A tholeiitic phase of the quartz-dolerite magma of central Scotland.

(With Plate XVI.)

By FREDERICK WALKER, M.A., D.Sc.,
Geology Department, University of St. Andrews.

[Read June 3, 1930.]

THE Permo-Carboniferous quartz-dolerites of central Scotland are generally holocrystalline, and only two intrusions amongst them with a fresh vitreous base have been recorded—those of Dalmeny in West Lothian, andKinkell near Kirkintilloch (north of Glasgow). Both rocks have already been described briefly, but in view of their many interesting features a more thorough treatment seems desirable, particularly as they have a bearing on some recent theories of magmatic differentiation advanced by Dr. C. N. Fenner.

The Dalmeny Tholeiite.

The first rock occurs as a thin sill exposed on the east side of the railway cutting near Bankhead Cottages, about 100 yards east of Dalmeny station, Linlithgowshire. Though neither contact is exposed, the sill is probably not more than 10 feet thick. It dips NW. at a small angle, and in the southern portion of the outcrop near the lower contact it has been converted to white trap. Elsewhere the rock is perfectly fresh, of fine grain, and black colour. Pyrites occurs along the joint cracks, but vesicles are absent except near the margin where the rock is in the condition of white trap. A very few veins of dark brown glass about 1·5 mm. in thickness are seen to traverse the unaltered portions. No complete published description of this rock has appeared, but it is referred to by Sir John Flett[1] as a good example of a quartz-dolerite with a vitreous base which he compares with that of the rock of Dalmahoy.

Under the microscope the rock presents a beautiful appearance, laths of unaltered plagioclase being the most conspicuous feature.

[1] Mem. Geol. Survey, Edinburgh District, 1910, p. 306.

These, together with subidiomorphic crystals of pale brownish-green pyroxene, are embedded in an abundant base of brown microlitic glass and green chlorophaeite. Grains of titaniferous iron-ore are also conspicuous and numerous needles of apatite may be detected in the mesostasis. The texture of the rock is clearly shown in pl. XVI, fig. 1.

Constituent minerals.—The plagioclase occurs as well-formed laths up to 1·2 mm. in length and not more than 0·2 mm. across. These are twinned on the Carlsbad, albite, and, less commonly, on the pericline laws, and show well-marked progressive zoning from the centre outwards. The margins usually show straight extinction and are oligoclase, but the bulk of the felspar consists of basic andesine or acid labradorite, $Ab_{55}An_{45}$ to $Ab_{45}An_{55}$. The mean refractive index of the central portions was found to be $1{\cdot}558 \pm 0{\cdot}002$, and the symmetrical extinction-angles measured on the albite lamellae yielded no greater value than 27°.

The pyroxene crystals form stumpy prisms up to 0·6 mm. in length and 0·3 mm. across, which often occur in groups. They are usually idiomorphic, but are sometimes penetrated by the ends of plagioclase laths or are moulded on iron-ores. This pyroxene is a monoclinic enstatite-augite of pale greenish-brown colour with little discernible pleochroism or zoning. The maximum extinction-angle ($\gamma : c$) is 44°, while the axial angle is in the neighbourhood of 60°; β, measured in oils, is $1{\cdot}685 \pm 0{\cdot}005$. Simple and lamellar twinning parallel to (100) are both common. Like the felspar, the augite is perfectly fresh.

The chlorophaeite is isotropic and dark green in colour, but may be stained brown by iron oxide.[1] It occurs as round or shapeless clumps in the glass, or moulded upon the crystalline constituents. The lack of form seems to indicate that it is not a replacement product of fayalite as in some of the Dalmahoy rocks. A few of the larger clumps contain central areas of carbonates or, more rarely, quartz.

Iron-ore is a conspicuous feature of the rock, occurring as shapeless grains or stout skeletal growths indicative of ilmenite. Some of the smaller grains are enclosed by pyroxene, but the skeletal growths

[1] Since the above was written a paper by Dr. M. A. Peacock (Geol. Mag., 1930, vol. 67, p. 177) has appeared, in which he demonstrates the existence of two separate varieties of chlorophaeite—a green and a brown. Both varieties seem to be present here.

may be of later crystallization although they occasionally penetrate felspar or augite. The larger growths may reach 0·5 mm. in length.

