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The tholeiite dikes of the north of England.[1]

(With Plates I and II.)

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Contents.

1. Introduction and Literature.

The suite of dikes that forms the subject of this paper is bounded on the south from Sleights Moor (south of Whitby) to Dalston (south of Carlisle) by the well-known series of dikes known collectively as the Cleveland–Cockfield–Armathwaite dike, and on the north by the nearly parallel and more continuous Acklington dike which

[1] The eight new chemical analyses (and calculations of norms) presented in this paper have been made by Dr. Harwood. The field work and petrological investigations have been carried out by Professor Holmes, who is also responsible for the writing of the paper.

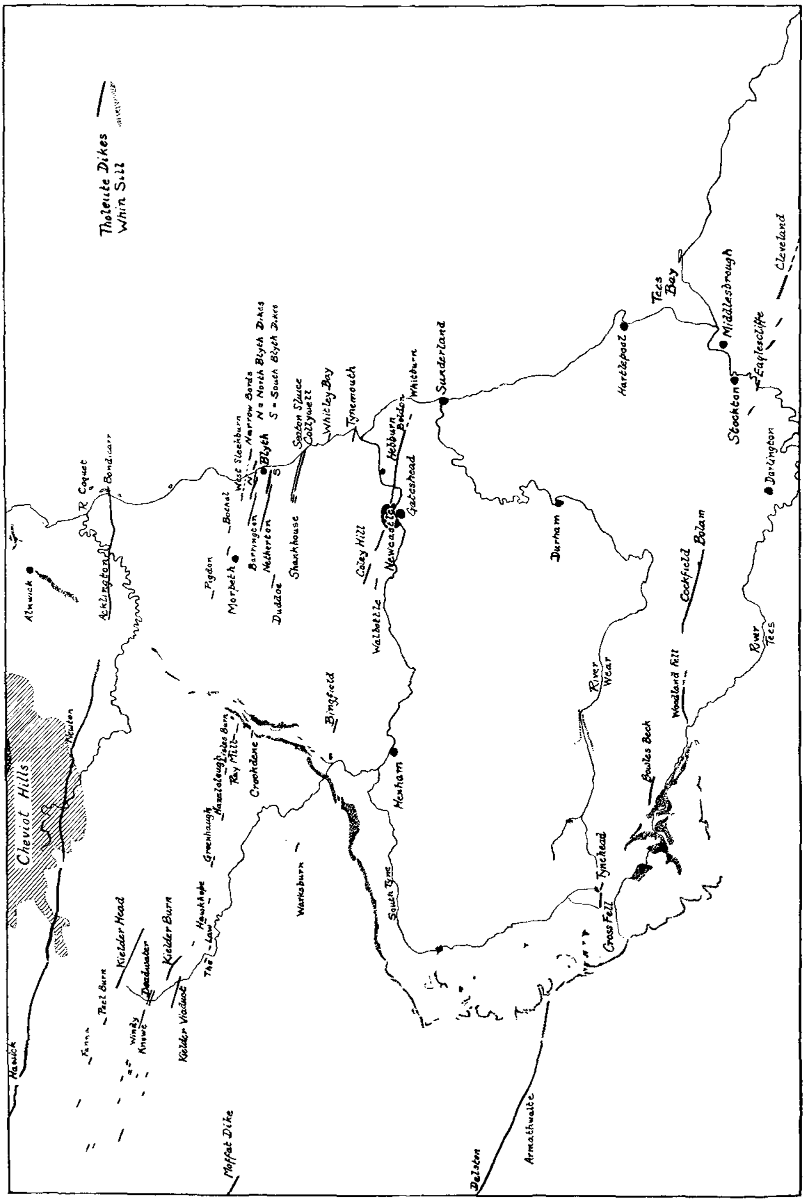

FIG. 1. Map of the tholeiite dikes of the north of England.

stretches from Bondicarr near Coquet Island across the southern margin of the Cheviots into Scotland.

Between these boundary dikes lie several sets of shorter dikes all trending north of west. The distribution of the suite is shown in fig. 1, which is complementary to a similar sketch-map of the Whin Sill group of dikes presented in a former pap^· (**26**). As mapped in

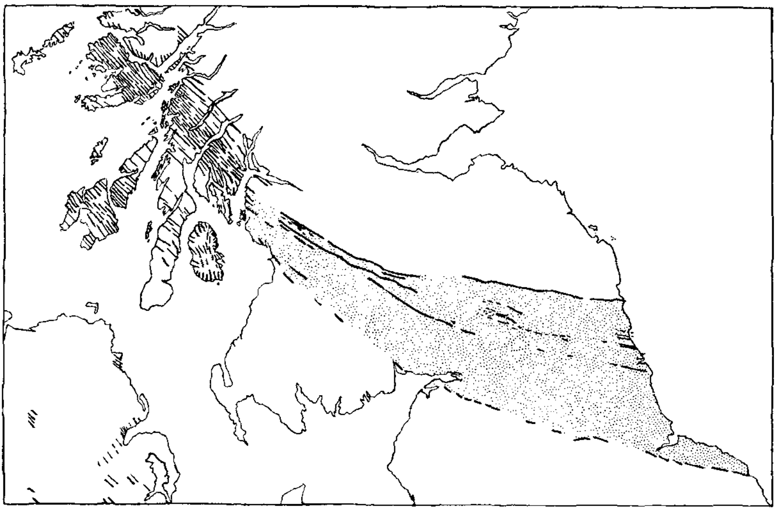

FIG. 2. Map showing the relation of the tholeiite dikes of the north of England to the Mull swarm of dikes. [The Arran swarm dies out south-east of the Girvan–Ballentrae coast, where the dikes are more thickly distributed than is indicated on the map.]

the limited region of fig. 1, the dikes appear to converge towards a focus in the neighbourhood of Arran. To correct this impression, and to show the relations of the suite to the Tertiary dikes of the south and west of Scotland, fig. 2 has been compiled. This diagram clearly brings out a regional change of direction in the trend of the suite as it traverses the Southern Uplands, a change which carries the whole suite into the Mull swarm by way of Great Cumbrae and the coast of Ayrshire. The dikes of Bute do not appear to belong wholly to the suite we are considering, since they swing round in the south of the island towards the Arran focus. It is possible, however, that the tholeiites of Bute and Arran may be satellites from the Mull swarm. Dr. G. W. Tyrrell has pointed out to us that crinanitic types are dominant in the Arran swarm. No example of such types has yet been found in the north of England. Thus, both distribution and petrological affinities lead to the interesting conclusion that the north of England tholeiite dikes represent an outlying extension of the Mull swarm.

As in the case of the Whin Sill and the late Carboniferous dikes, the pioneer investigation of the tholeiites was carried out by Teall (**2**). He described the Cleveland dike with great wealth of detail and recognized the close resemblance between many of its petrographic characters and those of the Acklington dike. Very little further work has since been done on the latter, but the Cleveland dike has received more attention, notably by Barrow in the district from which it takes its name (**6**); and by Miss Heslop and the late R. C. Burton, who jointly studied a tachylytic marginal facies of the dike occurring near the junction of the Lune with the Tees (**15**). In his 'Ancient volcanoes of Great Britain' Geikie drew attention to the probable continuation of the dike across south-west Scotland from the Solway to the Firth of Clyde (**9**, p. 144), but his statement that the suggested prolongation 'strikes out to sea near Prestwick' is too approximate to be a safe guide to its course. The dike in question leaves the Ayrshire coast at Barassie, north of Troon, and reappears at the other side of Irvina Bay, north of Saltcoats (see the one-inch geological map, Sheet 22, Scotland). It has also been stated that at the other end of its course the Cleveland dike is visible in Robin Hood's Bay, probably because it is shown as extending to the coast on the map of the volcanic districts of the British Isles by Geikie (**9**, end of vol. 2). Actually, however, the nearest exposure is nearly four miles from the Yorkshire coast.

Roughly midway between the boundary dikes a linear system of interrupted dikes can be traced from the Hebburn dike in the north-east corner of Durham, across the Tyne at Walker, through the Coley Hill dike near Newcastle-upon-Tyne, and the Bingfield dike east of the North Tyne to the Warksburn dike west of the North Tyne. In 1878 Lebour described the Coley Hill dike as a continuation of the Hebburn dike (**1**, p. 49), whereas Teall attempted to establish a connexion between the Coley Hill and Tynemouth dikes, basing this correlation on the similarity of their petrographic characters (**2**, p. 234). The field evidence is nevertheless in favour of Lebour's interpretation, though it should be clearly understood, as pointed out long ago by Winch, that the various sections of this dike system are not continuous either at the surface or in colliery workings. On the contrary, they constitute a nearly linear echelon. In addition to describing the Hebburn dike, Teall gave an account of the Bingfield dike under the mistaken impression that he was dealing with Lebour's 'Brunton dike'. As pointed out in our former paper (**26**, p. 521), the latter, now known as the St. Oswald's Chapel dike, is a characteristic member of the Whin Sill suite of quartz-dolerite dikes. The rock of the Bingfield dike, on the other hand, has been adopted by the petrologists of the Geological Survey as the type example of the Brunton type of tholeiite (**22**, pp. 285 and 372). The Hebburn–Bingfield series continues across Scotland as the Eskdalemuir, Moffat, and Dalraith dikes. The last of these comes within half-a-mile of the Barrmill dike, to which it is parallel.

North of the Tyne a number of tholeiite dikes are exposed along the Northumberland coast. The Tynemouth dike was closely investigated by Teall with special reference to the occurrence within it of porphyritic aggregates of anorthite (**2**, p. 233) and spherical amygdales occupied by calcite or mesostasis or both (**7**). At the north end of the sands of Whitley Bay a dike having similar characters was discovered in 1912 by Dr. J. A. Smythe (**17**). Still farther up the coast is the Collywell dike described by Teall under the name 'Hartley dike'. Smythe has since applied the latter name to a dike which he found in the cliffs (also in 1912) 30 yards south of the Collywell dike. There are several parallel dikes in this neighbourhood forming a belt which is represented in the Wansbeck valley, 24 miles to the west, by the Crookdene and Ray Mill dikes. The former of these has been described in great detail by Miss Heslop and Dr. Smythe (**12**), who regarded it as a continuation of the Collywell dike. Figs. 1 and 3 suggest a correlation with the Whitley Bay dike. The Ray Mill dike and its numerous linear associates carry on the belt to Kielder on the North Tyne (**8**). In fig. 3 (p. 42) the belt referred to is shown within dotted lines.

The dikes that strike inland north and south of Blyth on the Northumberland coast have not been previously described, but the olivine-bearing tholeiite that crosses the Wansbeck near Morpeth is well known from Teall's account (**2**, p. 239). It has also been investigated, together with the Collywell and Tynemouth dikes, by Miss Heslop and Dr. Smythe (**12**). The Morpeth–Blyth zone of dikes is unrepresented by exposures farther inland until the headwaters of the North Tyne are reached in the neighbourhood of Deadwater and Kielderhead. The dikes of the Kielder district have been described in detail by the late C. T. Clough (**8**). Farther on in Lanarkshire and Ayrshire the southern part of this composite zone is continued by the long dike which extends past Hart Fell, Muirkirk, and Barrmill, and by several shorter dikes that run parallel on the north-east. It is noteworthy that from sea to sea most of the northernmost members of the zone are found to be markedly olivine-bearing. North of the line of olivine-tholeiites lies the Acklington–Hawick dike and its long extension past Moneyacres towards Wemyss Bay and Cowal.

Five more or less definite lines or belts of dikes can therefore be recognized in the province (see fig. 3, p.42). In order from north to south these may be traced as follows:

(*a*) Acklington–Hawick–Moneyacres–Wemyss Bay–Cowal.

(*b*) Morpeth–Kielderhead–Middleton (Lugton)–Ayrshire coast (olivine-bearing dikes).

(*c*) Collywell-Blyth–Ray Mill – Deadwater – Hart Fell – Muirkirk – Barrmill.

(*d*) Hebburn–Bingfield–Eskdalemuir–Moffat–Dalraith.

(*e*) Cleveland–Armathwaite–Barassie–Stevenston–Great Cumbrae–Toward Point (Cowal).

The Scottish representatives of some of these dikes, particularly those in the Clyde area, have been described by Tyrrell (**19**), who was the first to point out that they provide a link between those of Mull and the north of England.

Direct field evidence of the age of the dikes is unfortunately scanty. The Cleveland dike is definitely post-Liassic, and this points at once to a Tertiary age. The Tynemouth dike was formerly to be seen cutting through the Permian Yellow Sands, according to Lebour (**3**, p. 87), but the critical section is no longer visible. A pre-Permian age has been thought possible in the case of the Hebburn dike because of the fact that it has not been found penetrating the Magnesian Limestone. Conversely, the presence of dolerite boulders on the beach at Whitburn has been held to suggest a post-Permian age. However, examination of thin sections of the boulders shows that most of them are of the Whin Sill type and that tholeiites are absent. Neither argument has therefore any application to the problem. From a petrological and tectonic point of view there can be little doubt that the dikes are of Tertiary age, forming as they do a single suite with obvious relations to the great igneous centre of Mull.

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2. Types of Tholeiites.

Steininger's term *Tholeiite* [1] was adopted by Rosenbusch in his 'Mikroskopische Physiographie' [2] for certain intrusive rocks occurring in the Saar-Nahe district which are composed of a framework of calcic plagioclase, pyroxenes, and titanomagnetite with patchy interstices occupied by a mesostasis of glass, globulitic glass, or devitrification products. Some of the rocks contain idiomorphic olivine or enstatite, and in a few examples porphyritic augite occurs. Tholeiite, unqualified, was regarded as typically free or almost free from olivine; those with conspicuous olivine were distinguished as olivine-tholeiite. The essential features are thus the basaltic composition of the crystalline framework and the development of intersertal texture.

In describing the Tertiary igneous rocks of Mull the Survey petrologists found it convenient to restrict the application of the term tholeiite to non-porphyritic varieties (**22**, pp. 280 and 284), and these they found to have a silica percentage below 55. Tyrrell, on the other hand, in his descriptions of the dikes of Arran [3] and the Clyde area (**19**) employed the term to include not only the porphyritic types recognized by Rosenbusch, but also rocks carrying phenocrysts of plagioclase approaching anorthite in composition. In the Arran Memoir (p. 240) he has clearly summarized the distinguishing characteristics of the dolerite-tholeiite-tachylyte groups of rocks. With increasing silica percentage the tholeiites pass into rocks in which a more continuous groundmass takes the place of patchy intersertal

[1] J. Steininger, Geognostische Beschreibung des Landes zwischen der untern Saar und dem Rheine (Trier, 1840). Nachträge (Trier, 1841), p. 26. The rock to which the name was given occurs on the Schaumberg at Tholey in the Saar district. A chemical analysis of this rock was given by C. Bergemann in Karsten's Arkiv Min., 1847, vol. 21, p. 12.

[2] H. Rosenbusch, 2nd edition, 1887, vol. 2, p. 504.

[3] Mem. Geol. Survey, Scotland. The geology of Arran, 1928, p. 240.

mesostasis. From the point of view of petrogenesis these rocks may be quite distinct from pyroxene-andesites, and in classifying the Mull representatives the Survey have wisely kept the issue clear by giving them special names such as *leidleite* and *inninmorite* (**18** and **22**).

