

*The part played by tholeiitic magma in the Carbo-Permian
vulcanicity of central Scotland*

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Summary. The end-Carboniferous quartz-dolerites form a curious tholeiitic interlude in the alkaline olivine-basalt vulcanicity which characterized central Scotland from the top of the Old Red Sandstone to the Lower Permian. The relationship of the two magma-types is discussed in the light of fresh evidence.

Introduction

THOUGH the work of Wahl (1908) on the diabases of Karelia established the importance of the tholeiitic magma-type in time and space, its relation to the equally important but more alkaline olivine-basalt was emphasized considerably later by Kennedy (1933) with special reference to Mull. Kennedy then regarded the tholeiitic magma as being associated only with continental masses and absent from the ocean basins while the olivine-basalt was, he considered, universal in its mode of occurrence. In 1950, however, Tilley showed that tholeiite had undoubted associations with oceanic islands, notably the Hawaiian group and Réunion where it occurred along with typical alkaline olivine-basalt.¹ Since then the subject has been investigated intensively by Tilley and others both in the field and in the experimental laboratory (Yoder and Tilley, 1962). One area, however, seems to demand further attention although it is a continental one. The Carbo-Permian province of central Scotland is representative, in the main, of alkaline olivine-basalt vulcanicity commencing at the base of the Carboniferous, or even at the top of the Old Red Sandstone and continuing into the early Permian. There was, however, a short but clear-cut interruption at the close of Carboniferous time when widespread injection of tholeiite with very different petrographic characteristics affected not only central Scotland but also the north of England, its best-known manifestation being the Great Whin Sill. The three most striking features of this phase of tholeiitic injection were: (i) the sudden change in the nature of the associated stress system; (ii) the apparently complete absence of volcanic lavas; and (iii) the marked poverty of types transitional between tholeiite and olivine-basalt. Extensive studies have

¹ In this paper alkali basalt and alkali dolerite = olivine-basalt.

been made of both magma-types but less attention has been given to their genesis and mutual relationship. By far the most comprehensive treatment of these problems is that of A. G. MacGregor (1948), though noteworthy contributions to the petrochemical and structural aspects have been made by Tomkeieff (1936) and Anderson (1951). The present article represents a reassessment of the position following further investigation of the tholeiites and of the sparse transitional types.

Field characters and age relations of the tholeiitic intrusions

Tholeiitic injection lasted only a short time, and seems to be confined to the end of the Carboniferous system, whereas olivine-basalt vulcanicity began probably at the top of the Upper Old Red Sandstone ('Kelso Traps') and continued into the Millstone Grit or Coal Measures resuming, after the brief tholeiitic interlude, in early Permian time. There is no evidence that tholeiite broke through to the surface and it is represented by dykes averaging 20 m in breadth and up to 130 km long trending E.-W. to ENE.-WSW. with aligned bosses of the same trend in the West Highlands and numerous sills up to 100 m thick intrusive into the Carboniferous strata of the Midland Valley. The dyke suite shows a change of trend from E.-W. to ENE.-WSW. from Strathmore to Buchan. Dykes become sparse towards the Atlantic but are strongly represented along the east coast. The basic dykes of south Norway and Sweden do not seem to belong to this suite (private communication from Professor T. F. W. Barth, and Hjemquist, 1939), but it is well represented in northern England by similar dykes in echelon form and by the Great and Little Whin Sills intrusive into the Carboniferous with a maximum thickness of 90 m. The Scottish and English injections may be linked on grounds of petrography, chemistry, and age relations but the English have no associated olivine-basalt vulcanicity.

The age of the Scottish tholeiites is quite clear. The dykes cut Carboniferous strata up to the productive Coal Measures, and also all the sills of olivine-basalt type which they encounter, but are themselves cut by Permian vents of olivine-basalt association (A. G. MacGregor, 1948, plate 8). Furthermore, they are contemporaneous and closely associated with the short-lived end-Carboniferous or Boreovician movements which were responsible for much E.-W. faulting in the Midland Valley. Some dykes are demonstrably feeders of sills and have risen along E.-W. faults while others may be thrown by these faults or may post-date them. No dyke cuts Permian strata (Anderson, 1951, p. 42). The north English intrusions have similar age relations but though the

Upper Carboniferous is absent here, the sills contribute pebbles to the Upper Brockram of the Lower Permian (Holmes and Harwood, 1928, p. 532).

General comparison of tholeiitic and olivine-basalt vulcanicity

The sharp contrast between the tholeiite and olivine-basalt activity is well seen in regions such as East Fife where sills of both types and of comparable thickness are intimately associated without the occurrence of any transitional types.

In the field the tholeiite and olivine-basalt intrusions show conspicuous differences, the chief of which is the absence of dykes from the latter and their abundance amongst the tholeiites. Columnar jointing is much more perfect in the olivine-basalts than in the tholeiites which form rectangular to rudely columnar blocks with distinctive and frequently spheroidal weathering producing a reddish-brown friable soil. The mesostasis and veining of the two sets is also dissimilar, being silicic and often vitreous in the case of the tholeiites and syenitic with a strong development of zeolites in the olivine-dolerites. Magnesian olivine is abundant in the olivine-basalts and often concentrated in picritic cumulates, which tend to be decomposed and friable, whereas it is much scarcer and almost always altered in the tholeiites. The pyroxene of the olivine-basalts is almost exclusively purplish titanite but that of the tholeiites, though always containing much light brown subophitic augite, generally has a high proportion of lime-poor varieties such as hypersthene or pigeonite forming elongated prisms of early crystallization. Pyrite is an abundant accessory of the tholeiites but rare in the olivine-basalts.

