Chapter 5 Review of Tertiary igneous activity in Britain

After the completion of the survey of the Island of Mull and the publication of the results in 1924, there remained, except for St. Kilda, only one important centre of Scottish Tertiary igneous rocks which had not received detailed description. This centre, situated in the peninsula of Ardnamurchan, has been mapped and studied in detail, while additional information has been forthcoming from other districts where Tertiary rocks are developed, namely, Ireland, Arran, the Outer Hebrides, the Shiant Isles, and Iceland. The time seems ripe, therefore, for a brief general review of Tertiary igneous activity. In the following pages, a summary is attempted of our knowledge of this igneous action, in which stress is laid on the more important points of general interest which have arisen from time to time.

Igneous action referable to early Tertiary times manifested itself over a large part of Britain, but was most pronounced in the West of Scotland and North-east Ireland, where, fortunately, the post-Cretaceous age of the igneous rocks as a whole can be clearly demonstrated.

This activity can be divided partly in accordance with its mode of expression and partly according to time sequence into four main episodes.

1. The outpouring of basalt lavas of enormous lateral extent and great aggregate thickness.
2. The establishment of central vents and the formation of vent-agglomerates.
3. The intrusion of plutonic and hypabyssal rocks of divergent petrographical types at localized centres.
4. The intrusion of a multiplicity of directionally orientated dykes, mainly of basaltic composition.

The Plateau Lavas

The earliest and most pronounced episode was the extrusion over a vast region of flow upon flow of basalt lava. These flows were erupted without explosive violence, had great lateral extent, and generally rest with a close approximation to horizontality upon a denuded platform of Cretaceous or older rocks. Such flows occupy the greater part of Co. Antrim in Ireland, and much of Mull, Morven, and Skye in Scotland; while farther afield they form the Faroe Islands and the older part of the volcanic platform of Iceland. The regions in Britain covered by these lavas are probably but remnants of a vast lava-field which have escaped complete destruction at the hands of denuding agencies. These lavas, visibly occupying in Britain some 2000 square miles of country, from their general approach to horizontality, great lateral extent, and scenic characters, are known as 'plateau lavas', and find their parallel elsewhere in such great outpourings as have covered enormous areas in the Deccan of Peninsular India and the Snake River region of the United States of America.

That they were poured out over a land-surface is proved by the absence of intercalated marine detrital sediments, and by the frequent reddening of their upper surfaces, as well as by the occurrence of beds of bole due to deep subaerial weathering. That such decomposition was of a lateritic nature is proclaimed by the highly aluminous character of the boles and clays intercalated with the lavas of Antrim, Mull, and other regions.

Further, the generally non-explosive character of the eruptions is proved by the almost complete absence of angular ejectamenta or even of fine-grained tuffs and ashes. In Mull and Ardnamurchan, however, the lava episode commenced with the spreading out over the old rock platform of a thin but far-reaching layer of basaltic ash.

The post-Cretaceous age of the lavas of Antrim was established at an early date, but a more precise pronouncement by Forbes as to the age of the Hebridean lavas followed the discovery by the Duke of Argyll, in 1850, of leaf-beds and other lacustrine deposits intercalated with the basalts of Mull. Gardner in 1887 expressed the opinion that the flora of these leaf-beds proved the basalts to be of Eocene age, and Seward and Holttum in 1924 (Mull) saw no reason to dissent from Gardner's opinion.

The lavas, although of small individual thickness, must have collectively constituted a great lava pile of several thousands of feet. Cliff-sections sometimes show about a thousand feet of basalt in Mull and Skye, and two thousand feet in the

Faroe Islands, while Ben More in Mull, a mountain made of slightly inclined plateau basalt lavas, rises from sea-level to a height of 3169 ft. The present areal distribution of the plateau lavas in Britain is approximately as follows

	Square miles
North-east Ireland	1550
Skye	400
Mull	280
Morvern	50
Small Isles	18
Ardnamurchan	6

Petrologically the lavas present a remarkable consistency in type over the whole Hebridean region; for the most part they are olivine-rich basaltic and doleritic rocks that carry a highly-coloured titaniferous augite and occasionally have interstitial analcite and natrolite (crinanites).