In the north of England few departures from the usual tholeiitic range of textures and compositions have been encountered. We shall use the terms *tholeiite* and *olivine-tholeiite* in the wider senses adopted by Tyrrell, limiting their application to particular rocks by reference to a series of closely defined types of which a number have already been discriminated by Tyrrell and the Survey petrologists.

Types of Olivine-tholeiites.

The Salen type.—Rocks of this type are defined in the Mull Memoir (p. 370) as 'even grained finely crystalline dark-grey rocks, usually without any trace of porphyritic constituents. Microscopically, they are seen to be composed mainly of augite and labradorite felspar, with subordinate olivine, iron-ore, and a variable quantity of residual glassy matter of relatively late consolidation. The augite is, usually, at least as prevalent as the felspar.' Ophitic texture is common. Among basalts the Salen type is represented by the Staffa type (**22**, p. 146), which includes the well-known columnar basalt of the Giant's Causeway. In some examples of the Salen type there is a suggestion of the stellate grouping of felspar laths which is a notable feature of the Brunton type. When this becomes characteristically developed with a marked increase in the proportion of mesostasis the rock is more conveniently described as belonging to an *olivine-bearing Brunton type.*

Tyrrell's *Corrie type* differs from the Salen type only in the possession of numerous small phenocrysts of bytownite-anorthite (**19**, p. 352). It corresponds chemically with the Porphyritic Central Magma-type of Mull. The *Largs type* of Tyrrell is further characterized by a greater abundance of olivine, which here occurs as large phenocrysts as well as in the groundmass. Whereas in the Salen and Corrie types the mesostasis is usually about 10 per cent., in the Largs type it is greatly reduced.

Types of Tholeiite without Essential Olivine.

The Brunton type.—In rocks of this type the mesostasis amounts to about 30 per cent., and intersertal texture is very conspicuously developed. Elongated laths of plagioclase embedded in, and radiating out from, discrete clots of granular pyroxene form stellate clusters. The latter are commonly separated from one another by a dark brown mesostasis of glass with globulitic and acicular inclusions, but they may also interpenetrate or touch tangentially. The three chief constituents are commonly present in about equal proportions. The black ores are rarely well crystallized and are for the most part restricted to the mesostasis. See pl. I, figs. 2–6, which illustrate the highly characteristic appearance of the Brunton type. The classic example is the rock of the Bingfield dike, Northumberland, first described by Teall (**2**, p. 236), and adopted in the Mull Memoir as the standard of the type (**22**, p. 372). As stated above, olivine may be present as a minor but essential constituent in certain rocks which otherwise have the distinguishing features of the Brunton type.

The Talaidh type (pronounced Tala) is described in the Mull Memoir (p. 284) as approaching leidleite ' in the frequent tendency to elongation of the augite '. Sheaves and fan-shaped cervicorn groups of slender augites fringed with grains of the black ores are present, as well as ophitic plates and columnar crystals. Acicular crystallization is common in the devitrified mesostasis.

The Acklington type, not previously described under this specific name, differs from the Brunton and Talaidh types in the absence of radiating sheaves of augite and the rarity of stellate clustering among the felspars. Haphazard strings and groups of granular or columnar augite are common ; the felspars are in broader prisms and the black ores are generally sharply crystallized and evenly distributed. The mesostasis is abundant and may be a clear colourless to sepia glass or more generally a turbid product of devitrification ; in both types globulites and skeletal reticulations of ores are abundant.

Some Northumbrian examples of the above three types carry corroded or fretted phenocrysts and aggregates of anorthite or bytownite-anorthite sharply zoned with a rim of less calcic plagioclase. For convenience these felspars will be referred to as anorthite, as internally they never fall appreciably below An_{90}. It does not seem expedient to continue to erect new types to distinguish the anorthite-bearing varieties from the normal types. The rock of the Tynemouth dike is sufficiently described as an anorthite-bearing Brunton type ; that of Crookdene as an anorthite-bearing Talaidh type ; and that of Coley Hill as an anorthite-bearing Acklington type.

The Cleveland type differs from the Acklington type mainly in the possession of numerous and evenly distributed small phenocrysts of

TABULAR CLASSIFICATION OF THOLEIITES AND RELATED TYPES.

[The names of types that are porphyritic (apart from the presence of anorthite) are printed in capitals.]

	Pyroxenes not conspicuously elongated; equidimensional plates and granular aggregates common.		Range of SiO_2 %.	Pyroxenes columnar to slender; sheaf-like groupings characteristic.	
	Anorthite absent or inconspicuous.	Anorthite-bearing.		Anorthite-bearing.	Anorthite absent or inconspicuous.
With essential olivine.	LARGS TYPE, Ayrshire (Porphyritic olivine).		42 to 46		
	Salen type, Mull ... Olivine-bearing Brunton type.	Corrie type, Arran	47 to 50		
Without essential olivine.	Brunton type, Bingfield, Northumberland.	Anorthite-bearing Brunton type, e.g. Tynemouth, Northumberland.	50 51	Anorthite-bearing Talaidh type, e.g. Crookdene, Northumberland.	
	Acklington type, Northumberland.	Anorthite-bearing Acklington type, e.g. Coley Hill, Northumberland.	52 53 54 55 56 57		Talaidh type, Mull.
	CLEVELAND TYPE, north of England (Porphyritic plagioclase and pyroxene).	CUMBRAE Great (Pyroxenes, granular,	58 59 60 61	TYPE, Cumbrae columnar, and slender).	Leidleite, Mull.
			62 63 64	INNINMORITE, Mull.	

plagioclase and pyroxenes, in which respect it approaches inninmorite. The rock of the Cleveland dike is so well known and so remarkably uniform over long stretches of its course that it would be inappropriate to describe it merely as a porphyritic example of the Acklington type. Not only does the Cleveland type represent a link between the Acklington type and inninmorite, but it also has many features in common with Tyrrell's *Cumbrae type* (**19**, p. 306). The latter differs mainly in the possession of conspicuous aggregates and phenocrysts of anorthite. In the Arran Memoir (p. 253) Tyrrell states that the groundmass is of Brunton type, especially rich in glass or its devitrified equivalent, but since in many specimens the groundmass shows little trace of stellate clustering,[1] it could now be more accurately described in terms of the new Acklington type. In the nomenclature here developed these varieties of the Cumbrae type represent a Cleveland type in which all the phenocrysts of plagioclase approximate to anorthite. There are other varieties, however, that resemble anorthite-bearing leidleite.

The Dalmahoy type of tholeiite[2] has a texture not unlike the Acklington type, but is distinguished by a high proportion of plagioclase relative to pyroxene, abundance of chlorophaeite, and a chemical likeness to the mugearites. No tholeiites having this assemblage of characters have been found in the north of England, and so far those recognized in Scotland are of Carboniferous age.

3. The Salen Type and other Olivine-Tholeiites.

The course of the Kielderhead dike has been described by Clough (**8**, p. 18), who states that hand-specimens 'show prominent porphyritic crystals of felspar'. Such specimens would correspond to the Corrie type, but, as those which we have collected are almost devoid of phenocrysts, they must be referred to the Salen type (pl. I, fig. 1).

Olivine crystals are conspicuous; as noted by Teall (**8**, p. 19) they are much broken and fissured, and serpentinization is general around borders and along cracks and has in places become complete. Felspar

[1] Tyrrell, for example, has indicated this departure from the normal appearance by the expression 'cf. Brunton'. The analysis of a 'cf. Brunton' rock (Arran Memoir, p. 254, no. 21) shows 54·52 per cent. of silica, corresponding with the Acklington type.

[2] R. Campbell and J. W. Lunn, The tholeiites and dolerites of the Dalmahoy syncline. Trans. Roy. Soc. Edinburgh, 1927, vol. 55, pt. ii, no. 21, pp. 489–505.

laths appear to be included within the larger olivines, but careful examination shows that this is due to later penetration between the disrupted and altered cores. No aggregates of olivine and felspar such as occur in the Largs type have been detected. Small inclusions of olivine rimmed with serpentine are to be found in some of the larger plates of augite. No certain trace of rhombic pyroxene has been found. The augite is colourless to pale yellowish-brown, the tint darkening outwards, and here and there becoming faintly purple-brown and pleochroic, especially in contact with titanomagnetite. Its relations with plagioclase are characteristically ophitic. A few small aggregates of externally zoned bytownite are present (about An_{75} with borders ranging from An_{50} to An_{30}). The common felspar laths are zoned throughout, the change accelerating towards the boundaries, which are about An_{30}, from an internal composition near An_{55}. Many of the laths are in pairs crossing at acute angles, but stellate clustering is not otherwise suggested. The ores are in sharply crystallized individuals or skeletal rows scattered between the other minerals of the rock with a special tendency to cling to the plates and grains of augite. The mesostasis is a nearly colourless to turbid brown glass charged with black globulites and skeletal growths and colourless acicular ill-defined microlites. Its distribution is patchy, some parts of a section showing very little, while others contain it conspicuously. Green-stained chalcedony also occurs irregularly as interstitial material, but this constituent is more abundant in small spherical amygdales sometimes enclosing a core of calcite.

The Kielderhead dike is continued across the Border in the well-exposed Peel Burn dike three-quarters of a mile north of the summit of Peel Fell, and in the Fanna dike, exposed in the Singdean Burn just over three miles farther on to the WNW. The Peel Burn dike (478) is of the Brunton type, but carries a little serpentinized olivine with few fresh cores (pl. I, fig. 2). The Fanna dike (464) is again olivine-bearing and has a remarkable resemblance to the Morpeth dike. It represents a passage between the Salen and olivine-Brunton types. The mineral compositions are listed below.

South of the Kielderhead line two parallel dikes cross the Deadwater Burn near Deadwater Farm (**8**, p. 19). Of these the rock of the northern dike is a Talaidh type, but that of the southern (437) is almost identical with the Kielderhead rock described above. It is less rich in olivine and in places has, exceptionally, very little mesostasis. No exposure is now visible in the Burn, but boulders of the rock are common (together with others of the northern dike and erratics of Lower Carboniferous basalts), and the dike itself is found in situ near the head of the small sike immediately to the east, some 300 yards from the farmhouse. The specimens collected in situ contain tiny amygdales of chalcedony. Clough mentions 'spherical pinhead vesicles filled with calcite' (**8**, p. 19), and boulders answering this description have been found in the Burn.

The Morpeth dike is also of the Salen type, but, as the published descriptions indicate (**2**, p. 239; and **12**, p. 14), there is a close resemblance to the rock of the Tynemouth dike, apart from the rarity of anorthite aggregates and the presence of olivine. The Morpeth dike thus represents an approach to the Brunton type, of which the Tynemouth dike is an anorthite-bearing example. The chief differences from the Kielderhead rock are increased proportions of mesostasis and amygdales, a slight decrease in olivine, and a noticeable tendency to diverse groupings among the felspar laths. Some of the augites have crystallized in roughly spherical groups of half a dozen radial sectors, of which opposite members extinguish simultaneously. The neighbouring dike of Bothal Woods also exhibits characters which are intermediate between those of the Salen and Brunton types. The West Sleekburn dike and its continuation beyond the coast (the Narrow Bords dike, exposed in the Low Main level of the Mill Pit, near Blyth) is an excellent representative of the olivine-bearing Brunton type.

Mineral composition.—The following table sets forth the results of a series of measurements made with a Shand micrometer. The figures in this and succeeding tables of the same kind are percentages by volume, except in the last column, where the ratio of felspar to the sum of pyroxenes (including olivine where present) and felspar is stated as a percentage.

Mineral proportions of Olivine-tholeiites.

Dikes.	Mesostasis.	Olivine[1] (O).	Pyroxenes (P).	Felspar (F).	F/(O+P+F).
307. Kielderhead ...	10·1	12·7	37·2	34·3	41 %
306. Kielderhead ...	12·3	10·2	34·7	33·0	42
478. Peel Burn ...	23·8	4·1	31·8	28·2	44
464. Fanna	17·6	7·4	36·1	30·1	41
341. Morpeth... ...	16·3	8·7	35·5	29·8	40
484. Narrow Bords	19·8	7·8	34·2	31·6	43

[1] Includes serpentine.

The results indicate a rather striking inverse relationship between olivine and mesostasis.[1] This may be regarded as continuing in the Brunton type where, with little or no olivine, the mesostasis rises to 30 per cent. or more. The possible implications of this interesting observation will be referred to in discussing the Brunton type (p. 24).

Chemical composition.—A fresh and typical specimen of the Kielderhead dike was sampled for analysis. The specimen (306) was from an exposure in a little sike that enters the Scalp Burn from the east about a mile up-stream from the junction of the Scalp Burn and the White Kielder. The results are tabulated below together with the norm and the 'calculated mineral composition', arrived at by the

Chemical composition of the Kielderhead Dike (306).

	Percentages.	Molecular proportions.
SiO_2	50·41	0·8391
Al_2O_3	15·14	0·1485
Fe_2O_3	2·71	0·0169
FeO	7·95	0·1104
MgO	6·57	0·1643
CaO	11·30	0·2018
Na_2O	2·29	0·0369
K_2O	0·82	0·0087
H_2O (+110° C.)	1·01	0·0561
H_2O (−110° C.)	0·72	0·0400
CO_2	0·07	0·0016
TiO_2	1·30	0·0163
ZrO_2	none	—
P_2O_5	0·15	0·0011
Cl	trace	—
S	0·06	0·0019
Cr_2O_3	trace	—
V_2O_3	0·05	0·0003
NiO	none	—
MnO	0·17	0·0024
SrO	0·05	0·0005
BaO	0·03	0·0002
Li_2O	trace	—
	100·80	
Less O for S	0·02	
	100·78	

Specific gravity = 2·98

Norm.

Quartz			1·43
Orthoclase			4·84
Albite			19·35
Anorthite			28·70
Diopside	$CaSiO_3$	10·89	21·27
	$MgSiO_3$	6·34	
	$FeSiO_3$	4·04	
Hypersthene	$MgSiO_3$	10·01	16·37
	$FeSiO_3$	6·36	
Magnetite			3·94
Ilmenite			2·46
Pyrite			0·12
Apatite			0·37
Calcite			0·16
			99·01
Water			1·73
			100·74

Calculated mineral composition.

Quartz	2·53
Alkali-felspars, $Or_{40}Ab_{60}$	0·10
Plagioclase, $An_{49}Ab_{41}Or_{10}$	47·67
Pyroxenes	41·65
Ores (as above)	6·52
Apatite	0·37
Calcite	0·16
	99·00

[1] The Deadwater south dike appears to be an exception to this rule.

Analyses of Olivine-tholeiites.

Salen and Corrie types.

	1. Kielderhead.	A. Ayrshire.	B. Bute.	C. Mull.	D. Arran.
SiO_2 ...	50·41	48·63	48·92	47·35	48·60
Al_2O_3 ...	15·14	13·23	14·25	13·90	18·27
Fe_2O_3 ...	2·71	3·16	1·95	5·87	3·19
FeO ...	7·95	7·62	11·54	8·96	7·17
MgO ...	6·57	7·97	5·56	5·97	6·29
CaO ...	11·30	12·30	10·23	10·65	10·15
Na_2O ...	2·29	1·20	2·67	2·73	1·63
K_2O ...	0·82	1·13	1·01	0·54	0·45
H_2O+ ...	1·01	0·65	0·45	1·16	1·65
H_2O- ...	0·72	0·75	0·82	1·04	1·60
CO_2 ...	0·07	0·21	trace	0·32	none
TiO_2 ...	1·30	2·32	1·88	1·75	0·70
P_2O_5 ...	0·15	0·01	0·17	0·24	0·09
S	0·06	—	—	0·23	trace
FeS_2 ...	—	0·37	0·30	—	—
Cr_2O_3 ...	trace	0·04	—	—	—
V_2O_3 ...	0·05	—	—	—	—
MnO ...	0·17	0·21	0·27	0·23	0·24
BaO ...	0·03	0·00	—	—	—
	100·80	99·80	100·20	100·94	100·03

1. Olivine-tholeiite (Salen type), Kielderhead, Northumberland. Analyst, H. F. Harwood (supra, p. 15). Total includes SrO 0·05.