As opposed to these differences the two sets show certain resemblances. For instance the maximum thickness of the sills is of the same order, round 100 m, and their horizons of intrusion confined to two or three in a given area. Analcitization and albitization are common in both sets but composite and multiple intrusions more frequent in the olivine-basalts.

The association of tholeiitic with olivine-basalt vulcanicity is restricted to the Carboniferous strata of the Midland Valley of Scotland where both magmas are abundantly represented and the poverty of transitional types surprising. They are indeed confined to only two sill groups, that of the Dalmahoy syncline south-west of Edinburgh, fully described by Campbell and Lunn (1927), and the Milngavie group north of Glasgow, relatively briefly dealt with in the Glasgow memoir (Bailey, 1911, p. 135). The former sill complex is the fresher and more highly

differentiated. It has been well known for some time for its high content of chlorophaeite. The Midland Valley province of Scotland differs in a few ways from those of oceanic island groups where tholeiite and olivine-basalt are closely associated, e.g. Hawaii (Macdonald, 1949), Réunion (Lacroix, 1936), and the Faeroes (Walker and Davidson, 1936). All the latter are of much more recent date and contain transitional types in greater abundance. The Scottish area is in fact the only one where tholeiitic and olivine-basalt types may be readily distinguished in the field, though this is in some measure due to the extrusive habit of the oceanic examples which promotes a finer grain-size.

As a subject for investigation the Scottish area has one very important twofold advantage over other volcanic centres where tholeiitic and olivine-basalt magma types are closely associated: the igneous rocks were emplaced amid gently folded, fossiliferous strata of economic importance containing valuable deposits of coal and oil-shale. Some of these are now exhausted but others still attract detailed investigation, not only at the surface, but underground in mine workings and bore-holes. The stratigraphy of the area is thus known much more accurately than in comparable island provinces of purely igneous paragenesis, e.g. Hawaii, Réunion, and especially Mull where so much pioneer work has been done on the association and mutual relationship of basaltic magma types (Bailey and Thomas, 1924). Not only do the Carboniferous sediments of the Midland Valley give an accurate time-scale of the contemporaneous igneous activity in relative and sometimes even in absolute terms, but their bedding set up channels of potential weakness along which ascending magma spread laterally to form sills. Though the exact mechanism of sill formation is still problematical it is clear that the Carboniferous strata of central Scotland provided optimum conditions for this mode of intrusion which are absent from the structurally similar and conformably underlying Upper Old Red Sandstone. Thus flat-lying to moderately inclined sheets of magma both of tholeiitic or olivine-basalt type were formed abundantly in the Carboniferous. Furthermore, the products of crystallization-differentiation, whether rising or settling, could accumulate against their roofs or floors. In Mull, Réunion, and Hawaii sill formation was relatively slight owing to the poverty or absence of sedimentary strata so that crystallization-differentiation took place mainly in vertical chambers such as volcanic pipes whereby the accumulative products are generally lost to view.

The igneous succession in the Carboniferous and early Permian of

mid-Scotland has been described fully yet cogently by A. G. MacGregor (1948) and his brief digest of the main episodes and problems is given below in slightly amended form, preceding a general comparative discussion.

Episodes and problems of Carboniferous and early Permian vulcanicity (amended from A. G. MacGregor, 1948, pp. 140-141):

1. Initial igneous activity in Forth and Clyde areas in early Calceiferous Sandstone times characterized by eruption and intrusion of alkaline olivine-basalt magma associated with widespread felsic differentiates which are absent from succeeding episodes except granophyric phase of end-Carboniferous tholeiitic injection. In the uplands of North Ayrshire, in Renfrewshire and across the Firth of Forth these felsic rocks follow WNW. lines of weakness.
2. Availability of alkaline olivine-basalt magma for injection *long before* (Calceiferous Sandstone-Millstone Grit) and *shortly after* (early Permian) tholeiitic episode of (1).
3. Alkaline olivine-basalt common as lavas in Carboniferous and early Permian times and contrasting strongly with absence of extrusions from tholeiitic episode of (1) and (2) which is entirely intrusive.
4. Teschenite confined to sills and kyllite to sills and plugs as opposed to widespread long, thick dykes sometimes feeding sills of the tholeiitic episode.
5. Frequency of monchiquite dykes with alkaline or ultramafic xenocrysts in Permian vent agglomerates.
6. Abundance of alkaline basalt dykes (basanite, camptonite, monchiquite) over large parts of Scotland injected very shortly after the tholeiitic episode of (4).
7. Possibility that episode (6) extended into southern Fennoscandia.

Carboniferous and Permian stress conditions in central Scotland

The products of tholeiitic and olivine-basalt vulcanicity in Carboniferous and Permian times in central Scotland differ much more in their petrological characteristics than do the same magma-types in the island provinces referred to above, so that one is forced to seek for some governing factor which produced such a marked and abrupt change in the late Palaeozoic. On the whole the stress systems seem the most promising subject for investigation since they too show contemporaneous and clear-cut alterations to which the associated coalfield strata provide a useful guide.

