THE BEN BULLEN PLUTONIC COMPLEX, N.S.W.

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(With two text-figures.)

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Contents.

1. Introduction.

The writer has recently described the exogenous[10] and endogenous[11] [12] contact-zones of the Ben Bullen Plutonic Complex, and in connection with the endogenous contacts brief descriptions of the igneous rocks taking part in the reactions have already been given. These are repeated here, however, and it is shown that the rocks are members of the complex.

The intrusion has been mapped by the Geological Survey of N.S. Wales, and Fig. 1 is based almost entirely upon the original map by the survey officers.[3] Internal boundaries and the subdivision of the mass into an earlier and later intrusion are due to the present writer.

2. Field Relations.

The igneous complex covers an area of about 350 acres, and is a composite stock-like mass of irregular shape. The most prominent directions of jointing are N.-S., E.-W., N. 55° W., N. 70° W., and N. 40° E.

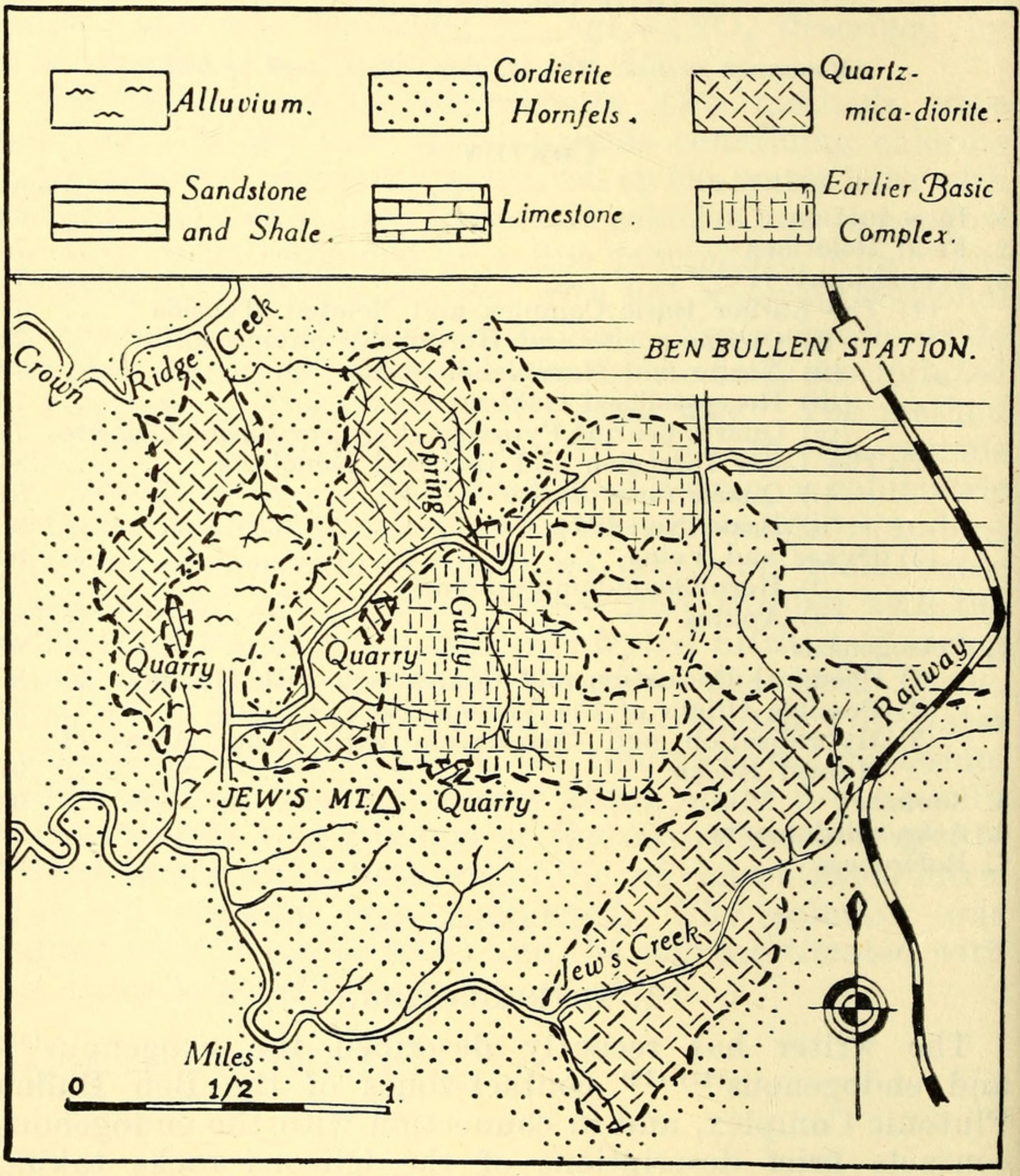


Fig. 1.—Geological Sketch Map of Ben Bullen.

The central portion is occupied by a basic mass which has been partly recrystallised and hybridised by a later intrusion of quartz-mica-diorite. The basic complex consists of a basified diorite enclosing numerous masses of norite in varying stages of hybridisation, together with occasional patches of recrystallised gabbro which may also be hybridised.

Banded hornblende-gabbros occur at a few localities, but these are believed to be due to contamination with the limestone and will be described in a later publication.

Small fragments of the earlier complex have been collected amongst the limestone *débris* in the quarry on Por. 45, 46 and 47, Par. of Ben Bullen, and it is evident that these represent remnants of the first intrusion which invaded the limestone and together with the sedimentary rock formed the roof of the second magma chamber.

The later intrusion of quartz-mica-diorite partly surrounds the earlier complex, and immediately west of the main mass a chain of low, quartzite hills separates an apparently detached outcrop of quartz-mica-diorite. These hills evidently represent a portion of the roof of the intrusion, and the diorite is possibly continuous beneath this cover. Small patches of limestone, appearing to rest on the igneous rock, also point to the incomplete removal of the roof.

Occasional small dykes and veins of aplite and hornblende-lamprophyre occur as an end-phase of igneous activity.

3. Petrography.

The Earlier Basic Complex and Related Hybrids.

Three main types make up the earlier complex, namely olivine-norite, norite or hypersthene-gabbro and recrystallised gabbro. It seems evident that the noritic complex was shattered and partly assimilated by a later intrusion of quartz-mica-diorite, and to avoid repetition the primary types will be described with the corresponding hybrids. The shattered norites are enclosed in a basified diorite, and, although this is a modified member of the later intrusion, it is so intimately related to the shattered norites that it is described with members of the earlier basic complex.

(i) *Olivine-norite and Hornblende-olivine-norite.*

The olivine-norite is believed to be the most basic member of the earlier complex, and one small mass, enclosed in the basified diorite, occurs about 40 chains S.W. of the N.E.

corner of Por. 1, Par. Ben Bullen. A small outcrop of the corresponding hybrid is met with in the middle of Por. 63.

In the hand specimen both are dense, dark, medium-grained rocks, and the hybrid type contains large (7 mm.), black " shimmer " plates of hornblende.

Under the microscope the normal type is panidiomorphic, granular, and sub-ophitic. The hybrid is highly poikilitic, and contains large irregular grains of hornblende, whilst the normal type shows only an incipient development of amphibole. The other minerals are plagioclase, augite, hypersthene, olivine, iron ores, and a little apatite.