A. Tholeiitic olivine-dolerite, NW. dike, 400 yards west of Middleton, near Lugton, Ayrshire. Analyst, B. E. Dixon (**23**, p. 128, no. 802).

B. Olivine-tholeiite (Salen type), 12-foot dike on foreshore of Kilchattan Bay, Bute. Analyst, W. H. Herdsman. Unpublished analysis by courtesy of Mr. H. J. W. Brown. See Geol. Mag., 1929, vol. 66, p. 94.

C. Olivine-tholeiite (Salen type), dike on the shore 2½ miles NNW. of Salen, Mull. Analyst, F. R. Ennos, Mull Memoir, 1924, p. 17, no. I.

D. Olivine-tholeiite (Corrie type), dike on the shore 1¾ miles south of Corrie Hotel, Arran. Analyst, W. H. Herdsman, Arran Memoir, 1928, p. 254, no. 20.

empirical method outlined in our former paper (**26**, p. 512).[1] There is no very marked difference in composition between this example of the Salen type and the Whin Sill type of quartz-dolerite (see p. 23), but magnesia is higher, as might be expected, and lime and alumina are higher in accordance with the greater abundance of anorthite in the felspar; balancing these differences the oxides of iron and titanium

[1] For data of the distribution of orthoclase in plagioclase see J. H. L. Vogt, The physical chemistry of the magmatic differentiation of igneous rocks. II. On the felspar diagram. Oslo, 1926, p. 48.

are lower. The small amount of normative quartz is accounted for by the amygdales present, but as this silica is clearly of late magmatic origin (since the minerals crystallizing after the early serpentinization of the olivine have remained perfectly fresh), the original magma must itself be regarded as having been slightly oversaturated in silica.

The analysis is repeated on p. 16 for comparison with that of other olivine-tholeiites from Ayrshire, Bute, Mull, and Arran. Each of these, like the Kielderhead tholeiite, is shown by the possession of normative quartz to represent a mildly oversaturated magma. It is noteworthy that the dike near Lugton, analysis A, is in the same line of dikes as that to which the Morpeth and Kielderhead series belong.

4. The Brunton Type.

The Bingfield dike.—The type-example of the Brunton type of tholeiite is the rock of the Bingfield dike which is exposed on the south bank of the Redhouse Burn close to the fifth milestone from Corbridge on the Watling Street. The hamlet of Bingfield lies half a mile to the north-east.

The circumstances which led to the adoption of the name *Brunton* have been described in a former paper (**26**, p. 520) and no further reference is necessary here, except a reminder that Teall described the rock under the name ‘ Brunton Dyke ’ (**2**, p. 236). Under the microscope the rock has an unmistakably characteristic appearance. It has been figured by Teall, Harker, and ourselves (**26**, pl. X, fig. 4). Other rocks of identical texture are also figured in plate I. Less typical are the figures by Tyrrell (**19**, p. 351) and the Geological Survey (Mull Memoir, fig. 62, p. 371).

As noted by Teall, glomeroporphyritic aggregates of plagioclase are not entirely absent, but they are small and easily overlooked. Measurements of extinction-angles and refractive indices on cleavage flakes of known orientation show that the composition lies near An_{88}, the extreme estimates being An_{84} and An_{92} in different specimens. External zoning is present exactly as in the larger aggregates of the Tynemouth dike. The long diversely arranged felspar laths of the body of the rock are mainly about An_{60}. Zoning is not conspicuous and does not appear to range beyond An_{40} on the borders of the broader crystals. The pyroxene plates and interdigitated granules are nearly colourless to pale grey-green and show very little of the patchiness of the Kielderhead pyroxene. A little enstatite or hypersthene is prob-

Chemical composition of the Bingfield Dike (370), Brunton type.

	Percentages.	Molecular proportions.
SiO_2	50·07	0·8337
Al_2O_3	14·53	0·1425
Fe_2O_3	1·76	0·0110
FeO	8·26	0·1150
MgO	6·77	0·1680
CaO	11·50	0·2051
Na_2O	1·93	0·0311
K_2O	0·85	0·0090
H_2O (+110° C.)	0·82	0·0456
H_2O (−110° C.)	0·52	0·0289
CO_2	1·61	0·0366
TiO_2	1·14	0·0142
ZrO_2	none	—
P_2O_5	0·16	0·0011
Cl	trace	—
S	0·08	0·0025
Cr_2O_3	0·02	0·0001
V_2O_3	0·06	0·0004
NiO	none	—
MnO	0·19	0·0027
SrO	0·02	0·0002
BaO	0·04	0·0003
Li_2O	trace	—
	100·33	
Less O for S ...	0·03	
	100·30	

Specific gravity = 2·91

Norm.

Quartz			3·95
Orthoclase			5·01
Albite			16·30
Anorthite			28·59
Diopside	$CaSiO_3$	7·26	14·22
	$MgSiO_3$	4·06	
	$FeSiO_3$	2·90	
Hypersthene	$MgSiO_3$	12·80	21·93
	$FeSiO_3$	9·13	
Magnetite			2·55
Ilmenite			2·16
Pyrite			0·14
Apatite			0·37
Calcite			3·66
Chromite			0·02
			98·90
Water			1·34
			100·24

Calculated mineral composition.

Quartz	5·03
Alkali-felspar, $Ab_{60}Or_{40}$ ...	1·30
Plagioclase, $An_{54}Ab_{36}Or_{10}$ ...	43·62
Pyroxenes	40·05
Ores	4·87
Apatite	0·37
Calcite	3·66
	98·90

ably present but has not been determined with certainty. The norm shows that the common pyroxene must belong to the hypersthene-augites, and this is confirmed by the optical properties. The restriction of the ores (including pyrite) to the mesostasis is a constant feature. The residual material is dark brown and opaque, and highly charged with black skeletal ores and tapering rods. It makes up about a third of the whole rock and forms a background against which the clustering segregations of plagioclase and pyroxene stand out in strong relief. Here and there the mesostasis clears to irregular patches of calcite, including or bordered with pyrite; calcite is also present in small spherical amygdales. Near the contact (366) the dike is poorly crystallized (small laths of felspar alone being determinable), and highly charged with calcite amygdales and veins. There are occasional thin linings of chalcedony, and irregular streaks and patches of pyrite are common in and around the amygdales and in the dark brown groundmass. The mineral proportions are given in the table on page 20.

Chemical composition.—As the type example of the Brunton tholeiite has hitherto remained unanalysed, a fresh specimen of the Bingfield dike reasonably free from amygdales was selected for analysis. The composition turns out, rather surprisingly, to be practically identical with that of the Kielderhead dike, except that the carbon dioxide is higher. Comparison of the 'calculated mineral composition' of the rock as a whole with the mode and with the Kielderhead rock shows that the mesostasis must contain the ingredients of plagioclase with almost as much anorthite as the crystallized felspar, together with the equivalent of part of the pyroxene and most of the ores. Trial calculations show that the composition of the mesostasis is as basic as the rock as a whole, and that it does not correspond to any known Tertiary type of tholeiite (p. 47). It does, however, show a definite approach towards a trachybasaltic type of magma.

The Warksburn dike (363) is exposed three miles due west of Wark village in the banks of the stream after which it is named, the best exposure being on the north bank below Horneystead Farm. It is almost exactly in line with the Bingfield dike, although the two are ten miles apart. The rock differs very slightly from that of Bingfield in having pyroxene in higher proportion; mesostasis relatively diminished; and ores, though still restricted to the interstitial matter, more distinctly individualized (pl. I, fig. 6). The anorthite aggregates are small and sparsely distributed, and correspond to An_{96}.

The Ray Mill dikes.—Eight miles north of the Bingfield-Warksburn line there are exposures of a number of short dikes which form an echelon series. Those that have been visited and examined are from west to east: (*a*) *Lisles Burn* (Acklington type); (*b*) *Cross Hollows* (Acklington type), exposed on the south bank of the Ray Burn west of Ray Mill; (*c*) *Ray Mill* (Brunton type), exposed in the little dene between Ray Mill and the road to Cornhills; (*d*) *Horncastle Wood* (Brunton type), lying well within the wood on the east side of the road; and (*e*) *Castle Dene* (Talaidh type), at the eastern end of Horncastle Wood. *The Crookdene dike* (Talaidh type) lies $1\frac{1}{4}$ miles south of Cross Hollows. Of these the Horncastle Wood dike differs from the Bingfield rock only in the better crystallization of its ores and in the possession of small circular amygdales occupied by chlorophaeite or interstitial matter, or occasionally by both, calcite being rare. In the Ray Mill dike the Brunton texture is developed even more strikingly than in the type-rock. The ores are here confined to minute rods thickly sprinkled through the mesostasis which in consequence is nearly black (pl. I, fig. 5). The amygdales, which are numerous on the sides of the dike, are varied and interesting. Some contain opal surrounding chalcedony; others have calcite in the interior; others contain calcite and chlorophaeite; and in some chlorophaeite occurs alone. As in Horncastle Wood, so here interstitial matter is a common infilling, sometimes alone, sometimes partly enclosing semilunar or spherical spaces occupied by chlorophaeite and calcite. The order of deposition appears to be mesostasis, opal, chalcedony, chlorophaeite, and calcite, with some overlapping of the last three.

Mineral proportions of Tholeiites of the Brunton type.

Dikes.	Mesostasis.	Pyroxenes (P).	Felspars (F).	F/(P+F).
369. Bingfield [1] ...	34·7	32·3	29·6	48 %
363. Warksburn ...	36·1	36·2	24·8	41
364. Warksburn ...	n.d.	30·1	27·4	48
330. Horncastle Wood	32·6	35·3	28·2	44
340. Ray Mill ...	37·2	29·7	26·7	47
358. Tynemouth [2] ...	28·8	34·3	32·2	48
482. Barrington ...	29·4	31·3	33·6	52

[1] For five sets of measurements see our Whin Sill paper (**26**, p. 521).

[2] These figures refer only to the groundmass, which makes up 92 % of the rock, the remaining 8 % being represented by megascopic anorthite.

The Tynemouth dike.—As a result of its investigation by Teall, this dike has become particularly well known (**2**, p. 233), and a later paper of two pages in which the cooling history is discussed has become one of the classics of petrological literature (**7**). The rock is noteworthy in containing large aggregates of anorthite, the individuals in contact with the groundmass showing definite faces within a sharply-zoned peripheral rim which is commonly toothed and serrated (pl. I, fig. 4). Streaks of inclusions of mesostasis are sometimes present just inside and roughly parallel to the zoned rim. Inside the periphery of each group the contacts of the anorthite individuals among themselves lack these features; as noted by Teall ‘the internal relations . . . are those of plutonic rocks’. The composition as given by Stead's analysis corresponds to An_{85} (**2**, p. 234), but refractive index determinations, confirming Teall's deduction from

Chemical composition of the Tynemouth Dike (358).

	Percentages.	Molecular proportions.
SiO_2	50·81	0·8459
Al_2O_3... ...	15·70	0·1536
Fe_2O_3... ...	2·80	0·0175
FeO	6·02	0·0838
MgO	6·41	0·1590
CaO	12·17	0·2171
Na_2O	1·96	0·0316
K_2O	0·87	0·0092
H_2O (+110° C.)	1·01	0·0561
H_2O (−110° C.)	1·21	0·0672
CO_2	0·55	0·0125
TiO_2	0·81	0·0101
ZrO_2	none	—
P_2O_5	0·10	0·0007
Cl	trace	—
S	0·12	0·0037
Cr_2O_3... ...	trace	—
V_2O_3	0·04	0·0003
MnO	0·17	0·0024
SrO	none	—
BaO	0·02	0·0001
Li_2O	trace	—
	100·77	
Less O for S ...	0·04	
	100·73	

Specific gravity = 2·84

Norm.

Quartz			4·17
Orthoclase			5·12
Albite			16·58
Anorthite			31·57
Diopside	$CaSiO_3$	10·32	19·98
	$MgSiO_3$	6·57	
	$FeSiO_3$	3·09	
Hypersthene	$MgSiO_3$	9·38	13·78
	$FeSiO_3$	4·40	
Magnetite			4·05
Ilmenite...			1·53
Pyrite			0·22
Apatite			0·23
Calcite			1·25
			98·48
Water			2·22
			100·70

Calculated mineral composition.

Quartz	5·19
Alkali-felspar, $Ab_{60}Or_{40}$ ...	0·78
Plagioclase,[1] $An_{56}Ab_{34}Or_{10}$ ...	47·76
Pyroxenes	37·42
Ores	5·80
Apatite	0·23
Calcite	1·25
	98·43

[1] Includes about 8 % of An_{85}, the remaining 40 % being approximately An_{50}.

extinction-angles, show that, excluding the zoned rim, the felspar is not below An_{90}. The distribution of the aggregates is not uniform, some specimens being nearly free from megascopic anorthite, while in others the proportion may rise to fully 10 per cent. Parts of the rock that are rich in amygdales rarely contain visible felspars. The general mass of the rock is identical with the Brunton type of Bingfield and calls for no further description. The mineral composition is given above (p. 20).

The Whitley Bay dike is also of the Brunton type. Smythe states that the felspars 'are frequently arranged in star-like clusters' and notes the resemblance of the rock to that of the Tynemouth dike (**17**, p. 331). *The Barrington dike* (482) west of Blyth is of Brunton type in part, but some specimens show a passage to the Acklington type.

Chemical composition.—A specimen of the Tynemouth dike was analysed, because it was thought unlikely that Stead's old analysis could be fairly representative of the rock. A specimen collected by Teall from Tynemouth station was selected (358). It contained about 8% of megascopic anorthite and only a few pin-head amygdales. The results gave 50·81 % of SiO_2 and 6·41 % of MgO in place of 58·30 and 2·68, the respective figures recorded by Stead. The analysis as a whole differs from that of the Bingfield rock only in showing slightly higher CaO and Al_2O_3, as would be expected.

In the adjoining table the analyses of the Bingfield and Tynemouth rocks are repeated for comparison with those of the Mull examples of the Brunton type, and an average of six analyses of the Whin Sill type of quartz-dolerite is added. It will be observed that the last does not differ in any significant way from the average Brunton composition. The Bingfield rock has lower iron-oxides and soda, but the Mull examples are higher in these constituents. The Bingfield magnesia is higher, but in the Mull rocks it is lower. The average Brunton type, with one-third of its substance remaining as a mesostasis of glass and poorly crystallized material, is apparently chemically identical with the Whin Sill type which is holocrystalline or nearly so.

Furthermore, on comparing the Salen types of the Firth of Clyde and Mull areas (p. 16) with the Brunton types of Mull, the differences in chemical composition are seen to be of the right order to accord with the presence of olivine in the former. Between the Kielderhead and Bingfield rocks, however, there are no obviously adequate differences. We have therefore to try and explain: (*a*) the presence of relatively abundant glass in the Brunton type, and (*b*) the appearance of olivine in the Kielderhead dike and its absence from, or paucity in, the Bingfield dike.