As Anderson (1951) recognized, the problem is the nature of the shift from the Armorican to the Borcovician stress system. Though the former is here less conspicuous than in England, and may be confused with late Caledonian or proto-Armorican movements, there is nevertheless definite evidence of dislocation from the Lower Limestone to the Millstone Grit along the NE.-ENE. Dron Line, the Paisley Ruck, and the Inchgotrick and Dusk Water faults. These disturbances resemble many Armorican movements in England. They are demonstrably younger than the Calciferous Sandstone when there was WNW. and ENE. relief of pressure giving rise to the emplacement of dykes with the same trend, especially near the Misty Law volcanic vent in north Renfrewshire and that of Meikle Binn in the Campsie Fells. Though many of the dykes are basaltic others are of felsitic or trachytic composition (Richey, 1939, pp. 411-413). Elongated bosses of this trend are also found.

Following the cessation of this relief of pressure, dyke intrusion is negligible in the Forth and Clyde lava plateaus, and the subsequent vulcanicity extending at least into the Millstone Grit is associated with vents of the central types, often ash-filled and without exception of olivine-basalt parentage.

The extrusive activity and initial dyke formation was accompanied by sill emplacement, largely teschenitic, whose early initiation is proved by the occurrence of sedimentary veins of Calciferous Sandstone facies in the roof portions of East Lothian sills (Barrow, East Lothian Memoir, 1911, p. 101). Teschenitic sills are common in the Carboniferous Limestone Series but absent from both the Millstone Grit and Coal Measures of east Scotland, though in the west volcanic lavas were poured out in the Millstone Grit and teschenitic sill emplacement may have continued even longer. It would seem, however, that the majority of the later sills cutting the Coal Measures are post-Borcovician and injected shortly anterior to the development of the early Permian vents of olivine-basalt association. Either set of sills may contain layers of picritic cumulates probably formed at lower levels and composite intrusions are numerous.

The abrupt change from the Armorican to the Borcovician stress took place during the Stephanian and in the Midland Valley gave rise to strong tension representing relief of pressure first from N. to S. and slightly later from NNE. to SSW. (Anderson, 1951, p. 42). This resulted in widespread faulting normal to these directions accompanied by abundant intrusion of long thick dykes with the same trend, the magma frequently spreading laterally to form sills. This stress was, however, short-lived

for the subsequent early Permian sills, vents, and lavas of olivine-basalt parentage were emplaced under quite different tectonic conditions which were responsible for the injection of WNW. monchiquite dykes. This last magma contains numerous ultrabasic and alkaline xenocrysts of plutonic habit and similar to those found in the vents of East Fife.

Perhaps the chief difference between the Borcovician tholeiitic injection and the preceding and following olivine-basalt vulcanicity is the much greater petrological uniformity of the tholeiitic magma. It would seem that the great dykes of quartz-dolerite welling up E.-W. tensional faults at the end of the Carboniferous acted as conduits from an extensive intratelluric reservoir of equally uniform magma which was untapped either before or after the Borcovician interlude. We must now attempt to account for these circumstances since they form the major problem under discussion.

Petrology, chemistry, and differentiation of tholeiitic and olivine-basalt magmas

Petrology. The chief petrographic characters of the two contrasting magmas have been already mentioned. In thin section the differences between rocks of tholeiitic and olivine-basalt parentage are so sharp that they are at once distinguishable. Apart from the general uniformity of the first group the strong development of pale, elongated early crystallizing lime-poor pyroxene is highly characteristic and also the occurrence of abundant micrographic or vitreous mesostasis. The olivine-basalt derivations show much more variation in the proportions of the chief minerals and have purplish titanite as their main pyroxene. The amount of olivine is extremely variable and the mineral often unaltered and the mesostasis is invariably alkaline but non silicic.

Tholeiitic intrusions often have fresh chilled contacts whereas those of olivine-basalt derivation are seldom exposed and almost always altered, particularly in teschenitic sills. Observation of the phenocrysts in tholeiitic contact basalts indicates that olivine (now serpentized) was the first mineral to separate, being closely followed by augite or lime-poor pyroxene and plagioclase (An_{55-70}). Owing to alteration no estimates can be made for the corresponding contacts of olivine-basalts, and one is forced to use the very similar but fresher Tertiary dyke rocks of the Hebridean swarms as an analogy (Walker, 1957). Here olivine has undoubted priority followed by labradorite with pyroxene distinctly later. It is the early separation of abundant olivine and its tendency to settle by gravity in a fluid, alkaline magma that give rise to the abundant

picritic cumulates associated with the Carboniferous, early Permian, and Tertiary sills of olivine-basalt magma-type.

