Metasomatism in the basalt of Haddenrig quarry near Kelso and the veining of the rocks exposed there.

By S. I. TOMKEIEFF, M.Sc., F.G.S.

King's College, University of Durham, Newcastle-upon-Tyne.

I. PETROLOGY AND CHEMISTRY OF THE ROCKS.

HADDENRIG (Haddon Rig) quarry is situated three miles east of Kelso in Roxburghshire, near the road from Kelso to Mindrum in Northumberland. The rock quarried is marked on the Geological Survey Map (Scotland, Sheet 26) as a basalt intrusive into the Lower Carboniferous lavas (Kelso traps). The absence of exposed contacts excludes any direct field evidence of its intrusive character, but the appearance of the fresh basalt from the quarry suggests that it belongs to a sill or a plug, as it is in many ways similar to other intrusive basalts of the Kelso district. The evidence of the orientation of the felspar laths in the basalt is not entirely conclusive. With the exception of the northern part of the quarry where the orientation is vertical, elsewhere it is more or less horizontal. This suggests a sill. The vertical orientation of laths in the northern part of the quarry may be due either to the presence of a feeding channel or to eddies in the sill.

TABLE I. Modal composition of basalts (weight %).

				1.	2.
Phenocrysts	Olivine ...	...	...	2.30	4·10
	Felspar	...	...	1·85	20·65
	Pyroxene	...	...	2·10	5·10
Groundmass	Felspar	...	...	58·10	25·05
	Pyroxene	...	...	20·05	20·30
	Iron-ore	...	...	11·90	11·85
	Chlorite, &c.	...	...	3·70	12·95

1. Fresh olivine-basalt (Dunsapie type).
2. Altered olivine-basalt (transition to metabasalt).

In the northern part of the quarry a perfectly fresh bluish-grey basalt is exposed (fig. 1). Although the phenocrysts are comparatively small and few in number this rock may be called olivine-basalt of Dunsapie

type (table I, no. 1). The olivine phenocrysts are partly serpentinized. The unaltered olivine appears to be a normal magnesia-rich type. The pyroxene phenocrysts have ragged edges and enclose small crystals of felspar and portions of the groundmass. The felspar phenocrysts are
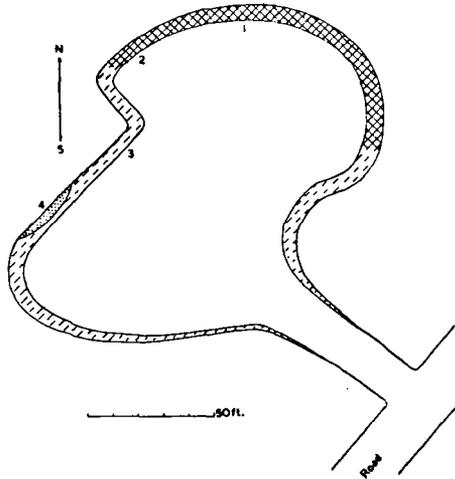

FIG. 1. Map of Haddenrig quarry. Basalt, cross-hatching; metabasalt, dashed lines, potash-spilite, stippling. The scale is approximate. 1–4, location of rocks analysed.

labradorite (table II, nos. 1, 2), while the groundmass laths are somewhat more alkaline (table II, nos. 3, 4, 5, 6). A small amount of interstitial alkali-felspar is also present, but analcime has not been detected. The pyroxene of the groundmass is a normal augite occurring in the form of small prismatic grains. Titanomagnetite, microfibrous chlorite, and apatite complete the groundmass. Occasionally small nests of amygdules are found surrounded by zones rich in pyrite. The amygdules are formed of chalybite which lines the walls of the cavity and calcite which infills the remaining space.

The chemical analysis of the fresh basalt (table III, no. 1) is very close to the average of Dalmeny-Dunsapie types of Carboniferous basalts (22, p. 62) although the alkalis are slightly above the average.

The olivine-basalt becomes progressively more alkaline in the southern direction. The plagioclase becomes distinctly albitized and dusty in appearance, but other constituents are not affected. The phenocrysts are increasing both in size and in number. An analysis of the albitized

basalt as given in table III (no. 2) shows an increase of alkalis and silica as compared with the fresh olivine-basalt.

Table II. Results of measurement of the felspars on the Fedorov stage.