Plagioclase occurs in laths with sutured boundaries, and these measure about 1 mm. The mineral is very clear and suggests an incipient recrystallisation, but no true crystalloblastic structures are developed. Mottling is suggestive of hybridisation.(8) The plagioclase is basic labradorite ($Ab_{32}An_{68}$) with $\alpha' = 1 \cdot 563$, $\gamma' = 1 \cdot 573$. It is optically positive, with a fairly large 2V. The extinction on sections $\perp$ to 010 is 38°.

The pyroxenes occur in subidiomorphic prisms measuring about 2 mm. The augite is optically positive, $Z \wedge C = 39°$, and polysynthetic twinning is common. The hypersthene shows relatively strong pleochroism. Both pyroxenes include olivine and iron ores, and in the hybrid type they are flecked with, and surrounded by, brown hornblende. In the normal type the pyroxenes show incipient amphibolization.

The olivine is optically negative, with a very large 2V ; $\alpha' = 1 \cdot 680$, $\gamma' = 1 \cdot 720$. According to Larsen and Berman(13) this indicates $Mg/Fe = 78/22$. Olivine occurs in rounded crystals which measure up to 1 mm. A good 010 cleavage is usually developed, and secondary magnetite often appears along cleavage planes and cracks. A little serpentine is sometimes present, but secondary amphibole is a more common alteration product. In the hybrid rock the olivine is included in brown hornblende.

Hornblende occurs in large (7 mm.) poikilitic plates in the hybrid type, and there is a slight development in the normal rock. In the latter narrow rims of pale green amphibole occur around all the minerals that are adjacent to plagioclase. This has already been figured.(9)

In the hybrid rock the brown hornblende appears to grow out into the plagioclase from cores of pyroxene, olivine and/or iron ores. The hornblende grows between the plagioclase laths and along the cleavages, and the felspar thus appears to form normal idiomorphic inclusions. The mineral is optically negative ; $\alpha' = 1\cdot662$, $\gamma' = 1\cdot690$; X = pale yellow, Y = reddish-brown, Z = reddish-brown ($Z \geqslant Y > X$) ; $Z \wedge C = 24°$.

An analysis of the hybrid is given in column I below.

	I.	II.
SiO_2	43·15	46·85
Al_2O_3	20·45	20·02
Fe_2O_3	3·79	2·30
FeO	7·98	4·60
MgO	7·82	10·16
CaO	14·03	13·84
Na_2O	0·71	1·32
K_2O	0·15	tr.
H_2O+	0·58	0·88
H_2O-	0·15	
TiO_2	1·37	0·30
P_2O_5	0·10	tr.
MnO	0·12	tr.
CO_2	tr.	—
	100·40	100·27
Sp. Gr.	3·02	2·996

Norms.

	I.	II.
Orthoclase	1·11	—
Albite	5·76	11·00
Anorthite	52·26	48·65
Diopside	13·47	15·90
Hypersthene	9·10	9·85
Olivine	9·59	10·05
Magnetite	5·57	3·25
Ilmenite	2·58	0·61
Apatite	0·34	—

I. Hornblende-olivine-norite, (Kedabekase, "III.5."5.4(5)) Por. 63, Parish of Ben Bullen. Anal. G. A. Joplin.

II. Gabbro-diorite, (Kedabekase, (II)III.5.(4)5.0) Pikesville, Baltimore County, Maryland. Anal. L. McCay. G. H. Williams, *U.S.G.S.* Bull. 28, 1886, p. 37. In W.T. p. 666, No. 4.

(ii) *Norite and Hornblende-norite.*

These rocks are abundant on the northern, north-western, and north-eastern slopes of Cleared Hill and on the saddle to the east. They are also met with in the gully to the east of this saddle and may continue down as far as the old Mudgee Road. The hybrid type is the commoner, and these masses evidently represent the shattered and partly assimilated remains of the earlier basic complex.

In the hand specimen they are dark, dense, gabbroid rocks and often contain large well-formed crystals of pyroxene. In the hornblende-rich varieties this mineral occurs in " shimmer " plates.

Under the microscope the rock is panidiomorphic granular, sub-ophitic, glomeroporphyritic and/or inter-granular. The constituent minerals are plagioclase, monoclinic and rhombic pyroxene, iron ores and, in the hybrid type, brown hornblende. Apatite and epidote are often present in small amount, and in one or two cases a little quartz and biotite have been noted.

Pyroxene tends to form clots measuring about 3 mm. These are made up of both monoclinic and rhombic crystals which measure about 1 mm. Irregular grains of iron ore are usually associated, and sometimes dendritic masses of iron ores suggest original olivine. Occasionally the pyroxene masses consist of a single crystal of monoclinic pyroxene.

The rhombic pyroxene, besides forming fairly large crystals in the clot, also occur in smaller stout subidiomorphic prisms or rounded grains between the plagioclase laths. Occasionally the monoclinic mineral occurs in this fashion.

The monoclinic pyroxene is optically positive and 2V is fairly small. The mineral is pale green and non-pleochroic. $\alpha' = 1 \cdot 690$, $\gamma' = 1 \cdot 710$; $Z \wedge C = 40°$. It therefore appears to be diopsidic in composition.

The hypersthene shows fairly strong pleochroism, with X = pale rose-pink, Y = faint yellowish-pink, Z = greyish-green. 2V is large and the mineral is sometimes optically positive. $\alpha' = 1 \cdot 695$, $\gamma' = 1 \cdot 710$. The plagioclase shows clearing and mottling and forms tabular crystals or stout laths averaging 2 mm. Occasionally small rounded crystals are developed, and the rock suggests slight recrystallisation. $\gamma' = 1 \cdot 569$. The extinction on sections $\perp$ to 010 is 36°, the plagioclase, therefore, has the composition $Ab_{38}An_{62}$.

In the hybrid types a poikilitic fabric is developed, and large irregular crystals of brown hornblende surround the pyroxenes and penetrate the neighbouring plagioclase. In the normal rocks narrow coronas of amphibole indicate incipient hybridisation.(9)

The brown hornblende is optically negative ; $Z \wedge C = 22°$; $\alpha' = 1 \cdot 662$, $\gamma' = 1 \cdot 683$; X = light yellow, Y = dark olive-green, Z = dark reddish brown ($Z > Y > X$).

Apatite is sporadic in its development and sometimes attains local abundance forming large subidiomorphic prisms.

A little epidote is often present as an alteration product and occasionally a little quartz and biotite are developed in the hybrid.

An analysis of the hybrid type is given in column I below.

	I.	II.	III.	IV.	V.
SiO_2 ..	45·36	45·31	44·52	44·04	44·40
Al_2O_3 ..	21·12	19·39	21·32	20·01	20·55
Fe_2O_3 ..	4·19	5·33	5·08	4·22	6·57
FeO ..	7·01	7·81	7·19	8·61	9·26
MgO ..	6·85	6·93	6·41	5·01	5·21
CaO ..	12·19	11·67	12·44	11·68	11·50
Na_2O ..	0·99	1·22	1·25	1·24	1·14
K_2O ..	0·37	0·35	0·15	0·15	0·19
H_2O+ ..	0·62	0·69	0·37	1·90	1·00
H_2O- ..	0·15	0·08	0·06	0·11	—
TiO_2 ..	1·64	1·33	1·04	2·24	—
P_2O_5 ..	0·07	0·31	abs.	0·52	—
MnO ..	0·10	0·17	0·09	0·28	—
CO_2 ..	abs.	tr.	tr.	abs.	—
Etc. ..	—	—	—	0·41	—
	100·66	100·59	99·92	100·42	99·82
Sp. Gr.	2·97	3·004	3·050	—	3·035

Norms.

