphism preceded metasomatism to some extent, and earlier-formed hornfelses were altered as a result of the later process. It is sometimes difficult to recognize the original hornfels, if such ever did exist; but in most cases both metasomatized and unmetasomatized hornfelses are preserved, and the history of the later process may be clearly traced.

As is usually the case, metasomatism is more pronounced in the calcareous rocks, but greisenization has affected the more argillaceous and arenaceous types, so that most of the primary hornfelses have been altered by the later process. Eleven new minerals owe their origin to metasomatism, and often a single one of these has been derived from more than one original mineral, as is shown below.

The possible derivation of the following will now be discussed: i, Muscovite; ii, Amphibole; iii, Epidote; iv, Andradite; v, Hedenbergite; vi, Scapolite; vii, Fibrous Mineral A, from Scapolite; viii, Apophyllite; ix, Prehnite; x, Fibrous Mineral B, from Vesuvianite; xi, Pyrites.

i. *Muscovite.*

Greisenization is apparent in the sandstone hornfelses, in a number of the cordierite-bearing assemblages and in the recrystallized felsites, and it may be attributed to the break-down of both orthoclase and cordierite. Some of the muscovite in the hornfelses occurs in parallel intergrowth with biotite and in the same specimens orthoclase is fresh and unsericitized. It is thus assumed that muscovite has arisen as a primary product of medium-grade thermal metamorphism at a temperature where conditions were stable for the production of both muscovite and orthoclase.

In other cases, however, large flakes of muscovite are numerous, orthoclase is much sericitized or absent, granular quartz is associated with the white mica and tourmaline is often abundant. In these rocks it is believed that muscovite is derived from orthoclase, and in some cases incipient changes may be observed.

$$3\{K[AlSi_3O_8]\} + H_2O = (OH)_2Al_2[AlSi_3O_{10}]K + K_2O + 6\ SiO_2$$

3 Orthoclase + Water = Muscovite + Potash + 6 Quartz.

In the cordierite-bearing hornfelses the cordierite frequently shows alteration to finely divided white mica, but in some cases large flakes of muscovite occur not only replacing orthoclase but also pseudomorphing grains of cordierite. The associated biotite is usually chloritized, and chlorite is also associated with the muscovite (see p. 23).

$$15\{Mg_2Al_3[Si_5AlO_{18}]\} + 8\ K_2O + 40\ H_2O = 16\{(OH)_2Al_2[AlSi_3O_{10}]K\} + 6\{(OH)_8Mg_5Al[AlSi_3O_{10}]\} + 9\ SiO_2$$

15 Cordierite + 8 Potash + 40 Water = 16 Muscovite + 6 Clinochlore + 9 Quartz.

The potash may have been derived from the magma in the form of a silicate, or it may have been set free in the break-down of the orthoclase molecule.

From an inspection of the petrography it is obvious that finely divided white mica may be derived from andalusite as well, but this is not regarded as an important source at Hartley.

ii. *Amphibole.*

It has been shown that amphiboles frequently arise as primary products of thermal metamorphism, but there is little doubt that they also replace pyroxenes, and in this case they are considered as products of metasomatism. There is some evidence of an overlap between the periods of thermal metamorphism and metasomatism, and primary amphibole is sometimes found side by side with amphibolized pyroxene. An example of this change is shown in a rock from Moyne Creek, which is essentially a diopside-plagioclase-biotite hornfels with a little primary amphibole. Much of the diopside is changed to a pale green amphibole with distinct pleochroism, a very small extinction angle and positive elongation. It is associated with chlorite and iron-ores.

Other examples of secondary amphibole are accompanied by epidote. A rock from the head of Marriott's Creek, and another from near its mouth, show large ovoid masses of amphibole and granular epidote. This ovoid structure has been noticed in some of the diopside-plagioclase rocks (p. 29). The ellipsoids consist either of masses of diopside or of granular aggregates of diopside and plagioclase, and it is assumed that the altered rocks from Marriott's Creek were originally of this type, and possibly arose according to the equation:

$$5\{CaMg[SiO_3]_2\} + 3(CaAl_2Si_2O_8) + 2\ H_2O + 2\ CO_2 = (OH)_2Ca_2Mg_5[Si_4O_{11}]_2 + 2\{OH.Ca_2Al_3[SiO_4]_3\} + 2\ CaCO_3 + 2\ SiO_2$$

5 Diopside + 3 Anorthite + 2 Water + 2 Carbon Dioxide = Tremolite + 2 Zoisite + 2 Calcite + 2 Quartz.

In one of these rocks carbonates are abundant; from the other they have apparently been removed.

iii. *Epidote.*

It has been shown above that zoisite may be derived from a mixture of diopside and plagioclase, and with the incoming of iron-bearing solutions epidote may be formed. By the addition of iron and lime, epidote may be formed directly from plagioclase according to the following equation:

$3(CaAl_2Si_2O_8) + 3\ Fe_2O_3 + 5\ CaO + 2\ H_2O + 6\ SiO_2 = 4 \{ (OH.Ca_2(Al.Fe)_3[SiO_4]_3) \}$
3 Anorthite + 3 Haematite + 5 Lime + 2 Water + 6 Quartz = 4 Epidote.