			Co-ordinates of the plane of association.					
			γ	β	α	Twin-law.	2V.	An %.
1.	a	... ...	26	66	82	Albite	+80	49
	b	... ...	25	67	80		+75	50
2.	a	... ...	29	63	80	Carlsbad	+79	54
	b	... ...	29	65	78		+80	52
3.								42
4.		(Zonal method)	...	...	...	... ...		45
5.								39
6.								41
7.	a	... ...	27	65	80	Albite	+86	51
	b	... ...	28	64	74		+82	59
8.	a	... ...	22	68	87	Albite	+86	40
	b	... ...	20	70	90		+86	35
9.		... ...	6	86	87	Albite	−88	25
10.		... ...	0	90	90	—	−8	Sanidine
11.		... ...	0	90	90	—	−72	Orthoclase
12.	inner ...	...	0	90	90	Carlsbad	−70	Orthoclase
	outer ...	...	26	65	80	Albite	+78	50
13.	inner ...	...	5	87	86	—	−52	Anorthoclase
	outer ...	...	33	63	72	—	+80	65

1, 2, phenocrysts in olivine-basalt; 3–6, groundmass laths in olivine-basalt ; 7–13, phenocrysts in potash-spilite.

a and b refer to two adjoining twin-individuals; the plane of association in all cases is (010).

The albitized basalt gradually passes southwards and upwards into a highly altered greenish-grey rock which may be called metabasalt. A rock transitional between basalt and metabasalt as measured on the Shand stage (table I, no. 2) shows a great increase in the amount of phenocrysts. The lower part of the metabasalt zone is equally rich in phenocrysts, but in the upper part of this zone the phenocrysts almost entirely disappear. In the metabasalt all the ferromagnesian minerals are transformed into chlorite, the felspar is greatly albitized, and the iron-ore is partly altered into leucoxene. The carbonates are abundant, not in vesicles, but in ragged patches replacing other minerals. An analysis of a non-porphyritic variety of metabasalt (table III, no. 3) shows a very high amount of combined water and a relatively low amount of alkalis. This analysis is not quite representative of the metabasalt zone as a whole. The inclusion of the porphyritic (felspar-

rich) fraction of metabasalt would no doubt raise the amount of alkalis and lower that of water.

TABLE III. Analyses of rocks from Haddenrig quarry and other rocks for comparison.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO$_2$	46·96	48·52	46·22	47·95	47·03	37·73	44·65	37·30	47·03	39·72
TiO$_2$	2·51	2·76	2·32	2·58	n.d.	2·38	1·91	2·70	1·89	0·90
Al$_2$O$_3$	14·68	13·86	15·52	15·82	22·45	16·49	14·18	14·79	17·78	12·37
Fe$_2$O$_3$	4·96	3·47	2·57	1·44	7·00	5·14	7·21	7·14	7·48	2·52
FeO	8·18	9·28	9·37	2·56		6·70	8·50	7·08	4·20	0·91
MnO	0·23	0·12	0·06	0·03	n.d.	0·09	0·05	trace	—	—
MgO	6·26	5·06	6·02	3·64	8·79	7·96	6·31	8·13	3·19	5·82
CaO	8·61	8·02	5·54	8·09	2·92	7·85	6·72	6·70	10·61	12·57
Na$_2$O	3·62	4·36	2·54	3·23	2·63	0·95	2·22	2·20	3·82	0·64
K$_2$O	0·90	1·29	0·85	5·24	4·55	1·41	1·81	2·56	0·80	4·18
P$_2$O$_5$	0·51	0·54	0·72	0·93	n.d.	0·27	0·28	0·34	0·40	0·49
FeS$_2$	—	—	—	—	—	0·06	trace	trace	0·35	0·29
CO$_2$	0·03	0·06	1·60	6·98	1·90	3·21	1·98	3·60	0·59	16·42
H$_2$O+	1·81	2·22	5·78	1·42	3·65	7·01	3·49	5·20	2·15	3·30
H$_2$O−	0·49	0·60	0·84	nil	—	2·23	0·82	2·20	—	—
	99·75	100·16	99·95	99·91	100·92	99·48	100·13	99·94	100·29	100·13
Sp. gr.	2·924	2·867	2·755	2·666	—	—	—	—	—	—