It should be noted that the proportions in which the contact phenocrysts occur in tholeiitic contacts are often similar to those of the same minerals in the unchilled rock and may thus form a reasonably reliable guide as to the course of crystallization (Walker, 1956, pp. 87-88). The

TABLE I

| | 1 | 2 | 3 | 4 | 5 | 6 |
|----------------------------|------|------|------|------|-----|------|
| Plagioclase (F) | 5.7 | 48.3 | 7.1 | 48.3 | 4.0 | 52.7 |
| Pyroxene (P) | 2.5 | 35.2 | 3.7 | 31.7 | — | 25.2 |
| Olivine (O) | — | — | — | — | 5.0 | 14.9 |
| $\frac{P \times 100}{P+F}$ | 30.5 | 42.1 | 34.1 | 37.6 | — | 32.3 |

1. Average percentages of contact phenocrysts from 42 chilled edges of tholeiitic intrusions from U.K., U.S.A., and S. Africa (Walker, 1957).
2. Averages of minerals in (1) from centres of same intrusions.
3. Average percentages of contact minerals from 7 chilled edges of Scottish Borcovician tholeiitic intrusions.
4. Averages of minerals in (3) from centres of same intrusions.
5. Average percentages of contact minerals from 19 chilled edges of U.K. Tertiary dykes.
6. Averages of minerals in (5) from centres of same intrusions.

same is true of the olivine-basalt group if one is justified in using the Tertiary swarms as an analogy. It is at any rate clear from microscopic data (table I) that pyroxene occurs in much greater abundance in undifferentiated tholeiitic rocks which is in keeping with its earlier appearance among the contact phenocrysts, and that in the olivine basalt it is of later crystallization and considerably less in quantity.

Chemistry. The chemical variation of the two magma-types is easier to show in graphic form than modal, for hydrothermal processes, which so often cause marked alteration in thin section, may leave the bulk composition of the rock relatively unchanged. It is thus possible to demonstrate the uniformity of the undifferentiated tholeiitic magma by a simple diagram (fig. 1) showing the range of the main oxides. A comparison with the much greater chemical variation of the olivine-basalt group is better illustrated by the ordinary FMA diagrams where the narrow band of variation outlined by the tholeiitic points contrasts strongly with the marked scattering of those representing the olivine-basalt derivatives (figs. 2 and 3). But the best means of distinguishing chemically between the two magma types is undoubtedly the alkali-

silica diagram (fig. 4), which shows a definite gap between the upper hollow circles of the olivine-basalt types and lower solid circles of the tholeiites.

Differentiation. In many ways the tholeiitic rocks of central Scotland are typical of this magma-type (Walker, 1953), but show even less tendency than normal towards crystallization-differentiation. The usual tendency of iron enrichment is here minimized, for instance, by the

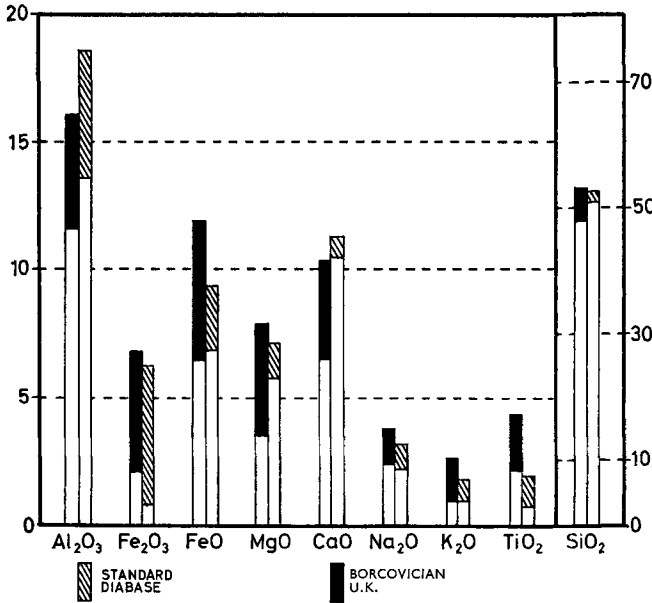


FIG. 1. Range of main oxides in 50 U.K. Borcovician tholeiites compared with range for standard diabase (single sample determined by 30 analysts, U.S. Geol. Surv. Bull. 980, 1951, pp. 10-11), U.K. analyses from Guppy, 1931 and 1956; Holmes and Harwood, 1928, Tomkeieff, 1929; and Walker, 1952.

early separation of iron-ore aided possibly by high oxygen partial pressure. Furthermore there seems no tendency for the early forming heavy minerals olivine and pyroxene to settle by gravity as in the Karroo, Palisadan, and Tasmanian provinces (Walker, *ibid.*) These tendencies are less marked in the co-magmatic intrusions of the Whin Sill region where one possible case of orthopyroxene settling has been recorded (Tomkeieff, 1929, p. 102) and the variation along the liquid line leads to dolerite pegmatites showing slight absolute enrichment in iron rather

than the curious granophyric types which characterize the upper portions of so many of the thicker quartz-dolerite sills of the Midland Valley.

The maximum thickness (100 m) of these Midland Valley and north English intrusions is admittedly on the low side to promote appreciable crystal settling but may not inhibit it in some cases (Grubb, 1961).

