Hornblendes from some basic hornfelses in the New England region, New South Wales

With Plates V and VI

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Summary. With progressive increase in grade of contact metamorphism, aluminous hornblendes in some New England basic hornfelses change from a pale blue-green variety with ragged actinolitic habit, to a deeper bluish-green variety, then to a deeply coloured brownish type with granular habit. At all stages the coexisting plagioclase is appreciably calcic. No outer aureole of albite-epidote-actinolite hornfels has been recognized. The higher grade hornblendes are richer in alkalis and titanium, and poorer in octahedrally co-ordinated aluminium than those formed at low grades. Two analysed hornblendes display an unusual excess of calcium, which occupies the *Y* site, and another has a very high content of ferrous iron and potassium.

Introduction

Although many analyses of hornblendes from regionally metamorphosed basic rocks have been reported in the literature, very little chemical information exists for their counterparts in contact metamorphic hornfelses.

Material ideal for the collection of such information occurs in the New England district of northern New South Wales, where greywackes, cherts, and basic lavas of the Siluro-Devonian Woolomin Beds (Benson, 1913; Crook, 1961) are intruded by granitic rocks of the epizonal New England Batholith, an intrusive complex of Upper Permian to Lower Triassic Age. Where the basic intercalations have been hornfelsed by the granitic rocks, it is usually possible to recognize progressive changes in the colour and textures of their constituent amphiboles as metamorphic grade increases towards the contact.

To evaluate the factors underlying the colour changes and to compare the chemistry of hornfels hornblendes with those in regional metamorphic rocks, two localities in the New England district have been selected for detailed study. The first lies at Tilbuster, seven miles north of the city of Armidale along the New England Highway (fig. 1), and the second in the Moonbi Ranges between the New England Highway and

Gill's Oakey Creek, just north of the township of Moonbi, near the city of Tamworth (fig. 2).

Contact metamorphism and metasomatism of basic rocks striking into an adamellite–monzonite intrusion (the Duval Adamellite, Boesen,

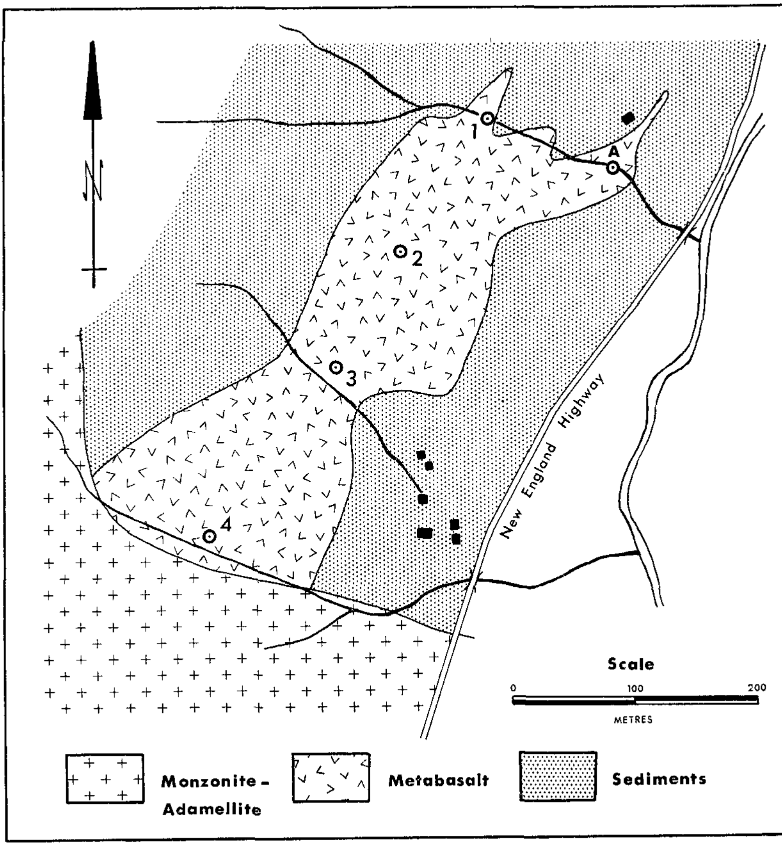

FIG. 1. Map of hornfels zone at Tilbuster, N.S.W. (after Spry, 1955), showing localities from which analysed material was collected.