1. Olivine-basalt (Dunsapie type), Haddenrig quarry. Anal. S. I. Tomkeieff.
2. Olivine-basalt (Dunsapie type, albitized), Haddenrig quarry. Anal. F. Herdsman.
3. Metabasalt, Haddenrig quarry. Anal. F. Herdsman.
4. Potash-spilite, Haddenrig quarry. Anal. F. Herdsman.
5. Potash-spilite, lava, Knot Law, Millers Dale, Derbyshire. Anal. H. C. Sargent (1917, p. 22).
6. Olivine-basalt (highly altered), lava, Tearsal farm, near Matlock, Derbyshire. Anal. S. I. Tomkeieff (new analysis).
7. Olivine-basalt (Dalmeny type), lava (lower part), Cottonshope, Northumberland. Anal. S. I. Tomkeieff (1931, p. 266). In the previously published analysis of this rock H$_2$O− was erroneously given as 1·98.
8. Olivine-basalt (Dalmeny type, altered), same locality, upper part of the lava flow. Anal. F. Herdsman (new analysis).
9. Olivine-basalt (Markle type), Carlekemp, North Berwick. Anal. T. C. Day (1928).
10. Vesicular silicified and carbonated basalt. Eel Burn, North Berwick. Anal. T. C. Day (1928).

In the eastern part of the quarry horizontal schlieren from one to six inches in thickness are found in the metabasalt. On both sides they show a continuous, although sharp, transition into a fine-grained meta-basalt. They are made of a very coarse dolerite-pegmatite with large patches of chloritic mesostasis. Large albitized felspar crystals and large chloritized pyroxene crystals project inwardly from the margins into the centre of the bands. The schlieren probably represent portions of highly hydrous magma drawn out during the intrusion. Another interesting feature of this rock is the presence of angular fragments of quartz rock. These are of frequent occurrence in the western part of the quarry and it may be that they are not confined to the metabasalt,

although none was found in the other parts of the quarry. These fragments vary in size from minute particles to platy inclusions a couple of inches across. They consist entirely of mosaic quartz and could justifiably be called quartzite. Each fragment is surrounded by a reaction rim of granular or vermicular pyroxene now altered to chlorite and this suggests that they are foreign inclusions. Inclusions of sedimentary material are frequently found in the Scottish Carboniferous lavas and intrusions. Day, for example, has described fragments of sandstone altered to quartzite enclosed in basalt at Upper Whitfield (8). The strata below the lavas into which the basalt complex of Haddenrig is intruded belongs to the upper Old Red Sandstone and it may be that the quartzite inclusions are the metamorphosed flaggy sandstone of this formation.

In the western part of the quarry a mass of light greenish-grey rock is exposed in the upper part of the quarry cutting. The exposed rock mass is approximately thirty feet long and ten feet in thickness and it fills a hollow in the metabasalt. The upper part of it and the surrounding metabasalt were probably removed by denudation. The transition between this rock and the metabasalt is rapid but continuous. Externally this rock looks like a trachyte and the first impression gained by microscopical examination is that of a highly altered carbonatized trachyte. It is a porphyritic rock, but unless the felspar phenocrysts are completely chloritized they are not clearly visible in the hand-specimen.

The felspars in this rock are greatly alkalinized, carbonatized, and chloritized. As a rule only a few relics of the original lime-plagioclase can be seen. The majority of phenocrysts are completely transformed into an alkali-felspar, but in the partly altered lime-plagioclase phenocrysts the alkali-felspar occurs in ragged patches and stringers. Quite frequently only the outer border of the original plagioclase is preserved. The replacing felspar has sometimes the appearance of perthite with albite and orthoclase patches and stringers.

Seven phenocrysts from this rock were measured on the Fedorov stage and the results of these measurements are given in table II. Nos. 7 and 8 probably represent the original unaltered or slightly altered plagioclase. No. 9 is composed of oligoclase with stringers of orthoclase, the whole resembling a perthite. No. 10 shows a very small optic axial angle and must be a sanidine. In this case the measurements were repeated several times to avoid any mistake. More phenocrysts of this type were noted. The presence of sanidine suggests a comparatively high temperature at which the replacement took place. No. 11

represents the commonest type of replacement felspar which is ortho-
clase. No. 12 is a plagioclase partly replaced by orthoclase. No. 13
shows that the replacing felspar is anorthoclase. Some phenocrysts are
completely replaced by carbonate and chlorite.

There is only a faint indication of the former presence of olivine or
pyroxene phenocrysts. The groundmass consists of highly altered and
turbid felspar laths, chlorite, carbonate, iron-ore, and leucoxene.