The mesostasis cannot be a result of sudden chilling following a final act of injection after the main crystallization had already been achieved. The texture is too delicate to bear such an interpretation, and, moreover, the grain becomes finer towards the edges and fades away into a vitreous border containing of the earlier minerals only minute felspar laths. The only other possibility appears to be akin to that suggested by Anderson and Radley in their investigation of the pitchstones of Mull (**18**), namely, that the primary content of water and other volatiles may steadily increase in the residual magma until it reaches such a proportion that crystallization can no longer continue. That this may indeed afford the basis of an explanation is supported

Analyses of the Whin Sill and of Tholeiites of the Brunton type.

	Whin Sill type.	2. Bingfield.	3. Tynemouth.	E. Mull.	F. Mull.
SiO_2 ...	50·52	50·07	50·81	51·53	51·63
Al_2O_3 ...	13·76	14·53	15·70	11·05	11·77
Fe_2O_3 ...	3·87	1·76	2·80	2·73	3·23
FeO ...	8·50	8·26	6·02	10·98	10·47
MgO ...	5·42	6·77	6·41	5·21	5·02
CaO ...	9·09	11·50	12·17	9·68	9·34
Na_2O ...	2·42	1·93	1·96	3·48	2·90
K_2O ...	0·96	0·85	0·87	0·86	0·91
H_2O+ ...	1·51	0·82	1·01	1·26	1·40
H_2O- ...	0·76	0·52	1·21	0·71	0·68
CO_2 ...	0·58	1·61	0·55	0·08	0·11
TiO_2 ...	2·39	1·14	0·81	1·57	2·00
P_2O_5 ...	0·26	0·16	0·10	0·22	0·29
{S ...	0·06	0·08	0·12	—	—
{FeS_2 ...	—	—	—	0·26	0·08
Cr_2O_3 ...	trace	0·02	trace	—	—
V_2O_3 ...	0·05	0·06	0·04	—	—
(Co,Ni)O	none	none	none	nt. fd.	0·04
MnO ...	0·16	0·19	0·17	0·45	0·35
SrO ...	trace	0·02	none	—	—
BaO ...	0·03	0·04	0·02	nt. fd.	0·03
	100·34	100·30	100·77	100·07	100·27

Whin Sill type. Average of six analyses of the Whin Sill and related quartz-dolerite dikes. Analyst, H. F. Harwood, Min. Mag., 1928, vol. 21, p. 530.

2. Tholeiite (Brunton type), Bingfield dike, Redhouse Burn, Northumberland (type locality). Analyst, H. F. Harwood (supra, p. 18).

3. Anorthite-bearing tholeiite (Brunton type), Tynemouth dike, Tynemouth Station, Northumberland. Analyst, H. F. Harwood (supra, p. 21).

E. Tholeiite (Brunton type), dike on shore 5½ miles SE. of Tobermory, Mull. Analyst, E. G. Radley (**22**, p. 17).

F. Tholeiite (Brunton type), dike on shore ¼ mile N. of Kintallen, Mull. Analyst, E. G. Radley (**22**, p. 17).

by the observation that there appears to be a rough relation between the proportions of calcite amygdales and mesostasis. Clough makes an indirect reference to this in the case of the Kielderhead dike (**8**, p. 18), and Teall notes that in the Morpeth dike the amygdales 'are not nearly so abundant or so large as in the Tynemouth rock' (**2**, p. 239). Field comparisons of dikes of the Salen and Brunton types, though not amenable to quantitative expression, suggest that there is some connexion between the original content of volatile constituents in the magma, notably carbon dioxide, and the proportion of residual magma that failed to crystallize effectively. Carbon dioxide was demonstrably far more abundant in the magma from which the Bingfield rock consolidated than in those of the Kielderhead dike and the Whin Sill, and this gas, possibly aided by water, was probably the inhibiting agent. It should be noted that chemical analyses are not as a rule made with a view to testing hypotheses such as this, for specimens with conspicuous amygdales are usually avoided as far as possible. In this respect the interpretation of analyses must be guided by field observations.

The olivine problem may also be solved by experimental work designed to test similar considerations. As we have seen, the proportion of olivine varies inversely with that of mesostasis, and therefore, presumably, inversely with that of calcite amygdales, and, finally, inversely with that of the volatile constituents in the magma. Is it possible that the latter inhibit the crystallization of olivine or bring about its early resolution? A partial association has been demonstrated, but in the absence of positive experiments the evidence as yet will hardly bear an assumption of causation.

5. The Talaidh Type.

The Coastal region.—Of the tholeiite dikes previously described by other authors, the 'Seaton and Hartley' dikes of Teall (**2**, p. 237) and the Collywell and Crookdene dikes of Miss Heslop and Smythe (**12**) belong to the Talaidh type. They are distinguished by the development of elongated pyroxenes often in radiating sheaves and feathery growths. It should be noted that in all Talaidh types clots of minutely granular augite may be seen wherever a section has cut across a sheaf-like bundle. The grain is generally finer than that of the Salen and Brunton types, and as a rule the patches of dark brown mesostasis are smaller and more numerous, and, as a result of much incipient crystallization, less sharply differentiated from the well-crystallized phases. The total amount of mesostasis falls between the average Salen and Brunton proportions.

Chemically, as shown by the two analyses by Smythe quoted on p. 28 the rocks of the Collywell and Crookdene dikes show a general resemblance to those of the Brunton type. Although neither of these dikes is variegated with anorthite crystals and aggregates as conspicuously as the Tynemouth dike, small patches of a similar felspar can generally be found in them without difficulty, and in the Crookdene dike Smythe discovered an aggregate six inches long. Analyses by Smythe of this material and of felspar aggregates separated from two other dikes are quoted below. The lower anorthite content of the latter relative to that of the much larger Crookdene aggregate is a necessary consequence of inclusion in the analysed material of a higher proportion of the zoned rims. Refractive index measurements and extinction-angles on basal plates suggest that internally all three felspars are about An_{94}–An_{96}.

In addition to the Seaton Sluice and Collywell dikes another of the *dikes of the coastal region in the neighbourhood of Blyth is also* of the Talaidh type. This is shown on the map, fig. 1, as the North Blyth dike. It is exposed in the Low Main level of the Isabella Pit, and, although somewhat altered, the rock (483) is clearly identical in texture with that of the Seaton Sluice dike.

Analyses of anorthite aggregates in Tholeiites of the Talaidh type, Northumberland (by J. A. Smythe).

	Crookdene (**12**, p. 7).	Hartley[1] (**17**, p. 336).	Collywell (**12**, p. 7).
SiO_2	45·88	45·77	46·61
Al_2O_3	34·31	34·20	35·13
Fe_2O_3	0·83	0·73	0·25
CaO	18·28	18·52	16·74
Na_2O	0·82	1·04	1·05
K_2O...	0·11	0·12	0·15
H_2O...	0·14	0·25	0·22
TiO_2	0·04	trace	0·13
	100·41	100·63	100·28
Norm (recalculated to 100%).—			
Anorthite	92·18	90·23	89·49
Albite	7·12	9·03	9·55
Orthoclase	0·70	0·74	0·96
	100·00	100·00	100·00

[1] This is Smythe's Hartley dike, thirty yards south of the Collywell dike.

Mid-Northumberland.—It is noteworthy that all the Talaidh types lie in a single broad belt defined at the coast by the Collywell-Blyth group of dikes (fig. 3). In mid-Northumberland the belt is represented by the Crookdene and Castle Dene dikes and on the Border by the dikes near Kielder and the northern member of the two Deadwater dikes. Other types of tholeiites occur within this belt, but outside it Talaidh types have not yet been found.

Although the Ray Mill and Horncastle dikes are typical Brunton types, their immediate neighbour to the east, the Castle Dene dike, is of very different texture. Certain parts resemble the Crookdene dike in every essential respect, while other sections show a passage towards the granular Acklington type, but in so far as sheaves of augite are nowhere absent, the dike may be described as Talaidh.

The Border.—The northern Deadwater dike has been traced in Kittythirst sike east of the farmhouse, and in the sikes between Deadwater and Saughtree stations to the north-west of the farm. From east to west the tendency to elongation and radial groupings of the augite becomes steadily more pronounced, culminating in the Windy Knowe exposure which provides an exceptionally good example of the Talaidh type. In the other direction (e.g. Kittythirst, 442) plates of nearly colourless pyroxene (some of which is probably orthorhombic) become more abundant, and the granular habit of the Brunton type begins to take the place of the Talaidh sheaves. In other respects, low mesostasis and abundant augite, the Talaidh characters are maintained.

The field characters of the two Kielder dikes have been well described by Clough (**8**, p. 20). They are distinguished on the map, fig. 1, as the Kielder Burn and Kielder Viaduct dikes. The latter has been referred to by Thomas and Bailey as a Northumbrian representative of leidleite (**18**, p. 207). In texture the rock is certainly near the leidleite end of the series (pl. II, fig. 1), but it is identical with that of the Crookdene dike (pl. II, fig. 2), and its specific gravity, mineral and chemical composition all show that it is definitely a tholeiite of the Talaidh type. The following micrometric analyses bring out the close resemblance between the Kielder dikes and those of Collywell and Crookdene. It should be noted that in the Talaidh type it is practically impossible to avoid overestimating the pyroxenes at the expense of the mesostasis. For this reason, the felspar ratio in the last column is probably too low.

Mineral proportions of Tholeiites of the Talaidh type.

Dikes.		Mesostasis.	Pyroxene (P).	Felspar (F).	F/(P+F).
344.	Collywell ...	23·4	36·4	34·5	49 %
311.	Crookdene ...	18·9	37·2	36·6	50
336.	Castle Dene ...	27·1	39·2	29·3	43
442.	Kittythirst [1] ...	14·7	40·1	34·7	46
460.	Windy Knowe [1]	24·2	36·3	28·9	44
310.	Kielder Viaduct	19·0	37·1	35·1	49
308.	Kielder Burn ...	21·3	34·0	31·8	48

[1] Deadwater north dike.

Chemical composition of the Kielder Viaduct Dike (310).

	Percentages.	Molecular proportions.
SiO_2	51·28	0·8538
Al_2O_3... ...	14·83	0·1455
Fe_2O_3... ...	2·49	0·0156
FeO	5·89	0·0820
MgO	7·45	0·1848
CaO	11·59	0·2067
Na_2O	1·93	0·0311
K_2O	0·66	0·0070
H_2O (+110° C.)	0·91	—
H_2O (−110° C.)	1·41	—
CO_2	0·45	0·0102
TiO_2	0·87	0·0109
ZrO_2	none	—
P_2O_5	0·14	0·0010
Cl	trace	—
S	0·06	0·0019
Cr_2O_3... ...	0·02	0·0001
V_2O_3	0·05	0·0003
NiO	none	—
MnO	0·20	0·0028
SrO	trace	—
BaO	0·01	0·00007
Li_2O	none	—
	100·24	
Less O for S...	0·02	
	100·22	

Specific gravity = 2·87

Norm.

Quartz			4·94
Orthoclase			3·89
Albite			16·30
Anorthite			29·95
Diopside	$CaSiO_3$	9·94	19·16
	$MgSiO_3$	6·56	
	$FeSiO_3$	2·66	
Hypersthene	$MgSiO_3$	11·98	16·86
	$FeSiO_3$	4·88	
Magnetite			3·61
Ilmenite...			1·65
Pyrite			0·12
Apatite			0·34
Calcite			1·02
Chromite			0·02
			97·86
Water			2·32
			100·18

Calculated mineral composition.

Quartz	6·00
Alkali-felspars, $Or_{40}Ab_{60}$ ...	none
Plagioclase, $An_{55}Ab_{36}Or_9$ ...	45·22
Pyroxenes	39·88
Ores (as above)...	5·40
Apatite	0·34
Calcite	1·02
	97·86

Chemical composition.—In order to investigate the Talaidh characters of the Kielder Viaduct rock as completely as possible, a typical sample (310) was selected for analysis. The results indicate that the composition of the rock does not differ in any appreciable way from those of Crookdene and Collywell. In comparison with the Brunton type of the Bingfield dike all three Talaidh types have relatively high CaO and Al_2O_3, and low Na_2O and iron oxides. The first difference is probably to be attributed to the variation from rock to rock in the proportion of anorthite (present either as such or in a reaction product). The second difference is an expression of the fact that in tholeiites having about the same amount of alkali-felspar ($Ab_{60}Or_{40}$), the total Na_2O varies with the total iron oxides. That is to say, Na_2O is proportional to two variables: (*a*) the total iron oxides, FeO, and (*b*) the alkali-felspar, $Ab_{60}Or_{40}$; the relationship being nearly $6FeO + Ab_{60}Or_{40} = 29Na_2O$, where each constituent is given its percentage value. This point will be referred to again on p. 47.

In the table below, the composition of a Talaidh type of tholeiite from Mull is added. As in some of the other Mull types, Na_2O and iron oxides are higher than in the north of England, and CaO and Al_2O_3 tend to be correspondingly low.

Analyses of Tholeiites of the Talaidh type.

	4. Kielder Viaduct.	G. Crookdene.	H. Collywell.	I. Mull.
SiO_2	51·28	51·31	51·10	53·97
Al_2O_3	14·83	14·55	16·75	14·65
Fe_2O_3	2·49	n.s.d.	n.s.d.	3·62
FeO	5·89	9·02	8·03	6·32
MgO	7·45	6·85	5·89	4·49
CaO	11·59	11·61	11·97	7·98
Na_2O	1·93	1·79	2·02	2·54
K_2O	0·66	0·60	0·66	1·52
$H_2O(+110°C.)$ ...	0·91	1·14	1·16	0·94
$H_2O(-110°C.)$ ...	1·41			1·92
CO_2	0·45	1·47	1·20	0·51
TiO_2	0·87	1·00	0·96	1·24
P_2O_5	0·14	—	—	0·27
S	0·06	—	—	—
FeS_2	—	—	—	0·09
Cr_2O_3	0·02	—	—	—
V_2O_3	0·05	—	—	—
(Co,Ni)O ...	none	—	—	nt. fd.
MnO	0·20	0·47	0·37	0·30
SrO	trace	—	—	—
BaO	0·01	—	—	0·04
	100·24	99·81	100·11	100·40

4. Tholeiite (Talaidh type), Kielder Viaduct dike, Kielder Burn, Northumberland. Analyst, H. F. Harwood (supra, p. 27).

G. Tholeiite (Talaidh type), Crookdene dike, Wansbeck, sixteen miles west of Morpeth, Northumberland. Analyst, J. A. Smythe (**12**, p. 3).

H. Tholeiite (Talaidh type), Collywell dike (= Hartley dike of Teall), Collywell Bay, Northumberland. Analyst, J. A. Smythe (**12**, p. 3).

I. Tholeiite (Talaidh type), basic margin of composite sill, Ruadh a 'Chromain, Mull. Analyst, E. G. Radley (**22**, p. 17).