The glass is of light brown colour and may be quite clear or slightly turbid. It contains abundant acicular crystals, microlites, and crystallites of oligoclase and augite; small rounded grains of magnetite about 0·03 mm. in diameter; and bundles of minute needles of apatite. The refractive index of the plagioclase is slightly above that of balsam, and the extinction either straight or at very small angles. The refractive index of the glass is $1{\cdot}495 \pm 0{\cdot}002$, which points to an acid composition. Besides occurring interstitially in the rock, it forms the thin veins mentioned above (see pl. XVI, fig. 2).

Mode, analysis, and norm.—The rock shows little variation and its mineralogical composition at any point differs little from the mode given below and accompanied by a chemical analysis made for the author by Professor J. Jakob. The norm of the analysis has been calculated and is appended, but the discussion of the analysis will be held over until a later stage.

Analysis.		Norm.		Mode.	
SiO_2 ...	50·44	Quartz	12·4	Plagioclase ...	33·7
TiO_2 ...	3·04	Orthoclase ...	7·8	Augite	26·1
Al_2O_3 ...	11·60	Albite	16·8	Chlorophaeite ...	6·9
Fe_2O_3 ...	6·29	Anorthite ...	18·9	Iron-ore... ...	14·3
FeO ...	6·16	Diopside	18·1	Apatite	1·0
MnO ...	0·10	Hypersthene ...	5·8	Glass	18·0
MgO ...	5·18	Magnetite ...	9·0		
CaO ...	9·03	Ilmenite	5·8		
Na_2O ...	1·97	Apatite	1·0		
K_2O ...	1·33	H_2O, &c.... ...	4·5		
H_2O+ ...	2·70				
H_2O- ...	1·59				
P_2O_5 ...	0·38				
S ...	0·03				
B_2O_3 ...	0·18				
	100·02				

The Kinkell Tholeiite.

Although the Dalmeny tholeiite is probably a representative of the Permo-Carboniferous quartz-dolerite magma, there is no proof of this, and it is therefore satisfactory to find a very similar rock forming a typical Permo-Carboniferous E.–W. dike running from Kinkell to Antermony Loch. The dike is about 3 miles long and 50 feet wide. It is best exposed in an old quarry a quarter of a mile NW. of Kinkell farm, near Kirkintilloch, Dumbartonshire. The occurrence was

described in a privately published paper by Mr. A. Veitch Lothian[1] and a few years later by Professor E. B. Bailey in the Glasgow Memoir.[2]

The present writer's observations agree in the main with those of the two earlier descriptions, but his determination of the felspar differs from both the previous ones, while chlorophaeite is added to the list of constituent minerals. Two distinct types of crystallization were also encountered.

The rock is exposed on the old working face of Kinkell quarry, but neither contact is visible, both being thickly overgrown. The southern half of the exposure consists of a dark, fresh rock, slightly coarser in grain than that of Dalmeny but otherwise exactly similar. In the northern part of the exposure, however, the tholeiite appears distinctly more glassy in the hand-specimen, although there is no sharp line of demarcation between the two types.

Under the microscope the constituent minerals of the Kinkell rock are seen to be the same as those of the Dalmeny tholeiite and were found to have the same optical properties, the mean refractive indices of both the felspars and the pyroxenes being identical in the two occurrences. The relative proportions of the minerals and the texture are different in both the Kinkell types.

Southern type.—The less glassy type in the southern part of the quarry is slightly coarser than the Dalmeny rock, the plagioclase laths sometimes reaching a length of nearly 2 mm., while the pyroxene shows a proportional increase in size. Both minerals have a greater tendency to form clumps. The pyroxene is apparently of distinctly earlier crystallization than the felspar by which it is often enclosed. The iron-ore is slightly more abundant, and the chlorophaeite exhibits vermicular structure in many places. The proportion of glass (refractive index 1·495) is greater and crystallites play a more prominent part in it than the microlites which are so common in the Dalmeny rock. (Pl. XVI, fig. 3.)