1960) at Tilbuster have been described by Spry (1955). Extensive introduction of material, accompanied in places by shearing, has taken place in the hornfels zone, leading to the crystallization in the metamorphosed basic rocks of scapolite, grossular, diopside, calcite, epidote, sphene, and plagioclase, and often to albitization of pre-existing plagioclase and replacement of hornblende by biotite. In this paper attention is restricted to basic hornfelses whose textures and mineral constitution suggest that they have not been affected by metasomatism. In such rocks, the plagioclase is always appreciably calcic except where it has formed by recrystallization of vesicle material.

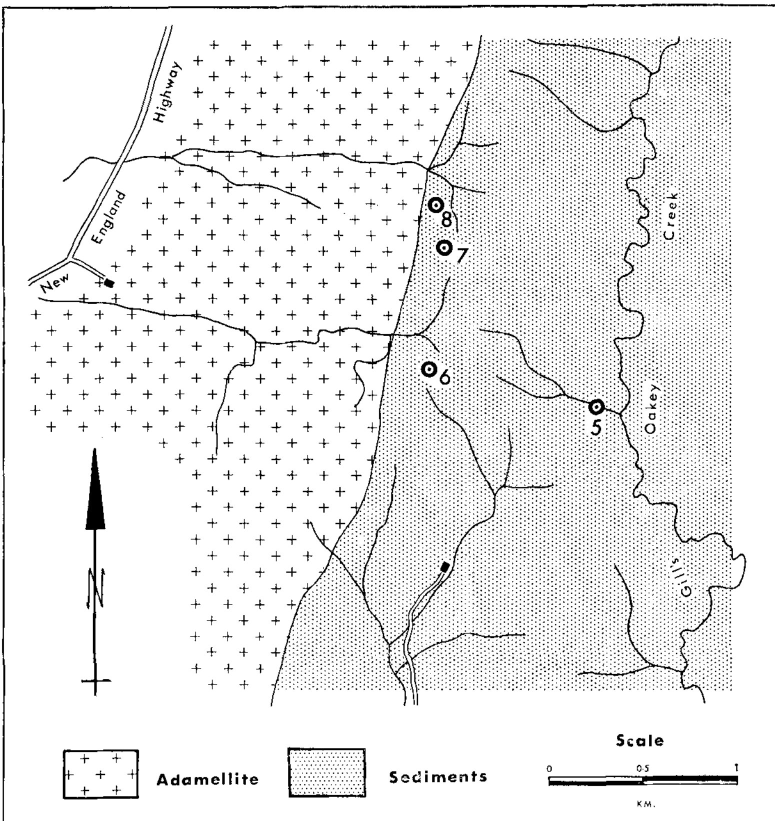

FIG. 2. Map of hornfels zone in the Moonbi Range, N.S.W., showing locality of basic lenses in the Woolomin Beds from which analysed material was collected.

The Moonbi Adamellite (Chappell, 1964) is a transgressive epizonal intrusion at the southern end of the New England Batholith. Its contact zone differs from that of the Duval Adamellite at Tilbuster in two respects; in the width of the aureole (about 1 km at Moonbi against 0·5 km at Tilbuster) and in the association of deformation with the thermal metamorphism along its eastern margin. The Woolomin Beds which it intrudes in the Moonbi Range have become moderately foliated and dragged into conformity with the vertical, northerly striking igneous margin. Bedding structures have been largely obliterated, those remaining being contorted about vertically pitching fold axes in a manner that suggests horizontal wrenching parallel to the contact. The greater width of the contact aureole reflects the difference in size of the two intrusions; the Moonbi Adamellite is a subcircular mass about 15 km in diameter while the Duval Adamellite is an elongate transgressive intrusion 6 km across.

The Woolomin Beds at Moonbi include greywackes, cherts, and siliceous semipelites. Basic rocks are not abundant but occur as lenticular intercalations of thickness ranging from a few metres to about 10 metres and of limited lateral extent. It is probable that the lenses nearer the igneous contact (localities 6, 7, and 8 on fig. 2) were formerly one unit, becoming separated during the shearing and folding that accompanied their metamorphism.

Outside the metamorphic aureole in both areas, basic rocks in the Woolomin Beds possess basaltic fabrics, with laths of plagioclase and intergranular or subophitic grains of clinopyroxene. Plagioclase is often mildly altered, calcite and fine-grained sphene (?) being among the alteration materials. Pale green, almost isotropic chlorite is commonly found in the groundmass. The iron–titanium oxide minerals may be partly or completely altered to sphene. Some spilites are known, but the plagioclase of most Woolomin basalts is andesine or labradorite. Modal and optical data for an unrecrystallized basalt from the north-eastern extremity of the basic rock mass at Tilbuster (locality A, fig. 1) are given in table I.