6. The Acklington Type.

The Acklington dike differs from the others in the north of England in its greater length and continuity and in its uniformity of composition (**2**, p. 242). The Cleveland dike has also a marked petrographic individuality but is less continuous at the surface. The rock of the Acklington dike (pl. II, fig. 3) is almost devoid of porphyritic crystals or aggregates with anorthite cores, though careful search shows that, though small, they are not entirely absent. Peripheral zoning of the felspar is strongly marked, and forms a broader rim than is usual in other dikes, suggesting a longer period of reaction with the enclosing magma. The dominant mineral is felspar, near labradorite but ranging down to andesine in small haphazardly arranged laths, with no special tendency to clustering about centres. The pyroxenes include rare stumpy prisms of slightly pleochroic enstatite or hypersthene, and an abundant pale grey-green pyroxene which closely resembles the common pyroxene of the Whin Sill and is devoloped in twinned columnar prisms and irregular grains. Streaks and frayed patches of fibrous alteration products generally give the pyroxenes a turbid appearance. Titanomagnetite, fairly well crystallized, is scattered through the rock in small irregular or skeletal individuals. The mesostasis varies considerably in amount from slide to slide. Miss Heslop has noted that the rock becomes richer in glass where it is in contact with the Cheviot andesites (**11**, p. 39). Locally the glass may be biscuit-coloured or brown, in clear and well-defined spaces containing a few skeletal forms and microlites of the prevalent minerals, and the rock then closely resembles the groundmass of the 'glassy' variety of the Eskdalemuir dike described by Tyrrell (**19**, p. 314). Generally, however, the mesostasis is like that of the 'stony' variety of the Eskdalemuir and Muirkirk dikes; that is to say, it is a product of devitrification consisting of a colourless or clouded felsitic base streaked with obscure grey-green shreds of probably chloritic matter and lightly powdered with a globulitic dust of black ores. Amygdales are few and small, and consist of calcite with a thin chloritic lining. According to Topley (**2**, p. 247), chlorophaeite was first detected in England in the Acklington dike, but it has not been found in the specimens we have examined.

The mineral proportions in specimens of the Acklington dike from three localities are given below (p. 30) together with those of other examples of the Acklington type.

It will be noticed that throughout this series the felspars are definitely more abundant than the pyroxenes and that in this respect there is an approach to the Whin Sill type of quartz-dolerite.

Chemical composition.—A representative specimen of the Acklington dike from near Newton (south-east corner of the Cheviots) was

Mineral proportions of Tholeiites of the Acklington type.

Dikes.		Mesostasis.	Pyroxenes (P).	Felspar (F).	F/(P+F)
303.	Acklington	36·8	23·3	33·7	59 %
302.	Newton (Acklington)	24·1	27·5	38·1	58
301.	Clennel (Acklington)	12·7	31·3	42·1	57
481.	Netherton	24·0	28·2	42·6	60
376.	Coley Hill[1] ...	29·8	30·0	35·7	54

[1] The figures refer to the groundmass, which amounts to 92 % of the whole rock, the remaining 8 % being anorthite.

selected for analysis; as the figures of the above table show, its minerals and mesostasis are in approximately average proportions. The rock is markedly richer in silica and poorer in lime and magnesia than the tholeiites already dealt with. Comparison of the calculated mineral composition with the modes shows that the mesostasis contains nearly all the quartz and alkali-felspar together with a varying amount of plagioclase and pyroxene (or their ingredients) in nearly the same proportions as they occur in the crystalline phases. Chemically the rock is thus equivalent to a quartz-dolerite of the Whin Sill type diluted with quartz and alkali-felspar of the composition $Ab_{60}Or_{40}$.

The uniformity of the dike is well shown by analysis J on p. 33, which represents the Moneyacres dike where it crosses Lugton Water (near the Renfrew border of Ayrshire, north of Dunlop). The dike at Lugton is notably richer in titanium dioxide, like some other Scottish representatives of the north of England types, but it is otherwise not significantly different. A specimen of the rock (416) confirms the identity; it is a typical representative of the Acklington tholeiite, differing only in the possession of a higher proportion of titanomagnetite. Another dike, nearer Dunlop, has again the same composition (K, on p. 33). In Mull the only analysed tholeiite of Talaidh type is almost identical in composition with the Acklington dike (G, on p. 28).

The Netherton dike (west of Blyth) has been driven through in the workings of Netherton colliery 420 feet below the surface. It there occurs in two practically vertical sections, 5 and 7 feet thick respectively, separated by 15 feet of dislocated and metamorphosed 'rubble'. The rock is of Acklington type, though somewhat finer in grain than that of the much thicker Acklington dike.

Farther inland the Cross Hollows and Lisle Burn dikes west of Ray Mill are typical Acklington types, with yellowish glass in the latter and easily visible anorthite in the former. Both contain amygdales

Chemical composition of the Acklington Dike (302), near Newton, Northumberland.

	Per-centages.	Molecular proportions.
SiO_2	54·67	0·9100
Al_2O_3... ...	13·48	0·1319
Fe_2O_3... ...	3·41	0·0214
FeO	7·26	0·1011
MgO	4·65	0·1153
CaO	8·57	0·1528
Na_2O	2·64	0·0426
K_2O	1·55	0·0165
H_2O (+110° C.)	1·17	0·0650
H_2O (−110° C.)	1·07	0·0594
CO_2	0·38	0·0086
TiO_2	1·35	0·0169
ZrO_2	none	—
P_2O_5	0·19	0·0013
Cl	trace	—
S	0·12	0·0037
Cr_2O_3... ...	none	—
V_2O_3	0·03	0·0002
NiO	none	—
MnO	0·17	0·0024
SrO	trace	—
BaO	0·03	0·0002
Li_2O	trace	—
	100·74	
Less O for S ...	0·04	
	100·70	

Specific gravity = 2·81

Norm.

Quartz			9·84
Orthoclase			8·90
Albite			22·54
Anorthite			20·36
Diopside	$CaSiO_3$	7·86	15·41
	$MgSiO_3$	4·40	
	$FeSiO_3$	3·15	
Hypersthene	$MgSiO_3$	7·15	12·31
	$FeSiO_3$	5·16	
Magnetite			4·86
Ilmenite			2·58
Pyrite			0·24
Apatite			0·34
Calcite			0·90
			98·28
Water			2·24
			100·52

Calculated mineral composition.

Quartz	10·67
Alkali-felspar, $Ab_{60}Or_{40}$ ...	13·75
Plagioclase, $An_{48}Ab_{42}Or_{10}$ ...	34·27
Pyroxenes	30·67
Ores	7·68
Apatite	0·34
Calcite	0·90
	98·28

with chlorophaeite and calcite, in which respect they show some affinity to the Ray Mill dike.

The Coley Hill dike, exposed near Newcastle-upon-Tyne (**1**, p. 49; **3**, p. 87), closely resembles the Tynemouth dike in the external appearance of its rock, as it contains conspicuous anorthite crystals and aggregates amounting on an average to 8–10 % of the rock. These are zoned with exactly the same peculiarities as those of Tynemouth, but the unzoned internal parts are about An_{94}, which is slightly more calcic than those of Tynemouth. Including the zoned rims the composition of the aggregates cannot be far from An_{90}, as the corresponding Tynemouth figures are An_{90} and An_{85}. The two rocks are also alike in the nature of their amygdales, beautiful examples of the latter filled with partly crystallized mesostasis being common in the Coley Hill dike (pl. II, fig. 4). The body of the

Chemical composition of the Coley Hill Dike (376), near Newcastle-upon-Tyne.

	Per-centages.	Molecular proportions.
SiO_2	53·92	0·8978
Al_2O_3	15·81	0·1551
Fe_2O_3	3·05	0·0191
FeO	5·06	0·0704
MgO	5·32	0·1319
CaO	10·22	0·1822
Na_2O	2·09	0·0337
K_2O	1·46	0·0155
H_2O (+110° C.)	1·01	—
H_2O (−110° C.)	1·19	—
CO_2	0·25	0·0057
TiO_2	0·79	0·0099
ZrO_2	none	—
P_2O_5	0·12	0·0008
Cl	trace	—
S	0·06	0·0019
Cr_2O_3	0·01	0·0001
V_2O_3	0·08	0·0005
NiO	none	—
MnO	0·11	0·0016
SrO	trace	—
BaO	0·03	0·0002
Li_2O	trace	—
	100·58	
Less O for S ...	0·02	
	100·56	

Specific gravity = 2·82

Norm.

Quartz			8·90
Orthoclase			8·62
Albite			17·67
Anorthite			29·59
Diopside	$CaSiO_3$	7·86	15·17
	$MgSiO_3$	5·16	
	$FeSiO_3$	2·15	
Hypersthene	$MgSiO_3$	8·08	11·46
	$FeSiO_3$	3·38	
Magnetite			4·42
Ilmenite			1·50
Pyrite			0·12
Apatite			0·27
Calcite			0·57
Chromite			0·01
			98·30
Water			2·20
			100·50

Calculated mineral composition.

Quartz	9·68
Alkali-felspar, $Ab_{60}Or_{40}$ ...	11·05
Plagioclase,[1] $An_{63}Ab_{27}Or_{10}$ ...	41·22
Pyroxenes	29·47
Ores	6·05
Apatite	0·27
Calcite	0·57
	98·31

[1] Includes about 8 % of An_{90}, the remaining 33 % being approximately An_{56}.

rock, however, is found to be of Acklington type, whereas that of Tynemouth is of Brunton type. A little overlapping of types may be indicated by the restriction to the mesostasis of a considerable proportion of the black ores and an occasional suggestion of stellate clustering by the felspar and pyroxenes. Mineral and chemical analyses, however, confirm the general evidence of the groundmass that the rock is of Acklington type.

Chemical composition.—The analysis of a specimen of the Coley Hill dike containing about 8 % of anorthite aggregates is given above. As will be seen, it differs from the Acklington analysis only in containing more lime and alumina and slightly less silica. That is to say, it represents the Acklington type plus anorthite. Comparison of this analysis with that of the Hebburn dike (no. 7, p. 40) confirms Teall's conclusion that the Coley Hill dike differs in its characters from those of the Hebburn dike, but comparison with the analysis of the Tynemouth dike (no. 3, p. 23) shows that here there is a greater difference than Teall suspected (**2**, p. 234).

Analyses of Tholeiites of the Acklington type.

	5. Acklington.	6. Coley Hill.	J. Ayrshire.	K. Ayrshire.	L. Arran.
SiO_2 ...	54·67	53·92	54·11	54·56	54·83
Al_2O_3 ...	13·48	15·81	11·65	11·03	14·10
Fe_2O_3 ...	3·41	3·05	2·76	2·87	3·57
FeO ...	7·26	5·06	7·02	6·62	5·87
MgO ...	4·65	5·32	5·30	5·35	4·88
CaO ...	8·57	10·22	8·77	8·98	7·90
Na_2O ...	2·64	2·09	2·63	2·83	2·32
K_2O ...	1·55	1·46	1·75	1·43	1·73
H_2O+ ...	1·17	1·01	0·81	0·88	1·23
H_2O- ...	1·07	1·19	0·68	0·71	0·48
CO_2 ...	0·38	0·25	0·05	0·10	1·90
TiO_2 ...	1·35	0·79	3·37	3·33	0·74
P_2O_5 ...	0·19	0·12	0·58	0·76	0·24
S ...	0·12	0·06	—	—	—
FeS_2 ...	—	—	0·22	0·26	nt. fd.
Cr_2O_3 ...	none	0·01	0·03	0·02	—
V_2O_3 ...	0·03	0·08	—	—	—
(Co,Ni)O	none	none	—	—	0·03
MnO ...	0·17	0·11	0·21	0·23	0·37
SrO ...	trace	trace	—	—	—
BaO ...	0·03	0·03	0·03	0·03	nt. fd.
	100·70	100·56	99·97	99·99	100·19

5. Tholeiite (Acklington type), Newton. Analyst, H. F. Harwood (supra, p. 31).
6. Porphyritic tholeiite (Acklington type), Coley Hill, near Newcastle-upon-Tyne. Analyst, H. F. Harwood (supra, p. 32).

J. Andesitic tholeiite (Acklington type), 60-foot NW. dyke (a continuation of the Acklington-Hawick dike), Lugton Water, 1,000 yards SW. of Smithy, Lugton, Ayrshire. Analyst, B. E. Dixon (**23**, p. 128, no. 800).

K. Andesitic tholeiite, NW. dike, 1¼ miles ENE. of Dunlop, Ayrshire. Analyst, B. E. Dixon (**23**, p. 128, no. 817).

L. Hypersthene-dolerite, holocrystalline equivalent of the basal tholeiite of the Bennan composite sill, shore at foot of Struey Falls, Bennan Head, Arran. Analyst, E. G. Radley, Arran Memoir, 1928, p. 204, no. 12.

Tyrrell's 'Tholeiite (cf. Brunton type), basic member of composite pitchstone-tholeiite dyke, Judd's No. II dyke, Tormore shore, Arran' is chemically a member of the Acklington type. Arran Memoir, 1928, p. 254, analysis no. 21 by E. G. Radley.

The two analyses of the Acklington type are repeated in the preceding table for comparison with some Scottish examples. The only comparable Arran rock which has been analysed is a hypersthene-dolerite representing the holocrystalline equivalent of what elsewhere in the same sill is a typical tholeiite. It is therefore of special interest to find that the mesostasis is stated by Tyrrell[1] to consist of 'alkali-felspar and quartz in micrographic intergrowth'. We have here a definite proof that our deduction of the nature of the Acklington mesostatis from the chemical and mineral analyses is correct.

7. THE CLEVELAND TYPE.

The Hebburn dike was formerly exposed at Walker and in a quarry near Brockley Whins station which has since been filled up, but at present, as when Teall described the rock, it is to be found in situ only in the workings of Hebburn and Boldon collieries. Superficially the rock is not unlike the Acklington type, and Teall's specimens from the interior of the dike seem to have been of this type (**2**, p. 231). Those that we have examined from the Hutton level are more closely related to the Cleveland type in three respects: the presence of enstatite, the slightly porphyritic character, and the chemical composition. Prisms of colourless enstatite fringed with green alteration products and grains of titanomagnetite are common. There are also long corroded phenocrysts of enstatite-augite mottled with inclusions that may represent altered enstatite (pl. II, fig. 5). Finally there is a grey-green pyroxene sprinkled through the body of the rock in small irregular granules. The felspar laths are haphazardly arranged as in the Acklington type; they are zoned and range from An_{55} to An_{40}. But larger and more equidimensional felspars with well-defined zoned rims are also present, and these are exactly like the still larger felspar phenocrysts of the Cleveland dike. Ores are small but well individualized, and there is an abundant evenly distributed cloudy mesostasis. Amygdales are few and are filled mainly with chalcedony, sometimes with a core of calcite.

The Hebburn dike is the most easterly representative of the linear series which includes the great Eskdalemuir dike of Dumfries, and it is therefore of interest to note that both in mineral development and chemical composition (M, p. 40) there is a striking resemblance between the Boldon and Eskdale rocks. The latter has been described

[1] G. W. Tyrrell, Arran Memoir, 1928, p. 205.

Chemical composition of the Hebburn Dike (380), Boldon Colliery, Co. Durham.

