The Eskdalemuir tholeiite and its contribution to an understanding of tholeiite genesis.

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Summary.—The Eskdalemuir tholeiite has the following modal composition: glass 42·2 %, felspar 24·4 %, pyroxene 30·6 %, magnetite 2 %, chlorite 1 %. The glass has been separated and analysed. It has 70 % SiO_2 and is of granitic composition. On a selected triangular diagram the plots of the Eskdalemuir rock, its residual glass, and its crystalline portion are spread along a narrow belt marking the compositions of the Tertiary tholeiites. Because the differences in the chemical compositions of the phases of the Eskdalemuir tholeiite are produced by crystallization, it is concluded that the variety of composition of the other Tertiary tholeiites is consistent with a genesis controlled by crystallization differentiation.

STRETCHING almost completely across the Lower Palaeozoic rocks of the Southern Uplands of Scotland is the north-west trending Eskdalemuir dyke, one of the great solitary Tertiary dykes of the south of Scotland. It appears on the southern edge of the Permian basin of the Snar valley, runs by Moffat to the vicinity of Langholm, a distance of almost 40 miles, and attains a width of 180 feet (Pringle, 1935).

In the past it has attracted the attention of many eminent petrologists who between them have investigated most of its aspects. Geikie (1880, 1897) described it fully and pointed out the salient petrographic character of a framework of basaltic minerals with interstitial glass (fig. 1); Teall (1888) figured it in 'British Petrography'; Tyrrell (1917) related it to other Tertiary dykes of the Clyde area; and Holmes and Harwood (1929) discussed its relationships to the tholeiites of the north of England. The only part which escaped direct investigation was the clear glassy base, which is present in sufficient quantity to be separated from its associated minerals and analysed.

The main purpose of this paper is to present the new analyses of tholeiite and mesostasis, to calculate the composition of the crystalline fraction, and to comment on the bearing of these analyses upon the genesis of the various members of the north of England and Scottish Tholeiite Series. Some new data on mineral composition and proportions are also given, but in view of the comprehensive literature it is not proposed to repeat the rock descriptions but rather to add supplementary notes, which can be read in conjunction with the earlier work.

FIG. 1. Tholeiite composed of plagioclase, pyroxene, magnetite, and glass. The large crystal in the centre of the field is hypersthene rimmed by a clinopyroxene.

Petrology of the tholeiite.

The specimens used in this investigation were collected on Eskdalemuir at the summit of Castle Hill about 10 miles north-west of Langholm. They agree in every way with the hemicrystalline rock of the earlier descriptions and differ from samples of the dyke from other localities only in their superior freshness. They may therefore be taken as representative of the dyke as a whole.

The principal minerals are pyroxene, plagioclase, and glass, which, from point-counter analyses under high magnification at about ten thousand points, are present in the following proportions: glass

$42{\cdot}2 \pm 0{\cdot}6$, felspar $24{\cdot}4 \pm 0{\cdot}5$, pyroxene $30{\cdot}6 \pm 1{\cdot}0$, magnetite 2 %, chlorite 1 %.

Felspars. The phenocrysts and smaller crystals alike are almost exclusively labradorite. Each crystal is slightly zoned and has a bulk composition of $Ab_{46}\,An_{54}$. So far as I could determine anorthite is completely absent and only one bytownite crystal, $Ab_{25}An_{75}$, was seen in all the thin sections examined. This was within a small cluster of labradorites.

Pyroxenes. The phenocrysts are of hypersthene, rimmed with monoclinic pyroxene, and pigeonite in approximately equal amounts and the small granules are of pigeonite and augite. Dr. I. D. Muir who has taken an interest in the pyroxenes has supplied the following details:

> There are four distinct pyroxene phases (all compositions as atomic percentages) (fig. 2).
>
> *H*— Hypersthene occurs as practically unzoned microphenocrysts, stout subhedral grains mostly jacketed by a discontinuous mantle of grains of monoclinic pyroxene. Where the identity of this mantling pyroxene has been established it has always proved to be pigeonite ($\beta \perp (010)$; average $2V = 15°$ but strongly zoned). The hypersthene has $2V_\alpha = 68°\text{–}66°$ and the probable composition is $(Ca_{0{\cdot}05}Mg_{0{\cdot}69}Fe_{0{\cdot}26})SiO_3$.
>
> *P*— Pigeonite occurs as practically unzoned microphenocrysts, stout subhedral greenish grains which are never jacketed. These have $\alpha = 1{\cdot}687$, $\beta = 1{\cdot}688$, $\gamma = 1{\cdot}714$; $2V_\gamma = 19° \rightarrow 14°$ margin; $\alpha \perp (010)$; $\gamma \wedge c = 43°$. The probable composition is $(Ca_{0{\cdot}09}Mg_{0{\cdot}60}Fe_{0{\cdot}31})SiO_3$.
>
> *Q*— Pigeonite is present in the groundmass as little greenish columnar prisms with cross fractures and strong zoning. These comprise about one quarter of the finer-grained pyroxene. They have $\beta = 1{\cdot}696\text{–}1{\cdot}702$ (approximate values), $\gamma = 1{\cdot}731$ (maximum value), $2V_\gamma = 10° \rightarrow 28°$ margin (average value 20°); $\beta \perp (010)$. The range of composition is from $(Ca_{0{\cdot}19}Mg_{0{\cdot}46}Fe_{0{\cdot}35})SiO_3$ to $(Ca_{0{\cdot}24}Mg_{0{\cdot}39}Fe_{0{\cdot}37})SiO_3$.
>
> *R*— Subcalcic augite is present as discrete roundish brownish grains which are practically unzoned. They have $\beta = 1{\cdot}702$ (approximate value); $2V_\gamma = 45° \rightarrow 38°$ (margin), average value 42°; $\beta \perp (010)$; $\gamma \wedge c = 41°$. The composition is
>
> $$(Ca_{0{\cdot}33}Mg_{0{\cdot}37}Fe_{0{\cdot}30})SiO_3.$$
>
> The normative pyroxene is
>
> $$(Ca_{0{\cdot}23}Mg_{0{\cdot}43}Fe_{0{\cdot}34})SiO_3.$$

Glass. This is mainly pale brown and completely transparent with very few inclusions or microlites. A small proportion of it is slightly clouded and a very few small patches are bright orange in colour, due, according to Vincent (1950), to incipient alteration. The specific gravity of the clear brown part is 2·38 and the refractive index is $1{\cdot}500 \pm 0{\cdot}004$.

Magnetite occurs as small scattered euhedra.

The chemical composition of the tholeiite is given in table I and it is clear that it is andesitic in spite of the basaltic nature of the crystals.

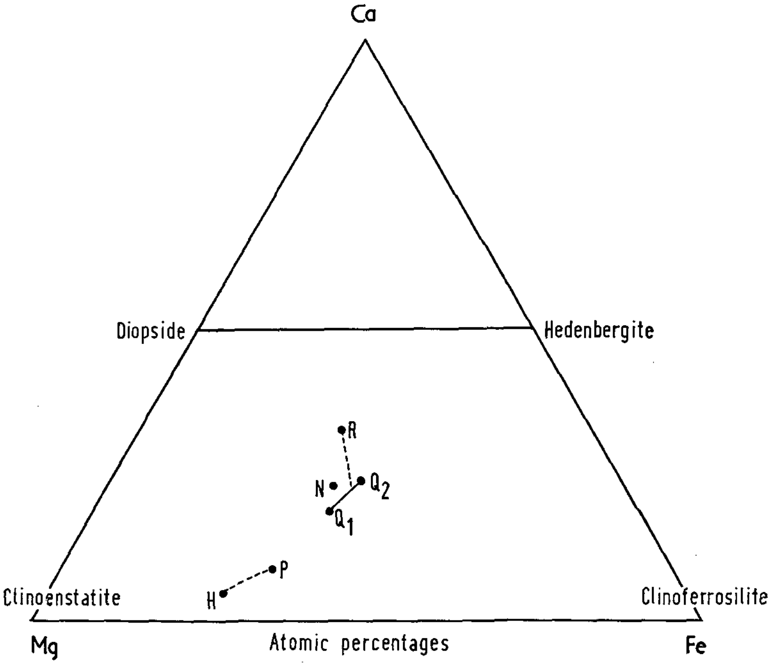

FIG. 2. Plot of the modal pyroxenes of the Eskdalemuir tholeiite. H, hypersthene microphenocrysts; P, pigeonite microphenocrysts; Q_1 and Q_2, limiting compositions of the groundmass pigeonite; R, subcalcic augite of the groundmass; and N, normative pyroxene of the crystalline material. Tie lines, - - - -, indicate the phases in equilibrium.

For a comparison with other Tertiary tholeiites the reader is referred to Holmes and Harwood (1929).

Tyrrell (1917) has discussed the nomenclature of rocks of this sort and has suggested the possibility of the name 'cumbraite of Eskdalemuir type'. Holmes on the other hand regards it pretty definitely as a minor variant of the Cleveland type of tholeiite but admits that if it should ever be thought necessary to split it off from the Cleveland group then Tyrrell's term of 'Eskdalemuir type' could be used.