In 1874 Judd expressed the view that the outpourings of plateau basalt were connected with central vents of Hawaiian type, and claimed Mull, Ardnamurchan, Rum, and Skye as basal wrecks of great central volcanoes. This explanation of the origin of the plateau lavas was, however, supplanted in general favour by that subsequently advocated by Sir A. Geikie. Geikie in 1880 and 1888, after visiting the lava-fields of western America, came to the conclusion that the plateau basalts were due to the quiet welling up of lava through a great number of fissures distributed over the whole area affected, and that their feeders were to be found among the abundant dykes that traverse the igneous province. Such an explanation was certainly tempting in view of the great lateral extent of the lava-field, the general horizontality of the individual flows, and the then unproved existence of anything in the nature of a central vent that could be connected with the outpouring of basic lavas. As detailed work progressed, however, it was recognized that the Tertiary dykes were in reality not equally distributed but were more or less restricted to definite belts of country, and that a large proportion of them belonged to late manifestations of igneous activity. Further, Mr. Bailey has demonstrated the former existence of a caldera-like vent in Central Mull, which is supposed to have been responsible for the outpouring of a great pile of lavas upon the top of the plateau group. As differentiation progressed within the reservoir that supplied the Mull plateau basalts, basic magmas of different composition came into being (Porphyritic and Non-porphyritic Central Magma-Types, p. 79 *et seq.*). These expressed themselves first as flows intercalated sporadically with those of the Normal Plateau Type, and were later responsible for the great pile of lavas connected with the central vent. The Mull lavas of Central Types succeed the plateau lavas with general conformity, and in the Faroe Islands, also, a great thickness of such outpourings, characterized by porphyritic felspar, followed the eruption of the normal plateau basalts.

Although there has been a general acceptance of the fissure origin of the plateau basalts, we find, when we come to examine the evidence, very little of a positive character to support this view. In fact, there are many features of the lava-field that appear to require an alternative explanation. It is clear from the writings of Sir Archibald Geikie<ref>Sir A. Geikie, The Ancient Volcanoes of Great Britain, vol. ii., 1897, p. 464.</ref> that he did not insist on a uniformly distributed series of fissures to feed the flows, for, when speaking of the later plutonic intrusions, he says that these were mainly determined by the position of the larger or more closely clustered vents of the plateau-period, where points of weakness consequently existed in the terrestrial crust.' Also, of all the dykes encountered within the existing lava-field no undoubted case of a dyke feeding a lava-flow has been recorded, and this in spite of abundant cliff-sections. If we assume that the lavas emanated from dyke-fissures it is remarkable that in certain districts we find very few dykes traversing the platform of older rocks overlooked by the basal escarpment of the plateau lavas. Further, the basic dykes are clustered together into longitudinally orientated swarms that pass through, and are most abundant in the vicinity of the localized plutonic intrusions (p 343), facts which go to prove that the loci of these centres were established prior to the main period of dyke-intrusion.

In spite of the great similarity in type which exists between the plateau lavas of the various disconnected regions, there are small but important differences in matters of succession that suggest eruption from independent centres. For instance, in Antrim a series of rhyolites and a period of great erosion divide the basalts into a lower and an upper series, while in the lower series Central Types of lava (*e.g.* Giant's Causeway) are not infrequent. Central Types are also a feature of the lower part of the Plateau Group in Staffa and South-west Mull, the sequence in the latter district differing in this respect from other parts of the island. In Central Mull the normal succession of plateau basalts is broken at about 2000 ft. from the base by a thick flow of mugearitic composition, and the plateau series is succeeded by a great thickness of flows erupted from a caldera. In Canna, conglomerates and agglomerates of considerable thickness seem to occupy a low horizon in the plateau series, while at Portree in Skye, and Carsaig in Mull, volcanic agglomerates and breccias are interbedded with the plateau lavas, near their base.