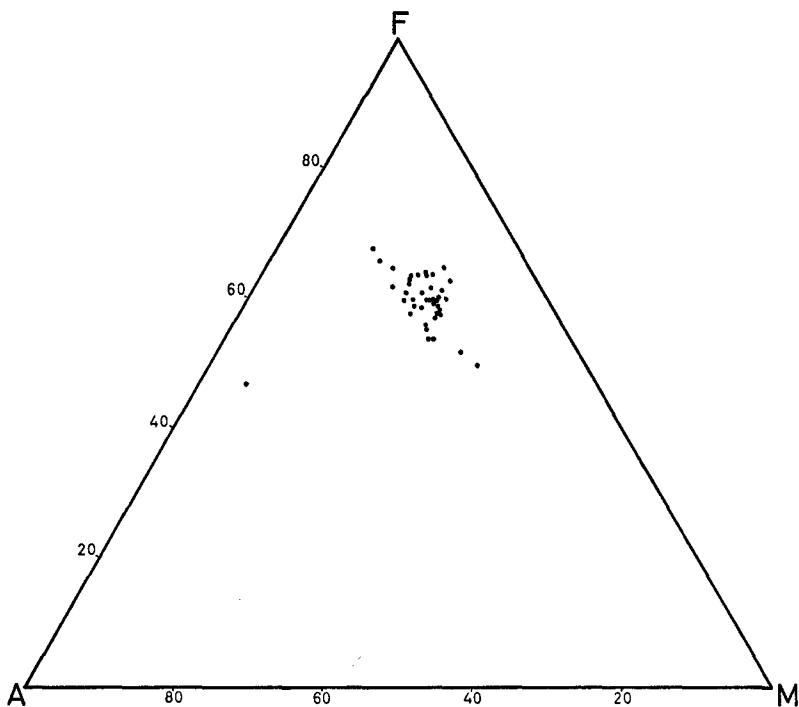


FIG. 2. FMA diagram of Scottish Borecivician tholeiites. Guppy, 1931, 1956; Walker, 1952.

In the olivine-basalt sills, which are mainly teschenitic, crystallization-differentiation is much more marked although some of them are even thinner. This is to be expected of a fluid aqueous magma in which early magnesian olivine separates in abundance and therefore sinks readily. Picritic cumulates are accordingly common though there is a definite tendency for the magma to be emplaced by a succession of heaves leading to the production of composite sills. It is difficult, moreover, to determine at what level the gravitational settling occurred.

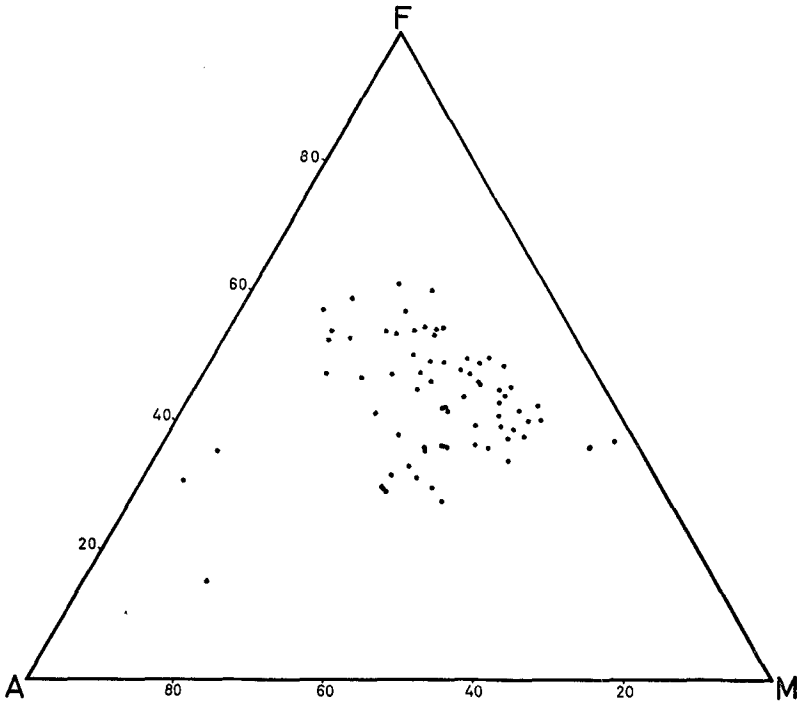


FIG. 3. FMA diagram of Scottish Carboniferous and Permian olivine-basalt types.

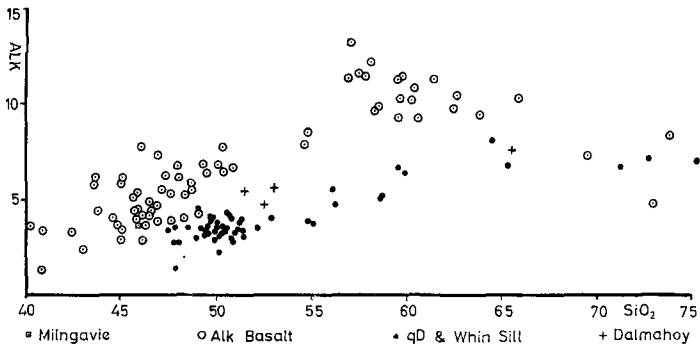


FIG. 4. Alkali-silica diagram of Scottish olivine-basalt types from Carboniferous and Permian (Alk Basalt \odot), Borecovician tholeiites (qD and Whin Sill \bullet), Milngavie sills \square , and Dalmahoy sills $+$. Analyses from Guppy, 1951 and 1956; Walker, 1952; Holmes and Harwood, 1928; Campbell and Lunn, 1927; and new analyses by W. H. Herdsman of Milngavie sill.