Northern type.—The second type in the north part of the exposure contains less plagioclase than the first, but the proportion of pyroxene remains the same, as do the sizes of both minerals. Some of the iron-ore has the same habit as in the two previous types, but chlorophaeite is absent, its place being taken by a late crystallization of skeletal

[1] A. V. Lothian, The petrology of the Kilsyth Hills. Privately printed, 1902, p. 15.

[2] E. B. Bailey, Mem. Geol. Survey, Glasgow District, 1911, p. 146.

ilmenite which everywhere crowds the glassy base with its delicate lattice structures. The glass makes up nearly 40 % of the rock, but its properties are rendered obscure by the iron-ore and abundant oligoclase microlites with which it is crammed. (Pl. XVI, fig. 4.)

A chemical analysis of the southern Kinkell rock made by Professor J. Jakob is given below, together with the norm and mode.

Analysis.		Norm.		Mode.	
SiO_2 ...	49·10	Quartz	7·6	Plagioclase ...	25·5
TiO_2 ...	4·02	Orthoclase ...	12·2	Augite	25·3
Al_2O_3 ...	12·13	Albite	17·8	Chlorophaeite ...	4·6
Fe_2O_3 ...	4·61	Anorthite ...	17·5	Iron-ore... ...	17·6
FeO ...	8·92	Diopside	15·8	Apatite	1·2
MnO ...	0·15	Hypersthene ...	9·7	Glass	25·9
MgO ...	4·50	Magnetite ...	6·7		
CaO ...	8·20	Ilmenite	7·6		
Na_2O ...	2·14	Apatite	1·3		
K_2O ...	2·10	H_2O, &c.... ...	3·6		
H_2O+ ...	2·50				
H_2O- ...	1·02				
P_2O_5 ...	0·51				
S ...	0·03				
	99·93				

Nomenclature and Discussion of Analyses.

If a type name for the above tholeiites be deemed desirable, it is suggested that 'tholeiites of the Bankhead type' be used, since the locality Dalmeny is already associated with a well-known type of Carboniferous olivine-basalt.

The table of analyses (p. 373) makes it clear that the tholeiites of Dalmeny and Kinkell can be matched in chemical composition fairly closely by several British tholeiites and dolerites of Carboniferous or later age. Their closest analogue, however, is perhaps to be found in the basalt or dolerite of Sassendal in Spitzbergen, which contains a glassy mesostasis and a small proportion of serpentinized olivine. The average Whin Sill magma (A), from which the Dalmeny and Kinkell rocks were presumably derived, differs in its higher alumina and greater FeO/Fe_2O_3 and Na_2O/K_2O ratios, while the analysis (B) of the somewhat similar Dalmahoy rock shows distinct resemblances to I and II but is decidedly more alkaline.

The distinguishing features of British chlorophaeite-tholeiites, if one may judge from the analyses I, II, and B, appear to be low

alumina (11·60–13·02), low Na_2O/K_2O ratio (1–1·75), low FeO/Fe_2O_3 ratio (0·94–1·93), and high percentage of water (3·73–4·29). The last two features are a reflection of the chlorophaeite present, and it should be emphasized that all three analyses are of perfectly fresh rocks. It is doubtful, however, if much of the formless chlorophaeite is not due to deuteric replacement of fayalitic olivine as Dr. M. A. Peacock (loc. cit.) suggests. The presence of chlorophaeite is probably due to a high content of water in the magma, and its absence from the north part of the Kinkell exposure may be due to a local paucity of that constituent. Other dolerites and tholeiites may show two of the four distinguishing features of chlorophaeite-tholeiites, but, apparently, not more.

Comparison of Analyses with others of similar Magma-type.