The chemical analysis of this rock (table III, no. 4) shows high amounts
of potash and carbon dioxide and comparatively low amounts of iron
oxides and magnesia. This is in perfect agreement with the micro-
scopical evidence, e.g. the abundance of potash-felspar and carbonates.
The chemical analysis may be interpreted as that of a basalt enriched
in potash and carbon dioxide, but the mineralogical composition of this
rock is far removed from that of basalt. This rock may in certain
respects be compared with marloesite described by H. H. Thomas,
with the keratophyre-spilite described by E. Lehmann, with the trachy-
basalt described by T. C. Day (10), and finally with spilite. The non-
carbonate portion of the rock in its chemical composition (table IV) has
a resemblance to a variety of åkerite described by Brögger under the
name of hurumite (4, p. 71), but hurumite has a different mineralogical
composition.

In my opinion the best name for this rock is potash-spilite. Some
petrologists will at once object to this name on the ground that the
name spilite ought to refer only to soda-rich rocks. All this depends
on the connotation of a rock name. The name spilite (meaning spotted)
was proposed by Brongniart in 1827 (5, p. 98) and he applied it to
amygdaloidal calcite-rich rocks of basaltic composition. It was in this
sense that the term was used until in 1911 Dewey and Flett (11) added
another character to the definition, namely richness in soda which
manifested itself in the abundance of albite or oligoclase in the rock.
Strange to say, this additional character became the dominant one to
the exclusion of the original character as defined by Brongniart. Mean-
while Sargent in 1917 described certain carbonate- and potash-rich
basaltic lavas from Derbyshire under the name of potash-spilite (18).
These rocks are similar to other spilites except that they have more
potash than soda, and in my opinion they are true spilites. A new
name is unnecessary when it is possible to extend the connotation of
the existing term spilite. Thus extended the definition of spilite is as
follows: a carbonate-rich rock of basic composition and often amygda-
loidal, with alkali-felspar (usually, but not always, soda-rich), pyroxene

(usually chloritized), and sometimes olivine (in small amounts and serpentinized). According to this definition the carbonate-rich rock from Haddenrig quarry is a potash-spilite.

The Haddenrig intrusive complex consists therefore of several rock facies showing a perfect gradual transition from one to the other. Above is the potash-spilite, then metabasalt, then albitized basalt, and finally normal olivine-basalt. As comparison of chemical analyses is rather difficult in the case of altered rocks two attempts have been made to recalculate them—the first on the basis of equal volumes of rocks (table IV, nos. 1–4) where the figures of each analysis are multiplied by the quotient—specific gravity altered rock/specific gravity fresh rock. The second is a recalculation of the analyses omitting the carbonates (table IV, nos. 1a–4a). The analyses recalculated to the equal volumes of rocks is probably the best way of comparing the composition of the different members of a rock series.

TABLE IV. Analyses (table III) recalculated to equal volumes of rocks (nos. 1–4); the same without the carbonates (1a–4a); A, hurumite (Brögger, 1931, p. 71).

	1.	2.	3.	4.	1a.	2a.	3a.	4a.	A.
SiO_2 ..	46·96	47·57	43·50	43·65	47·11	48·52	48·12	57·26	59·85
TiO_2 ..	2·51	2·70	2·18	2·35	2·52	2·76	2·47	3·08	1·61
Al_2O_3 ..	14·68	13·59	14·60	14·43	14·70	13·86	16·19	18·90	15·88
Fe_2O_3 ..	4·96	3·40	2·42	1·31	4·97	3·47	2·68	1·72	0·19
FeO ..	8·18	9·10	8·82	2·33	8·21	9·21	7·97	0·31	5·94
MnO ..	0·23	0·12	0·06	0·03	0·23	0·12	0·06	0·04	0·09
MgO ..	6·26	4·96	5·66	3·32	6·28	5·06	6·25	3·52	2·15
CaO ..	8·61	7·85	5·21	7·37	8·64	7·99	5·07	2·26	4·46
Na_2O ..	3·62	4·27	2·39	2·94	3·63	4·36	2·65	3·86	2·87
K_2O ..	0·90	1·26	0·80	4·78	0·90	1·29	0·89	6·25	5·95
P_2O_5 ..	0·51	0·53	0·68	0·85	0·51	0·54	0·75	1·11	0·04
CO_2 ..	0·03	0·06	1·51	6·37	—	—	—	—	—
H_2O+ ..	1·81	2·18	5·25	1·29	1·81	2·22	6·03	1·69	0·95
H_2O- ..	0·49	0·59	0·79	—	0·49	0·60	0·87	—	—
	99·75	98·18	93·87	91·02	100·00	100·00	100·00	100·00	99·98