	I.	II.	III.	IV.	V.
Quartz ..	0·66	0·96	—	1·20	0·96
Orthoclase	2·22	1·67	0·83	1·11	1·11
Albite ..	8·38	9·96	10·48	12·58	9·43
Anorthite	51·49	46·70	52·26	47·26	50·32
Diopside	6·24	7·85	7·42	5·91	5·50
Hypersthene ..	20·97	21·70	18·28	18·72	21·90
Olivine ..	—	—	1·21	—	—
Magnetite	6·03	7·66	7·42	6·03	9·51
Ilmenite	3·92	2·43	1·98	4·26	—
Apatite	0·34	0·67	—	1·34	—

I. Hornblende-norite (Corsase near Kedabekase, II(III).5.(4)5.4). Por. 1 Parish of Ben Bullen. Anal. G. A. Joplin.

II. Hornblende-pyroxene-gabbro or "Reaction"-gabbro (Kedabekase, III.5(4).5.4(5)) Por. 27, Parish of Lowther, Cox's River, Little Hartley. Anal. G. A. Joplin. *Proc. Linn. Soc. N.S.W.*, 1931, *56*, p. 53.

III. Recrystallised Pyroxene-gabbro (leucocratic phase). (Corsase near Kedabekase, II(III).5.(4)5.3″). S. end of Por. 239, Par. Lowther, Little Hartley. Anal. G. A. Joplin. *Ibid.*, 1933, *58*, p. 130.

IV. Hornblende-diorite (Hessose, II(III).5.4(5).″5). Rising Sun, Cecil County, Maryland. Anal. W. F. Hillebrand. A. G. Leonard, *Amer. Geol.*, 1901, *28*, p. 146. In W.T., p. 530, No. 19.

V. Segregation in Norite (Corsase, II(III).5.″5.0). The Bluff, Otago, New Zealand. Anal. L. J. Wild. *Trans. N.Z. Inst.*, 1911 (1912), *44*, p. 325. In W.T., p. 552, No. 10.

(iii) *Recrystallised Gabbros.*

About twelve small patches of recrystallised gabbro are recorded in the Earlier Basic Complex, and among these are represented (*a*) types that are unaffected by hybridisation, (*b*) types that are slightly acidified, and (*c*) types that are definite hybrids containing hornblende or biotite or both.

These rocks have been collected in the depression N.E. of Little Jew's Mt. near the Old Mudgee Road, near the summit of Cleared Hill, just north of the road in Por. 65, and a few boulders of the hybrid type occur among the quarry *débris* on Por. 45, 46 and 47.

In the hand specimen these are fine-grained dense rocks and hornblende may usually be discerned in the hybrids. The blocks found in the limestone quarry are peculiar. They are often veined with the later quartz-mica-diorite, and are believed to have been tongues of the earlier complex injected into the limestone. Some show limestone contamination as well as hybridisation from the later magma. These rocks contain large crystals of brown hornblende measuring up to 14 mm. and often altered to criss-cross flakes of biotite, and in addition biotite may form perfect idiomorphic crystals up to 10 mm. across. This rock has been figured in an earlier publication.(9)

Under the microscope the recrystallised gabbros show a granoblastic and porphyroblastic structure, and in addition the hybrid types contain a poikilitic development of hornblende and/or biotite. The porphyroblasts may be either plagioclase or augite and the ground mass consists of small granules of augite, hypersthene and iron ore, and granules and small laths of plagioclase felspar. The laths and the felspar porphyroblasts are indented by the smaller granular minerals and present sutured boundaries.

The plagioclase is often quite limpid, and, in the more felspathic types, may contain minute granular inclusions of pyroxene and iron ores. These small inclusions are grouped in the centre of the crystal and are often zonally arranged (see Figs.).(8) (9) A glomero-porphyritic grouping of the felspar porphyroblasts is also common. The plagioclase occasionally shows inverted zoning, but zoning is not a common feature. The extinction measured on sections $\perp$ to 010 is 26°, $\alpha'=1\cdot552$, $\gamma'=1\cdot560$ and the composition is therefore $Ab_{53}An_{47}$. In the hybrid types the felspars often show mottling and may be bordered with a plagioclase of the composition $Ab_{64}An_{46}$.

Hypersthene forms small subidiomorphic prisms or rounded grains which usually measure about 0·8 mm. Pleochroism is relatively strong, $\alpha'=1\cdot685$, $\gamma'=1\cdot693$.

Augite has a similar habit to the hypersthene, and in the rocks containing porphyroblasts of this mineral it forms sub-idiomorphic crystals measuring 3 mm., $Z\wedge C=46°$, $\alpha'=1\cdot680$, $\gamma'=1\cdot705$.

Hornblende is present in the hybrid types and may occur as large independent crystals or as poikilitic crystals including iron ores, pyroxenes and felspar. Pyroxene porphyroblasts often show a border of brown hornblende. The mineral is strongly pleochroic, with X=pale golden yellow, Y=yellowish brown, Z=reddish brown ($Z \gg Y > X$), $Z\wedge C=24°$, $\alpha'=1\cdot662$, $\gamma'=1\cdot687$.

Biotite also occurs as independent or highly poikilitic crystals and may sometimes form criss-cross flakes pseudomorphing hornblende $\beta=1\cdot625$, X=golden yellow, Y=golden brown, Z=reddish brown.

Iron ores are fairly abundant and usually form rounded grains associated with the ferromagnesian minerals. Apatite is usually present in small amount.

An analysis of a felspathic type of unhybridised recrystallised gabbro is given in column I, p. 78.

(iv) *Quartz-bearing Pyroxene-diorite or Basified Diorite.*

In the hand specimen the rock has the appearance of a typical diorite consisting of hornblende and plagioclase. The grain size is medium and the density fairly high.

Under the microscope the rock is hypidiomorphic to panidiomorphic granular, and the fabric is subophitic to poikilitic. The grain size averages about 1·5 mm., and

	I.	II.	III.	IV.
SiO_2	48·42	47·23	47·41	50·50
Al_2O_3	21·53	18·49	20·40	21·07
Fe_2O_3	3·09	6·14	3·35	1·85
FeO	7·84	8·79	7·24	3·62
MgO	4·96	3·92	7·53	5·26
CaO	9·12	7·89	9·70	13·20
Na_2O	2·43	2·84	2·14	2·09
K_2O	0·39	0·51	0·42	0·36
H_2O+	0·25	1·26	1·20	0·92
H_2O-	0·09	0·04	—	none
TiO_2	1·41	2·04	1·11	0·29
P_2O_5	0·39	0·14	—	0·36
MnO	0·11	0·63	—	—
CO_2	abs.	0·11	—	0·32
Etc.	—	0·18	—	0·33
	100·03	100·21	100·50	100·17
Sp. Gr.	2·98	—	—	—

Norms.

	I.	II.	III.	IV.
Quartz	2·76	2·88	—	3·24
Orthoclase	2·22	2·78	2·22	2·22
Albite	20·44	24·10	17·82	17·82
Anorthite	42·81	36·14	45·04	46·70
Corundum	1·43	—	—	—
Diopside	—	1·83	2·48	12·91
Olivine	—	—	4·23	—
Hypersthene ..	21·77	17·75	20·47	11·50
Magnetite	4·41	8·82	4·87	2·78
Ilmenite	2·74	3·95	2·13	0·61
Apatite	1·01	0·34	—	1·01

I. Recrystallised Pyroxene-gabbro (Hessose, II.5.4.(4)5). Por. 1, Parish of Ben Bullen. Anal. G. A. Joplin.

II. Beerbachite (Hessose, II″.5.4.(4)5). Samoyed Urals, Russia. Anal. H. Bucklund. *Mem. Imp. Ac. Sci. St. Pet.*, 1912, *38*, No. 3, p. 30. In W.T. p. 542, No. 113.