	Percentages.	Molecular proportions.
SiO_2	57·09	0·9505
Al_2O_3	13·76	0·1350
Fe_2O_3	2·74	0·0171
FeO	4·98	0·0693
MgO	4·29	0·1060
CaO	8·12	0·1448
Na_2O	2·51	0·0405
K_2O	1·95	0·0207
H_2O (+110° C.)	1·43	—
H_2O (−110° C.)	1·45	—
CO_2	0·73	0·0165
TiO_2	0·80	0·010
ZrO_2	none	—
P_2O_5	0·13	0·0009
Cl	0·10	0·0028
S	0·03	0·0009
Cr_2O_3	0·01	0·0001
V_2O_3	0·07	0·0005
NiO	none	—
MnO	0·12	0·0017
SrO	none	—
BaO	0·05	0·0003
Li_2O	trace	—
	100·36	
Less O for S and Cl ...	0·03	
	100·33	

Norm.

Quartz			14·47
Orthoclase			11·52
Albite			20·50
Anorthite			21·05
Diopside	$CaSiO_3$	5·79	11·25
	$MgSiO_3$	3·55	
	$FeSiO_3$	1·91	
Hypersthene	$MgSiO_3$	7·09	10·91
	$FeSiO_3$	3·82	
Magnetite			3·96
Ilmenite			1·52
Pyrite			0·05
Apatite			0·30
Calcite			1·65
Halite			0·08
Chromite			0·01
			97·27
Water			2·88
			100·15

Calculated mineral composition.

Quartz	15·13
Alkali-felspar, $Ab_{60}Or_{40}$ ...	21·40
Plagioclase,[1] $An_{63}Ab_{27}Or_{10}$ ...	28·61
Pyroxenes	24·55
Ores	5·54
Apatite	0·30
Calcite	1·65
Halite	0·08
	97·26

Specific gravity = 2·81

[1] See the reference to this on p. 36.

as the 'Eskdalemuir type of cumbraite' by Tyrrell (**19**, p. 314), who has thus indirectly drawn attention to the relation of the Cumbrae type to the Acklington and Cleveland types, the main distinguishing features of the Cumbrae type being the presence of conspicuous aggregates of anorthite and prismatic crystals of enstatite. If in the future it should be thought desirable to distinguish the rock of the Hebburn dike from the Cleveland type, Tyrrell's term *Eskdalemuir type* is available for its reception.

Chemical composition.—The analysis of a specimen of the Hebburn dike from Boldon colliery is presented above. The higher silica as compared with the Acklington dike cannot be wholly accounted for by the presence of chalcedony in the amygdales, and is probably to be correlated with the higher percentage of potash. The 'calculated mineral composition' in this case leads to an impossible result for plagioclase (An_{63}), since the actual plagioclase is only An_{55} to An_{40}. Part of the albite of the calculated alkali-felspar must therefore go with the plagioclase, leaving an excess of orthoclase over the $Ab_{60}Or_{40}$ proportion. The composition of the glass of the Cumbrae type has the same characteristic to a marked degree (**19**, p. 309). The presence of chlorine calls for a word of explanation. It occurs in the rock in a soluble form, and is due to the percolation up the walls of the dike of salt water. Stalactites of sodium chloride are common in Boldon colliery workings. The source of the salt is at present unknown.

The Cleveland dike has been previously so fully described (**2**, p. 209; and **6**, p. 60) that it will suffice here to give a brief general description. Of the main mass of the rock two principal varieties may be distinguished according as the mesostasis is vitreous or devitrified. In addition there is a distinctive tachylytic marginal facies which may itself be glassy or stony according to the degree of incipient crystallization within it (**15**); devitrified tachylyte also occurs as small cognate inclusions. In all of these and throughout the whole course of the dike and its marginal offshoots, limpid porphyritic felspars ranging in size up to 1–2 × 3–5 mm. are uniformly distributed, making on an average three or four per cent. of the rock. They vary from idiomorphic to fragmentary and honeycombed forms, inlets and patchy inclusions of mesostasis being common as well as strings of similar material arranged in bands just within the periphery. In the tachylytic facies zoning is not conspicuous but it becomes marked in the normal rock. Teall noted that some of his measurements suggested the presence of a felspar near anorthite, and this has been confirmed by refractive index determinations. Specimens from Bolam (Co. Durham) and Wind Hill (east of Whitby) were found to contain anorthite aggregates approximating to An_{92} and An_{90}, but in these rocks most of the phenocrysts were found to range internally from An_{55} to An_{50}. One of the Bolam felspars, however, gave An_{62}. In specimens from Eaglescliffe, Buckheads, Bowles Beck, Tynehead, Armathwaite, and Dalston all the tested porphyritic felspars fell between An_{55} and An_{50}. Zoning carries the range of composition down to oligoclase. At least two kinds of felspar-phenocrysts are therefore present in the Cleveland dike, those normal to the rock, ranging from labradorite to oligoclase, and anorthite individuals and aggregates of exactly the same kind as those carried by the tholeiites already described. Anorthite is much more difficult to detect in the Cleveland dike because of its resemblance to the normal phenocrysts in hand-specimens.

Among the larger pyroxenes enstatite is distinctly rare. It has been detected in specimens from Bowles Beck, Woodland Fell, and Armathwaite. Large prisms of colourless to grey-green enstatite-augite or green to brownish-green hypersthene-augite are constant porphyritic elements. As first shown by Miss Heslop (**14**, p. 173) most of these are uniaxial or nearly so, common values of 2V being about 8° to 12° in a range of 0° to 30°. Some of these prisms have an altered fibrous axis which may represent an original nucleus of rhombic pyroxene. The granular augite of the groundmass has a larger optic axial angle and resembles, as far as can be tested, the common augite of the Whin Sill.

The groundmass of the rock is of Acklington type. The felspar laths range from labradorite to oligoclase, but zoning is slight. Occasional stellate groupings with a central cluster of tiny augite-granules may be seen. These are found also in an incipient stage in the marginal facies where the second generation felspars are little more than microliths. It is clear, therefore, that the stellate clusters formed after the main act of injection. There must have been more than one movement of the magma, for irregular inclusions of devitrified tachylyte up to 1 cm. or more are not rare, and the acicular felspars of the margins are often bent or broken.

In some specimens clusters of tiny augites thickly embedded in a sparse felspathic base and accompanied by a few ore individuals form granular colonies ranging in diameter from 1 to 10 mm. (e. g. Dalston, Eaglescliffe, and Barwick). Mesostasis is entirely absent. Barrow has noted that in these remarkable colonies the augite grains do not actually touch one another (**6**, pp. 62–3). It is as if the structures represented a colloidal system—a thin continuous framework of felspathic material serving as a medium for dispersed cells of pyroxene material—which afterwards crystallized.

Titanomagnetite is evenly distributed in idiomorphic and skeletal forms, and grains and shreds of biotite are occasionally to be found moulded on the ores. With regard to the remaining minerals, quartz, apatite, pyrite, alteration products, amygdale infillings (chalcedony and calcite), and the varied types of mesostasis, it will suffice here to refer to Teall's careful and detailed descriptions (**2**).

The mineral composition of a series of specimens of the Cleveland dike is given in the following table. The figures for felspars refer only to the groundmass and approximately 4 % should be added in each case to allow for the phenocrysts. In the last column the bracketed figures represent the felspar ratio thus corrected.

Mineral proportions of Cleveland and Cumbrae types.

Dikes.	Mesostasis.	Pyroxenes (P).	Felspars (F).	F/(P+F).
Hebburn dike:				
380. Boldon Colliery ...	33·7	23·6	32·7	58 %
Cleveland dike:				
411. Wind Hill ...	39·4	24·7	29·5 (+4)	55 (58)
402. Bolam	34·2	25·3	33·8 (+4)	56 (59)
386. Bowles Beck ...	38·1	22·6	31·3 (+4)	58 (61)
381. Dalston	33·6	26·1	32·9 (+4)	56 (59)
Cumbrae type: [1]				
Eerie Port (glassy) ...	42	22	26	54
Eerie Port (stony) ...	42	20	31	61

[1] Measurements by G. W. Tyrrell (**19**, p. 309). The glassy and stony varieties contain in addition 7 and 10 % respectively of megascopic anorthite.

The Wind Hill rock makes a beautiful section. The mesostasis is a sepia-brown glass becoming clear and colourless around microliths and ores; in consequence, the minerals, which are all fresh, stand out with unusually clean-cut outlines. There is a marked resemblance to the glassy variety of the Eskdalemuir dike. The Bolam rock is the analysed specimen, and in it the mesostasis is almost wholly devitrified (pl. II, fig. 6). The Bowles Beck sections closely resemble the Cumbrae type in all respects save the presence of anorthite.

Chemical composition.—A typical specimen of the Cleveland dike from the quarry in the laccolithic overflow at Bolam gave the following results on analysis. The composition differs in no important respects from that of the Hebburn dike, and the comments made on the calculated plagioclase (An_{63}) in the latter case apply equally here. The Cleveland mesostasis must contain an excess of orthoclase over the $Ab_{60}Or_{40}$ proportion to an even greater extent than that of the Hebburn dike. The very acid character of the glass is proved in a general way by Stock's investigation, recorded in Teall's paper (**2**, p. 224). Unfortunately the alkalis were not separately determined (see E_2, p. 47).

Chemical composition of the Cleveland Dike (402), Bolam, Durham.

	Per-centages.	Molecular proportions.
SiO_2	57·57	0·9580
Al_2O_3... ...	13·11	0·1290
Fe_2O_3... ...	3·12	0·0195
FeO	6·60	0·0919
MgO	4·29	0·1064
CaO	7·10	0·1266
Na_2O	2·62	0·0423
K_2O	2·21	0·0235
H_2O (+110° C.)	1·20	0·0667
H_2O (−110° C.)	0·94	0·0522
CO_2	0·28	0·0064
TiO_2	1·24	0·0155
ZrO_2	none	—
P_2O_5	0·19	0·0130
Cl	trace	—
S	0·13	0·0041
Cr_2O_3... ...	none	—
V_2O_3	0·04	0·0003
NiO	none	—
MnO	0·12	0·0017
SrO	none	—
BaO	0·06	0·0004
Li_2O	trace	—
	100·82	
Less O for S ...	0·05	
	100·77	

Specific gravity = 2·77

Norm.

Quartz			13·23
Orthoclase			13·08
Albite			22·18
Anorthite			17·66
Diopside	$CaSiO_3$	6·13	12·00
	$MgSiO_3$	3·46	
	$FeSiO_3$	2·41	
Hypersthene	$MgSiO_3$	7·22	12·28
	$FeSiO_3$	5·06	
Magnetite			4·51
Ilmenite			2·35
Pyrite			0·24
Apatite			0·44
Calcite			0·64
			98·61
Water			2·14
			100·75

Calculated mineral composition.

Quartz	13·95
Alkali-felspar, $Ab_{60}Or_{40}$ ...	27·10
Plagioclase, $An_{63}Ab_{27}Or_{10}$ ...	22·49
Pyroxenes	26·88
Ores	7·10
Apatite	0·44
Calcite	0·64
	98·60

The general uniformity of the dike is proved by the three older analyses (N, O, and P) quoted in the following table. Rocks of the Cleveland type other than those of the north of England have not been analysed, but the Barrmill dike of Ayrshire, described as a quartz-dolerite, is chemically very similar (**23**, p. 128), and so also is a 'basic craignurite' of Mull (**22**, p. 19).

The Ayrshire dikes which lie on the line of the Cleveland dike are representatives of the Cumbrae type. The NW. dike about six miles east of Ayr has already been recorded by Tyrrell as 'closely resembling the typical cumbraite' (**19**, p. 313), and this description also applies to specimens of the Barassie and Stevenston dikes (known locally as the 'Caponcraig Gaw') kindly sent to us by Dr. Tyrrell. Each of these contains zoned crystals and aggregates of anorthite of the same

Analyses of Tholeiites of the Cleveland type.

	7. Hebburn.	M. Eskdale.	8. Bolam.	N. Ayton.	O. Armathwaite.	P. Teesdale.
SiO_2 ...	57·09	58·67	57·57	57·57	58·07	55·19
Al_2O_3 ...	13·76	14·37	13·11	14·25	13·22	12·30
Fe_2O_3 ...	2·74	1·64	3·12	6·04	10·10	10·23
FeO ...	4·98	6·94	6·60	3·95	n.s.d.	n.s.d.
MgO ...	4·29	4·65	4·29	4·24	4·46	4·12
CaO ...	8·12	7·39	7·10	6·87	7·04	7·53
Na_2O ...	2·51	3·01	2·62	2·98	2·59	2·13
K_2O ...	1·95	1·42	2·21	1·08	1·58	1·30
H_2O+ ...	1·43	2·02	1·20	1·25	1·50	1·55
H_2O- ...	1·45		0·94			
CO_2 ...	0·73	—	0·28	0·30	—	3·64
TiO_2 ...	0·80	—	1·24	'trace'	—	1·03
P_2O_5 ...	0·13	—	0·19	0·15	—	—
S ...	0·03	—	0·13	0·19	—	—
FeS_2 ...	—	—	—	—	—	—
Cr_2O_3 ...	0·01	—	none	—	—	—
V_2O_3 ...	0·07	—	0·04	—	—	—
MnO ...	0·12	'trace'	0·12	0·27	—	0·63
SrO ...	none	—	none	—	—	—
BaO ...	0·05	—	0·06	—	—	—
	100·33	100·11	100·77	99·14	98·56	99·65

7. Tholeiite (Cleveland type), Hebburn dike, Boldon colliery, NE. Durham. Analyst, H. F. Harwood (supra, p. 35). Total includes Cl 0·10.

M. Tholeiite (Cleveland type), NNW. dike, Eskdale, Dumfriesshire. Quoted from A. Geikie, Proc. Roy. Phys. Soc. Edinburgh, 1880, vol. 5, p. 253. See also 'Ancient volcanoes of Great Britain', 1897, vol. 2, p. 137.

8. Tholeiite (Cleveland type), Cleveland dike at Bolam quarry, Co. Durham. Analyst, H. F. Harwood (supra, p. 39).

N. Cleveland dike, Great Ayton, Yorkshire. Analyst, W. F. K. Stock, quoted from Teall (**2**, p. 224, and **5**, p. 206).

O. Cleveland dike, Armathwaite, Cumberland. Analyst, W. F. K. Stock, quoted from Teall, loc. cit.

P. Tachylyte border of the Cleveland dike, junction of Tees and Lune, near Middleton-in-Teesdale. Analyst, R. C. Burton (**15**, p. 61).

kind as those of the Great Cumbrae, Coley Hill, and Tynemouth dikes. These Ayrshire dikes may therefore be regarded as a link between the Cleveland dike and those of the Great Cumbrae (**19**, p. 313) and the Cowal peninsula (Cumbrae types) of Argyllshire.[1] Along the seaboard of Argyll tholeiite dikes appear to be common and one of these, near Easdale, is of Cleveland type,[2] judging from the published

[1] Mem. Geol. Surv. Scotland. The geology of Cowal, 1897, pp. 130 et seq. See also, The geology of mid-Argyll, 1905, p. 119.

[2] The geology of the seaboard of mid-Argyll, 1909, p. 87, and pl. 8, fig. 2.

description. In Mull the nearest approach to the Cleveland type is inninmorite (**18**, p. 209).