In the series of Haddenrig the most significant is the variation of soda, potash, water, and carbon dioxide. This is illustrated on fig. 2 which is drawn on the basis of table IV (nos. 1–4). Soda reaches its maximum in the zone of albitized basalt, water in the zone of meta-basalt, and potash and carbon dioxide in the zone of potash-spilite. This suggests that these compounds have diffused through the magma at a different rate, and of the two alkalis potash has overtaken soda.

Potash diffusion, in contrast to soda diffusion, is not a well-studied process. The majority of igneous rocks give rise to soda-rich differen-

tiates and contact adinoles testify to the penetrative power of soda. Here are a few recorded facts demonstrating the diffusion of potash. In her brilliant study of the transfusion of quartzite Miss D. L. Reynolds (16) has shown that potash is highly diffusible. In her analyses the potash index

$$(K_2O \times 100 : K_2O + Na_2O)$$

of hornblendite (original magma) is 39, while that of syenite (transfused quartzite) is 51. Brögger in his study of the essexites of Oslo district (4) gives three analyses of essexites from Randvikholmen in which the potash index of the central part of the intrusion is 33 and that of the margin 44, while the potash index of hurumite, which according to Brögger is a differentiation product of essexite, is 67. In the case of the Eel Burn basalt described by Day (9) the potash index of the fresh basalt is 17 and that of the metasomatized basalt 87. It is also interesting to note that in the Fen district (4) the potash index of the melteigite-urtite series is 28, while in the differentiation products of this magma it rises steadily — in the kåsenite-sövite series to 90 and in the damkjernite-rauhaugite series to 60.

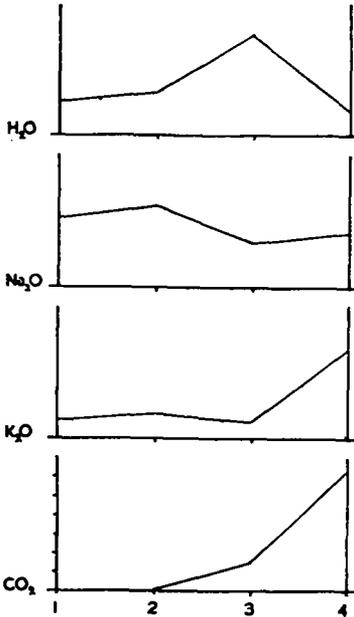
Fig. 2. Variation diagram for H_2O, Na_2O, K_2O, and CO_2 in olivine-basalt (1), albitized basalt (2), metabasalt (3), and potash-spilite (4).

The majority of the British Carboniferous igneous rocks are soda-rich, but occasionally one finds among them potash-rich facies, like those described by Day (9) and Sargent (18). Some years ago while working on the igneous rocks of Derbyshire I analysed a highly altered lava from the Matlock district. This analysis, hitherto unpublished, is given in table III (no. 6). Strictly speaking, the rock analysed cannot be called spilite, but the analysis shows a higher amount of potash than soda. Another example may be drawn from Northumberland. An analysis of the lower part of a Carboniferous lava flow from Cottonshope was published by me in a previous paper (21). A new analysis