III. Gabbro inclusion in Basalt (Hessose, II(III).5.4.(4)5). Schluckenau, Bohemia. Anal. C. v. John. *Jb. G.R.-A., Wien,* 1903, *52,* p. 150. In W.T. p. 540, No. 98.

IV. Gabbro (Hessose, II.5.4″.(4)5). Seeheimer Bruch, Odenwald. Anal. G. Butzbach. G. Klemm, *Nb. Ver. Erdk.* (4), 1906, *27,* 12. In W.T. p. 540, No. 88.

the constituent minerals are plagioclase, hornblende, augite, biotite, quartz, iron ore, apatite, and a little prehnite.

The plagioclase forms irregularly bounded laths and is usually zoned. The greater part of the plagioclase has $\alpha'=1\cdot552$, $\gamma'=1\cdot562$, it is optically positive and the extinction on sections $\perp$ to 010 is 30°. This indicates $Ab_{48}An_{52}$. The outer rim of many of these crystals has an extinction of 18° and appears to be andesine ($Ab_{62}An_{38}$).

The hornblende is greenish-brown in colour and forms sub-idiomorphic prisms about 1·5 mm. in length. Z=olive green to brownish-green, Y=olive-green to brownish-green, X=yellowish-green to brownish-yellow, ($Z \gg Y > X$); $Z \wedge C=18°$, $\alpha'=1\cdot660$, $\gamma'=1\cdot685$.

Biotite is not abundant but shows local concentrations. X=golden-yellow, Y=reddish-brown, Z=chocolate-brown ($Z>Y>X$). This mineral shows alteration into chlorite and sometimes to epidote. Occasionally lens-like masses of prehnite occur between the cleavages of the biotite. The mineral is biaxial and positive; $\alpha'=1\cdot615$, $\gamma'=1\cdot630$; and the elongation is negative; extinction is straight; and a cleavage is developed parallel to the elongation of the lenses and therefore parallel to the cleavage of the biotite. The writer recognised a mineral with a similar occurrence in the quartz-mica-diorites at Hartley,[7] but owing to the paucity of the material it could not be satisfactorily determined. Stillwell[15] described lawsonite occurring in an exactly similar manner in the biotite of the actinolite-schists of Adélie Land, and it was thus suggested that the Hartley mineral might also be lawsonite.[7] It is now believed that it is prehnite, as it appears to be identical with the Ben Bullen mineral. Friedlaender and Niggli[5] have described and figured lenses of phenacite in the biotite of the granodiorites of the Voges.*

* H. von Eckermann (*Geol. Fören. Stockholm Förhandl.*, 1936, *80,* 255) has recently described an unidentified mineral with a higher R.I. occurring as lenses in chlorite.

Augite forms subidiomorphic prisms, but usually occurs as cores within the hornblende. It is often uralitised.

All three ferromagnesian minerals may be highly poikilitic and contain inclusions of plagioclase, apatite, and iron ores. Small (0·7 mm.) quartz grains are interstitial and in a few slides a little orthoclase has been noted.

An analysis of this type is given in column I below.

	I.	II.	III.	IV.	V.	VI.
SiO_2 ..	47·95	48·78	46·49	52·41	49·80	47·64
Al_2O_3 ..	21·20	22·07	19·22	20·11	17·77	19·98
Fe_2O_3 ..	1·69	1·92	6·68	4·18	2·29	4·83
FeO ..	8·85	7·73	6·02	5·59	8·75	7·26
MgO ..	4·95	5·22	5·89	4·12	5·67	7·14
CaO ..	9·50	9·67	10·88	9·06	8·85	9·62
Na_2O ..	1·70	1·81	2·16	2·28	1·48	1·23
K_2O ..	0·76	1·17	0·65	0·88	0·48	1·03
H_2O+ ..	0·60	1·68	0·96	0·36	2·62	0·12
H_2O- ..	0·02	—	0·17	0·16	1·04	—
TiO_2 ..	1·59	0·37	0·92	0·78	1·56	1·20
P_2O_5 ..	0·38	0·44	0·40	0·32	tr.	—
MnO ..	0·18	tr.	0·20	0·19	—	—
CO_2 ..	0·74	—	tr.	tr.	—	0·28
	100·11	100·86	100·64	100·46	100·31	100·43
Sp. Gr. ..	2·92	—	2·967	2·836	2·932	2·979

Norms.

	I.	II.	III.	IV.	V.	VI.
Quartz ..	4·50	1·20	0·96	8·34	7·38	2·28
Orthoclase	5·00	6·67	3·34	5·56	2·78	6·12
Albite ..	14·15	15·20	18·34	19·39	12·58	10·48
Anorthite	40·31	45·31	40·87	41·70	40·31	45·59
Corundum	2·75	1·43	—	—	—	—
Diopside ..	—	—	8·64	1·11	2·97	1·57
Hypersthene	24·81	24·98	14·93	15·71	24·36	24·53
Magnetite	2·55	2·78	9·74	6·03	3·25	6·96
Ilmenite ..	3·04	0·76	1·67	1·52	3·04	2·28
Apatite ..	1·01	1·01	1·01	0·67	—	—
Calcite ..	1·60	—	—	—	—	—

I. Quartz-bearing Pyroxene-diorite or Basified Diorite (Hessose, II″.″5.4.4.). Head of Spring Gully, Por. 1, Parish of Ben Bullen. Anal. G. A. Joplin.

II. Gabbro (Hessose, II.5.4.4.). Near Abu Uruf, Kordofan. Anal. Sprockhoff. G. Linck, *N.J.B.*, *B.*, 1903, *17*, p. 412. In W.T. p. 544, No. 118.

III. Diorite-gabbro (Hessose, II(III).5.4.4(5)). Moyne Farm, Little Hartley. Anal. G. A. Joplin. *Proc. Linn. Soc. N.S.W.*, 1931, *51*, p. 41.

IV. Quartz-mica-diorite (Hessose, II.(4)5.4.4.). Marriott's Creek, Cox's River Intrusion, Little Hartley. Anal. G. A. Joplin. *Ibid.*, p. 38.

V. Diabase (Hessose, II(III).(4)5.4″.4.). Auchinstarry, Kilsyth, Dumbartonshire, Scotland. Anal. D. P. Macdonald. G. W. Tyrrell, *Geol. Mag.*, 1909, (5), *6*, p. 361. In W.T. p. 538, No. 75.

VI. Diabase (Hessose, II(III).5.4″.(3)4.). Förväxlings Point, Spitzbergen. Anal. H. Buckland. H. Buckland, *Ref. N.J.*, 1911, *11*, p. 243. In W.T. p. 538, No. 72.

The Later Intrusion and Included Xenoliths.

(i) *Quartz-mica-diorite.*

The narrow north-south strip lying to the west of the main mass consists of quartz-mica-diorite, and this type also makes up the bulk of the north-western part of the intrusion as well as its southern lobe. The southern outcrop is slightly more acid but is essentially the same rock.