	I.	II.	A.	B.	C.	D.	E.	F.
SiO_2 ...	50·44	49·10	50·52	52·90	50·78	50·17	54·11	51·63
TiO_2 ...	3·04	4·02	2·39	2·35	2·92	2·93	3·37	2·00
Al_2O_3 ...	11·60	12.13	13·76	13·02	11·37	13·66	11·65	11.77
Fe_2O_3 ...	6·29	4·61	3·87	6·62	3·27	5·40	2·76	3·23
FeO ...	6·16	8·92	8·50	6·?1	10·72	6·59	7·02	10·47
MnO ...	0·10	0·15	0·16	—	0·26	0·15	0·21	0·35
MgO ...	5·18	4·50	5·42	2·86	5·12	5·31	5·30	5·02
CaO ...	9·03	8·20	9·09	6·37	9·62	9·26	8·77	9·34
Na_2O ...	1·97	2·14	2·42	3·51	2·31	2·06	2·63	2·90
K_2O ...	1·33	2·10	0·96	2·00	0·70	1·00	1·75	0·91
H_2O+ ...	2·70	2·50	1·51	3·73	0·86	1·28	0·81	1·40
H_2O- ...	1·59	1·02	0·76		0·77	1·02	0·68	0·68
P_2O_5 ...	0·38	0·51	0·26	0·90	0·21	0·28	0·58	0·24
Etc. ...	0·21	0·03	0·69	—	1·14	0·82	0·33	0·23
	100·02	99·93	100·31	100·57	100·05	99·93	99·97	100·27

I. Tholeiite, Dalmeny, Linlithgowshire. Analyst, J. Jakob.

II. Tholeiite, Kinkell, Dumbartonshire. Analyst, J. Jakob.

A. Average Whin Sill type. Analyst, H. F. Harwood. Min. Mag., 1928, vol. 21, p. 539.

B. Tholeiite, Dalmahoy, Edinburghshire. Analyst, T. C. Day. Trans. Roy. Soc. Edinburgh, 1927, vol. 55, p. 501.

C. Quartz-dolerite dike, Insch, Aberdeenshire. Analyst, E. G. Radley. Mem. Geol. Survey, Huntly district, 1923, p. 164.

D. Quartz-dolerite sill, Sassendal, Spitzbergen. Analyst, H. F. Harwood. Min. Mag., 1918, vol. 18, p. 206.

E. Andesitic tholeiite (Acklington type), Lugton, Ayrshire. Analyst, B. E. Dixon. Summ. Progr. Geol. Survey, Great Britain, for 1925, 1926, p. 128.

F. Tholeiite (Brunton type), Kintallen, Mull. Analyst, E. G. Radley. Mem. Geol. Survey, Mull, 1924, p. 17.

Application of the results to Petrogeny.

In a recent paper of great interest Dr. C. N. Fenner[1] has advanced evidence from many sources that in the crystallization of basaltic magma the earlier ferromagnesian silicates contain excess of magnesia, while excess of iron is concentrated in the residual liquid. Thus the residual glass or liquid of plateau-basalts is supposed by him to be rich in iron and to crystallize, if conditions permit, as magnetite, pyroxene, and felspar, the last two of which are richer in iron and alkalis respectively than the corresponding minerals of earlier crystallization. Applying these conclusions to dolerites (diabases), he argues that the micropegmatite so often present interstitially is not the normal result of crystallization-differentiation, but the product of hydrothermal activity after the complete solidification of the rock. The refractive index of the residual glass of one of the Deccan traps—a typical plateau-basalt—was, however, found by him to be as low as 1·510, indicating a glass of dacitic composition; but Fenner suggests that the low index is due to the presence of phosphates, borates, or silicofluorides, and to the escape of iron with the volatiles.[2] It will now be seen how these conclusions apply to the tholeiites of Dalmeny and Kinkell.

The pyroxene of both rocks shows little zoning, but the plagioclase, whose crystallization extended over a long period, exhibits a progressive change from acid labradorite to oligoclase, pointing to the 'normal response of solid solutions to crystallization in a liquid of changing composition'. The absence of flow structure and phenocrysts shows that the rock was probably entirely liquid when intruded, while the presence of residual glass may be taken as a sign of fairly rapid cooling comparable to that in a basalt-lava. Their chemical composition closely resembles that of several of the Deccan traps analysed by Washington[3] except for the lower Na_2O/K_2O ratio (1 and 1·75), which may, however, be matched by the plateau-basalts of Oregon in one of which the ratio sinks to 1·54.[4]

The rocks of Dalmeny and Kinkell might, then, be expected to have a basic residual glass rich in iron, if Fenner's theories are

[1] C. N. Fenner, The crystallization of basalts. Amer. Journ. Sci., 1929, ser. 5, vol. 18, pp. 225–253.