Although apart from Mull there is no direct evidence of a central vent erupting basic lavas, a logical deduction is that similar conditions may have prevailed elsewhere, and thus Judd's contention that the plateau basalts originated from a series of central volcanoes of Hawaiian type cannot be dismissed as untenable. There is in fact little doubt that the Hawaiian type of centralized volcano fulfils many of the conditions demanded by the observed facts. Such vents are capable, without explosive violence and in the absence of an elevated crater, of covering thousands of square miles with thin layers of lava; and one such volcano, if comparable to Mauna Loa in extrusive power, might well account for a basaltic plateau as large or even larger than that embracing all the known Hebridean occurrences of plateau lavas. Away from the areas at present occupied by the basalts, and occasionally breaking through the lower lavas, we encounter plugs of plateau-basalt composition, and these may quite well have played a part in the formation of the basalt plateau.

Tertiary Central Complexes

Following upon the eruption of the plateau lavas, we enter a period during which the centralization of the igneous activity becomes increasingly obvious, by the establishment of vents and the production of vent-agglomerates, and by the intrusion of hypabyssal and plutonic rocks at clearly defined centres. These centres of localized intrusion are for the most part distributed along an approximately north and south line bordering the western coast of Great Britain and east coast of Ireland (Figure 4). Where their relations to other Tertiary rocks can be studied the intrusions invariably succeed the lavas and sometimes can be observed to follow the formation of central vents (p. 75). Those of unquestionably Tertiary age are Slieve Gullion, Carlingford, and the Mourne Mountains in Ireland, and Arran, Mull, Ardnamurchan, Rum, Skye, and St. Kilda in Scotland. The north and south alignment of these centres, other than St. Kilda, appears to be more than a matter of coincidence, and points to a definite determining line of crustal weakness, unrelated to the direction followed by the Majority of the dykes that form the respective swarms. The Tertiary age of certain less important centres of intrusion may be inferred from the rock-types and structures presented by the various masses, and of these may be mentioned the Wolf Rock (phonolite), south of Land's End, Lundy Island (granite), off the north coast of Devon, and Ailsa Craig (Riebeckite-microgranite). In addition, there are minor plugs and bosses, such as those of the north of Mull, South Argyll (Sithan-t-Sluin), Antrim, and Galway, which are removed from the major plutonic centres but which take their place in the general scheme. A Tertiary age for the gabbro and granophyre of Carrock Fell in Cumberland has been suggested by Dr. Harker on account of their general similarity to Scottish Tertiary types, but precise evidence of their post-Palaeozoic age is wanting.

The rock-types presented by the various centres are in many cases remarkably similar, gabbros and granophyres, which may be regarded as complementary types, being dominant. Such rocks, either alone or in conjunction, constitute the bulk of the intrusions of Slieve Gullion, Central Arran, Mull, Ardnamurchan, Rum, Skye, and St. Kilda, gabbros being more prevalent in some and granophyres in others. Granites are the chief types in the Mourne Mountains, Lundy Island, and North Arran, while in Ardnamurchan tonalitic and monzonitic masses form the latest members of the plutonic sequence. Rocks of alkaline affinities such as alkalisyenites (Mull), trachytes (Mull), riebeckite-microgranite (Ailsa Craig), and phonolite (Wolf Rock) occur as small isolated bodies of plug-like form, but seldom, except in the agglomerates of the vents, enter into the composition of the central complexes.

The manner of intrusion and the form of She plutonic bodies has been the subject of much consideration. In Skye Dr. Harker suggested that the main intrusions were of laccolithic nature, and the North Arran granite has certainly produced a dome-like elevation of the surrounding rocks. In Mull, Ardnamurchan, Central Arran, the Mourne Mountains, Carlingford and Slieve Gullion, however, the ring-dyke type of intrusion appears to be exhibited by all the more important masses, and evidence of laccolithic intrusion, except in the case of certain smaller masses, has not been observed. In Central Mull there is a remarkable series of concentric folds partly surrounding the South-east Caldera. These have been attributed to the pressure of an acid magma, intruded along the caldera margin.

Vents and vent-agglomerates

Frequently, as in Central Arran and Ardnamurchan, the formation of explosion-vents is the first real evidence offered of definitely centralized activity. Usually the vents are due to the uprise and explosive condition of an acid magma of alkaline affinities, which occupied the same magma reservoirs as were later responsible for the ring-dyke and other central intrusions of the respective areas.