The fact that iron-bearing solutions of magmatic origin are abundant during the period of metasomatism has been established by many workers, but there is a difference of opinion concerning magmatically derived lime. In the case of the Hartley rocks, however, there is no need to postulate a magmatic origin for the lime, as there has probably been a circulation of this substance within the calcareous beds themselves. Barrell (1907, p. 127) considers that both lime and silica, derived from the rock itself, may circulate during metasomatism.

iv. *Andradite.*

Andradite occurs very abundantly among the calc-silicate hornfelses at the head of Liddleton Creek, on the hillside north-west of the junction of Liddleton and Bonnie Blink Creeks, and at the diorite contact just south of Deep Ravine. The most notable occurrence is that above the junction of the creeks, where the garnet may be seen veining and impregnating a quartz-plagioclase-diopside hornfels. At this locality an ellipsoidal nodule measuring about 2″ x 1″ was collected. It was enclosed in the normal quartz-plagioclase-diopside rock and evidently represented a more calcareous portion. The host rock is granoblastic with large (0·2 mm.) grains of quartz surrounded by a fine (0·06 mm.) mosaic of diopside and plagioclase. The nodule was much coarser in grainsize (3·0 mm.) and consisted of large grains of diopside, epidote, garnet, orthoclase, quartz and a little sphene.

A partial analysis was made of the garnet from this nodule with the following results:

SiO_2	36·46	Sp. Gr., 3·64*
Al_2O_3	10·14	Anal. G. A. Joplin.
Fe_2O_3	19·80	
FeO	1·59	
MgO	abs.	
CaO	30·94	
TiO_2	0·38	
	99·31	

* Possibly slightly low on account of small air bubble.

The calculated composition is thus Andradite ($Ca_3Fe_2''[SiO_4]_3$) = 57% and Grossular ($Ca_3Al_2[SiO_4]_3$) = 43%, and the garnet may be regarded as an aluminous andradite.

The colour is deep brown in the hand-specimen, and yellowish-brown in thin section, and the R.I. lies between 1·822 and 1·832, which is in accord with the calculated composition.

The refractive indices of the accompanying minerals were determined with a view to ascertaining their iron content:

Diopside, $\alpha' = 1\cdot688$; $\gamma' = 1\cdot714$; FeO = 10%; $Di_{68}He_{32}$. *Epidote*, $\alpha' = 1\cdot728$; $\gamma' = 1\cdot753$; Fe_2O_3 = 17%.

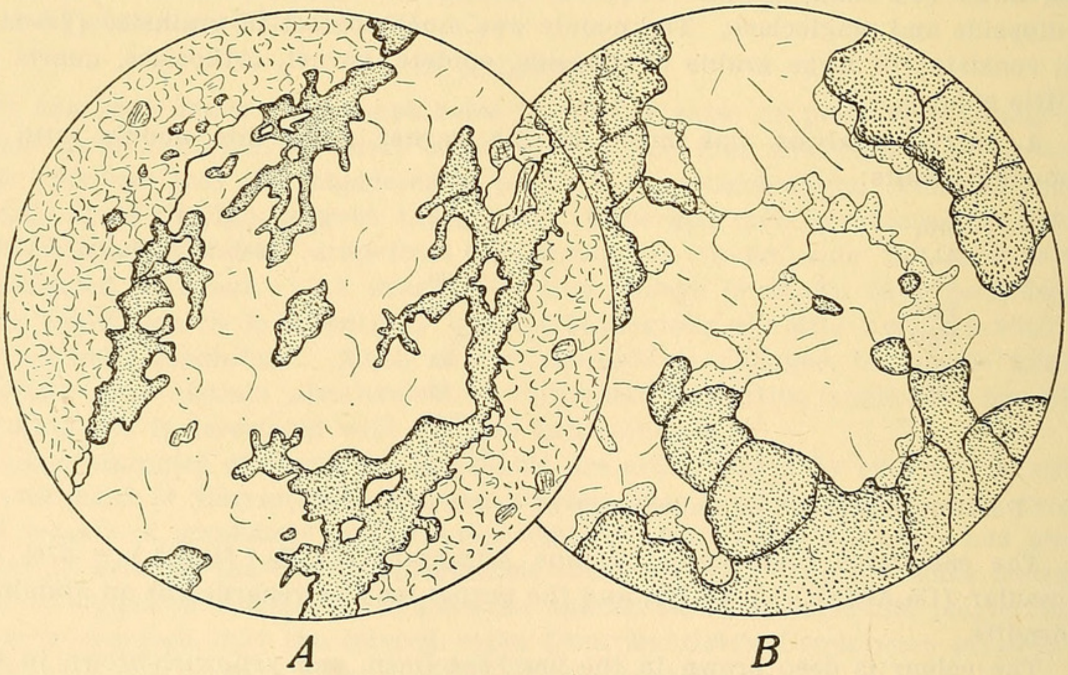
There appears to be no difference between the garnet of the nodule and that which impregnates the surrounding rocks, and in a few cases lower refractive indices have been measured, so it is assumed that the garnets contain at least 43% of the grossular molecule.

As the original composition of the nodule is unknown, the origin of the garnet and epidote is obscure. The nodule appears to have been more calcareous than its host, however, and it is possible that grossular was originally present. The epidote may represent an alteration product of grossular (Tilley, 1923) and, as in the case of the wollastonite-grossular-diopside hornfels (p. 31), the andradite may have been formed by the simple addition of iron to the lime garnet and wollastonite.

$$2 \{ Ca_3Al_2[SiO_4]_3 \} + 2\ Fe_2O_3 + 3 \{ Ca_2[Si_2O_6] \} = 4 \{ Ca_3(Al.Fe)_2[SiO_4]_3 \}$$

2 Grossular + 2 Haematite + 3 Wollastonite = 4 Aluminous Andradite.

The garnet in the plagioclase-diopside assemblage, however, must have been of different origin. It appears that the alumina of the garnet was derived from the plagioclase felspar by the action of lime- and iron-bearing solutions. The plagioclase has been determined as Labradorite, $Ab_{28}An_{72}$ with R.I. $\alpha' = 1\cdot565$, $\gamma' = 1\cdot575$. Occasionally epidote or clinozoisite may be seen separating the garnet and the felspar, and this is regarded as an intermediate stage (see equation, p. 37). Text-figures 2 and 3, A and B, illustrate the occurrence of the aluminous andradite in these rocks. The garnet is often associated with quartz veins, thus giving a clue to its extraneous origin. Text-figure 2 shows the garnet passing out laterally into the felspar at the margins of the vein.