of the upper part of the same flow shows a marked increase in potash
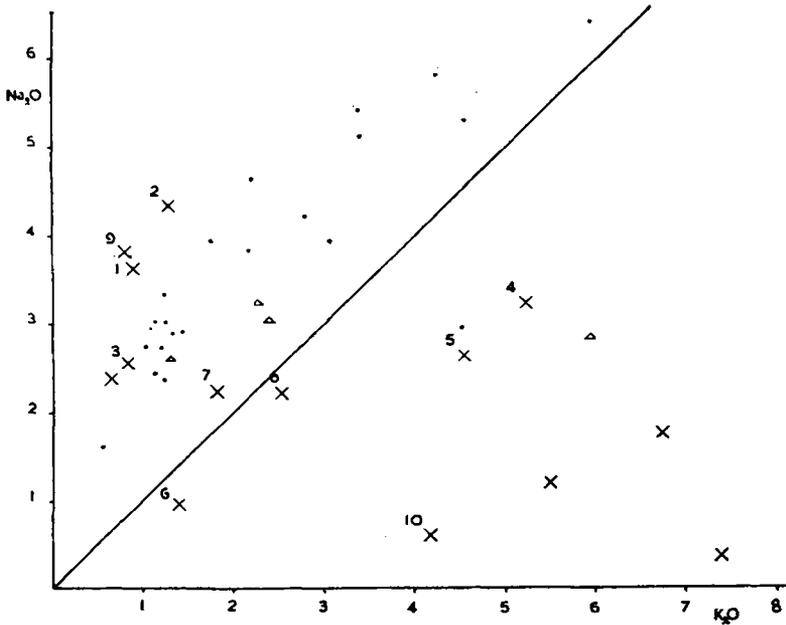(table III, nos. 7 and 8).

FIG. 3. Na_2O–K_2O diagram. The averages for various types of British Car-.
boniferous-Permian igneous rocks are represented by dots; the analyses of Hadden-
rig rocks and other rocks given for comparison (table III) are represented by
crosses; the unnumbered crosses represent other analyses of spilites from Derby-
shire as given by H. C. Sargent; the triangles represent the essexite-hurumite series
as given by W. C. Brögger.

A clear idea of the relation between soda and potash in the Carboni-
ferous igneous rocks may be derived from fig. 3. With the exception
of rhyolite all the averages of the principal rock types (22, p. 62)' fall
in the soda-rich region. The analyses of Haddenrig basalt and meta-
basalt are also situated in the same region, while that of Haddenrig
potash-spilite as well as the potash-spilites from Derbyshire fall in the
potash-rich region of the diagram. On the same diagram Brögger's
essexite-hurumite series is represented by triangles. In the majority
of cases the enrichment in potash takes place without any reduction in
soda, but in the case of the Eel Burn rocks (nos. 9 and 10) the sum of
the alkalis remains more or less constant.

II. The Vein Rocks and Carbonates.

The complex of Haddenrig is penetrated by numerous vertical veins with an approximate strike NW.–SE. The veins vary from a fraction of an inch to six inches in thickness. The contacts with the surrounding rocks are sharp and as a rule each vein is fringed by a narrow contact zone of silicified or carbonatized rock. Three types of vein rocks may be distinguished:

(1) Carbonate veins. These are composed almost entirely of carbonates distributed in patches of unequal grain-size. Fragments of spilite and metabasalt are frequent. The cavities are infilled by quartz which seals up the carbonate rhombohedra.

(2) Carbonate-silica veins. These are composed of small corroded carbonate rhombohedra embedded in a quartzose groundmass. The poikolitic quartz grains usually show an undulose extinction or brush structure passing into flamboyant structure. This suggests a meta-colloidal nature of quartz.

(3) Quartz veins. These are frequently banded. The bands vary from 0·5 to 3 mm. in thickness and are composed of coarse and fine quartz grains, chalcedony, and finely fibrous and flamboyant quartz. Small amounts of carbonate, chlorite, prehnite, and gouge clay are also found in these veins.

The cross-cutting relations of these veins show that their order of formation was as follows: carbonate, carbonate-silica, and finally quartz veins.

The fine-grained nature of the carbonates made impossible a mechanical separation of the minerals and the carbonates of the rocks and veins were therefore analysed in bulk. In each case CO_2 was determined in a separate portion. The finely ground material was treated by hot dilute HCl; and CaO, MgO, and the sesquioxides were determined in the usual way. MnO was in all cases present in minute quantities and was not determined. It was found that the amount of CO_2 was never sufficient to satisfy the amounts of the determined oxides and that the most soluble mineral other than the carbonate was the iron-ore. It was decided, therefore, to calculate all CaO and MgO as carbonates and the remaining CO_2 to allot to FeO. The results of these approximate analyses are given in table V. When placed in the order: fresh rock— altered rock—early veins—late veins, the analyses show a steady increase of $CaCO_3$ and decrease of $FeCO_3$, while $MgCO_3$ remains small. Charlewood, in his review of vein carbonates (7), suggested grouping

Table V. Composition of the carbonates in rocks and veins.