Transitional types

Only two sill groups are at all transitional, those of Milngavie and Dalmahoy, the latter being more varied and thoroughly investigated (Campbell and Lunn, 1927). The alkali-silica diagram of fig. 4 shows clearly that both are chemically intermediate between tholeiite and

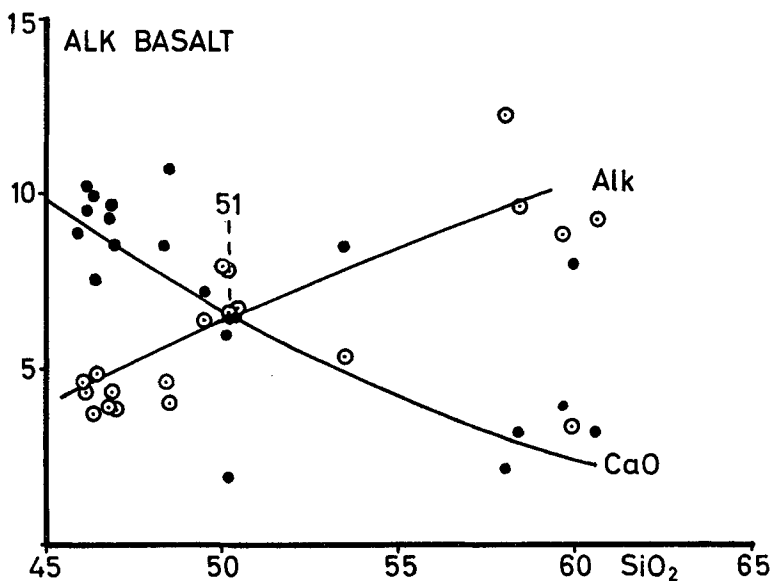


FIG. 5. Alkali-lime index of olivine-basalt types from Carboniferous of Midland Valley. Analyses from Guppy, 1931 and 1956.

olivine-basalt especially the Dalmahoy group which covers a wide differentiation range. Here the analyses allow the alkali-lime index to be determined (figs. 5, 6, 7) and the Dalmahoy sill again falls in an intermediate position with an index of 56 on the border of the alkali-calcic division between tholeiitic Northfield sill (Walker, 1952) with 60 and the alkali olivine-basalts with 51 (Peacock, 1931). The Dalmahoy differentiation trend is towards rhyodacite rather than trachyte, for the most felsic veins contain 18.5% of normative quartz. There is no tendency towards iron enrichment.

Petrologically the Dalmahoy sills are of individual character. The augitic clinopyroxene and the fresh interstitial glass of the normal rock resemble superficially the corresponding minerals in the Kinkell tholeiite

(Walker, Vincent, and Mitchell, 1952) but the plagioclase is much more sodic (An_{44} against An_{56}).

Field relations help little. Stratigraphically the Dalmahoy sills seem linked to extrusive mugearites near the base of the Carboniferous and

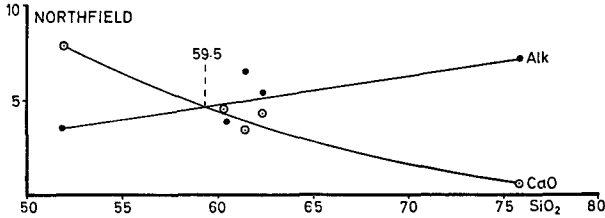


FIG. 6. Alkali-lime index of quartz-dolerite types from Northfield Sill. Analyses from Walker, 1952.

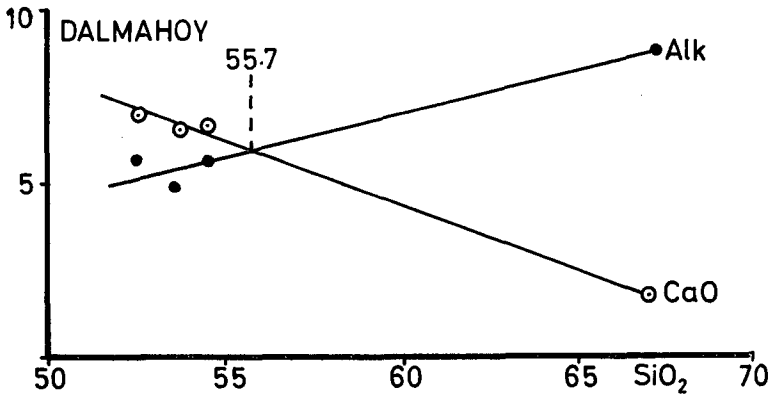


FIG. 7. Alkali-lime index of types from Dalmahoy Sill. Analyses from Campbell and Lunn, 1927.

resemble them to a certain extent in chemical composition but they are quite different petrologically. The only E.-W. Borcovician tholeiitic dyke in their neighbourhood (Ravelrig and Dalmahoy House) is of quite different character and jointing, the Dalmahoy escarpment being closer in appearance to the columnar teschenitic sills. It is thus evident that the Dalmahoy sills cannot be satisfactorily linked with either the E.-W. quartz dolerites or the sills which they feed and still less with the teschenitic group.