Text-fig. 2.

A.—Quartz-garnet vein intruding diopside-plagioclase hornfels. Garnet may be seen passing out into the plagioclase at the margins of the vein. x 27.

B.—Margin of the same vein highly magnified. Much of the garnet is separated from the plagioclase by grains of clinozoisite. x 123.

Actually the garnet may be derived by the addition of lime to the equation on page 37, thus:

$2 \{ OH.Ca_2(Al.Fe)_3[SiO_4]_3 \} + 5\,CaO + 3\,SiO_2 = 3 \{ Ca_3(Al.Fe)_2[SiO_4]_3 \} + H_2O$

2 Epidote + 5 Lime + 3 Quartz = 3 Aluminous Andradite + Water.

The presence of clinozoisite as an intermediate stage indicates that the lime-bearing solution sometimes acted first, and that it was the advent of the iron-bearing fluid that changed the clinozoisite, with the addition of a little more lime, into the garnet. In many cases, however, no intermediate stage is observed and the two reactions possibly took place simultaneously.

The formation of garnet from plagioclase recalls a somewhat similar change recorded by McLintock (1915) from Ben More. Here zeolites pass to prehnite and epidote and finally to garnet.

In the wollastonite-orthoclase-diopside rocks the garnet appears to have obtained its alumina from the orthoclase according to the following equation:

$2 \{ K[AlSi_3O_8] \} + 3 \{ Ca_2[Si_2O_6] \} + Fe_2O_3 = 2 \{ Ca_3(Al.Fe)_2[SiO_4]_3 \} + K_2O + 6\,SiO_2$

2 Orthoclase + 3 Wollastonite + Haematite = 2 Garnet + Potash + 6 Quartz.

v. *Hedenbergite.*

No pyroxene containing more than 60% of the hedenbergite molecule is present in the Hartley aureole, and in most instances this occurs in banded pyroxene-plagioclase rocks, and appears to represent the recrystallization of original iron-rich bands (see page 29).

On Liddleton Creek, however, there are rocks associated with the garnetiferous wollastonite-diopside assemblage that contain small patches of deep green pyroxene and a good deal of orthoclase. These rocks appear to have been impregnated with igneous material, and occur only a few yards from the granite contact. This pyroxene has refractive indices $\alpha' = 1{\cdot}708$; $\gamma' = 1{\cdot}730$, and thus, according to Winchell, has the composition $Di_{44}He_{56}$, and contains 17% of FeO.

It is possible that the same solutions as were responsible for the formation of the iron-garnet also attacked the original diopside in these hornfelses. The orthoclase of these rocks seems to be of magmatic origin. The fact that the diopside remains so little affected by the iron-bearing solutions, which were so abundant at the contact in Por. 27, Parish of Lowther, is a little difficult to explain. An insufficiently high temperature is the only explanation that suggests itself. It is possible that the temperature for the formation of iron-garnet is below that for the conversion of diopside into hedenbergite.

vi. *Scapolite.*

Scapolite is not abundant in the Hartley aureole, though it is fairly widely distributed and occurs on Delaney's Creek, Moyne Creek, Cox's River, Bonnie Blink Creek and Liddleton Creek. It is found in a plagioclase-diopside assemblage and in wollastonite-diopside rocks where a little plagioclase may or may not be present.

In the rock from Delaney's Creek the scapolite forms poikiloblastic plates enclosing grains of diopside. These are set in a fine mosaic of diopside, plagioclase and quartz. The birefringence of the scapolite is fairly high and the mineral appears to be approaching the meionite end of the series. In the wollastonite-bearing rocks the scapolite is usually closely associated with the wollastonite, and its lower birefringence indicates its approach to marialite.

No definite statement can be made regarding its origin, but its association suggests that it has been derived from plagioclase during metasomatism. The fact that labradorite occurs in the plagioclase-diopside rocks, and that andesine is met with in the wollastonite-bearing types, is in accord with the probable composition of the scapolite in these assemblages.

vii. *Fibrous Mineral A (from Scapolite).*

A good deal of the scapolite is fringed by or entirely replaced by a light brownish fibrous mineral, which has not been identified. This unknown mineral is biaxial and positive, with negative elongation and straight extinction. The optic axial plane lies parallel to the cleavage, and to the elongation of the fibres. The optic axial angle is very small. The mineral appears to be rhombic. The refractive indices determined by the Immersion Method lie between 1·480 and 1·490, though these readings are not regarded as satisfactory owing to the tendency for the mineral to break up on crushing, and the difficulty attending the identification of small fragments. In thin section the double refraction has been determined as 0·009. Fragments treated with concentrated hydrochloric acid became powdery and appeared to dehydrate, and when this material was tested for lime a weak positive reaction was obtained. There is not sufficient of this material for an analysis, but the above simple tests point to a hydrous silicate of lime, and the association with scapolite suggests the presence of soda and alumina.

viii. *Apophyllite.*

Apophyllite is abundant in the calcareous bed on the northern limb of the Moyne anticline, and it has also been met with in a boulder from Bonnie Blink Creek. Although it is not possible to trace every stage in its development, it is fairly evident that it arises in a diopside-orthoclase-wollastonite assemblage which, on Moyne Creek, is interbedded with vesuvianite-diopside types.