In Central Mull such explosive activity as a recurring feature of the igneous cycle. There, the early caldera connected with the eruptions of basic lavas was followed by the intrusion of granophyre (Glas Bheinn), succeeded by the formation of extensive vents that were due to the explosive action of acid magma. Later still in the intrusive history, similar explosion-vents were again formed.

Often the vents are occupied mainly by masses of agglomerate consisting of shattered fragments of the country rock. Great masses of the vent-walls have occasionally slipped back into the vent, and thus blocks of plateau basalt, or of the Mesozoic rocks upon which the lavas rested, have been preserved, where otherwise all trace of such rocks has been removed from the neighbourhood by denudation (Arran). Other cases of the preservation of masses of plateau basalt may be instanced from Skye and Ardnamurchan.

Non-basaltic lavas are occasionally found within the areas of the vents, or, in a disrupted form, enter into the composition of the agglomerates. We may quote as examples the rhyolites of Mull and the pitchstones of Ben Hiant in Ardnamurchan. According to one interpretation the Sgùrr of Eigg pitchstone is a lava that filled a valley eroded in the plateau basalts.

Cone-sheets

Amost important class of centralized intrusion of hypabyssal type was first detected by Dr. Harker in Skye, when he discovered and mapped in the Cuillin Hills a great group of centrally inclined basic sheets. He demonstrated their circular distribution and regular inclination towards a focus situated within the great gabbro-intrusion of the Cuillins, and proved that, although younger than the gabbro, they were clearly related to the same intrusive centre. Such inclined sheets, or cone-sheets as they have been renamed in the 'Tertiary Mull Memoir, consist of relatively thin sheets, which, viewed as members of a suite, occupy conical fissures that have a common apex and common vertical axis. Generally the sheets are moderately open-spaced, but occasionally they may be so numerous and frequent as almost to obliterate the country rock into which they have been intruded. The apex to which the sheets converge may be designated the cone-sheet focus. Their outcrops, taken collectively, may be idealized as a series of concentric circles (Figure 5). The average inclination of the cone-sheets is as a general rule about 45°. There is, however, a definite tendency for sheets nearer to the centre to be more highly inclined than those farther away (Skye, Mull, Ardnamurchan). The central area around the axis is always devoid of cone-sheets.

Calculations from the inclination of the sheets bring out the interesting fact that in all the Tertiary centres where such sheets are developed the foci were situated at a depth of about three miles below the present surface. It also follows that such foci must have been located within or upon the surface of a reservoir capable of supplying magma to fill the fissures. This conclusion as to the depth of the cone-sheet foci is arrived at by plotting the underground continuation of the various suites of cone-sheets, assuming that the inclination of individual sheets is constant.

Cone-sheets are important features in Skye, Rum, Mull, Ardnamurchan, and Carlingford, and are clearly connected with the plutonic centres of these regions where there is evidence to show a relation between ring-dyke and cone-sheet intrusion. The idea of the development of cupolas on the main magma basin seems necessary to explain the origin of cone-sheets and ring-dykes. Such cupolas are assumed to be steep dome-like or paraboloidal upward extensions of the main magma-reservoir into relatively cool regions of the crust. From the nature of cone-sheets it is practically certain that their formation is due to an excess of magmatic pressure acting vertically upwards upon a relatively thin crustal covering, in a successful attempt on the part of the magma to raise its roof. Such was the suggested explanation of the formation of cone-sheets put forward by E. M. Anderson in 1924 (Mull), and all later work has tended towards its confirmation.

The uplift of the roof, with attendant doming of the central area above the magma-reservoir, must in every case of abundant cone-sheet injection have been of the order of thousands of feet, and an uplift of 4000 feet is regarded as the probable rise attributable to the cone-sheet intrusions of Centre 2 in Ardnamurchan (p. 178). As it appears that cone-sheet injection is dependent upon locally applied magmatic pressure there is no reason why such should not occur, or recur, whenever the magmatic pressure within the reservoir was sufficient to overcome the downward pressure of the crust. Such excessive magmatic pressure, accompanied by the intrusion of cone-sheets, was developed at more than one period and at more than one centre both in Mull and Ardnamurchan.