The Milngavie sills are somewhat indeterminate in the field but their purple clinopyroxene is of teschenitic type. Their mesostasis contains

neither quartz nor olivine and is much calcified (3.70% CO₂ in the analysis) so that it can only be classed as individual in character. There are no veins or associated dykes, and their horizon varies between the top of the Calciferous Sandstone and the bottom of the Carboniferous Limestone. Perhaps the most definite difference between the transition rocks and the Borcovician tholeiites is shown by the mineral composition as given in table II, where the modes of the Dalmahoy and Milngavie

TABLE II

| | 1 | 2 | 3 |
|------------------------------|------|------|------|
| Felspar (F) | 46.5 | 59.0 | 47.4 |
| Pyroxene (P) | 33.6 | 14.6 | 26.4 |
| Olivine | 0.3 | — | 4.4 |
| Iron ore | 8.7 | 5.4 | 5.0 |
| Mesostasis | 10.9 | 16.6 | 21.2 |
| $\frac{P \times 100}{P + F}$ | 42.0 | 20.0 | 35.8 |

1. Mean mode of 34 undifferentiated Scottish Borcovician tholeiites.
2. Mode of Dalmahoy tholeiite, Kaimes Quarry.
3. Mode of Milngavie dolerite, Dam of Milngavie reservoir.

rocks are compared with the mean of thirty-four Scottish Borcovician tholeiites newly determined for this paper. The relatively low pyroxene/felspar ratio of the two transition types is also noteworthy.

Thus the Dalmahoy and Milngavie sills, though bearing superficial resemblances to both the tholeiites and olivine-basalts, can only be regarded as individual phases of injection with no clear genetic connexion with either magma-type.

Abnormal Borcovician tholeiites of the West Highlands

The Whin Sill dolerites differ slightly from the co-magmatic Borcovician intrusions of mid Scotland, having a finer texture and a variation trend towards dolerite-pegmatite slightly enriched in iron, and in Scotland itself a group of intrusions round Lochs Shiel and Sunart show abnormalities of comparable magnitude. These rocks form elongated bosses trending E.-W. like the normal dykes. Three of them from near Strontian, Dalilea, and Arisaig have been briefly described by the Geological Survey and those from Strontian and Arisaig have been analysed (Guppy, 1956). All three have been re-examined and analysed micrometrically by the writer (table III).

The chemical and micrometric analyses of the normal rock from these intrusions differ little from the mean for the Scottish Borcovician suite

except for an abnormally high proportion of olivine and high percentage of MgO in the Strontian boss. The optical properties of the main constituents in all three are quite normal.

In one respect the Dalilea boss is unique. It has caused appreciable mobilization and recrystallization of the surrounding quartzo-felspathic Moine Schist with development of considerable micropegmatite. The only comparable occurrence of such a phenomenon is in the East Lomond sill of Fife (Walker, 1958) where it is on a microscopic scale.

TABLE III

| | 1 | 2 | 3 | 4 |
|------------------------------|------|------|------|------|
| Felspar (F) | 50.2 | 56.7 | 52.3 | 46.5 |
| Pyroxene (P) | 36.8 | 30.0 | 33.4 | 33.6 |
| Olivine | — | 5.3 | 2.1 | 0.3 |
| Iron ore | 5.4 | 3.4 | 4.2 | 8.7 |
| Mesostasis | 8.5 | 4.6 | 8.0 | 10.9 |
| $\frac{P \times 100}{P + F}$ | 42.3 | 34.8 | 38.8 | 42.0 |

1. Mode of boss Morroch Point, Arisaig.
2. Mode of boss 1300 yd N. 20° W. of Longrigg, Strontian.
3. Mode of boss of Dalilea.
4. Mean mode of 34 Scottish Borcovician tholeiites.

Mode of emplacement and magmatic synthesis of olivine-basalt and olivine

It is clear that the olivine-basalt magma, whether pre- or post-Borcovician, was greatly diversified by crystallization differentiation in a fluid alkaline medium. The mode of emplacement, however, remains doubtful. The SW. dyke swarms associated with the great vents of Misty Law and Meikle Binn indicate ascent through fissures in early Carboniferous Sandstone times, but A. G. MacGregor (1948, pp. 146–147) also suggests continued fissure feeding for the later Carboniferous vulcanism though linear conduits are almost absent at the surface. The formation of explosive vents of central type is considered by him to take place at high levels through advanced crystallization-differentiation on vertical fissures and he points to a similar mode of origin in Permian times when comparable vents demonstrably arose on monchiquite dykes. A. G. MacGregor (1948, pp. 147–148) also criticizes the vent on sill-cupola theory of Daly (1933, p. 392) as well as Tomkeieff's petrochemical synthesis of the two magmas (1937). It must be admitted that A. G. MacGregor's hypothesis is the only one to be backed up by ample field and microscopic evidence. Amplifying the crustal layering suggestions of Anderson (Kennedy and Anderson, 1938, p. 59) he postulates the sequence

illustrated by fig. 8 (modified from A. G. MacGregor, 1948, pp. 144-145), viz. (1) fusion at *B* in early Calciferous Sandstone times; (2) fusion at *A* in late Calciferous Sandstone times; (3) fusion at *C* in Permo-Carboniferous times; (4) fusion at *A* in Permian times. A. G. MacGregor does not favour Kennedy's suggestion of simultaneous large-scale melting at *B* and *C* for the two magmas do not appear to have mingled (Kennedy and Anderson, 1938, p. 37), nor does he believe that the Lower Intermediate Layer was uniform, assimilating solid granitic or tholeiitic material during ascent, since there is no petrological evidence of this. A. G. MacGregor's theories have so far remained unchallenged and are accepted by the present writer in spite of their somewhat revolutionary nature. They have the obvious advantage of explaining satisfactorily the Borcovician injection of tholeiitic magma, the subject now under discussion, as well as the olivine-basalt vulcanicity which preceded and followed it.