In the more altered rocks no remnant of wollastonite or orthoclase is evident, and the vesuvianite assemblage appears to be seamed by bands of apophyllite into which project blade-like crystals of prehnite (see Text-fig. 3, C).

A parallel band, half an inch above an apophyllite seam, consists of much carbonated wollastonite set in plates of kaolinized orthoclase, and in one or two places small patches and veins of apophyllite are apparent, and a little granular prehnite is associated. Apophyllite would thus seem to arise according to the equation:

$$2\{K[AlSi_3O_8]\} + 5\{Ca_2[Si_2O_6]\} + 18\ H_2O + 3\ SiO_2 =$$
$$2\{[K(H_2O)_8]\ (OH.Ca_4[Si_8O_{20}])\} + H_2Ca_2Al_2Si_3O_{12}$$

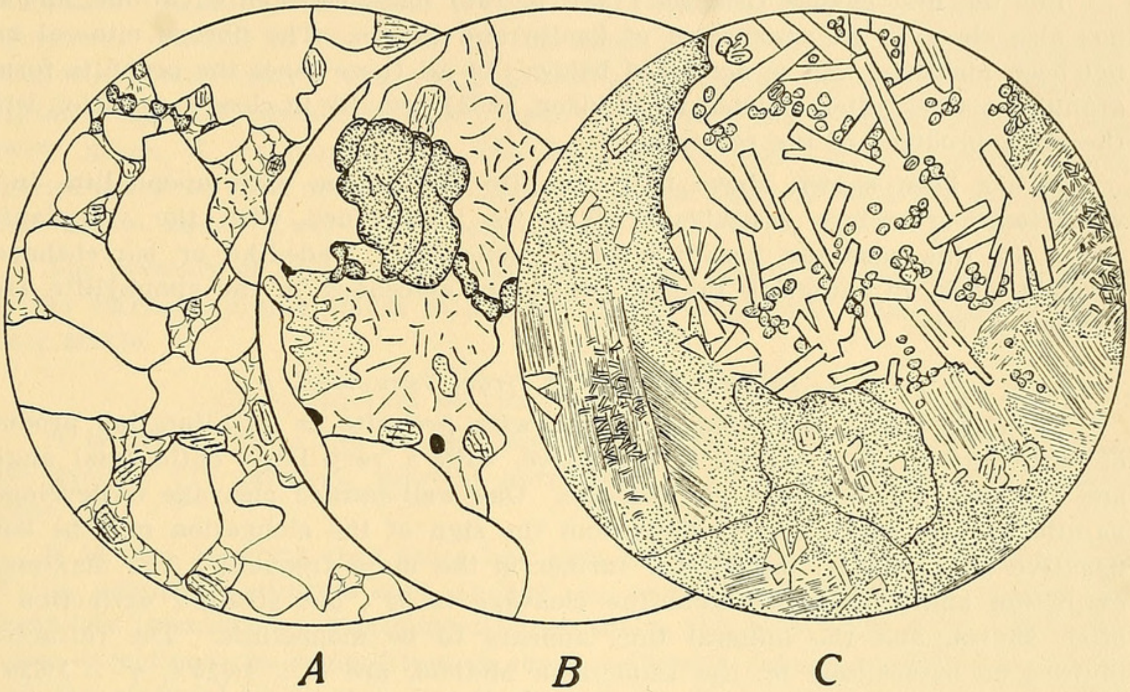
2 Orthoclase + 5 Wollastonite + 18 Water + 3 Quartz = 2 Apophyllite + Prehnite.

The preliminary break-down of orthoclase into kaolin and potassium carbonate, and of wollastonite into calcite possibly occurs as an intermediate stage, carbonated magmatic water acting as a catalyst.

In the rock from Bonnie Blink Creek the apophyllite occurs in vein-like patches associated with iron-garnet, scapolite and its alteration product, in a rock which consists almost entirely of wollastonite and diopside. This rock is so much altered by metasomatism that it is difficult to postulate its original composition, and to say how the apophyllite has arisen.

Hutchison (1933, p. 588) has shown by an equation that apophyllite may be formed by the action of potassium carbonate on wollastonite. With regard to the Hartley aureole it has already been suggested that K_2O may be released as a result of the formation of garnet from orthoclase, and of muscovite from orthoclase, and it is conceivable that a quantity of potash is present in the magmatic waters that were responsible for this late stage of metasomatism.

The close association of andraditic garnet and scapolite with the apophyllite in this rock suggests that the original hornfels may have been a wollastonite-orthoclase-diopside assemblage with a little plagioclase, and that the garnet arose from orthoclase, thus setting free K_2O, which immediately reacted with a further quantity of wollastonite and quartz to give apophyllite.



Text-fig. 3.

A.—Diopside-plagioclase hornfels showing large grains of quartz surrounded by a fine granular matrix of plagioclase and pyroxene. Garnet is seen replacing plagioclase in the top left-hand corner. × 25.

B.—Portion of the same highly magnified. Grains of garnet and clinozoisite are intimately associated with plagioclase. × 73.