The residual glass.

The glass concentrate was prepared as follows. The rock was first crushed to pass a 300-mesh sieve, after which the rock flour of fine silt and clay grade was washed away with water by decantation.

Separation was done in two stages; initially in a beaker with a bromoform-acetone mixture of sp. gr. 2·6 and secondly in a centrifuge with a mixture of sp. gr. 2·42. It was necessary to centrifuge many times to reach a purity of 98 %. At this stage, considered sufficiently clean for analysis, the impurities were in part felspar, in part pyroxene, and in part an indeterminate reddish-brown substance.

TABLE I. Chemical compositions of the Eskdalemuir dyke and of its components.

	Chemical compositions.					Norms.		
	A.	B.	C.			A.	B.	C.
SiO_2	60·22	70·58	53·4		Q	14·46	35·04	1·62
Al_2O_3	14·06	11·62	15·3		or	8·34	18·30	3·06
FeO	6·58	1·52	9·5		ab	24·60	28·80	22·53
Fe_2O_3	0·90	1·35	0·63		an	21·10	5·84	28·08
TiO_2	0·64	0·65	0·63		C	nil	0·51	nil
MnO	0·08	0·02	0·10	di	wo	6·38	nil	10·56
CaO	7·36	1·36	10·75		en	3·20	nil	5·20
MgO	4·28	0·72	6·3		fs	3·17	nil	5·15
K_2O	1·36	3·10	0·34	hy	en	7·50	1·80	10·60
Na_2O	2·95	3·44	2·64		fs	7·12	0·53	10·82
H_2O-	0·22	nil	0·34		mt	1·39	2·09	0·93
H_2O+	1·53	4·98	nil		il	1·21	1·22	1·22
CO_2	nil	nil	nil		ap	0·34	0·34	nil
P_2O_5	0·11	0·18	0·06		H_2O	1·75	4·98	0·34
	100·29	99·52	99·99			100·56	99·45	100·11

A, Eskdalemuir tholeiite (Anal. W. H. Herdsman).
B, glass from Eskdalemuir tholeiite (Anal. W. H. Herdsman).
C, calculated composition of crystalline phase of Eskdalemuir tholeiite (from columns A and B).

The chemical analysis and norm are given in table I along with those of the parent tholeiite. One affinity is clear, the glass is approximately 'granitic' in composition and this is emphasized by the fact that it falls within the field of analysed granites plotted in terms of their normative Or, Qz, and Ab (Carnegie Institute of Washington Year Book no. 51). More local affinities are appreciated by comparing the analyses with existing analyses of pitchstones, leidleites, inninmorites and of the various other members of the Tholeiite Series (Tyrrell, 1917). In general, comparisons are facilitated by the use of triangular diagrams chosen with care to emphasize important composition variations and to eliminate subsidiary fluctuations. In the case of the tholeiite series there is only insignificant Fe enrichment and the standard

$$MgO—(FeO+Fe_2O_3)—(Na_2O+K_2O)$$

diagram is consequently not satisfactory. On the other hand, the felspars

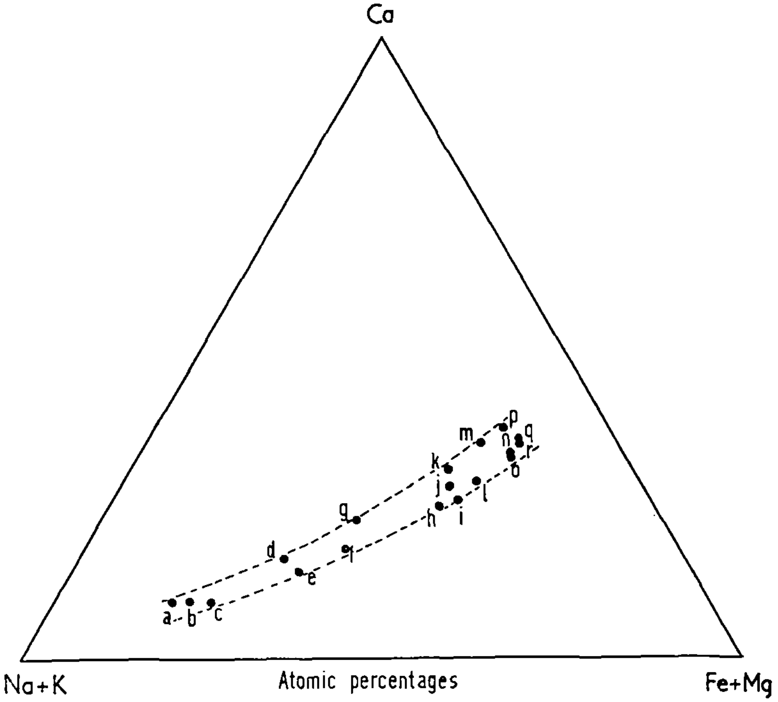

FIG. 3. Plot of the chemical compositions of Tertiary tholeiites.