In the hand specimen the rock is a typical diorite consisting of about equal proportions of light and dark minerals. The grain size is usually medium, but fairly coarse types may occur. Small, dark, fine-grained xenoliths are very common in the quartz-mica-diorite.

Under the microscope the rock is seen to be hypidiomorphic granular and the fabric is sub-ophitic to poikilitic. The grain size averages about 2 mm., but occasionally the rock is slightly porphyritic and plagioclase phenocrysts may measure up to 3 mm., whilst the ground mass averages 0·5 mm.

The constituent minerals are plagioclase, hornblende, biotite, quartz, iron ores, apatite and a little prehnite, epidote, chlorite, and white mica. A small quantity of orthoclase has been noted in the more acid varieties, and the presence of uralite suggests original pyroxene in a few of the slides.

Plagioclase occurs in tabular crystals or in laths and averages 1 to 2 mm., but two generations are sometimes developed. The refractive indices are variable; the mineral may be either positive or negative and extinction angles measured on sections $\perp$ to 010 vary from 27° to 21°. The felspar is therefore andesine and ranges in different specimens from $Ab_{52}An_{48}$ to $Ab_{59}An_{41}$. The plagioclase phenocrysts are often highly zoned and range from $Ab_{49}An_{51}$ to $Ab_{63}An_{37}$.

Hornblende is developed in subidiomorphic prisms (averaging two mm.) or in poikilitic crystals wrapping and enclosing plagioclase. It is optically negative ; $Z \wedge C = 19°$; X = pale yellowish-green, Y = olive-green, Z = dark bluish-green ($Z \gg Y > X$). Simple and polysynthetic twinning are often developed on 100. Refractive indices vary in the different specimens from $\alpha' = 1\cdot652$–$1\cdot665$, $\gamma' = 1\cdot681$–$1\cdot687$.

Biotite is usually abundant, but may vary considerably in amount. In one case it completely takes the place of hornblende, and in another it is entirely absent. It occurs in ragged flakes from 5 to 2 mm. X = golden-yellow, Y = light brown or reddish-brown, Z = chocolate-brown, ($Z > Y > X$) ; $\beta' = 1\cdot600$. The mineral shows alteration into chlorite and epidote and lenses of prehnite are fairly common.

Quartz occurs in interstitial allotriomorphic grains from three mm. to less than 0·5 mm. It is more abundant in the rocks of the southern lobe of the intrusion. Iron ores are always accessory and apatite forms small, acicular inclusions.

An analysis of this type is given in Column I below.

	I.	II.	III.	IV.	V.
SiO_2 ..	55·30	55·42	54·37	58·30	57·15
Al_2O_3 ..	20·87	21·35	19·64	19·43	19·26
Fe_2O_3 ..	3·62	3·37	4·30	4·40	1·36
FeO ..	5·20	4·87	4·87	3·33	4·17
MgO ..	2·75	3·87	2·94	2·64	3·58
CaO ..	7·44	7·51	8·07	7·46	7·13
Na_2O ..	2·49	2·94	2·55	3·07	2·88
K_2O ..	0·82	0·68	1·01	0·88	1·10
H_2O+ ..	0·76	0·37	0·96	0·37	1·41
H_2O- ..	0·08		0·11		0·68
TiO_2 ..	0·90	0·33	1·14	0·49	0·84
P_2O_5 ..	0·41	tr.	0·34	0·22	0·10
MnO ..	0·10	—	0·07	—	0·42
Etc. ..	—	—	—	—	0·12
	100·74	100·71	100·37	100·57	100·20
Sp. Gr.	2·83	—	2·861	—	—

Norms.

	I.	II.	III.	IV.	V.
Quartz ..	16·44	11·52	13·14	17·34	13·02
Orthoclase	5·00	3·89	6·12	5·00	6·67
Albite ..	20·96	24·63	20·96	26·20	24·63
Anorthite	34·19	37·25	38·09	35·03	34·47
Corundum	3·37	2·14	0·41	0·51	0·61
Hypersthene ..	12·05	15·38	11·00	8·18	14·18
Magnetite	5·34	4·87	6·26	6·50	2·09
Ilmenite	1·67	0·61	2·13	0·91	1·67
Apatite	1·01	—	0·67	0·67	0·34

I. Quartz-mica-diorite (Bandose, II.4.4.4″). Por. 57/58, Parish of Ben Bullen. Anal. G. A. Joplin.

II. Diabase Inclusion in Andesite (Bandose, II.4(5).4.4(5)). Mount Pélee, Martinique, W. Indies. Anal. A. Pisani. A. Lacroix, Mt. Pélee, 1904, p. 573. In W.T. p. 410, No. 36.

III. Quartz-mica-diorite (Bandose, II.4″.4.4.). Moyne Farm, Little Hartley. Anal. G. A. Joplin. *Proc. Linn. Soc. N.S.W.*, 1931, *56*, p. 37.

IV. Andesilaborite (Bandose, (I)II.4.″4.4″.). Carbet, Martinique, West Indies. Anal. A. Pisani. A. Lacroix, Mt. Pélee, 1904, p. 573. In W.T. p. 410, No. 31.

V. Andesite (Bandose, II.4″.″4.4.). Thames Mine, Hauraki, Auckland, New Zealand. Anal. J. S. Maclaurin. C. Frazer, *N.Z.G.S.*, Bull. 10, 1910, p. 24. In W.T. p. 418, No. 88.

(ii) *Basic Xenoliths.*

Basic xenoliths of igneous origin occur throughout the quartz-mica-diorite mass and are particularly abundant on Jew's Creek. They are always darker and finer grained than their host and usually occur in small rounded patches which may measure up to three inches in diameter. Under the microscope they present a great variety of structures, grain size and mineral content, and it is believed that this variation is largely due to the degree of contamination and incorporation which each has attained. Some of the xenoliths show evidence of an earlier recrystallisation, and granoblastic and sieve structures are sometimes preserved. Other xenoliths show highly poikilitic plates of hornblende and biotite which appear to be due to hybridisation, and in those that are beginning to develop a coarser grain size, and to become completely incorporated in the quartz-mica-diorite, large crystals of plagioclase and biotite are developed.[14]

The rock may contain hornblende to the exclusion of biotite, or *vice versa*, and many contain about equal proportions of these two minerals. Some of the hornblende occurs in subidiomorphic prisms which are very slender and have sutured boundaries. They average 1 mm. in length. The hornblende is a green variety with X = yellowish-green, Y = dark olive-green, Z = dark bluish-green; it is often twinned; $Z \wedge C = 18°$; and alteration to chlorite is frequent.

Biotite occurs in small flakes and/or in large poikilitic sheets. In those rocks which are almost incorporated, biotite occurs in large flakes comparable to that of the diorite and the poikilitic structure is not well marked. The poikilitic flakes and the smaller units both have fairly high refractive indices ($\alpha' = 1 \cdot 622$, $\gamma' = 1 \cdot 665$); X = pale yellowish-brown, Y = deep reddish-brown, Z = very dark reddish-brown.

Plagioclase forms small laths, irregular grains or small tabular crystals, and averages about 0·25 mm. Larger tabular crystals are present in the more highly disintegrated types, and this felspar appears to have the same composition as that of the host. The composition of the smaller crystals is variable, and they often show basic cores ($Ab_{48}An_{52}$) and more acid rims ($Ab_{63}An_{37}$). Alteration to epidote or sericite is frequent.

No analysis of a xenolith has been made, as they vary a good deal in composition and in degree of contamination, and it is fairly certain that there has been mechanical addition of material from the surrounding magma.