The magma that filled any particular suite of cone-sheet fissures was remarkably constant in composition, and this proves beyond doubt that all the fissures of any one set of cone-sheets were filled from a common source. Different suites, however, and cone-sheets related to different centres, usually show some magmatic variation. For instance, the early cone-sheets of Mull, belonging to the Southeast Centre of the island, are mostly olivine-dolerite, while the later cone-sheets of Mull (North-west Centre), as well as the Ardnamurchan and Carlingford suites, are chiefly of quartz-dolerite composition.

Even in a suite related to one centre there is evidence of some progressive magmatic change. For example, the earlier sheets connected with Centre 2 in Ardnamurchan consist of an outer and presumably older group of quartz-dolerites of the Normal Magma-Series, and an inner group for which a magma of Porphyritic Central Type was responsible.

Ring-dykes

The conception of ring-dyke intrusion was the result of work carried out by Messrs. Clough, Maufe, and Bailey on the cauldron subsidence of Glencoe. They found that outside a circular fault, which bounded an area of subsidence, plutonic rocks had been intruded in annular form, and to these intrusions the name ring-dyke was eventually applied on account of their vertical or almost vertical junctions. This circular fracturing and subsequent uprising of plutonic masses as annular intrusions was not recognized to be of wide application until the detailed mapping of Mull was taken in hand. Here ring-fractures and annular intrusions were found to be the dominant features. It is now realized that some, at any rate, of the plutonic masses of the Red Hills of Skye are of this nature, while in Ardnamurchan and Slieve Gullion typical ring-dykes are developed.

The general theory of subsidence, as originally enunciated for Glencoe, appears to be the only one that explains the observed facts, and therefore it is assumed that most of the plutonic rocks of the British Tertiary Centres have risen into their respective positions as the result of the subsidence into a magma-reservoir of a steep-sided conical crustal block (Figure 5). Such subsidence would cause the welling up of magma into the fissure that bounds the subsiding mass, and, if the ring-fracture reached the surface, a central type of lava eruption would be likely to ensue, as in the case of the South-east Caldera of Mull. If, however, the subsiding block was detached from the under part of the solid crust, the fractures would not of necessity reach the surface and then the space formed over the subsiding mass would be filled with magma that would be continuous with the lateral steep-sided ring-dyke intrusion, but be more or less horizontal in disposition. Such conditions were claimed for certain granites of the Glen Coe district and appear to have been fulfilled in the Red Hills of Skye and the Mourne Mountains, and also in Ardnamurchan and Mull, where cappings of rock older than the intrusions upon which they rest suggest more or less horizontal extensions from ring-dykes beneath a roof of country rock.

Repeated subsidence at the same centre has often allowed further influxes of magma to fill reopened fissures, or to be injected up fresh circular fractures, with the result that we are presented with a succession of arcuate intrusions arranged about a common centre and vertical axis. As a general rule, in cases of repeated intrusion the older masses occur towards the outside of the complex and the younger occupy more central positions, as is exemplified by the ring-dykes of Centre 3 in Ardnamurchan and by the granites of the Mourne Mountains.

It would appear, in contradistinction to cone-sheets (p. 57), that the formation of ring-dyke fissures and the concurrent intrusion of magma are independent of excessive magmatic pressure but are consequent on crustal collapse.