Petrography of the hornfelses

The first indication of metamorphism in the outer portions of the contact aureole both at Tilbuster and Moonbi is the crystallization of a very pale bluish green amphibole with ragged or fibrous actinolitic habit, formed by reaction between the plagioclase and clinopyroxene of the original basaltic rocks (plates VA, VIA). With increase in grade the colour of this amphibole intensifies to a moderately deep bluish green, then to dark green while at the same time its habit becomes less ragged (Plates VB, VIB). Finally, close to the contact, deep brown or brownish-green hornblende crystallizes with a granular habit.

The modal and optical data presented in table I show that with increase in metamorphic grade the proportion of plagioclase in the basic

TABLE I. Approximate modes and optical data

	Tilbuster					Moonbi			
Specimen No.	A	1	2	3	4	5	6	7	8
Mode (vol. %)									
Hornblende	—	69	64	56	50	70	69	64	60
Plagioclase	57	25	28	38	40	12	20	30	33
Clinopyroxene	18	—	3	2	8	—	—	—	—
Iron ore	—	1	—	—	2	13	6	5	5
Sphene	6	5	5	4	—	tr.	tr.	—	—
Chlorite	19	—	—	—	—	—	—	—	—
Biotite	—	—	—	—	—	5	—	—	—
Quartz	—	—	tr.	—	—	tr.	5	1	2
Refractive indices									
Plagioclase, β ($\pm$0·002)	1·557	1·550	1·565	1·554	1·555	1·552	1·553	1·553	1·552
Hornblende, β (average)	—	1·673	1·673	1·718	1·688	1·672	1·670	1·679	1·665
Clinopyroxene, β ($\pm$0·002)	1·695	—	1·694	1·715	1·695	—	—	—	—
Plagioclase (mol. % An)	48	35	62	42	44	39	40	40	39

A, 1–4, basic rocks from Tilbuster; 5–8, basic rocks from Moonbi, localities shown on figs. 1 and 2. Specimen numbers below refer to collections housed in the Department of Geology, University of New England.

A. R9342. Unrecrystallized basalt. Colourless clinopyroxene and pale green, almost isotropic chlorite occur interstitially between plagioclase laths (0·3 to 0·5 mm long). Plagioclase is clouded and altered to varying degrees, the fresher laths having refractive indices and composition quoted in the table, and the more altered having β = 1·550 (An 37). Sphene occurs in aggregates replacing original iron-titanium oxide.

1. R9346. Low-grade metabasalt illustrated on plate VA. Except for larger grains in the ovoid patches, the pale amphibole contains many inclusions of sphene. An X-ray powder photograph of the analysed amphibole concentrate shows a normal hornblende pattern with extraneous lines at d = 3·23 (faint) and 2·99 Å (very faint) due to the sphene inclusions. The analysis of the concentrate (1, table II) has been corrected for 2 % sphene impurity (1′, table II), a figure which brings its titanium content into line with that of hornblende 2.
2. R9366. A similar metabasalt to R9346. The plagioclase is unusually calcic. Its pale amphibole resembles that of R9346 but contains fewer sphene inclusions. A little clinopyroxene accompanies larger hornblende crystals in the ovoid patches. The analysed hornblende concentrate is 98 % pure, a little clinopyroxene occurring as contaminant. Its normal hornblende X-ray powder pattern is modified by extra lines at d = 2·99 (faint) and 2·52 Å (very faint) due to the clinopyroxene. No sphene line at d = 3·23 Å is detectable. A correction for 2 % of clinopyroxene has been applied in analysis 2′, Table II.
3. R9360. This specimen displays similar metabasaltic texture to other Tilbuster hornfelses but differs from them chemically. Andesine, occurring as laths 0·1 mm to 0·5 mm in length and as scattered larger phenocrysts, in places shows recrystallization to mosaic plagioclase. Deep blue-green hornblende, whose iron-rich nature is reflected by its high refractive index and low optic

TABLE I (*cont.*)

axial angle, occurs interstitially with sphene as granules (0·05 mm) of less ragged habit than the amphibole of R9346 and R9366. Patches and irregular veinlets composed mainly of larger grains (0·2 mm) of the same hornblende with some clinopyroxene and clear plagioclase at their centres occur sporadically throughout the rock. The average mode quoted in this table includes many such veinlets and fits well into the general trend of decreasing amphibole and increasing modal plagioclase with increasing metamorphic grade, suggesting that the veinlets were formed by segregation processes operating during metamorphism. Metasomatic effects or control by some pre-metamorphic fabric are other possible explanations. The high iron and potassium content of the hornblende imparts an unusual composition to the rock which could be the result of pre-metamorphism weathering. The purity of the analysed hornblende concentrate exceeds 99·5 %.