Dykes and Veins.

(i) *Hornblende-lamphrophyres.*

A small dyke of hornblende-lamprophyre strikes across the creek near the S.W. corner of Por. 87, and veins measuring only about an inch in width are occasionally met with in different parts of the igneous mass. One such vein occurs in the Cleared Hill Quarry and the development of epidote and clinozoisite suggests limestone contamination.

The rocks are porphyritic and contain slender idiomorphic or subidiomorphic prisms of hornblende which may measure up to 2·5 mm., and tabular crystals of plagioclase averaging

0·5 mm. These are set in a fine-grained ground mass of plagioclase and hornblende which averages about 0·1 mm.

The hornblende phenocrysts sometimes form groups and are often altered to uralite. A peculiar brown blotching is also common, and the crystals may have a brown outer rim.

The large plagioclase crystals are frequently zoned, and are free from alteration products, whilst the small laths of the ground mass show alteration.

Sphene is moderately abundant and may form irregular grains. Biotite may or may not be developed, and iron ores occur as small inclusions.

In the smaller veins the slender hornblende prisms and felspar laths are roughly parallel to the length of the vein.

(ii) *Aplites.*

A few veins of aplite occur in different parts of the igneous mass, the largest being about six inches wide and outcropping for a few feet in the cutting of the quarry tramline on Por. 63. The rock appears to consist only of quartz and felspar, but it is much altered and has not been sectioned.

4. Petrogenesis.

Chemical Discussion and Comparison with Hartley.

The analyses numbered I to V on page 88 represent hybrid, recrystallised and unmodified rocks from Ben Bullen, but it will be seen that there is a graduation in chemical and normative composition, and that all these types take their places on a variation diagram characteristic of a calcic series. (Fig. 2.)

With the exception of the relative proportions of the alkalies and iron oxides there is a very close correspondence between the composition of the recrystallised gabbro and that of the basified diorite. It seems evident that the recrystallised rock is the most acid member of the earlier complex, and that it has not suffered hybridisation. Assuming this to be the case, it is evident that the earlier intrusion was relatively richer in iron and poorer in potash. The hybrids of the earlier complex do not show this difference, and it is probable that the addition of potash has been an important factor in hybridisation.

The Ben Bullen series as a whole is characterised by the fact that FeO is always higher than MgO, and in this it compares with the Hartley complex, which is illustrated by analyses A to F. Like the Hartley series the Ben Bullen

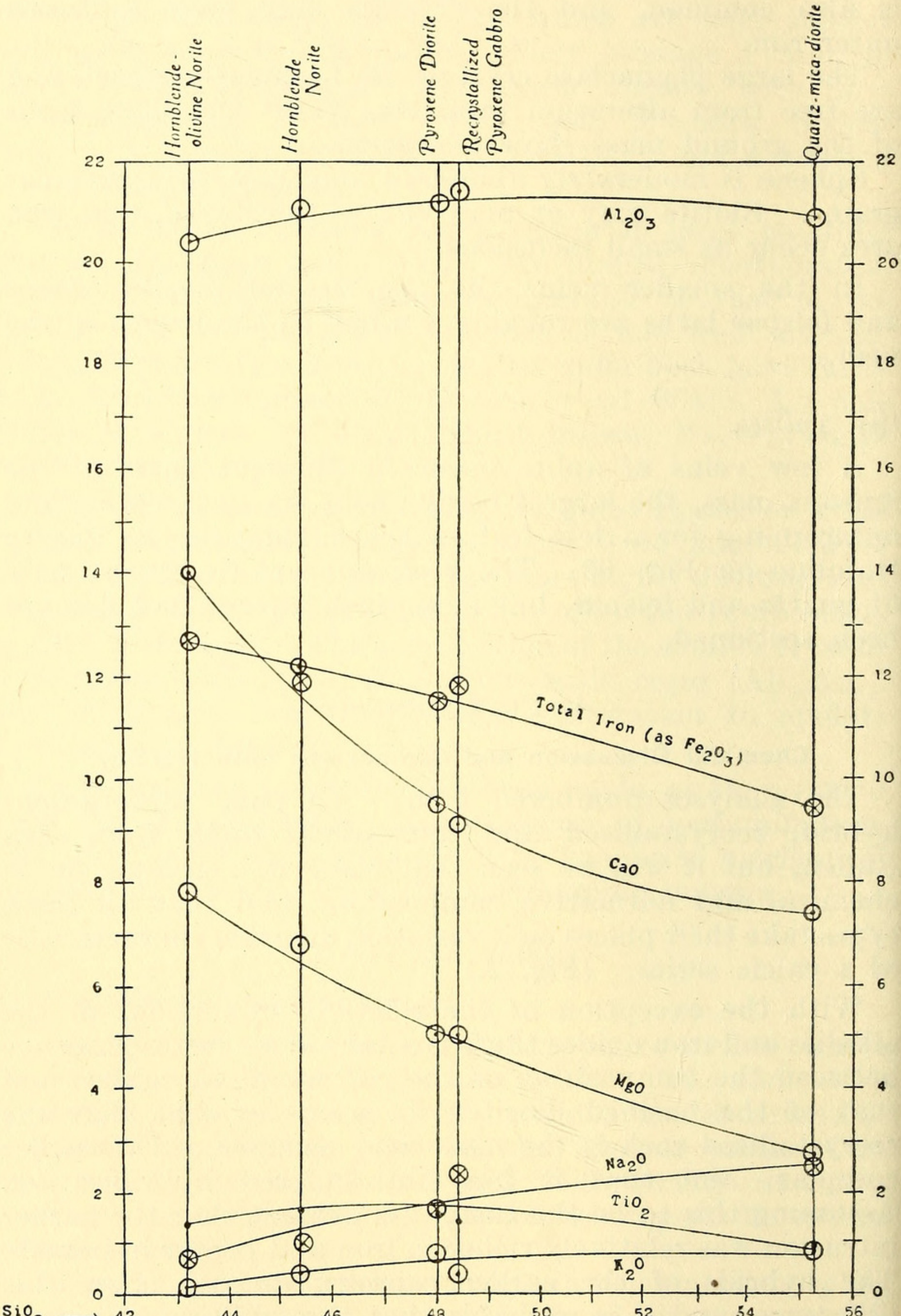


Fig. 2.—Variation diagram of Ben Bullen Plutonic Complex.

rocks also show high alumina, but in the latter area it is consistently higher than at Hartley. Titania is also a little higher at Ben Bullen, though it is present in appreciable amounts in the Hartley complex and is apparently characteristic of all intrusions of the Kanimbla epoch[1] and of Late-Palæozoic age.[2]

A comparison of the Ben Bullen and Hartley analyses also shows that Fe_2O_3 and Na_2O are higher at Hartley, but it seems likely that these minor differences are quite local and may be due to differentiation in place. Apart from the dissimilarities pointed out above, there is a striking resemblance between the two complexes, and the slight differences might be expected in any series of analyses of consanguineous rocks outcropping over a wide area. It seems evident, therefore, that the Hartley and Ben Bullen magmas arose from the same magma reservoir and that differentiation *in situ* caused slightly different trends. Ben Bullen lies about eighteen miles N.N.W. of Hartley, and this assumption would thus suggest a northerly extension of the Hartley-Bathurst bathylith.

Possible Origin of the Various Rock Types.