C.—Banded vesuvianite-diopside hornfels with apophyllite-prehnite-diopside seams. Vesuvianite is shown changing to fibrous mineral B, and small crystals of prehnite appear interlaced in the fibres of the unknown mineral. The clear area represents colourless apophyllite in which are set blade-like and barrel-shaped crystals of prehnite, and small granules of diopside. × 19.

ix. *Prehnite.*

Prehnite has been found only on Moyne Creek, where it is present in the calcareous bed on both limbs of the Moyne anticline. In the southern outcrop it forms large poikiloblastic plates in a rock which, in the field, looks like an aplite injected along the bedding-plane of a banded calc-silicate hornfels. The coarser aplite-like type and the finer hornfels which it appears to invade both consist largely of prehnite, the only apparent difference being one of grainsize and a larger percentage of iron-ore inclusions in the finer grained rock. The prehnite plates include grains of diopside, and a little wollastonite and plagioclase are occasionally associated. These rocks are so highly prehnitized that it is impossible to surmise their original composition, though the presence of remnants of wollastonite and plagioclase suggests that prehnite may have arisen according to the equation suggested by Hutchison (1933, p. 587).

On the northern limb of the fold, it is quite obvious that prehnite has been formed from more than one mineral, and that prehnitization of a single mineral has advanced in different directions, giving rise to several distinct assemblages.

Vesuvianite is the main source of this mineral, and three associated assemblages may be recognized: (i) Prehnite, grossular, calcite and quartz; (ii) prehnite and a fibrous mineral; (iii) prehnite, kaolin, calcite.

For the first change Osborne (1931, p. 297) has suggested equations, and he has also observed an association of kaolin and calcite. The fibrous mineral has not been identified, but is described below. In all these cases the prehnite forms granular masses, often clouded (Hutchison, 1933), usually in close association with the other products of the reaction.

It has been shown above that prehnite also arises with apophyllite in a wollastonite-orthoclase assemblage which is interbedded with the vesuvianite rock. In this case the prehnite forms well-shaped blade-like or barrel-shaped crystals, often in radiating groups, which are embedded in the apophyllite (see Text-fig. 3, C).

x. *Fibrous Mineral B (from Vesuvianite).*

As noted above, this mineral occurs with prehnite as an alteration product of vesuvianite. It is biaxial and positive, with a very large optic axial angle, and the axial plane across the cleavage. One well-marked cleavage is developed parallel to the length of the fibres, and the sign of the elongation may be both negative and positive, though the former is the more frequent. The maximum extinction angle measured from the cleavage is 30°, but straight extinction is often shown, and the mineral thus appears to be monoclinic. The refractive indices, as determined by the Immersion Method, are $\alpha' = 1{\cdot}610+$, $\gamma' = 1{\cdot}630+$. From these it would appear that the double refraction was about 0·020, but in thin section it appears to be higher. A polysynthetic twinning parallel to the fibres has been observed in a few sections.

xi. *Pyrites.*

Small quantities of pyrites occur throughout the aureole and it sometimes carries a little arsenic. It is also met with in the plutonic rocks themselves, and is often concentrated along joint planes. Although a little pyrites is disseminated through most of the types within the contact aureole, it is particularly abundant in the altered porphyrites, and usually occurs within the hornblende phenocrysts.

Many years ago an attempt was made to work a small concentrate of arsenical pyrites in a porphyrite in the valley of Yorkey's Creek (M.L.1, Por. 214, Parish of Lowther). A shaft was put down at a distance of about 700 yards from the diorite contact, but the venture was unsuccessful and was abandoned.

Grade of Metamorphism and Comparison with Other Areas.

Reference to the petrography will show that primary muscovite is by no means uncommon among the more argillaceous hornfelses at Hartley. C. E. Tilley (1926) has suggested that muscovite arises in place of orthoclase when an abundance of water is present in the aureole. Not only is muscovite suggestive of the presence of water, but such hydrous minerals as biotite, vesuvianite and epidote (Tilley, 1924) are also characteristic. An abundance of water implies a concomitant lowering of the temperature, and amphiboles are thus formed instead of pyroxenes, muscovite instead of orthoclase, etc.

There is no doubt that equilibrium has been attained for the prevailing temperature conditions in the inner zone of hornfelses at Hartley, but it is also evident that the grade of metamorphism is fairly low. The aureoles of Christiania (Goldschmidt, 1911) and Comrie (Tilley, 1924) belong to a higher grade than that of Hartley. In these no muscovite occurs as a primary mineral, amphiboles and epidote though present are not characteristic, and biotite is a little less abundant. In the aureoles of Devon and Cornwall, however, muscovite is a prominent mineral in the killas of the inner aureole, and such assemblages as plagioclase-biotite-quartz and biotite-quartz are common (Reid, 1910). The calc-flintas frequently contain tremolite and vesuvianite, and everything points to a "wet" grade of metamorphism. The Skiddaw aureole (Rastall, 1910) is also characterized by the presence of muscovite, and there is evidence of complete equilibrium under lower grade conditions.

The presence of both muscovite and orthoclase, and of amphibole and pyroxene in the Hartley aureole points to a temperature range over which both minerals were stable.

Classification of the Sedimentary Hornfelses.

It is evident from the petrography that the hornfelses may be divided into two groups, (1) primary, thermal hornfelses, and (2) metasomatically altered types.