Nomenclature.—It may be questioned whether it is justifiable to extend the term tholeiite to include the Acklington and Cleveland types, as in this paper, and the Cumbrae type, as in the Arran Memoir (p. 253). In these three types the F/(P+F) ratio ranges from 54 to 61, whereas in the Salen, Brunton, and Talaidh types, the range is from 41 to 50.[1] The apparent gap, however, has no real existence, for, as stated already, the Talaidh ratios are certainly too low, and the analysed Talaidh tholeiite of Mull has the same composition as the Acklington type. No natural line can anywhere be drawn which would limit the tholeiite series in such a way as to exclude any of the types under consideration. Chemically the rocks lie between Loewinson-Lessing's[2] andesito-basalt ($\alpha = 2{\cdot}16$, as in the Cleveland type) and basalt ($\alpha = 1{\cdot}70$, as in the Salen and Brunton types).[3] There can therefore be no objection to distinguishing 'andesitic tholeiites' from the tholeiites proper on arbitrary chemical grounds. This has already been done by the Survey (**23**, p. 128), and it may be regarded as symptomatic of a growing tendency to use the term tholeiite generically without restricting its utility by a too-precise specific definition. The real difficulty in arriving at a satisfactory naming of the tholeiites in terms of the usual nomenclature is that the suite as a whole is made up of four distinct classes of material: (*a*) anorthite crystals and aggregates; (*b*) framework of basaltic minerals; (*c*) iron-rich mesostasis; and (*d*) quartz-alkali-felspar mesostasis. It is only in its reference to the bulk composition when the last of these is abundant that the qualifier 'andesitic' has any special significance. The erection of specific types, each precisely defined, within the general field of the tholeiite series seems to be the only way of avoiding confusion.

8. Relationships and Genetic Considerations.

Distribution.—It is a remarkable feature that wherever Tertiary tholeiites occur several different types are to be found in proximity. This contrasts strikingly with the lack of variation of the quartz-

[1] The ratio for the measured specimen of the Barrington dike (p. 20) is 52, but is not typical, as the rock is transitional to the Acklington type.

[2] F. Loewinson-Lessing, On the delimitation of the families of basalts and andesites. Bull. Com. Geol. U.R.S.S., 1925, p. 411 (English abstract, p. 420).

[3] The Whin Sill type of quartz-dolerite has $\alpha = 1{\cdot}72$.

dolerites (**26**, p. 530). It is true of Mull, Argyll, Ayrshire, Arran, and Bute, and of the type area, the Nahe district of Germany. The following diagram (fig. 3) brings out the peculiarities of distribution in the north of England. The capital letters refer to the initials of the type-names, S being used for all olivine-bearing types.

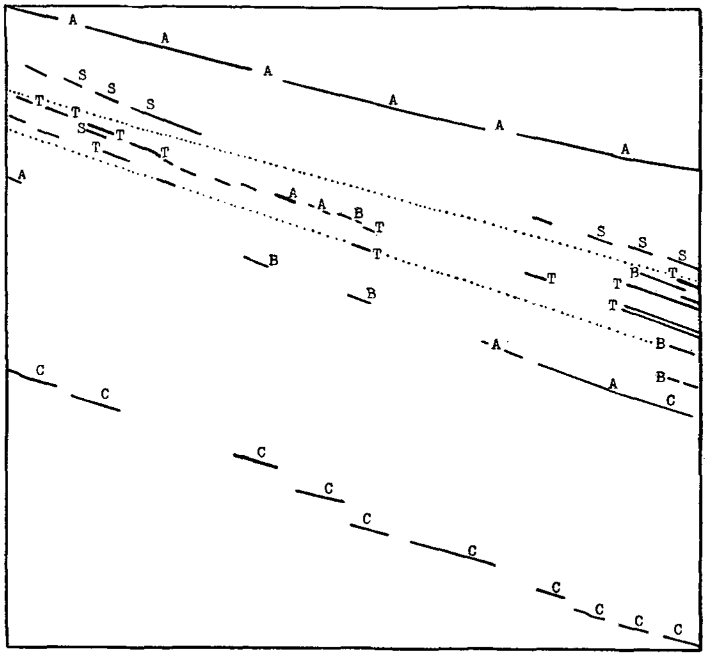

FIG. 3. Diagram illustrating the distribution of types among the tholeiite dikes of the north of England. For localities see fig. 1.

The distribution is clearly not entirely haphazard. The thick Acklington and Cleveland dikes maintain their individuality throughout the region studied. With one exception Salen types (including olivine-bearing Brunton types) are restricted to a single echelon series; and Talaidh types to the dotted belt. Traced farther across Scotland thick dikes of Acklington type become predominant until the coastal region of Ayrshire is approached; there olivine-bearing and anorthite-bearing types also become common. It is noteworthy that while thin dikes may be of any type, the thicker dikes are always of Acklington or Cleveland types.

Until the details of distribution have been determined throughout the whole belt up to its focus in Mull any attempt at an explanation would be premature. The magma of the underlying source may have varied longitudinally, transversely, and in depth. It was probably streaky in composition and gas content, and it may have extended over an area far greater than that to which the dikes are confined. The unknowns are at present too many for deductions from surface samples to be drawn with any confidence. The relation to Mull, however, suggests the hope that sooner or later the distribution of dikes will help to elucidate the nature of the currents and other processes that determine or accompany igneous activity of the central type.

Anorthite aggregates.—Practically all the Tertiary tholeiites can be shown to contain anorthite, and locally the mineral is abundant. The problem of origin has been discussed by Teall (**7**, p. 482), Miss Heslop and Smythe (**12**, p. 16), and Harker.[1] The phenomenon is not an isolated one. Anorthite lumps thickly covered with flakes of graphite occur in the iron-bearing basalt of Uifak, Greenland, and in certain other basalts of Disko Island.[2] Quasi-porphyritic crystals and aggregates of anorthite occur in some of the dolerite dikes and sheets of Skye and Mull, and very small examples are to be found in the Whin sill and its related dikes (**26**, p. 502). The anorthite may have been

(*a*) picked up from troctolites, eucrites, or other anorthite-bearing rocks transversed by the magma;

(*b*) produced by interaction of magma and aluminous sediments, as has occurred in Mull;[3] or

(*c*) produced at an early stage from the parent magma of that which later gave rise to the enclosing rock.

In case (*a*) other minerals should be present, as in the glomeroporphyritic patches of olivine and anorthite in the dolerite of Fair Head, Antrim.[4] Moreover, if the anorthite had been broken from a rock previously in existence, it is difficult to understand why rock fragments of other kinds should be entirely missing. In case (*b*) there should be evidence of the presence of corundum or spinel, as in Mull (**22**, p. 276). In the north of England no evidence of either class has

[1] A. Harker, Tertiary igneous rocks of Skye, 1904, p. 362.

[2] O. B. Bøggild, Mineralogia Groenlandica, Kjøbenhavn, 1905.

[3] H. H. Thomas, Certain xenolithic Tertiary minor intrusions in the Island of Mull. Quart. Journ. Geol. Soc. London, 1922, vol. 78, p. 229.

[4] J. W. Judd, Quart. Journ. Geol. Soc. London, 1886, vol. 62, p. 71, and pl. 7, fig. 3.

ever been detected despite most careful search, and like earlier investigators we are driven to adopt hypothesis (*c*) as the most probable. The existence of an early magma from which rocks containing anorthite could crystallize is supported by ample evidence in Skye and Mull and other Tertiary centres. In his investigation of the rocks of Mont Pelée, Lacroix[1] describes phenocrysts in andesite which are dominantly An_{45}–An_{52}, with a central core of An_{92}–An_{95}. The grouped phenocrysts of miharaite (Ōshima, Japan) have alternate zones, of which the more calcic members are An_{87}.[2] Comparison between the lavas of 1912 (in which the phenocrysts occur) and the older comagmatic lavas suggests to Tsuboi that 'as the cooling of the magma proceeded, olivine, pyroxene, and plagioclases separated out in the magma basin. Of these minerals, the last one, matching the magma closely in density, remained practically suspending in the magma basin; while the other two, being much heavier than the magma, sank down '.[2]

It seems likely that some such process led to the isolation of the anorthite found in the tholeiite dikes, but some other factor or factors at present unknown must have been involved to make possible the sudden break in composition between the original anorthite and the zoned rim. It may be that in the presence of abundant iron oxides the normal crystallization of albite in plagioclase is deferred. Notwithstanding our ignorance of the actual conditions it seems safe to refer the anorthite to an early stage of the magmatic history. Presumably the dike-area was either a belt of low vertical pressure (at magmatic levels) towards which magma was squeezed from bordering regions of greater pressure, or a belt in which the internal bursting pressure rose by local accumulation of volatiles.[3] In either case the anorthite aggregates would tend to collect in roof corrugations and to be drawn into streaks as a result of differential viscous flow. Once the stress differences rose sufficiently to shatter the overlying rocks, dikes locally enriched in anorthite would be formed wherever a particular fissure tapped an accumulation of anorthite, or wherever an injection current carried up an anorthite-rich streak. Every dike

[1] A. Lacroix, La Montagne Pelée et ses éruptions, Paris, 1904, p. 505; see also J. Stansfield, Assimilation and petrogenesis, Urbana, Ill., U.S.A., 1928, pp. 80–81.

[2] S. Tsuboi, Notes on miharaite. Journ. Geol. Soc. Tokyo, 1918, vol. 25, p. 47. [Min. Abstr., vol. 1, p. 209.]

[3] G. W. Morey, The development of pressure in magmas as a result of crystallization. Journ. Washington Acad. Sci., 1922, vol. 12, p. 219.

would have traces of anorthite on this hypothesis, but the distribution of the richer patches would be quite haphazard.

Magmatic variation.—The most suitable analyses to employ for the construction of a variation diagram are those of Bingfield (Brunton), Coley Hill (Acklington), and Hebburn (Cleveland), for they lie on a single line of dikes and exhibit almost a maximum range of composition. The Coley Hill rock is abnormal in its content of anorthite,

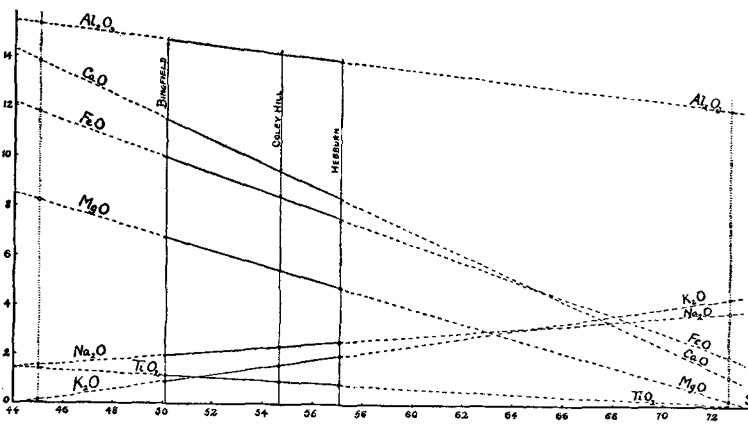

FIG. 4. Linear variation-diagram of the Bingfield–Coley Hill–Hebburn dike-system.

but, as the presence of the latter is accidental, comparison of the magma of this rock with those of the others can be fairly made only after 8 % of anorthite has first been subtracted from the bulk composition.

This has been done, using Smythe's analysis of the Hartley anorthite (p. 25) to represent the optically identical Coley Hill anorthite. The resulting composition of the body of the rock is plotted in fig. 4 with the other two analyses, and, as shown, the figures make a straight-line diagram. Although not inserted, the Kielderhead and Tynemouth (less anorthite) analyses also fit the Bingfield end of the diagram. The composition C of any rock in this series can therefore be expressed as $C = B + nE + mA$, where B is the composition of the Bingfield rock; E is a quartz-alkali-felspar 'end product'; A is anorthite; and n and m are constants for any given rock.

The Acklington and Cleveland analyses, together with some of the Scottish representatives, systematically fail to fit this straight-line diagram by having low CaO and Al_2O_3. Relative deficiency of anorthite is thus disclosed, but there is no way of estimating the deficiency, and consequently the analyses cannot be accommodated in the diagram as those of Coley Hill and Tynemouth have been. The straight-line diagram implies uniform variation between the Bingfield rock (the basaltic framework plus the iron-rich mesostasis) on the one hand, and a quartz-alkali-felspar mesostasis on the other. Superimposed on this, the simplest case, we have at least two other possible variables: (*a*) the irregular distribution of anorthite already referred to; and (*b*) variation in the proportion of the iron-rich mesostasis, or in the proportion of iron oxides within it. It is in consequence of (*b*) that the Talaidh analyses (and also the Acklington analysis) would depart from straight-line variation even if (*a*) could be allowed for.

Returning to the analyses that do conform to straight-line variation we can apply the data on fig. 4 to determine roughly the composition of E. Obviously it may lie anywhere to the right of the line representing the Hebburn analysis. The composition of the Hebburn mesostasis can be estimated by subtracting from the bulk analysis the estimated composition of the basaltic framework. This clearly shows that E is mainly quartz plus alkali-felspar near $Ab_{60}Or_{40}$, and that the silica percentage is between 72 and 76. Adopting $SiO_2 =$ 72·66 %, we read off the composition given below under E_1. For comparison E_2 is added, representing an approximation to the base of the Armathwaite dike. The felspar of E_1 is $Or_{42}Ab_{54}An_4$, which corresponds in type exactly with that of Vogt's 'ternary eutectic'. In 1921 Vogt deduced $Or_{42}(Ab+An)_{58}$ from the evidence then available,[1] but in 1926, as a result of a more detailed study, he adopted $Or_{40}(Ab+An)_{60}$.[2]

A magma of Coley Hill or Hebburn composition could be produced from one of Bingfield composition not only by the addition of material like E_1 but also by subtraction of material like C_1. The composition of C_1, as shown in the table below, differs beyond all possibility of error from the composition of the crystalline phase C_2, that actually did separate from the Bingfield magma. If the latter had been able to free itself from crystals it would have changed in the direction of trachybasalt. It is probably because this kind of process has operated

[1] J. H. L. Vogt, Journ. Geol. Chicago, 1921, vol. 28, p. 339, table IV.

[2] J. H. L. Vogt, The physical chemistry of the magmatic differentiation of igneous rocks. II. On the felspar diagram Or : Ab : An. Skrifter Norske Vidensk. Akad. I. Mat.-Nat. Kl. Oslo, 1926, no. 4, pp. 84 and 101.

	E_1.	E_2.	C_1.	C_2.	M.
SiO_2 ...	72·66	70·76	45·0	51·1	49·1
Al_2O_3 ...	11·94	10·93	15·3	15·2	13·0
FeO ...	2·00	3·59	11·8	9·0	11·5
MgO ...	0·20	4·21	13·8	7·6	4·9
CaO ...	1·18	3·29	8·2	12·4	9·8
Na_2O ...	3·80	7·22	1·5	1·9	2·0
K_2O ...	4·32		0·1	0·5	1·7
TiO_2 ...	—	—	1·4	—	3·3

E_1. From fig. 4 at SiO_2 = 72·66 %.
E_2. Composition of insoluble residue from the Armathwaite dike. Analyst, W. F. K. Stock in **2**, p. 224.
C_1. Composition of a hypothetical crystalline differentiate, from fig. 4 at SiO_2 = 45·0 %.
C_2. Estimated composition of the crystalline phase of the Bingfield dike.
M. Estimated composition of the mesostasis (including ores) of the Bingfield dike. Calculated by subtracting C_2 from the bulk analysis of the rock (p. 18).

to a very limited extent that the soda varies with the proportion of iron oxides as well as with that of the 'end-product', E.