It seems evident that there were two injections of partial magma in the Ben Bullen area—first, norite, and secondly, quartz-mica-diorite. The second intrusion partly surrounds the first, and the present basic mass possibly represents a portion of the roof of the second magma chamber. The field occurrence points to a shattering and partial assimilation of the earlier complex by the later more acid magma.

Reference to the petrography will show that the earlier complex consisted originally of three main types—olivine-norite, norite or hypersthene-gabbro and a more acid type of gabbro. The latter is recrystallised, and, as only one analysis has been made of this type, it is uncertain whether all the recrystallised rocks, unaffected by hybridisation, are of comparable acidity, though this is not an unreasonable assumption.

These three types possibly arose from the noritic magma by differentiation *in situ*. The second intrusion of partial magma then occurred and the earlier complex was partially recrystallised. The reason for this incomplete or selective recrystallisation is rather obscure, but two explanations suggest themselves. First, the rocks which are now recrystallised may have been immediately adjacent to the

	I.	A.	B.	C.	II.	D.	III.	IV.	E.	F.	V.
SiO_2	43·15	44·52	44·79	45·31	45·36	46·49	47·95	48·42	52·41	54·37	55·30
Al_2O_3 ..	20·45	21·32	19·56	19·39	21·12	19·22	21·20	21·53	20·11	19·64	20·87
Fe_2O_3 ..	3·79	5·08	6·01	5·33	4·19	6·68	1·69	3·09	4·18	4·30	3·62
FeO ..	7·98	7·19	7·79	7·81	7·01	6·02	8·85	7·84	5·59	4·87	5·20
MgO	7·82	6·41	6·16	6·93	6·85	5·89	4·95	4·96	4·12	2·94	2·75
CaO ..	14·03	12·44	11·81	11·67	12·19	10·88	9·50	9·12	9·06	8·07	7·44
Na_2O ..	0·71	1·25	1·21	1·22	0·99	2·16	1·70	2·43	2·28	2·55	2·49
K_2O ..	0·15	0·15	0·06	0·35	0·37	0·65	0·76	0·39	0·88	1·01	0·82
H_2O+ ..	0·58	0·37	0·64	0·69	0·62	0·96	0·60	0·25	0·36	0·96	0·76
H_2O- ..	0·15	0·06	0·10	0·08	0·15	0·17	0·02	0·09	0·16	0·11	0·08
TiO_2	1·37	1·04	1·14	1·33	1·64	0·92	1·59	1·41	0·78	1·14	0·90
P_2O_5	0·10	abs.	0·18	0·31	0·07	0·40	0·38	0·39	0·32	0·34	0·41
MnO ..	0·12	0·09	0·15	0·17	0·10	0·20	0·18	0·11	0·19	0·07	0·10
CO_2	tr.	tr.	tr.	tr.	abs.	tr.	0·74	abs.	tr.	abs.	abs.
	100·40	99·92	99·60	100·59	100·66	100·64	100·11	100·03	100·46	100·37	100·74
Sp. Gr. ..	3·02	3·050	3·055	3·004	2·97	2·967	2·92	2·98	2·836	2·861	2·83

Norms.

	I.	A.	B.	C.	II.	D.	III.	IV.	E.	F.	V.
Quartz ..	—	—	2·04	0·96	0·66	0·96	4·50	2·76	8·34	13·14	16·44
Orthoclase ..	1·11	0·83	0·56	1·67	2·22	3·34	5·00	2·22	5·56	6·12	5·00
Albite ..	5·76	10·48	9·96	9·96	8·38	18·34	14·15	20·44	19·39	20·96	20·96
Anorthite ..	52·26	52·26	47·82	46·70	51·49	40·87	40·31	42·81	41·70	38·09	34·19
Corundum ..	—	—	—	—	—	—	2·75	1·43	—	0·41	3·37
Diopside ..	13·47	7·42	8·10	7·85	6·24	8·64	—	—	1·11	—	—
Hypersthene ..	9·10	18·28	19·14	21·70	20·97	14·93	24·81	21·77	15·71	11·00	12·05
Olivine ..	9·59	1·21	—	—	—	—	—	—	—	—	—
Magnetite ..	5·57	7·42	8·82	7·66	6·03	9·74	2·55	4·41	6·03	6·26	5·34
Ilmenite ..	2·58	1·98	2·13	2·43	3·92	1·67	3·04	2·74	1·52	2·13	1·67
Apatite ..	0·34	—	0·34	0·67	0·34	1·01	1·01	1·01	0·67	0·67	1·01
Calcite ..	—	—	—	—	—	—	1·60	—	—	—	—
Class ..	''III	II(III)	(II)III	III	II(III)	II(III)	II''	II	II	II	II
Order ..	5	5	5	5(4)	5	5	''5	5	(4)5	4''	4
Rang ..	''5	(4)5	(4)5	5	(4)5	4	4	4	4	4	4
Subrang ..	4(5)	3''	5	4(5)	4	4(5)	4	(4)5	4	4	4''
Magmatic name ..	Kedabekase	Corsase nr. Kedabekase	Kedabekase nr. Corsase	Kedabekase	Corsase nr. Kedabekase	Hessose	Hessose	Hessose	Hessose nr. Bandose	Bandose	Bandose

I. Olivine-norite, Por. 63, Parish of Ben Bullen. Anal. G. A. Joplin.

A. Recrystallised Pyroxene-gabbro (leucocratic phase), Cox's River Intrusion, Little Hartley. Anal. G. A. Joplin. *Proc. Linn. Soc. N.S.W.*, 1933, *58*.

B. Recrystallised Pyroxene-gabbro (normal type), Cox's River Intrusion, Little Hartley. Anal. G. A. Joplin. *Ibid.*

C. " Reaction "-gabbro or Hornblende-pyroxene-gabbro, Cox's River Intrusion, Little Hartley. Anal. G. A. Joplin. *Ibid.*, 1931, *56*.

II. Hornblende-norite, Por. 1, Parish of Ben Bullen. Anal. G. A. Joplin.

D. Diorite-gabbro, Moyne Farm, Little Hartley. Anal. G. A. Joplin. *Ibid.*

III. Quartz-bearing Pyroxene-diorite or Basified Diorite. Head of Spring Gully, Ben Bullen. Anal. G. A. Joplin.

IV. Recrystallised Pyroxene-gabbro, Por. 1, Parish of Ben Bullen. Anal. G. A. Joplin.

E. Quartz-mica-diorite, Cox's River Intrusion, Little Hartley. Anal. G. A. Joplin. *Ibid.*

F. Quartz-mica-diorite, Moyne Farm, Little Hartley. Anal. G. A. Joplin. *Ibid.*

V. Quartz-mica-diorite, Pors. 57/58, Parish of Ben Bullen. Anal. G. A. Joplin.

uprising magma, and at a later stage they were rifted off and scattered in the magma. Rocks that had escaped this first impress of metamorphism would therefore be brought into contact with the magma when the temperature was such that hybridization could take place, but not recrystallisation. Some of the recrystallised rocks may have escaped hybridisation on account of their geographical position. Secondly, it is possible that recrystallisation was selective. These rocks, being of a more acid type, may have contained hornblende which was unstable at the initial temperature of the second intrusion. The hornblende would then break up into augite, hypersthene, and anorthite[8] and crystalloblastic structures would be developed. It is likely that some of the hornblende-norites are of slightly more acid type and represent the original acid differentiate which has escaped recrystallisation.

The quartz-mica-dorite magma then began to react with the solid rocks of the earlier complex, and the olivine-norite thus became a hornblende-olivine-norite, and the norite a hornblende-norite. Some of the recrystallised rocks were also made over to hornblende-bearing assemblages.