4. R9335. High grade metabasalt illustrated on plate VB. The deep brown hornblende is distinctly granular in outline, especially where occurring as larger crystals in ovoid patches. Ilmenite is the sole opaque mineral. The analysed amphibole is 99·5 % pure, and shows a normal hornblende X-ray powder pattern.
5. R9382. Low-grade hornfels illustrated on plate VIA. Decussate hornblende is accompanied by some pale brown biotite. Ilmenite is abundant, occurring in trails of granules parallel to a vague foliation. Sphene forms scattered small granules. Purity of hornblende concentrate 99 % (ilmenite impurity).
6. R9394. Basic hornfels in which hornblende occurs as squat ragged grains 0·3 mm across and as smaller needles associated with finer granoblastic plagioclase (grain size 0·03 mm). The larger crystals show faint colour zoning. Purity of hornblende concentrate 99·5 %.
7. R9407. Granoblastic high grade hornfels illustrated on plate VIB. A foliation is marked by orientation and banding of hornblende (grain size 0·2–0·3 mm) and ilmenite. Occasional large crystals of hornblende (1 mm) may contain some clinopyroxene at their cores. Purity of hornblende concentrate 99 % (ilmenite impurity).
8. R9409. Granoblastic high-grade hornfels similar to R9407 but with brown hornblende which in places shows slight colour zoning. Purity of hornblende concentrate 99 % (ilmenite impurity).

hornfelses increases and that of hornblende decreases. At Moonbi, the composition of the plagioclase (andesine) is remarkably constant throughout the aureole, while at Tilbuster there is some variation, unrelated to metamorphic grade, from andesine to labradorite. It is clear that chemical changes in the hornblendes due to increase in grade have released some of the plagioclase that was lost in the amphibole-forming reactions at lower grades.

The quantity of *titanium-bearing accessory* also decreases with increase in grade. Sphene is stable except at the very highest grade in the Tilbuster hornfelses, but ilmenite is present from the lowest grade stage at Moonbi. This difference is probably due to the relative calcium content of the rocks in the two areas rather than to any difference in physical conditions during metamorphism.

The unmetasomatized basic hornfelses at Tilbuster suffered no deformation during their metamorphism and preserve metabasaltic textures. The larger plagioclase laths of low-grade hornfelses are much attacked along their margins and the smaller laths entirely consumed as a result of the amphibole forming reaction (Plate VA). Usually the laths remain as discrete crystals but in some specimens they are replaced by pseudomorphous mosaics of fine grained andesine or labradorite, showing that calcic plagioclase is indeed stable and not merely retained as an igneous relic. Pale amphibole often replaces the central portions of plagioclase laths, generally along the composition planes of twins. At higher grades, the plagioclase laths may also be replaced by deeper coloured hornblende along twin composition planes and are accompanied by granoblastic plagioclase (Plate VB).

The pale amphibole of the lowest grade Tilbuster hornfelses usually includes many tiny platelets of sphene. These represent the excess titanium from the original clinopyroxene that could not be accepted by the replacing amphibole. Sphene also occurs as aggregates of small granules, replacing original iron–titanium oxide minerals. In the highest grade hornfelses, brown-green hornblende is accompanied by smaller prisms of colourless clinopyroxene (cf. modes in table I).

Most Tilbuster hornfelses contain ovoid patches several millimetres across, composed of larger grains of amphibole similar to that found interstitially between plagioclase laths (illustrated in Plates VA, VB). These amphibole grains are ragged, relatively free of sphene inclusions, and sometimes accompanied by stubby prisms of clinopyroxene in lower grade hornfelses, but show regular sub-rounded outlines at higher grades. They appear to be derived from original pyroxene phenocrysts.