It is also apparent that there has been a considerable range of composition of the original sediments and, though no unaltered material is exposed, the hornfelses themselves indicate sandstones, shales and calcareous types. With but a few exceptions the composition of these sediments must have been comparable with the material which gave rise to some of the Christiania (Goldschmidt, 1911) and Comrie (Tilley, 1924) hornfelses, yet reference to the petrography shows that many of the index minerals of Goldschmidt's Classification are absent or not abundant at Hartley; and, again, minerals which are not prominent in the Christiania and Comrie aureoles are well developed at Hartley.

Amphiboles, epidote, muscovite, etc., which find no place in the Goldschmidt Classification, are found close to the contact at Hartley, and there is evidence to show that they occur as primary minerals in the *inner* zone of hornfelses, and cannot be attributed either to the unattainment of equilibrium or to metasomatism.

The foregoing discussion on metamorphic grades has shown that there has been an abundance of water during metamorphism, and probably a concomitant lowering of the temperature. It seems evident, therefore, that sediments of the same chemical composition will give different mineral assemblages under lower grade conditions. The relation between these mineral assemblages depends upon four important mineral transformations, which are brought about in the presence of water:

(1) Cordierite + Orthoclase = Biotite;
(2) Monoclinic Pyroxene + Rhombic Pyroxene = Amphibole;
(3) Grossular + Anorthite = Epidote;
(4) Grossular + Wollastonite = Vesuvianite.

These changes may be represented by the following equations, and in each case the right-hand side of the equation represents the lower grade conditions.

(1) $Mg_2[Al_4Si_5O_{18}] + 2\{K[AlSi_3O_8]\} + 2\ H_2O + 4(Fe_3O_4) =$

$$\left\{ \begin{array}{l} K_2H_4Al_6Si_6O_{24} \\ Mg_2Fe_4Si_3O_{12} \end{array} \right\} + 2\ SiO_2 + 4\ Fe_2O_3.$$

Cordierite + 2 Orthoclase + 2 Water + 4 Magnetite = Biotite + 2 Quartz + 4 Haematite.

(2) $2\{ CaMg[SiO_3]_2 \} + 3\{ Mg[SiO_3] \} + SiO_2 + H_2O = (OH)_2Ca_2Mg_5[Si_4O_{11}]_2$
2 Diopside + 3 Enstatite + Quartz + Water = Tremolite.

(3) $Ca_3Al_2[SiO_4]_3 + 5(CaAl_2Si_2O_8) + 2\ H_2O = 4\{ OH.Ca_2Al_3[SiO_4]_3 \} + SiO_2$
Grossular + 5 Anorthite + Water = 4 Zoisite + Quartz.

(4) $2\{ Ca_3Al_2[SiO_4]_3 \} + Ca_2[Si_2O_6] + 2\ H_2O = 4\{ Ca_2AlSi_2O_7(OH) \}$
2 Grossular + Wollastonite + Water = 4 Vesuvianite.

Table I shows the relation between similar sediments that have suffered high grade "dry" conditions, and those that have been subjected to a medium grade "wet" thermal metamorphism.

TABLE I.

Class.	High Grade (dry).	Medium Grade (wet).
I	Andalusite-cordierite-biotite-orthoclase Hornfels.	Andalusite-biotite-orthoclase-muscovite Hornfels.
I Mg i (*a*) and (*b*)	Cordierite-quartz Hornfels. (*a*) With Biotite. (*b*) Without Biotite.	Biotite-quartz Hornfels.
III	Cordierite-plagioclase Hornfels.	Biotite-plagioclase Hornfels.
VI	(Plagioclase-diopside-hypersthene Hornfels).	Amphibole - plagioclase - biotite Hornfels (*near Class V*). Amphibole - diopside - plagioclase - biotite Hornfels. Amphibole-diopside-plagioclase Hornfels (*near Class VII*).
VII	Plagioclase-diopside Hornfels.	
VIII	(Plagioclase-diopside-grossular Hornfels).	Plagioclase-diopside-epidote Hornfels.
IX	(Diopside-grossular Hornfels). *Unstable* Wollastonite-plagioclase-diopside Hornfels.	
X	Wollastonite-grossular-diopside Hornfels. *Unstable* Wollastonite-plagioclase diopside Hornfels.	Vesuvianite-diopside Hornfels.

NOTE.—Hornfelses in brackets are *not* developed at Hartley.

It will be noticed that three types have been included as the medium grade equivalents of Class VI, and these show a progressive increase of lime. The amphibole-plagioclase-biotite assemblage must have a composition very close to a hornfels of Class V, but the amphibole contains sufficient lime to inhibit its inclusion in that class. Again, the amphibole-plagioclase-diopside rock is excluded from Class VII, because there is an excess of magnesia in the amphibole. Actually there can be no "wet" equivalent of Class VII, since the change from diopside to tremolite involves a change of composition.

The unstable assemblages that have been placed as the equivalents of Classes IX and X are rather difficult to account for. This assemblage occurs abundantly in the Carlingford (Osborne, 1932) and Deeside (Hutchison, 1933) aureoles, and has been interpreted differently by each of these authors. Hutchison considers that instability was caused by the relief of static pressure, whilst Osborne explains them on the presence of the albite molecule in the original sediment. With regard to the Hartley occurrences the present writer is inclined to agree with Osborne.

At the same time it might be pointed out that the Carlingford, Deeside and Hartley aureoles all indicate a "wet" type of metamorphism, and though inexplicable, this may possibly have some significance, and the unstable types might be included more correctly under medium grade (wet) metamorphism.