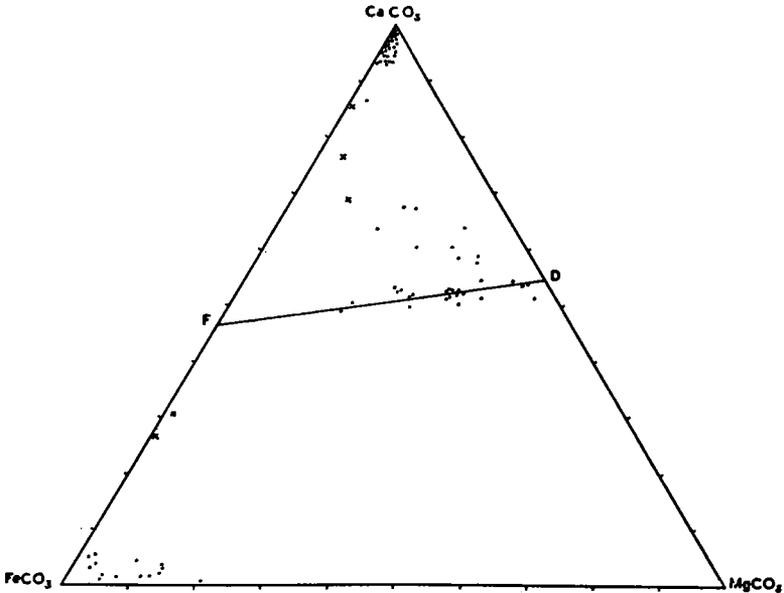|	CaCO₃.	MgCO₃.	FeCO₃.	% carbonate in the rock.
Olivine-basalt (albitized) ...	26·20	0·65	73·15	0·16
Metabasalt	30·15	1·50	68·35	4·01
Potash-spilite	68·50	8·45	23·05	16·13
Carbonate-silica vein ...	76·15	3·75	20·10	46·90
Quartz vein	85·50	0·50	14·00	1·50

FIG. 4. Triangular diagram representing the composition of 78 analyses of carbonates from veins. The analyses of carbonates from the Haddenrig rocks and veins are represented by crosses. F = ferrodolomite, D = dolomite.

them, in three groups according to their degree of occurrence in veins. Calcite, ankerite, ferrodolomite, and dolomite are frequently found, chalybite is less common, while magnesite and rhodochrosite are rare According to Hawkes and Smythe (14) ankerite represents an isomorphous mixture of dolomite ($MgCO_3.CaCO_3$) and ferrodolomite ($FeCO_3.CaCO_3$) and that it may hold up to 20 % $CaCO_3$ in solid solution. I have recalculated 78 analyses of vein carbonates collected from various sources in terms of three components, $CaCO_3$, $MgCO_3$, $FeCO_3(+MnCO_3)$, and have made a plot of them on a triangular diagram (fig. 4). This diagram suggests the abundance of calcite, chalybite, dolomite, and

ankerite. Magnesite was not recorded, probably because it is found only in veins associated with ultrabasic intrusions, which I did not collect. The analyses of the carbonates from the rocks and veins of Haddenrig are marked by crosses on the diagram. They probably represent mixtures of chalybite and calcite. Basalt and metabasalt are apparently richer in chalybite, while spilite and the vein rocks are richer in calcite. One may infer from this that chalybite, as being the less soluble of the two, was formed at a higher temperature and near the source, and that calcite was deposited farther away from the source at lower temperature.

III. CONCLUSIONS.

The magmatic complex of Haddenrig presents a fine example of metasomatism within a single rock mass. The gradual transition from basalt to metabasalt and from metabasalt to potash-spilite suggests a process of endomorphic metasomatism being responsible for these changes. Processes of this kind have been called autolysis, proto-pneumatolysis, autopneumatolysis, and autometamorphism. There is, however, no direct evidence as to the nature of the agent of metasomatism. It is difficult to identify it either as liquid or as gas, or to name the process itself—hydrothermal or pneumatolytic. It is almost certain that this process took place during the later stages of the consolidation of the magma and that the agents of metasomatism attacked already formed minerals, such as calcic-plagioclase and pyroxene. The results of this metasomatism are: the alkalinization of felspar, the chloritization of pyroxene, and the carbonate replacement of all minerals. This suggests that the principal agents of metasomatism were the alkalis, water, and carbon dioxide. The alkalinization of calcic-plagioclase also requires additional silica and this means that silica must also have been present. The unused portions of the carbonates and of silica were probably precipitated in the veins. Were the agents of metasomatism juvenile or resurgent, or, in other words, did they belong to the magma itself or were they derived from some assimilated sediments? Although it is true that quartzitic xenoliths are found in the metabasalt, there is, apart from this, no indication whatever that the magma has assimilated sediments. If we compare analyses of basalt and potash-spilite we can see no evidence of assimilation of either calcareous or siliceous sediments. The difference between the composition of the two rocks lies mainly in the amounts of K_2O and CO_2 and this cannot be explained by addition of sedimentary material. The Scottish Carboni-