It is interesting to note that the areal dimensions of the ring-dyke complexes lie between somewhat narrow limits, the average diameter being in the neighbourhood of five miles. In the appended table are given measurements of the various complexes made along maximum and minimum diameters:

	Direction of measurement.	Diameter in miles.
Ardnamurchan, Centre 1	N.–S.	4¼
Ardnamurchan, Centre 2	N.W.–S.E.	4¼
Ardnamurchan, Centre 3	N.W.–S.E.	3¾
	N.E –S.W.	4¼
Mull, Centre 1	N.E.–S.W.	6 approx.
Mull, Centre 2	N.W.–S.E.	5
Mull, Centre 2	N.E.–S.W.	5¾
Arran, Central Ring Complex	N.W.–S.E.	2¾
Arran, Central Ring Complex	N.E.–S.W.	3½
Slieve Gullion	N.W.–S.E.	7
Slieve Gullion	N.E.–S.W.	7
Carlingford	N.W.–S.E.	5¼
Carlingford	N.E.–S.W.	4¼
Eastern Mourne Mountains	N.W.–S.E.	6
Eastern Mourne Mountains	N.E.–S.W.	7½

It will be seen from the above table that the several ring-dyke complexes are seldom truly circular in form but exhibit eccentricity in varying degree, with one axis definitely longer than that drawn at right angles to it. It is noteworthy that when, as is often the case, the centre of ring-dyke intrusion moves to a new site, the movement takes place in the direction of the long axis of the earlier complex. Such is particularly noticeable in South-east Mull where the centre of intrusion moved to the region outlined by the Loch Ba ring-dyke, a distance of 2½ miles. In the case of Ardnamurchan, the eccentricity of the later ring-dyke complex is accentuated along an east-north-east axis, and the displacement of focus from Centre 2 to Centre 3 has taken place in this direction. The eccentricity of a ring-dyke complex and the direction of shift of the intrusive centre are probably both dependent upon the underlying magma-reservoir having a slightly asymmetric form.

Screens and cappings

The term screen was first applied by Mr. Wright while working in Mull to denote a narrow partition of older rock separating two steeply bounded intrusions. In Mull many arcuate screens are recognizable, intervening between ring-dykes.

Both in Mull and Ardnamurchan they are frequently of composite nature and may consist of agglomerates, lavas, and portions of older ring-dykes, and may be cut by cone-sheets that are earlier than the bounding ring-dykes. For example, the somewhat massive screen of Meall nan Con in Ardnamurchan is composed of basalt lava, agglomerate, and gabbro (p. 312). Having been contact-altered on both their inner and outer sides by intrusive rocks, screens usually show high-grade thermal alteration.

It has been pointed out that ring-dykes when in juxtaposition frequently exhibit merging junctions, and their relative age or even their separate existence may be a matter of doubt. The separation by a screen, however, along a portion of their outcrop may serve to demonstrate their individuality. In fact the importance of screens in unravelling the history of a complex cannot be stressed too greatly.

Cappings are also remnants of country rock, forming part of the roof of an intrusion, which have escaped complete denudation. Like the screens, they may be composed of any rock older than that with which they are in contact, such as pre-Tertiary sediment, basalt lava, agglomerate, or any older member of the plutonic complex.

Dykes and dyke-swarms

There is no suite of Tertiary dykes of definitely pre-plateau lava age, unless it be the camptonite dykes that in certain districts cut the older rocks beyond the basalt plateau in considerable numbers. The Tertiary age of these dykes is, however, open to grave doubt, for no typical camptonite has been found to cut either the Mesozoic sediments or the Tertiary lavas.

The dykes of which the Tertiary age is certain, and which cut the lava plateau, generally have a N.W.–S.E. direction, and are closely clustered together in broad, far extending, belts that pass through the major plutonic centres. Such belts of clustered dykes are known as dyke-swarms and may be seen to traverse the centres of Skye, Mull, Arran, and North Ireland ((Figure 4), p. 53). Similar linearly directed dyke-swarms passing through plutonic centres have also been described in connexion with the Lower Old Red Sandstone granites of Loch Etive and Ben Nevis. The Tertiary dykes are mainly of basaltic or tholeiitic composition and are due to tensional stresses acting across a steeply inclined or vertical plane of considerable extent, which passes through some already determined centre. Similarly orientated acid dykes are occasionally encountered, but it has been found that these are more usually restricted to the neighbourhood of the plutonic centres and do not stretch so far afield as their basic companions. Detailed mapping has demonstrated that the period of dyke-intrusion as represented by these dykes of basic composition was of great duration and that intrusion was continued, probably spasmodically, throughout the whole period of localized igneous activity. The majority of the basic dykes, however, belong to the latter end of the period.