[2] C. N. Fenner, loc. cit., p. 242.

[3] H. S. Washington, Bull. Geol. Soc. Amer., 1922, vol. 33, p. 774.

[4] H. S. Washington, loc. cit., p. 779.

applied, but the reverse appears to be the case. The refractive index of the glass is even lower than that of the Deccan examples measured by him and corresponds with the values given by Tilley [1] for rhyolitic obsidians. We have not sufficient knowledge of the composition of the ferromagnesian silicates to make an accurate calculation of the composition of the residual glass, but taking the silica percentages of the plagioclase, pyroxene, and chlorophaeite as 60, 50, and 36 respectively, the glass will be found in the case of the Dalmeny rock to have a silica percentage of about 80, and in the Kinkell rock, in which errors of assumption are not magnified to the same extent, a percentage of 75. It will also be found, if the alkalis are distributed between the plagioclase and the glass, that the latter is highly potassic in both cases. Had the glass been permitted to crystallize it would, doubtless, have formed the interstitial micropegmatite so characteristic of the British Permo-Carboniferous quartz-dolerites. It may be added at this point that there is no evidence that this micropegmatite is of deuteric formation, for it may be found in absolutely fresh rocks (e.g. that of Auchterarder station).[2] Hydrothermal alteration has certainly taken place in some examples, and it may be detected by the albitization or analcitization of the plagioclase which it causes. The light quartzo-felspathic veins which so commonly represent the last magmatic residue often contain twinned albite-oligoclase and acicular hornblende or augite, which cannot be regarded as other than normal products of crystallization. Moreover, the well-marked linear variation of the major oxides in the normal dolerites and the segregation veins in the Bathgate Hills has been already emphasized by Professor Bailey.[3]

In order to test the validity of Dr. Fenner's suggestion that the low values obtained for the refractive indices of residual glass may be due to borates, silico-fluorides, or phosphates, a spectrographic examination of the Dalmeny rock was made with great care by Mr. A. S. Roy with the kind permission of Professor H. S. Allen. This proved conclusively that boron was present, a result confirmed by the subsequent quantitative estimation of Professor Jakob. Phosphate cannot be present in the glass, for the normative and modal apatite agree closely in both rocks. It is, however, extremely doubtful if the presence of B_2O_3 in the glass (in this case under 1 %) would lower

[1] C. E. Tilley, *Min. Mag.*, 1922, vol. 19, p. 279.

[2] F. Walker and J. Irving, Trans. Roy. Soc. Edinburgh, 1928, vol. 56, p. 12.

[3] E. B. Bailey, loc. cit., p. 147.

the refractive index, for the three best-known boro-silicates, tourmaline, axinite, and dumortierite all have high refractive indices.

Both tholeiites support Dr. Fenner's contention that iron is concentrated in the residuum of basaltic rocks; for the chlorophaeite —a mineral rich in iron—is of late formation in both rocks and so is the ilmenite in the northern exposures of Kinkell quarry. The author believes, however, that this late crystallization of minerals rich in iron left a still later residue much poorer in that constituent —a constituent whose presence in any abundance would raise the refractive index of the glass far above the recorded values. An examination of the residual glasses of many more plateau-basalts, careful determination of their refractive indices, and if possible of their density and chemical composition, seem desirable to test adequately the conclusions of Dr. Fenner, but the evidence provided by the tholeiites of Dalmeny and Kinkell, though limited in scope, cannot be considered to confirm some of his views.

Summary.—The tholeiites of Dalmeny and Kinkell are considered to be a phase of the quartz-dolerite magma of central Scotland. They are re-described and shown to contain chlorophaeite. It is demonstrated by means of analyses and refractive index determinations that the residual glass is of acid composition in both cases—a conclusion which does not support some of the writings of Dr. Fenner on basaltic crystallization.

Acknowledgements.—The author is greatly indebted to Professor E. B. Bailey for access to literature otherwise unobtainable, to Mr. A. S. Roy for his spectrographic determination of the Dalmeny rock, and to the Carnegie Trust for the Universities of Scotland for a grant, by the aid of which the two chemical analyses were made.