The deformation that accompanied recrystallization at Moonbi has destroyed the basaltic textures of the basic rocks throughout the contact aureole. Textures of the resulting hornfelses are decussate or granoblastic, depending on grade (Plate VI). Plagioclase is granular and usually poorly twinned. Vague alignment of amphibole or faint segregation banding of the mineral constituents often produces a poor foliation. Many Moonbi hornfelses possess scattered blasto-phenocrysts of hornblende, at times including relics of the clinopyroxene from which they were formed.[1]

[1] To the south of the Moonbi area, Benson (1915) has recorded 'spilitic' rocks which have been metamorphosed to albite–'actinolite' hornfelses and 'schists' by the Moonbi Adamellite. In view of the chemical analyses presented in this paper, the identification of actinolite is probably erroneous. Basic hornfels with calcic plagioclase are found associated with these albitic rocks and it is clear that the albite owes

The change towards a more regular granular habit at higher metamorphic grades shown by hornblendes in both the Moonbi and Tilbuster hornfelses is explained by the higher temperatures and the longer period for which these temperatures were maintained closer to the cooling granitic intrusion.

Further information on the textures and mineralogy of the various hornfels types and on the distance from the contact at which the various stages of metamorphism occur may be obtained from table I and from the legends to the Plates and the Figures.

Metamorphic grade at the contacts

Orthopyroxene has not been found in basic hornfelses at the Tilbuster locality, probably as a result of the relatively high calcium content of the parent rocks. However a basic hornfels (S 2771) from the opposite side of the adamellite intrusion, some four miles to the south-west, contains a granular assemblage of hornblende, orthopyroxene, clinopyroxene, and ilmenite, from which it appears that the metamorphic grade at the immediate contact has reached the threshold of the pyroxene hornfels facies. Other minerals found in pelitic and semipelitic rocks adjacent to the contact include cordierite, andalusite, and orthoclase (Boesen, 1960).

In the higher grade basic hornfelses at Moonbi, occasional veins containing diopsidic pyroxene, grossular, quartz, and plagioclase have been formed by local metasomatic introduction of material. Pyroxene is rarely found as a product of isochemical metamorphism and orthopyroxene in particular does not occur in the Moonbi hornfelses and has not been described to date in basic hornfelses or xenoliths from other portions of the margin of the Moonbi Adamellite.

Semipelitic rocks adjacent to the contact at Moonbi contain biotite, cordierite, and both orthoclase and muscovite. At the southern margin of the intrusion, limestones within the Tamworth Group have been recrystallized to marbles containing diopside and grossular, some of which is formed from impurities and some from metasomatically introduced material. Wollastonite is restricted to the immediate vicinity of the adamellite and is largely metasomatic in origin. These mineralogical features imply that metamorphism reached high hornblende hornfels facies at the contact of the Moonbi Adamellite.

its origin to abnormal rock chemistry rather than to low grade of metamorphism. Some epidote is also found in these rocks, but it is a variety very rich in ferric iron ($\beta = 1{\cdot}758$) and appears to be present as a result of metasomatic processes. No distinct low-grade zone of albite–epidote–actinolite hornfelses has been recognized either in the area studied by Benson, at Moonbi, or at Tilbuster.

TABLE II. Analyses and structural formulae of hornblendes

	1	1′	2	2′	3	4	5	6	7	8
SiO_2	42·96	43·38	41·92	41·68	36·34	40·26	45·12	45·72	44·46	46·14
TiO_2	1·96	1·18	1·26	1·28	0·94	2·75	1·11	0·94	1·84	1·04
Al_2O_3	11·88	12·17	13·29	13·54	14·06	14·12	11·91	9·83	9·33	10·37
Fe_2O_3	2·70	2·77	1·51	1·49	4·38	1·55	1·94	3·08	3·85	1·14
FeO	13·51	13·85	13·58	13·62	22·99	12·93	16·96	15·52	16·36	14·37
MnO	0·46	0·47	0·38	0·39	0·75	0·24	0·49	0·30	0·34	0·34
MgO	7·52	7·71	10·66	10·66	3·14	10·63	9·72	9·69	8·94	12·15
CaO	14·11	13·91	13·49	13·27	11·82	12·58	10·01	11·77	11·64	11·38
Na_2O	1·27	1·30	2·08	2·12	1·14	2·54	0·95	1·09	1·14	1·28
K_2O	1·15	1·18	0·48	0·49	2·66	0·79	0·03	0·03	0·30	0·06
H_2O^+	2·03	2·08	1·39	1·42	1·81	1·53	1·82	1·73	1·65	1·51
H_2O^-	0·02	—	0·08	—	0·01	0·00	0·00	0·00	0·20	0·17
Cr_2O_3	n.d.	—	0·04	0·04	n.d.	n.d.	n.d.	n.d.	n.d.	0·08
F	n.d.	—	0·00	—	0·02	n.d.	n.d.	n.d.	0·06	0·03
Total	99·57	100·00	100·16	100·00	100·06	99·92	100·06	99·70	100·11	100·06
Less O for F					0·01				0·03	0·01
					100·05				100·08	100·05