Hutchison has shown that wollastonite and plagioclase arise from grossular according to the equation:

$$Ca_3Al_2[SiO_4]_3 + SiO_2 = Ca[Al_2Si_2O_8] + Ca_2[Si_2O_6]$$

Grossular + Quartz = Anorthite + Wollastonite.

If a very small quantity of wollastonite be present, the assemblage is considered to be an unstable member of Class IX, but if there be an abundance of wollastonite it is likely that it would be present in the hornfels represented by the left-hand side of the equation, and that the assemblage is an unstable hornfels of Class X.

Reference to Table I shows that certain hornfelses, described in the petrographical section, do not fall into this scheme, because the original sediment from which they arose did not belong to the shale-limestone series, for which this classification was drawn up. The wollastonite-orthoclase-diopside rocks were evidently calcareous sandstones, not argillaceous limestones, and thus do not find a place in the table. The hornfelsed sandstones and grits are excluded for a similar reason.

The presence of both high and medium grade types points to local variations in the conditions, and there is no evidence to show that the higher grade hornfelses are related to the contacts of the more basic plutonic rocks. It is found that both high and medium grade thermal types have suffered a subsequent metasomatism.

The discussion on metasomatism has shown that certain new minerals have arisen from those of the primary hornfelses. Table II shows the relation of the metasomatic assemblages to the primary types.

Origin of the Hornfelses, and Evidence of pre-Metamorphic Alteration.

In the preliminary discussion on incipient metamorphism, it has been pointed out that the original sediments at Hartley probably corresponded to well-known types at Rydal. Having examined the mineral constitution of the hornfelses, we shall now make an enquiry into the possible mineral assemblages of the sediments from which they arose.

The cordierite-andalusite, cordierite-plagioclase and some of the cordierite-quartz hornfelses undoubtedly represent original shales. Some of these types, however, contain more quartz than normal shales, and it is evident that they were sandstones with an argillaceous matrix. The origin of such thermal assemblages has been discussed by Prof. C. E. Tilley (1924), and equations are given to show that they may arise from mixtures of sericite and chlorite. The appearance of plagioclase indicates a little admixed calcite.

The andalusite-biotite-orthoclase-muscovite assemblage described on page 23 has been classed as the medium grade equivalent of an andalusite-cordierite hornfels, but at the same time it is interesting to note that another origin for

TABLE II.

Primary Hornfels.	Metasomatic Assemblage.
Sandstone Hornfels.	Greisenized types.
Andalusite-cordierite-biotite Hornfels.	Andalusite-cordierite (altered)-biotite-muscovite-chlorite.
Cordierite-quartz Hornfels.	Greisenized types.
Plagioclase-diopside Hornfels.	1. Plagioclase-diopside-aluminous andradite. 2. Plagioclase-diopside-epidote-aluminous andradite. 3. Diopside-epidote-aluminous andradite. 4. Diopside-aluminous andradite. 5. Diopside-amphibole-plagioclase. 6. Diopside-amphibole-epidote. 7. Amphibole-epidote. 8. Plagioclase-hedenbergite. 9. Diopside-plagioclase-scapolite. 10. Diopside-prehnite.
Diopside-plagioclase-wollastonite Hornfels.	1. Diopside-plagioclase-scapolite-wollastonite. 2. Diopside-wollastonite-aluminous andradite. 3. Diopside-wollastonite-aluminous andradite-scapolite-mineral A. 4. Diopside-wollastonite-epidote.
Wollastonite-grossular-diopside Hornfels.	Wollastonite-grossular-andradite-epidote-diopside.
Wollastonite-diopside-orthoclase Hornfels.	1. Wollastonite-diopside-orthoclase-aluminous andradite. 2. Wollastonite-diopside-prehnite-apophyllite. 3. Diopside-prehnite-apophyllite.
Vesuvianite-diopside Hornfels.	1. Vesuvianite-diopside-prehnite-mineral B. 2. Vesuvianite-diopside-prehnite-grossular.

this assemblage is possible. A great abundance of sericite in the original sediment (such as might be derived from an acid-granite terrain) would inhibit the presence of cordierite, and at the same time give rise to an abundance of biotite, orthoclase and andalusite according to the equation:

$$4\{(OH)_2Al_2[AlSi_3O_{10}]K\} + 3\{Mg_2Al_3[AlSi_5O_{18}]\} =$$
$$\left\{\begin{matrix} K_2H_4Al_6Si_6O_{24} \\ 3\,Mg_2SiO_4 \end{matrix}\right\} + 2\{K[AlSi_3O_8]\} + 8(Al_2SiO_5) + 4\,SiO_2 + 2\,H_2O.$$

4 Sericite + 3 Cordierite =

Biotite + 2 Orthoclase + 8 Andalusite + 4 Quartz + 2 Water.

Quartz is almost absent in this rock, however, and this equation is included to show that a similar assemblage may be produced in this way, rather than to suggest that this was the origin of the Hartley rock.

The biotite-quartz and biotite-plagioclase-quartz assemblages appear to represent fine-grained tuffaceous material with admixed detrital quartz. These rocks are interbedded with calcareous silts, and with gradual increments of lime, derived from the silts, they pass into amphibole-bearing hornfelses.

The silts themselves, uncontaminated by tuffaceous material, give rise to diopside-plagioclase rocks, and with increasing lime wollastonite-plagioclase and vesuvianite-bearing assemblages are produced. The original silt evidently consisted of a mixture of chlorite, calcite and sericite, there being only a very small quantity of the last.