The earliest stage in the reaction is to be seen in the development of narrow coronas of amphibole about iron ores, olivine, and pyroxenes that are adjacent to felspars.[8] [9] Gradually the pale green amphibole assumes a brown colour and large irregular crystals of brown hornblende began to surround pyroxenes, etc., and push their way between and envelop crystals of plagioclase. Finally the rock became highly poikilitic and very rich in hornblende, which appears to arise at the expense of all the other minerals, including plagioclase.

Eventually the invading magma consolidated as a basified diorite, so the pyroxene-diorite is thus intimately associated with the more basic types and acts as a kind of cement to the shattered norite mass.

It has been shown in an earlier publication[11] that tongues of basified diorite have been injected into the limestones and thereby contaminated. The tongues often contain small recrystallised xenoliths, and it is thus evident that the pyroxene-diorite was actually a magma, but that it contained solid fragments. The tongues probably cooled fairly quickly, and there was not sufficient time for complete assimilation of the xenoliths. In the main mass of basified diorite the smaller basic fragments have lost their identity, and only large scattered masses of the norite remain.

Those portions of the quartz-mica-diorite magma which were not in immediate contact with the roof remained unbasified, and small fragments of the basic hybrids became incorporated as xenoliths without much further hybridisation. The means by which their fine grain size was produced has already been discussed in an earlier publication.[9]

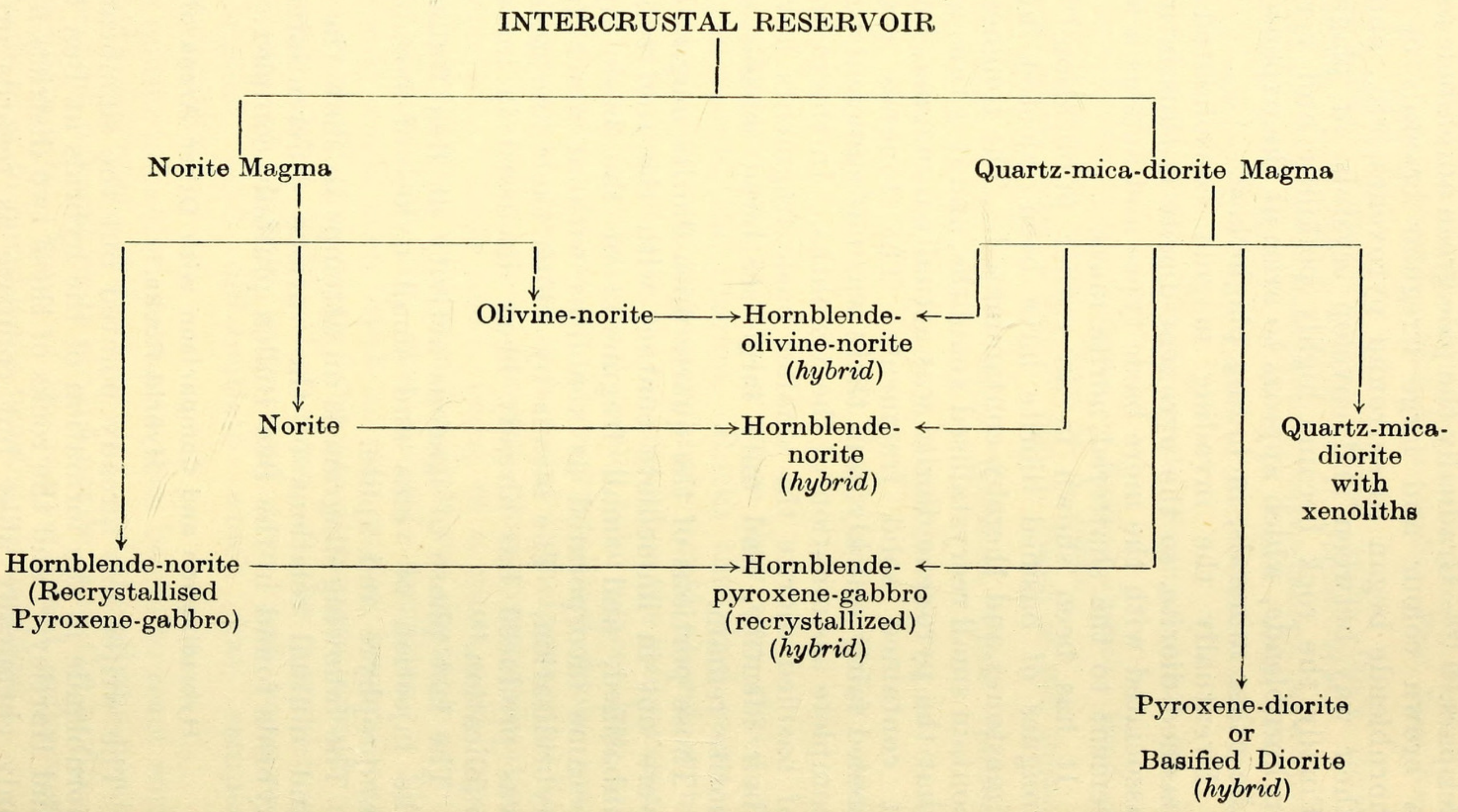
The last phase of igneous activity at Ben Bullen was the injection of veins and small dykes of hornblende-lamprophyre and aplite.

The following diagram is an attempt to show the origin and mutual relations of the various differentiates and hybrids found in the Ben Bullen plutonic complex.

Hybridisation and Comparison with Other Areas of Hybrid Rocks.

The writer has already pointed out the significance of hornblende in the formation of the hybrids at Ben Bullen and Hartley,[9] and the rocks of these two districts are not only chemically alike but compare as regards order of intrusion and mutual relations of the various differentiated and hybridised types.

DIAGRAM TO SHOW POSSIBLE RELATION OF DIFFERENTIATES AND HYBRIDS.



Olivine has not been found at Hartley, but in this area the most basic rocks have been recrystallised and it is possible that olivine may have occurred in the primary differentiate.

The term "norite" has been applied to certain of the Ben Bullen types, and rocks of the same composition at Hartley have been designated "pyroxene-gabbros". At Ben Bullen the hypersthene appears to be of primary consolidation, and it is fitting that the rocks should be called norites, whilst at Hartley it is uncertain whether the hypersthene is primary or whether it has arisen by recrystallisation of augite and hornblende. The Hartley pyroxene-gabbros may have been norites originally, but owing to this uncertainty it seems better to use the term "norite" only for those rocks which contain definite, primary hypersthene.

The basic complex with its related hybrids at Ben Bullen and the Cox's River intrusion at Hartley have many points in common with noritic hybrids of other areas. A parallelism with certain of the hybrid reactions has already been drawn with the rocks of Trégastel,[16] and they may also be compared with types from Loch Doon[6] and Cairnsmore of Carsphairn,[4] Scotland.

5. Summary.

The Ben Bullen complex has been shown to consist of two separate consanguineous intrusions, the earlier and more basic of which has differentiated *in situ*. The later intrusion has reacted with the solid rocks of the first intrusion and a series of cognate hybrids have been formed.

Primary differentiates and hybrids take their places on a variation diagram typical of a calcic series, and certain chemical peculiarities indicate that the Ben Bullen and Hartley complexes are probably co-magmatic. The hybrids and method of hybridisation at Ben Bullen also compares with Hartley.

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