a, pitchstone. Glen Shurig type. The Geology of Arran, p. 234.
b, pitchstone. Judd's No. II dyke. Ibid.
c, residual glass from Eskdalemuir dyke. New analysis.
d, inninmorite. Pitchstone II. The Geology of Ardnamurchan, N.W. Mull and Coll, p. 84.
e, inninmorite. Pitchstone I. Ibid.
f, inninmorite. Tyrrell, 1917, p. 310.
g, leidleite III. The Tertiary and Post-Tertiary Geology of Mull, &c., p. 19.
h, leidleite II. Ibid.
i, tholeiite of Cleveland type, Cleveland dyke. Holmes and Harwood, 1929, p. 39.
j, tholeiite of Cleveland type, Eskdalemuir dyke. New analysis.
k, tholeiite of Cleveland type, Hebburn dyke. Holmes and Harwood, 1929, p. 35.
l, tholeiite of Acklington type, Acklington dyke. Ibid., p. 31.
m, tholeiite of Acklington type, Coley Hill dyke. Ibid., p. 32.
n, tholeiite of Salen type, Kielderhead dyke. Ibid., p. 15.
o, calculated composition of crystals of the Eskdalemuir dyke.
p, tholeiite of Brunton type, Tynemouth dyke. Ibid., p. 21.
q, tholeiite of Talaidh type, Kielder Viaduct dyke. Ibid., p. 27.
r, tholeiite of Brunton type, Bingfield dyke. Ibid., p. 18.

clearly have a large role in tholeiite evolution and this factor must be taken into account. The diagram finally selected for use here was one using atomic percentages of Ca, Na+K, and Mg+Fe as triangular coordinates (fig. 3). This has two main advantages; firstly, the plotting of Ca allows the part played by the felspars to be fully recorded, and secondly, the use of atomic percentages eliminates the constant oxygen which only diminishes the pictorial amplitude of the variations as shown on the triangular diagram. The standard AFM diagram is also given for comparison (fig. 4).

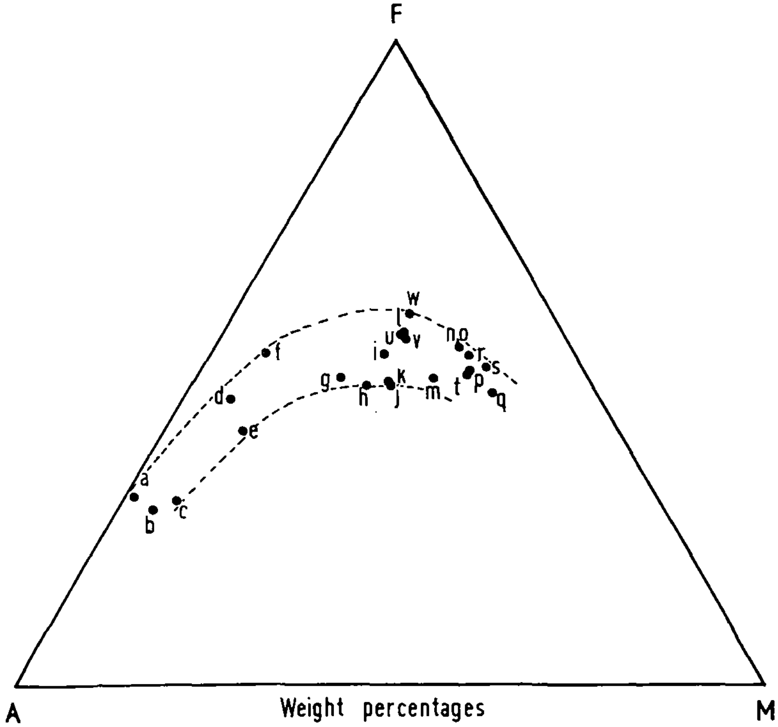

FIG. 4. Plot of the chemical compositions of tertiary tholeiites for the oxides $FeO+Fe_2O_3$ (F), MgO (M), alkalis (A). Data as for fig. 3 supplemented by:
s, tholeiite of Talaidh type, Crookdene dyke. Holmes and Harwood, 1929, p. 28.
t, tholeiite of Talaidh type, Collywell dyke. Ibid., p. 28.
u, tholeiite of Cleveland type, Great Ayton. Ibid., p. 40.
v, tholeiite of Cleveland type, Armathwaite. Ibid., p. 40.
w, tholeiite of Cleveland type, Teesdale. Ibid., p. 40.