1 to 4, hornblendes from Tilbuster; 5 to 8, hornblendes from Moonbi, numbered as in table I.
1′, analysis 1 corrected for 2 % sphene impurity and recalculated to 100 %.
2′, analysis 2 corrected for 2 % clinopyroxene impurity (same Fe:Mg) and recalculated to 100 %.
Analyst: W. H. Herdsman, Glasgow. Total iron redetermined by R.A.B.

	1′	2′	3	4	5	6	7	8
Structural formulae based on 23 oxygen atoms, water-free								
Si	6·50	6·18	5·81	5·99	6·66	6·78	6·66	6·75
Al^{iv}	1·50	1·82	2·19	2·01	1·34	1·22	1·34	1·25
Al^{vi}	0·65	0·55	0·46	0·46	0·73	0·50	0·31	0·53
Ti	0·13	0·14	0·11	0·31	0·12	0·11	0·21	0·11
Fe^{+++}	0·31	0·17	0·53	0·17	0·21	0·34	0·43	0·13
Fe^{++}	1·73	1·69	3·07	1·60	2·09	1·93	2·05	1·76
Mn	0·06	0·05	0·10	0·03	0·06	0·04	0·04	0·04
Mg	1·72	2·35	0·75	2·36	2·14	2·14	1·99	2·65
Ca	2·23	2·10	2·02	2·00	1·59	1·87	1·87	1·78
Na	0·38	0·61	0·35	0·73	0·27	0·31	0·33	0·36
K	0·23	0·09	0·54	0·15	0·01	0·01	0·06	0·01
$\Sigma (Y)$	4·60	4·95	5·02	4·93	5·35	5·06	5·03	5·22
Refractive indices								
α	—	1·661	1·700	1·674	1·659	1·668	—	—
β	1·667–1·680	1·673 ± 0·002	1·718 ± 0·003	1·688 ± 0·002	1·672 ± 0·002	1·670 ± 0·002	1·676–1·682	1·660–1·669
γ	—	1·685	1·725	1·698	1·683	1·682	—	—
δ ($\pm$0·002)	0·024	0·024	0·025	0·024	0·024	0·024	0·023	0·022
$2V_\alpha$	—	—	45±2°	—	—	—	—	—
Absorption colours								
α	very pale yellow	very pale yellow	pale yellow-green	pale straw	very pale yellow	pale yellow-green	pale yellow-green	pale yellow-green
β	pale apple green	pale olive green	deep olive green	deep brown	pale apple green	apple green	deep olivine green	brown
γ	pale blue-green	pale bluish green	deep blue-green	deep brown	pale blue-green	blue-green	deep green, bluish tinge	greenish brown

Available stratigraphic information does not permit an estimation of the thickness of sediments under which the Moonbi and Duval Adamellites were emplaced, but it is probable that the latter was intruded at a rather shallower depth than the former. The relatively small differences in metamorphic facies at their immediate contacts may therefore be due to different fluid pressures rather than to different temperatures. Although the Duval Adamellite intrusion includes some granodioritic, monzonitic, and dioritic phases (Boesen, 1960) and may therefore have crystallized at a slightly higher overall temperature than the Moonbi Adamellite, the mafic mineralogy of its more acid phases (biotite and hornblende with some clinopyroxene and orthopyroxene) as compared with that of the Moonbi Adamellite (biotite and hornblende) further suggests lower water pressure conditions in and around the Duval Adamellite.

Chemistry of the hornblendes

Modal and optical data, and notes on eight specimens from which the amphiboles have been separated and analysed (table II) are included in table I.