Final comparison of Scottish Borcovician tholeiite magma with tholeiites of oceanic islands and their relationship to associated olivine-basalt

The petrological difference between the end-Carboniferous quartz-dolerites of mid-Scotland and the associated rocks of olivine-basalt derivation is, as has been emphasized above, very marked. It is indeed much greater than the corresponding differences between the two magma-types in the oceanic islands where they are associated, viz. Hawaii, Réunion, and, to a lesser extent, Mull. Not only are transitional types absent, as has been shown, but the field characters of the two mid-Scottish suites are so very different that one is forced to envisage a completely divergent mode of origin.

The active Hawaiian province has been investigated in unexampled detail by Macdonald (1949) *et al.*, and the subsequent experimental work of Yoder and Tilley (1962) has shown that at elevated pressures the two magma trends can be derived from a liquid of the same bulk composition. These authors believe then that a single parental magma exists from which all derivative magmas may be obtained by suitable reversible or irreversible physicochemical processes.

Detailed descriptions of such provinces as Hawaii (Macdonald, 1949) and Réunion (Lacroix, 1936) bear out the theories of Yoder and Tilley and it is to be observed that both contain rock-types which may be regarded as transitional from all points of view. We seem to be dealing here with an initial magma capable of differentiating either from tholeiite to rhyolite or from alkali basalt (= olivine-basalt) to trachyte, according to the existing physicochemical conditions. Not only are

gradual transition types present but the optical properties of the mineral series are also gradational. The available data for Réunion (Lacroix, 1936) and for Mauritius (Walker and Nicolaysen, 1954) indicate the same, though in the latter island there is a normatively undersaturated olivine-poor or -free series corresponding to a truly tholeiitic.

CRUSTAL LAYERS IN A KRATONIC REGION

(Modified after A. G. MacGregor, 1948, p. 144)

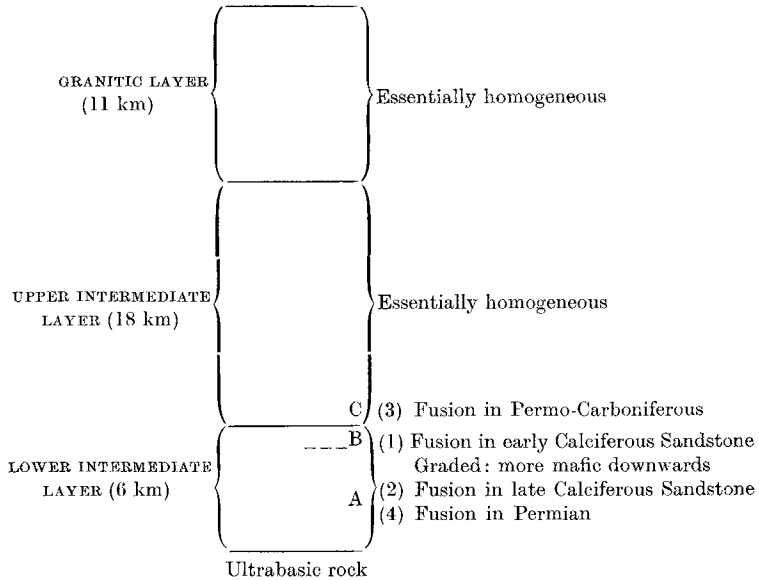


FIG. 8.

In the end-Carboniferous tholeiites of mid Scotland no such gradation of rock-types or mineral series occurs and a single parental magma is much harder to envisage. The short-lived Borcovician stresses undoubtedly produced vertical fissures through which a saturated and undifferentiated basalt magma of very uniform composition ascended rapidly. There is evidence also that this magma came from a reservoir having no contact with deep-seated ultrabasic material for there is a complete absence of olivine nodules or indeed of any xenoliths in the quartz-dolerites.

A. G. MacGregor's modification of Anderson's concept of crustal layering seems the only one to fit the facts and the Borcovician stresses alone seem competent to produce such marked tension as to lead up the

tholeiitic magma from a higher level reservoir with sufficient speed as to prevent appreciable differentiation.

Lastly, one anomaly should be noted though no explanation has been found. The sequence of crystallization in the Borcovician tholeiitic intrusions as indicated by the proportions of the contact phenocrysts is the same as that given by Macdonald (1949, pp. 1470-4) for the Hawaiian province: viz. olivine, plagioclase, hypersthene (where present), augite, and iron-ores (which may be earlier in Scotland). Yet the f norm of Barth, which is generally a very good guide as to the relative order of crystallization of plagioclase and pyroxene, is 126 for the Hawaiian average, indicating crystallization to commence within the pyroxene field, whereas 111 for the Borcovician tholeiites seems to indicate that plagioclase was definitely the first to separate.

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