The dykes of the Skye Swarm stretch from the Outer Hebrides through the plutonic centre of Skye to about the same distance towards the south-east, but no member of the swarm has been proved to pass south-eastward of the Great Glen Fault. The Mull Swarm also makes itself evident as far out as the Outer Hebrides, and of all the swarms has the greatest linear extension. It passes across Loch Fyne and the Firth of Clyde, and in a less dense form can be traced through the southern uplands of Scotland into England, where, swinging into a more nearly east and west direction, it is represented by the Cleveland, Tynemouth, Acklington, and other well-known dykes.

The Arran Swarm passes outwards through Kintyre, Islay, and Jura, as far as Colonsay, and to the south-east reaches the mainland of Ayrshire and Kirkcudbrightshire.

An extensive Irish Swarm stretches across the north of Ireland north-west from Carlingford and Slieve Gullion, and in the other direction is apparently represented by numerous dykes in Anglesey and Carnarvonshire, while other members occur in Snowdonia. Its furthest extension is probably found in the post-Triassic dykes of Butterton and Swinnerton, and of Acton Reynold in the English Midlands. It is interesting to note that a dyke-swarm with a N.W.–S.E. trend passes through the plutonic centre of Lundy Island. The island is formed of a mass of granite which presents remarkable similarity to that of the Mourne Mountains, but of which the Tertiary age is still unproved.

In addition to passing through the various plutonic centres the density of the dyke-swarms is greater in their neighbourhood. Increases in density, however, are met with in the case of the Arran and Irish Swarms far to the north-west of the plutonic centres concerned. The increase in the case of the Arran Swarm is found in Islay and South Jura; in the Irish Swarm it occurs on the west coast of Donegal. The reason for this is not apparent, but it may be connected with the presence of other centres hidden beneath the sea. Calculations of the crustal stretch from the number of the dykes forming a swarm in the proximity of a centre show that the amount in the case of the Mull Swarm is one mile in twenty-four, while in the case of the Arran Swarm the figure is as large as one in eight or ten.

Radial dykes

In the neighbourhood of practically every plutonic centre a certain number of dykes depart from the normal direction of the dyke-swarms, and in the Cuillin Hills of Skye and in Rum arrange themselves as a subsidiary radial system (Figure 4). Although of general magmatic similarity to the dykes of the respective north-west swarms their origin is probably connected with a different set of tensional forces.

The formation of a radial system of dykes is evidently connected with the doming of the roof of a magma-reservoir, and thus radial dykes and cone-sheets may be regarded in a measure as related though independent phenomena. The factor that determines whether the uplift of the roof should be effected by the intrusion of a multiplicity of cone-sheets or whether by simple doming with a formation of radial fissures is probably the form and depth of the magma-reservoir. For the formation of cone-sheets it appears that the upward force must be applied to a restricted area, as would be the case if the magma-cupola had steep sides and a much greater vertical than lateral extent. Doming without the intrusion of cone-sheets, and with the probable formation of radial dykes, would be effected in the case of a magma-reservoir having a gently arched roof of much greater lateral extent and, in all probability, situated at a greater intercrustal depth.

In the case of the dykes that have a north and south direction, and which are met with on the northern sides of the plutonic districts of Skye, Ardnamurchan, Mull, and Arran, it must be remembered that this direction is that of the line joining the major Tertiary plutonic centres (p. 54). They, in part, therefore, may be determined by conditions similar to those which were responsible for the north and south linear disposition of the main intrusive masses.

Sills

Under the heading of sills are grouped those minor intrusions usually of low inclination and great lateral extent which conform to the bedding or some other plane of structural weakness of the rocks in which they occur. Owing to the generally accepted greater fluidity of a basic magma it is not surprising to find that the most typical examples are of basic composition. Where an acid magma has intruded under sill-conditions there is often a tendency for the intrusion to be restricted in lateral extent and for it to assume a laccolithic habit.