Despite their pale colour and ragged actinolitic habit the lowest grade amphiboles possess aluminium contents comparable to those of higher grade equivalents. They must consequently be regarded as true hornblendes. Total aluminium content tends to increase with metamorphic grade in the Tilbuster hornblendes but in their Moonbi counterparts shows a slight overall decrease. Tetrahedrally co-ordinated aluminium replacing silicon increases markedly with grade at Tilbuster but remains roughly constant at Moonbi. With the exception of specimen 8, the hornblendes from both hornfels zones show a significant decrease in the amount of octahedrally co-ordinated aluminium as metamorphic grade increases.

In both areas, the alkali content of the amphiboles increases with metamorphic grade. It is difficult to reconcile this feature and the variations in aluminium content with the constancy in composition of the coexisting plagioclase and the observed trends in modal composition of the hornfelses, for the increase in plagioclase content implies that both alkali and alumina contents of the higher grade hornfelses are appreciably greater than those of their lower grade equivalents. Since a similar progressive change in original rock composition towards the contacts in both areas would be an unlikely coincidence, it appears that some mobilization of material, particularly of alkalis, has taken place within the broadly isochemical conditions of metamorphism.

The brown coloration of higher grade hornblendes is due to their higher titanium content, this being balanced in the rocks by decrease in the modal proportion of sphene or ilmenite (Table I). Hornblende 8 is unusual in its low titanium content and the brown coloration here appears to be influenced by low ferric-iron content. Ferric-iron content of the hornblendes in general is irregular.

The pale colour of the lower grade hornblendes is not accounted for by their titanium and ferric-iron content since regional metamorphic amphiboles with similar contents of these two cations are often quite deeply coloured. The ratio of iron to magnesium also shows no correlation with depth of colour; with the exception of hornblende 3 this ratio is relatively constant throughout the hornfels zones. In a series of regional metamorphic hornblendes from Broken Hill, N.S.W. (Binns, 1965), depth of colour has been correlated with filling of the vacant site in the amphibole structure. However, while a trend towards increased occupation of this site at higher grades is observed in the Moonbi and Tilbuster hornblendes, filling of the vacant site, especially in the low-grade varieties from Tilbuster, is no less than in many relatively deeply coloured regional metamorphic hornblendes.

The calcium content of the Moonbi hornblendes is normal for aluminous amphiboles, being least in the lowest grade specimen. The Tilbuster hornblendes, on the other hand, are noteworthy for their high calcium contents, particularly in the low-grade varieties where calcium exceeds two cations per formula unit. The corrections applied to analyses 1 and 2 in table II for small amounts of sphene or clinopyroxene impurity have slightly reduced their calcium content (analyses 1′, 2′). If greater corrections were to be applied, the excess calcium might be eliminated altogether. However, examination of grain mounts and X-ray powder patterns does not justify any further corrections, and the excess calcium must be regarded as real. The high calcium in hornblendes 1′ and 2′ (Ca = 2·23, 2·10 respectively) is accompanied by a deficiency in the Y group ($\Sigma\ Y = 4{\cdot}60$, $4{\cdot}95$) and it is probable that some calcium substitutes into the octahedrally co-ordinated Y site. Although hornblende 4 shows no actual excess of calcium, it is also slightly deficient in the Y group. The high calcium content of the Tilbuster hornblendes is in harmony with a comparatively high lime content of the host rocks (cf. Spry, 1955, table I, specimen 6732). In view of the lower calcium content of hornblende 5 from Moonbi, high calcium cannot be regarded as a peculiarity of low-grade hornfels hornblendes in general.

Hornblende 3 is notable for its high iron and potassium contents, its low magnesium, and its extensive replacement of silicon by tetrahedrally co-ordinated aluminium. In other aspects of its chemistry it resembles the remaining Tilbuster hornblendes.

Although hornblende 2 is an exception, water content tends to be higher in lower grade hornblendes. Fluorine is not a significant component. Deficiencies in structural water are not accompanied by unusually high ferric-iron content, and it is doubtful whether any 'oxyhornblende-type' substitution has taken place. As noted elsewhere (Binns, 1964), analytical figures for structurally combined water must be treated with some caution. The practice of calculating structural formulae on the basis of 23 oxygen anions, exclusive of those combined with hydrogen has been adopted in this paper.

With the exception of the lower grade Tilbuster hornblendes, whose high calcium content is due to chemistry of their host rocks, the New England hornfels hornblendes chemically resemble their counterparts in regional metamorphic rocks. Similar trends towards increased alkali and titanium contents, and decrease in octahedrally co-ordinated aluminium at higher grades of metamorphism are especially noteworthy (cf. Shidô and Miyashiro, 1959; Binns, 1964).