On the diagram selected the entire Tholeiite Series, including the

Eskdalemuir dyke, lie on a well-defined belt with surprisingly little scatter. The plots both of the residual glass and of the crystals of the Eskdalemuir tholeiite also fall on and at opposite ends of the same belt. From these observations it seems at least logical to conclude that the process that operated within the single tholeiite to produce the contrasted compositions of crystals and glass could have operated on a larger scale to produce the several members of the tholeiite series. The process that took place within the tholeiite was crystallization. It is therefore concluded that the Tholeiite Series was probably the product of fractional crystallization.

Before this hypothesis can be accepted as a reasonable possibility the objections to it, put forward by Holmes (1929), must first be answered. These objections are:

1. The chemical composition of the crystals in one of the low SiO_2 tholeiites (Bingfield dyke) does not agree with the theoretical composition required to be extracted from that tholeiite to form other tholeiites of higher SiO_2 content.
2. Pyroxene crystallization in each of the tholeiites begins with hypersthene, whereas in a series of successive residual magmas this would not be expected.
3. The anorthite content of the plagioclase does not fall with the rise in the felspar ratio.
4. The $F/(P+F)$ ratio[1] only reaches that of the Whin Sill (quartz-dolerite) whereas in a residual product it ought to be higher.
5. The $MgO/(MgO+FeO)$ ratio is higher in some of the high SiO_2 tholeiites than it is in some of the lower SiO_2 tholeiites.

These objections can be answered severally in the following manner:

1. The evidence of the Bingfield dyke, based upon estimated compositions, is contradicted by that of the Eskdalemuir dyke, based on measured compositions. The accuracy of estimated chemical compositions of rocks depends upon the accuracy of two measurements, those of mineral composition and mineral frequency. In the Bingfield dyke it could be objected that neither of these measurements can be made with great precision; the felspars are zoned and somewhat variable and the relative quantities of the several pyroxenes present are unknown. In addition the micrometric analysis of such a fine-grained rock has inherent inaccuracies. Under these circumstances the estimated compositions of the phases cannot be considered to be known with certainty

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[1] F = modal felspar, P = modal pyroxene.

and it is felt that conclusions drawn from them should be discounted when specifically contradicted by those of the measured Eskdalemuir rock.

2. Modern theory about the pyroxenes holds that hypersthene is stable under intratelluric conditions of crystallization so that the presence of this mineral throughout the Tholeiite Series can be explained by some crystallization prior to high-level intrusion. The groundmass pyroxenes, which crystallized under different conditions, are all monoclinic.

3. The chemical and petrographic evidence are at variance on this point. I cannot comment on the petrography of the whole series, but the conclusions to be drawn from the chemical data plotted on the triangular diagram are quite clear; they are that later members of the series have less Fe+Mg, i.e. less coloured minerals, but a higher Na/Ca ratio. The apparent contradiction may be due to the fact that much of the felspar is occult in the glass. If it should be true that the An content of the crystalline felspar systematically increases with the number of felspar crystals we would have a phenomenon to tax any postulate of petrogenesis severely.

4. The low $F/(P+F)$ ratio is due to the presence of the glass which contains potentially a lot of felspar. If the rock was fully crystallized then the ratio would be higher.

5. The MgO/(MgO+FeO) ratio is variable, even haphazard, and there is no simple explanation of the variability. In terms of crystal fractionation it is possible to speculate on the role of magnetite. On any other genetic hypothesis the variability is equally or even more difficult to explain in simple terms. This criticism cannot, therefore, be levelled specifically at crystallization differentiation as the mechanism, but must apply equally to all the processes which have so far been postulated.

Conclusions.

The evidence from this study of the Eskdalemuir dyke goes a long way towards answering Holmes's objections to crystallization differentiation as the mechanism producing the range of compositions observed in the north of England tholeiites and by itself suggests that crystal fractionation has, in fact, been the important process.

There is nothing in the new data to disprove directly the hypotheses that the more basic tholeiites may be modified in the direction of a more granitic composition either by the incorporation of granitic material produced by the selective fusion of crustal rocks or by admixture with a coexisting magma of granitic composition. On the other hand, should these hypotheses be accepted, the fact that the phases of the Eskdalemuir tholeiite fit the main tholeiite curve ceases to be significant and becomes merely an awkward coincidence.

In conclusion I would like to thank Dr. I. D. Muir for providing the detailed data on the pyroxene phases.

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