The association of iron oxides and soda is of particular interest in connexion with the genesis of alkali-rocks, as it suggests a means whereby residual magmas unsaturated in respect of both silica and alumina might be generated. It is possible, as already suggested on p. 44, that early anorthite may crystallize with less than the normal amount of albite because of the withholding of soda in the presence of abundant iron oxides. If for any reason the soda-iron-rich residuum were to be strained away from the anorthite it would constitute a magma in which soda and iron oxides could combine with silica and so provide the conditions necessary to the production of alkali-rocks. It should be noted that in quartz-dolerites and tholeiites relatively little of the iron occurs as silicate; if most of it had joined with silica the rocks would not have been oversaturated. In the Brunton tholeiites we see a process of differentiation of exactly the same kind as was observed in a basalt flow in Mozambique.[1] In the Brunton example the reaction of the magma with anorthite already produced has hidden the tendency towards alkalinity; in Mozambique, on the contrary, the associated rocks are tephrite and phonolite.

Separation of M and C_2 has certainly not operated in generating the tholeiite suite of the north of England. To produce from the

[1] A. Holmes, The Tertiary volcanic rocks of the district of Mozambique. Quart. Journ. Geol. Soc. London, 1917, vol. 72, p. 243.

magma of the Bingfield rock a more acid type of tholeiite it would be necessary to withdraw material having the composition of C_1. This represents an assemblage of constituents which it has not been possible to match with any known rock. We may therefore deduce that differentiation by crystallization and separation of the residual liquid was not the process involved in the production of the different types of tholeiites. This follows even more convincingly from the haphazard distribution of anorthite, and from the implication of the straight-line diagram.[1]

The mineral assemblage of the rocks further supports the conclusion. As shown in our Whin Sill paper (**26**, p. 507), in rocks formed by the consolidation of successive residual magmas produced from basalt by crystallization-differentiation, the pyroxenes would not be expected to begin afresh in each successive rock with hypersthene. This argument suggests that hypersthene-andesites may be basic representatives of a 'sial' magma, or a consequence of assimilation of aluminous sediments, but not residual products from an uncontaminated basaltic magma.[2] Our Cleveland and Acklington types, however, are not andesites. Their crystalline framework is typically basaltic. The felspar ratio F/(P+F) reaches but does not exceed the corresponding figure for the Whin Sill, and is generally lower, whereas in a residual product a higher value would be expected. The anorthite-content of the plagioclase does not fall with the rise of the felspar ratio as would be expected on the hypothesis of crystallization-differentiation.[3] Similarly, the normative pyroxene ratio MgO/(MgO+FeO) in the Cleveland and Acklington dikes (0·59 and 0·58) is as high as in the Bingfield dike (0·58), while in the Coley Hill and Hebburn dikes the ratio is actually very much higher (0·71 and 0·72). All are higher than the Whin Sill value (0·52). The tholeiites thus behave as basaltic rocks which in some cases have been merely diluted with the quartz-alkali-felspar material, *E*.

In further accordance with this conclusion is the important fact that the Whin Sill type of magma is generally characterized by widespread regional constancy. It does not, in its most spectacular developments, differentiate towards the possibility of rocks like those of Acklington and Cleveland types. Why then should the very similar

[1] C. N. Fenner, The Katmai magmatic province. Journ. Geol. Chicago, 1926, vol. 34, pp. 765 et seq.

[2] See Footnote 3 on pp. 49–50.

[3] J. H. L. Vogt, Journ. Geol. Chicago, 1921, vol. 29, p. 427.

magma of the Brunton type readily appear to do so ? The only significant difference is the greater content of volatiles in the Brunton-type magma, but even this cannot be assumed for the magmas of the Acklington and Cleveland dikes. Abstraction of material of type *E* from one part of a magma and its concentration in another by gaseous transfer is evidently not a process that can be assumed in our problem, for volatiles are commonly low where *E* is greatest, and dikes in which *E* is negligible come to a head in a confusion of carbonates through which textural relics still testify to an original composition like that of the depths of the dike (**12** and **17**). Moreover, gaseous transfer, if one may judge from the assemblage of lavas found in oceanic volcanoes, leads to the trachybasalt-trachyte association of rocks. Tholeiites, like quartz-dolerites (**26**, p. 541), are continental rocks and have no place in oceanic islands.

There remains the possibility that the Brunton-type magma changes towards *E* not as a result of differentiation but by selective assimilation of material of composition E_1 or by admixture with a coexisting magma of composition E_1. The magma most easily formed from 'sial' heated up by its long-continued contact with a basaltic magma would presumably be one corresponding closely to the ternary eutectic of quartz, albite, and orthoclase. It would be idle to speculate as to the precise way in which magmatic mixing might occur, for there are many plausible possibilities. Our study, however, finally leads to the belief that there is no satisfactory alternative to the assumption of mixing by one process or another. Similar arguments apply to many of the puzzling rocks of Mull, such as ininmorite and the rocks of the 'differentiation column' (**22**, p. 320) ; to the common association of rocks of strongly contrasted composition in composite dikes and sills in Mull and other Tertiary centres ;[2] and indeed, to all provinces in which gabbros, dolerites, and basalts, on the one hand, occur dominantly with granites, granophyres, quartz-porphyries, and rhyolites, on the other, without any noteworthy development of intermediate types.[3] The restriction of all such associations to the

[1] For a recently described case of this kind, see D. R. Grantham, Proc. Geol. Assoc. London, 1928, vol. 39, pp. 327 et seq.

[2] E. M. Guppy and L. Hawkes, Quart. Journ. Geol. Soc. London, 1925, vol. 81, p. 325; and H. K. Cargill, L. Hawkes, and J. A. Ledeboer, ibid., 1928, vol. 84, p. 505.

[3] In the second of the papers referred to above a 'quartz-diorite' from the Vestur Horn intrusion in south-east Iceland is described (p. 513). It contains both potash-felspar and plagioclase, and hypersthene is present. The authors

continents (or to areas like Iceland which for isostatic and seismological reasons are assumed to be underlain by 'sial') is strong evidence that they are the product, not of basaltic magma alone, but of both basaltic and granitic magmas generated in their respective 'sima' and 'sial' levels. If it be agreed that crystallization-differentiation and the idea of immiscible separations from a parent intermediate magma alike fail to explain this characteristically Tertiary and continental assemblage of rocks, then the long-despised conception of Bunsen[1]—that *two* fundamental magmas, basic and acid, are the parents of all the igneous rocks of Iceland and similar provinces—again becomes worthy of serious attention.

9. Acknowledgements.

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Explanation of Plate I.

Magnification ×20. Ordinary light.

Fig. 1. *Olivine-tholeiite* (Salen type). Kielderhead dike, Northumberland (no. 306). The field shows partly serpentinized olivine, near the centre; the characteristic ophitic relations between augite and plagioclase; and the relatively small proportion of mesostasis. Description, pp. 12–13. Analysis, p. 15.

Fig. 2. *Olivine-tholeiite* (olivine-bearing Brunton type). Peel Burn dike, Roxburghshire (no. 478). This differs from fig. 1 in the higher proportion of

remark, 'The patchy distribution of the dark minerals in this rock is strongly suggestive of admixture.' On p. 533, however, they assume the extreme magmas to be products of *differentiation* operating during the igneous cycle.

[1] R. W. Bunsen, Ann. Phys. Chem. (Poggendorff), 1851, vol. 83, pp. 197–272.

mesostasis and the clustering of the minerals. Olivine, being almost wholly serpentinized in this field, is not easily distinguished from the mesostasis. Description, p. 13.

FIG. 3. *Tholeiite* (Brunton type) from the type locality, Bingfield dike, Red-house Burn, Northumberland (no. 369). Plagioclase and pyroxene are segregated into stellate clusters, 'partly in contact with one another, partly separated by mesostasis'. Description, p. 17. Analysis, p. 18.

FIG. 4. *Tholeiite* (anorthite-bearing Brunton type). Tynemouth dike, Northumberland (no. 356). The field is selected to illustrate one of the smaller quasi-porphyritic crystals of anorthite with fretted edges and inclusions. Description, p. 20. Analysis, p. 21.

FIG. 5. *Tholeiite* (Brunton type). Ray Mill dike, Northumberland (no. 340). Part of the dark background is brownish-green chlorophaeite. Description, pp. 19–20.

FIG. 6. *Tholeiite* (Brunton type). Warksburn dike, Northumberland (no. 363). The field shows the typical Brunton texture and a calcite amygdale. Description, p. 19.

Explanation of Plate II.

Magnification × 20. Ordinary light.

FIG. 1. *Tholeiite* (Talaidh type). Kielder Viaduct dike, Northumberland (no. 310). The texture is finer than in the Brunton type and sheaf-like bundles of pyroxene largely take the place of granular aggregates. Description, p. 26. Analysis, p. 27.

FIG. 2. *Tholeiite* (Talaidh type). Crookdene dike, Northumberland (no. 311). The texture is identical with that shown in the preceding figure, but is broken by four small amygdales. The top one (*a*) is filled with chlorophaeite, chalcedony, and quartz. The other three, in order, from left to right, are occupied by (*b*) mesostasis; (*c*) mesostasis followed by calcite and chlorophaeite; (*d*) chlorophaeite and calcite.

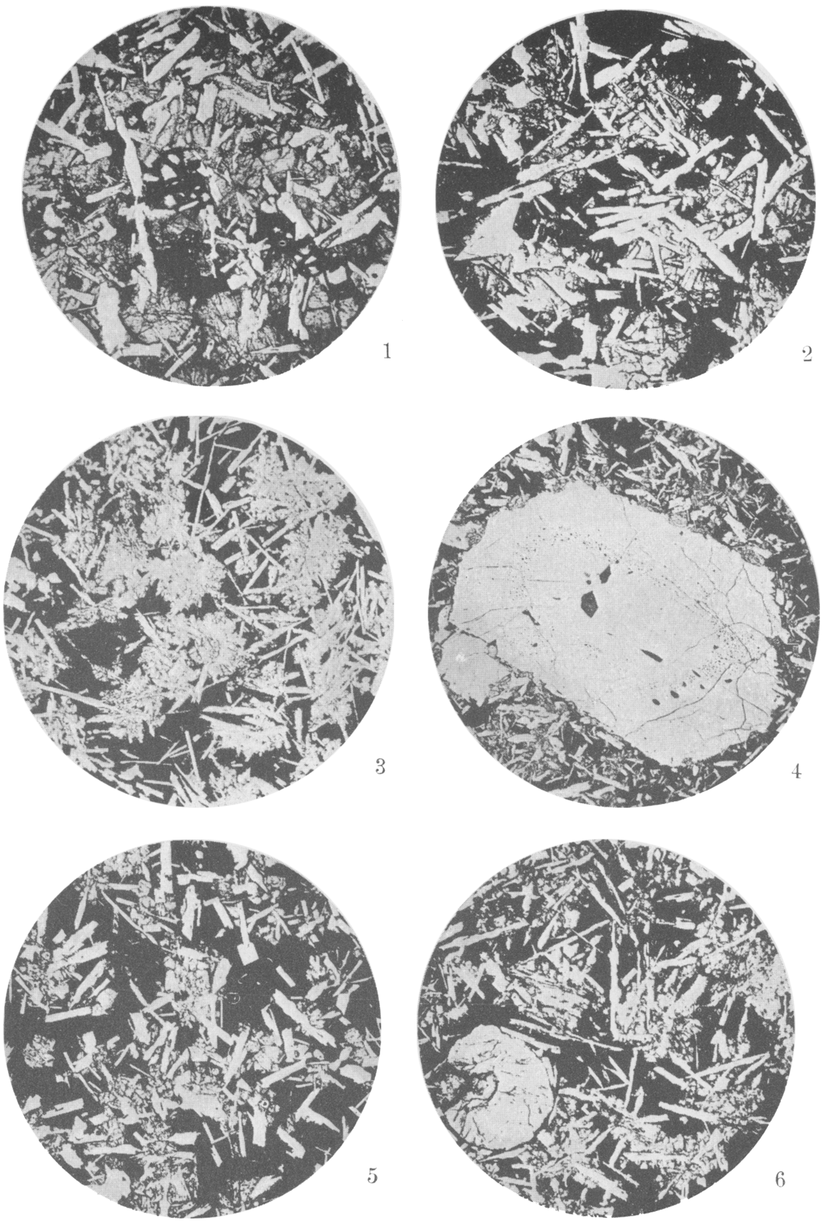
FIG. 3. *Tholeiite* (Acklington type). Acklington dike, near Newton, south-east corner of the Cheviots, Northumberland (no. 302). Here the felspars are in broader laths and the pyroxenes are characteristically granular. Description, p. 29. Analysis, p. 31.

FIG. 4. *Tholeiite* (anorthite-bearing Acklington type). Coley Hill dike, near Newcastle-upon-Tyne (no. 376). The field illustrates the body of the rock (anorthite not being shown) and includes an excellent example of a mesostasis-filled amygdale. Description, p. 31. Analysis, p. 32.

FIG. 5. *Porphyritic tholeiite* (Cleveland type). Hebburn dike, Boldon colliery, Co. Durham (no. 380). The field shows phenocrysts of plagioclase and pyroxene in a groundmass of Acklington type. Description, p. 34. Analysis, p. 35.

FIG. 6. *Porphyritic tholeiite* (Cleveland type). Cleveland dike, Bolam quarry, Co. Durham (no. 412). A small porphyritic crystal of pyroxene and part of a corroded phenocryst of plagioclase with inlets and inclusions of mesostasis are shown in a groundmass of Acklington type. Description, p. 36. Analysis, p. 39.

Acknowledgements. With the exception of figs. 3 and 4, plate I, which are the work of Mr. G. S. Sweeting, of the Geology Department of the Imperial College, the photomicrographs here reproduced were prepared by Mr. G. O'Neill, of the Geology Department of the Durham Colleges, from thin sections which, together with a large number of others, were also made for this investigation by Mr. O'Neill. For the willing and efficient services thus rendered we desire to add a special word of acknowledgement and thanks.



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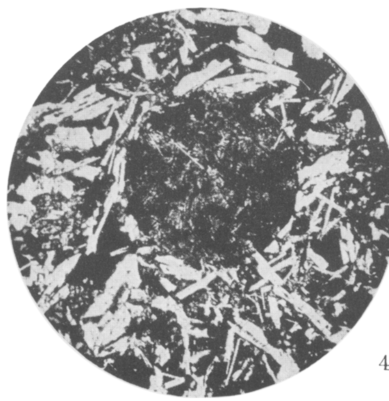

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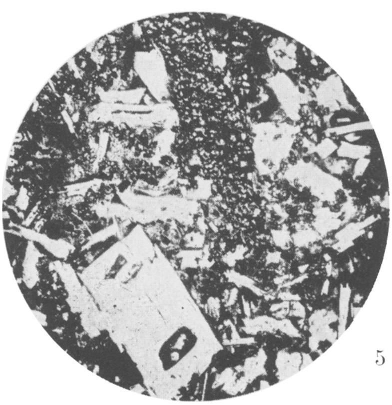

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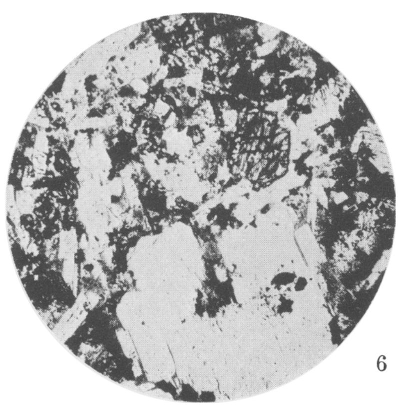

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