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Explanation to Plates

Plate V

A. Low-grade metabasalt R9346 (Tilbuster, locality 1). Pale blue-green hornblende interstitial to the plagioclase laths is crowded with inclusions of sphene. The small dark patches are not opaque minerals but aggregates of tiny sphene granules. The plagioclase laths show replacement by amphibole along central twin planes. In the upper left-hand corner is an ovoid patch of larger hornblende crystals free of sphene inclusions, apparently an altered pyroxene phenocryst.

B. High-grade metabasalt R9335 (Tilbuster, locality 4). Deep brown granular hornblende occurs as large crystals in an ovoid patch on the upper right and as smaller grains associated with occasional tiny clinopyroxene prisms, scattered ilmenite granules and some granoblastic plagioclase in the metabasaltic portion. Several relic plagioclase laths are shown (top left, lower centre); these retain axial zones of hornblende.

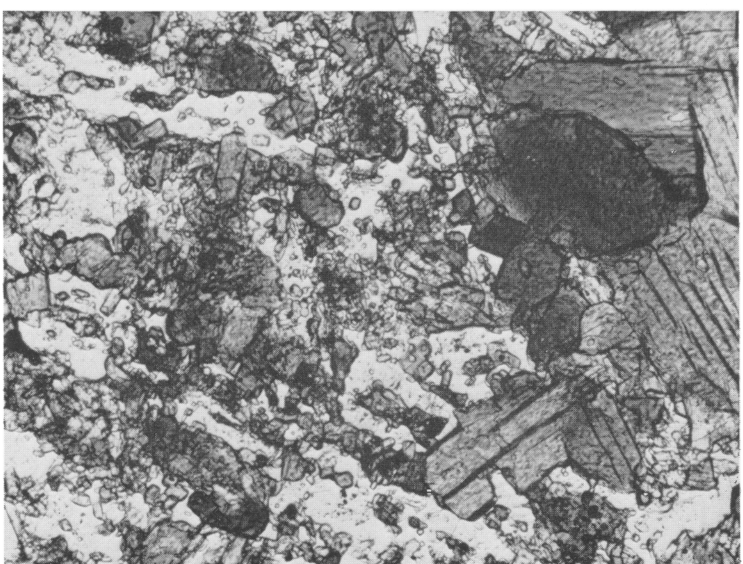
PLATE VI

A. Low-grade basic hornfels R9382 (Moonbi, locality 5), consisting mainly of decussate pale blue-green amphibole, accompanied by a little pale biotite, and aggregated ilmenite grains. Plagioclase is more abundant in the lower portions of the field.

B. High-grade basic hornfels R9407 (Moonbi, locality 7), an assemblage of granoblastic deep green hornblende, plagioclase, and ilmenite with a faint foliation (roughly vertical). All photomicrographs taken with unpolarized light.

A

0·5 mm



B

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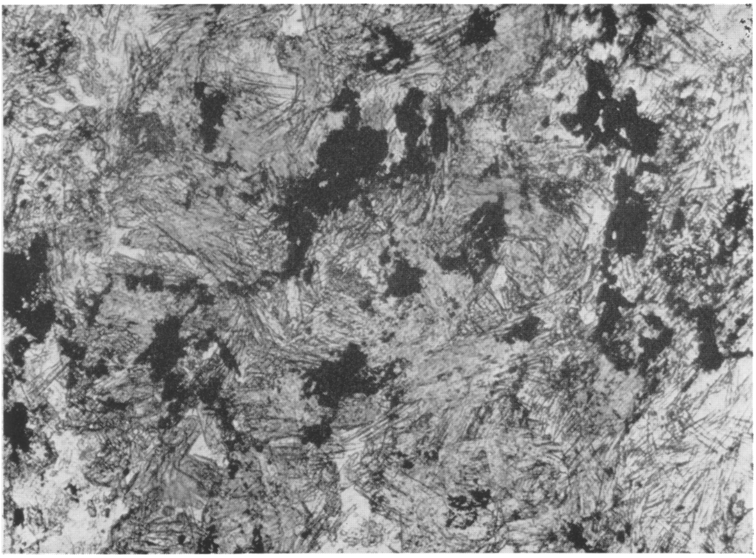

A

0·5 mm

B

R. A. BINNS: HORNBLENDES FROM BASIC HORNFELSES