ferous igneous rocks are relatively rich in carbon dioxide. This is shown by the calculated average composition of basalt in which the amount of CO_2 is 0·32 %. Considering that the majority of published analyses refer to compact fresh rocks and do not, as a rule, include carbonate-rich vesicular varieties, the actual amount of CO_2 in the magma was probably many times greater. It is thought, therefore, that the agents of metasomatism of the Haddenrig magmatic complex were of juvenile origin.

The transfer of volatiles to the upper part of the magmatic body could not have been easily achieved during the later stages of the consolidation of the magma. This transfer took place probably through diffusion in a still liquid magma. Thus in the upper, volatile-rich zone of the magmatic body the early formed minerals—olivine, pyroxene, plagioclase, and iron-ore—were reacted upon by the hydrous alkali-carbonate-silicate residual solution or gas, and this gave rise to a series of late-magmatic or deuteric minerals such as alkali-felspar, chlorite, leucoxene, and carbonate. Calcic-plagioclase, for example, can be transformed into an alkali-felspar according to the equation:

$$CaO.Al_2O_3.2SiO_2 + (Na,K)_2CO_3 + 4SiO_2$$
$$= (Na,K)_2O.Al_2O_3.6SiO_2 + CaCO_3.$$
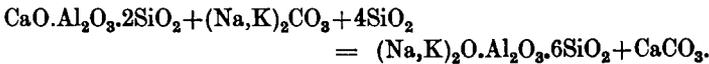
This reaction has been successfully tested experimentally by Eskola, Vuoristo, and Rankama (12). The best presentation of the process of albitization (this applies to alkalinization in general) was given by Bailey and Grabham in the following words (1, p. 253):

'We are thus led to suppose that the albitization was performed shortly after the consolidation of the ground-mass, and that the agency at work consisted of residual solutions. We may advance the hypothesis that in certain volcanic centres, e.g. Arthur's Seat, some portions of the magma were discharged exceptionally rich in carbon dioxide (or some other unknown constituent); that during crystallization of the lava an unusual proportion of soda was thus retained in solution; and that the residual liquors then began to react with the minerals which had crystallized. Olivine was converted into serpentine and chlorite, while the most basic felspars were replaced by albite. The process may be crudely expressed by saying that *the lava at this stage was stewing in a concentrated solution of sodium carbonate.*'

The comparison of analyses (tables III and IV; fig. 3) suggests that the rate of diffusion of potash was higher than that of soda. The nature of the agents of metasomatism can only be conjectured. Probably alkali carbonates, hydrous alkali silicates, and even alkali phosphates were active.

During recent years a number of works have been published dealing

with the deuteric alteration of rocks, soda, potash, and carbonate metasomatism, and hydrothermal veins. Here is a brief summary of some of them in chronological order.

Knopf (15) described a sericite-ankerite-albite-quartz-rock from the contact-zone of a greenstone. Gillson (13) described orthoclasization of plagioclase and quartz in the border phase of quartz-monzonite by means of ascending potash-bearing emanations. Singewald (20) described autometasomatism in monzonite-porphyry, the stages of alteration of which were: albitization, sericitization, and carbonatization. Butler (6) quite justifiably extended Bowen's reaction series to deuteric and hydrothermal formations. Ross (17) gave an illuminating picture of the late-magmatic processes linked up with vein formation. Bastin (2) explained the well-known 'red rock' of Pigeon Point as being due to hydrothermal alteration of the diabase. And, finally, Schwartz (19) gave a review of our knowledge of the hydrothermal alterations of igneous rocks.

Present-day petrologists are not solely interested in the normal igneous rocks. More and more they are becoming convinced that not only are the early magmatic stages important, but that an equal importance is attached to the late magmatic and even the post-magmatic stages.

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