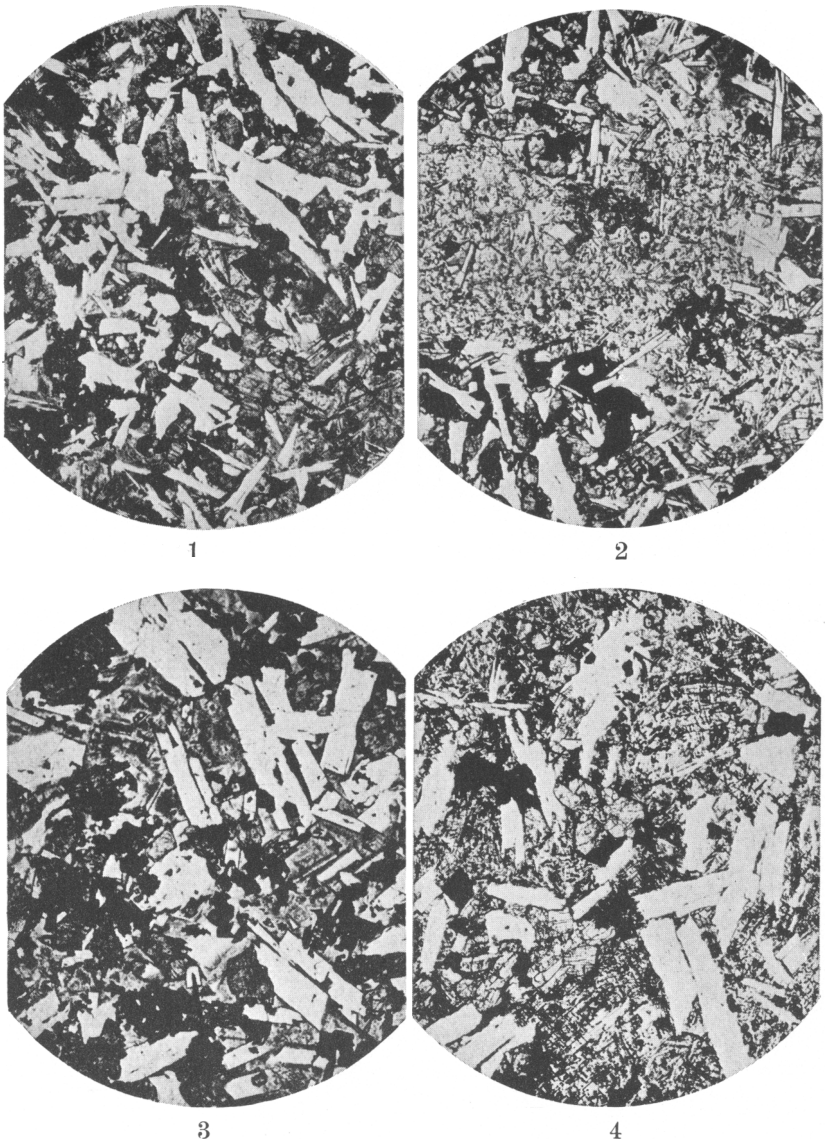
EXPLANATION OF PLATE XVI.

FIG. 1. Tholeiite, Dalmeny, Linlithgowshire. Ordinary light, ×18. Laths of plagioclase, subidiomorphic augite, dark chlorophaeite, and ilmenite are embedded in a microlitic glass.

FIG. 2. Tholeiite, Dalmeny. Ordinary light, ×18. The same rock as fig. 1 traversed by a vein of microlitic glass.

FIG. 3. Tholeiite, south part of Kinkell quarry, Dumbartonshire. Ordinary light, ×18. Similar to Dalmeny rock in fig. 1, but slightly coarser and richer in glass.

FIG. 4. Tholeiite, north part of Kinkell quarry. Ordinary light, ×18. Poorer in plagioclase than fig. 3. The place of chlorophaeite is taken by lattices of ilmenite.



1 2

3 4

FREDERICK WALKER: THOLEIITES FROM CENTRAL SCOTLAND.