Most of the wollastonite-plagioclase rocks contain very little plagioclase and a good deal of orthoclase, and thus stand very close to the wollastonite-orthoclase-diopside assemblage. The texture, composition and field occurrence of these rocks all point to an original sandstone with shell bands. This sediment was probably of the nature of an arkose and contained a certain amount of unaltered felspar. The paucity of alumina in these rocks indicates a deficiency of sericite, and the fairly abundant orthoclase could not have derived its potash from this mineral, but must represent recrystallized original orthoclase.

The analogous type, containing a small amount of plagioclase, possibly represents similar sediments which consisted of quartz, orthoclase and a little acid plagioclase, with intercalated shell bands and a calcareous matrix. During metamorphism the acid plagioclase became more calcic (Osborne, 1932).

The sphene-plagioclase assemblage described on page 29 calls for comment. It occurs bordering a pyroxene seam and appears to be a case of pre-metamorphic alteration. The magnesia has been withdrawn from the surrounding material and deposited in the seam, possibly as original chlorite. On account of the withdrawal of magnesia from the outer bands available lime has combined with quartz and rutile to form sphene instead of diopside.

The banded hornfelses, showing alternations of the cordierite-biotite and the cordierite-orthoclase-magnetite assemblages, are another indication of pre-metamorphic alteration, the former seams arising from altered bands rich in hydrous minerals.

Grainsize of the Hornfelses.

Reference to the petrography shows that most of the hornfelses are very fine grained, and in most parts of the aureole there is no difference in the grain-size as the contact is approached. At the mouth of Moyne Creek, however, plagioclase-biotite, plagioclase-cordierite and amphibole-plagioclase-biotite hornfelses are coarser than similar assemblages elsewhere. These rocks lie within a few yards of the contact, and both field evidence and mineral constitution point to their being the equivalents of hornfelses that are very fine grained in other parts of the aureole. It is possible that at this locality a coarser grainsize was produced at the granite contact.

Relation of Metasomatism to Fracture.

At least two well-marked faults occur near the granite contact on the hillside west of the junction of Liddleton and Bonnie Blink Creeks. Actually the granite is difficult to map at this locality, as numerous aplitic dykes and apophyses thread through the sediments, and everything points to an intimate penetration of igneous material.

In the calcareous sandstone hornfelses themselves innumerable small fractures may be noted, and the rocks are impregnated by quartz and iron-garnets. These garnet veins frequently follow bedding planes, and in the hand-specimen they are sometimes suggestive of limy seams in the original sediments. In the field, however, it may be seen that the veins just as frequently cross the bedding, and sometimes form small dykes and sills up to about 4 inches in width. The larger intrusions are essentially garnet-quartz rocks with minute quantities of pyroxene and epidote.

It is thus suggested that shattering either accompanied or immediately followed the plutonic intrusion, and that these lines of weakness gave ready access to the metasomatic solutions. In his study of the Marysville contacts Barrell (1907) has come to a similar conclusion.

On Moyne Creek there is evidence to show that a certain amount of post-metasomatism shattering has occurred, but this may be of comparatively recent date. The calcareous bed containing banded vesuvianite and apophyllite assemblages provides excellent examples of miniature faults.

Relation of Metamorphic Grade to the Age of the Sediments.

The Hartley sediments are of late Devonian age and the plutonic complex responsible for their metamorphism is believed to belong to the Kanimbla Epoch (Sussmilch, 1914), which may have closed the Devonian Period. It is probable, therefore, that the sediments were only partially consolidated at the time of their metamorphism, and that their water content must have been fairly high. This suggests that the "wet" grade of metamorphism may be connected with the age and condition of the invaded sediments.

The fact that dry magmas such as the charnockite series (Holland, 1898) are associated with the older crystalline rocks, and that members of the mica-diorite stem invade geosynclinal deposits is regarded as significant, and it is believed that the magma derived part of its water from the rocks through which it passed. The relation of the metamorphic grade to the age of the sediments, however, seems to have received but little attention.

Typically "wet" aureoles such as those of Cornwall (Ussher, 1909; Reid, 1910) and New Galloway (Gardiner, 1890; Tilley, 1926) evidence intrusion closely following upon sedimentation, whilst the "dry" aureole of Comrie (Tilley, 1924) is an example of a long time lapse between the deposition of the sediments and their subsequent metamorphism.

Other examples appear to disprove this relation, but the fact that higher grade conditions are often connected with the more basic rocks must not be overlooked, and the suggested relation between metamorphic grade and the age of the sediments may be worthy of closer examination.

Unfortunately the higher grade hornfelses at Hartley cannot be related to the type of igneous rock.

Summary.

1. The structure of the Upper Devonian (Lambian) Series at Hartley has been described and the sequence compared with that of the type area at Mt. Lambie, Rydal.

2. The difficulties attending observations on incipient metamorphism and the measurement of the contact zone have been discussed.

3. A detailed petrographical account of sixteen primary hornfelses and two interbedded lavas is given, and the subsequent metasomatism of some of the primary types has been treated genetically, and rock equations adduced to show the possible formation of some of the more important secondary minerals.

4. The primary hornfelses have been related to Goldschmidt's Classification, by means of a comparative table and a series of rock equations.

5. A table has been constructed to show the relation between the primary hornfelses and twenty-four metasomatic assemblages.

6. It has been shown that the Hartley aureole is an example of a medium grade "wet" type of metamorphism.

7. The metasomatism has been related to a period immediately following the intrusion with concomitant fracture.

8. Certain suggestions have been made regarding the relation between the grade of metamorphism and the age of the invaded sediments.

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EXPLANATION OF PLATE I.

Geological Sketch Map of the Hartley District.