Sills are well represented among the Tertiary minor intrusions, generally grouping themselves in well-defined areas adjacent to the plutonic complexes. Excellent examples are furnished by the great group of sills of Loch Scridain in Mull and the sills of Southern Arran. The Loch Scridain sills are mainly intermediate in composition, are frequently xenolithic, and appear to have been intruded from a relatively shallow magma-reservoir subsidiary to the main reservoir of Central Mull. They furnish a most varied and interesting series of rock-types such as leidleites, inninmorites and craignurites.

A well-marked series of sill-intrusions is also developed to the north of the plutonic centre of Skye, in the Mesozoic rocks along the eastern sea-board. Dr. Harker believes that a great group of basic sills also extends generally throughout the plateau region of Skye, the Small Isles, and Mull, but this late group of basic sills has been questioned by other workers, especially in Mull. Certain sills of great thickness occur far removed from any recognized plutonic centre. They are generally of basic composition and good examples are furnished by sills in the Jurassic rocks of the Shiant Isles (p. 64), and by the Fair Head Sill in Antrim.

Composite and multiple dykes and sills

Composite intrusions of these types have the peculiarity of exhibiting a marked but orderly variation in the composition of the magma that filled the fissure. Usually such intrusions have basic exteriors with a more acid centre. The basic magma has invariably been chilled against the country rock, but the central portion of the intrusion, while exhibiting a marked difference in composition, as a rule does not chill against its more basic associate, but merges rapidly into it. It thus appears that, generally, the fissure was first filled by a basic magma that partially solidified, and that this was followed immediately by a magma of different composition, the latter naturally occupying the centre of the sill or dyke. The more acid magma presumably replaced all the basic magma that had not previously solidified and resorbed as much of the solid as its superfluous heat would allow. Such intrusions are common throughout the Tertiary Province and good examples may be cited from Skye, Mull, Arran, and elsewhere. They vary in different cases from a few feet to as much as 200 ft. in thickness. The origin of composite sills and dykes has always been a difficult problem, a final solution of which has not yet been found. Judging by the form and relations of the rocks involved, however, there appears to be no reasonable doubt of the simultaneous availability of two compositionally different magmas and of their coexistence in the same magma-reservoir, one magma following upon the other along the same fissure after a very short interval of time, before the first had an opportunity to solidify completely. There is reason to believe that in some cases the later intrusion of acid magma was aided or accompanied by a widening of the fissure.

Dr. Harker, on the evidence of the composite intrusions of Skye, considered it proved beyond doubt that the magmas responsible coexisted in subterranean reservoirs, and that the lighter acid magma overlay the denser basic one. Further, he suggested that the two magmas involved were complementary and that their production had been effected by differentiation in one and the same local reservoir. In this connexion the authors of the Mull Memoir (p. 33) agreed with Dr. Harker in assuming the coexistence of two complementary magmas produced by differentiation in the same reservoir. They further accounted for the order of intrusion by suggesting that the hotter and more mobile basic magma found access to a cold fissure more easy than would be the case for a cooler and more viscous acid magma. But, that when once the basic magma had occupied the fissure and warmed it up, the acid magma found it possible to proceed along the path that had been prepared for it.

The evidence afforded by composite intrusions that magmas of different composition can coexist in the same magma-reservoir has a considerable bearing upon other petrogenetic problems, for all the phenomena connected with ring-dyke intrusion and the observed sequence of rock-types are more readily explained on this assumption.

Multiple intrusions are usually sills or dykes that consist of several members in parallel arrangement, each member being chilled either against the country rock or against one or other of its associates. There is no difficulty in accounting for their formation, for they clearly occupy a repeatedly opened fissure that has been the passage for magma at several successive periods but not of necessity supplied from the magma-reservoir. Each influx of magma was followed by complete solidification. Another important distinction between multiple and composite intrusions is that in the former there need be no symmetrical arrangement of their component members, and that the magmas involved are not necessarily complementary. Many examples could be mentioned from the Tertiary Province, but as might be expected from their manner of formation they are sporadic and not definitely connected with any one period of intrusion or intrusive centre.

Differentiation in situ

Another type of variation in composition is found in certain gabbro-granophyre ring-dykes of Mull and in the great picrite-dolerite sill of the Shiant Isles described by Dr. Walker. In these there is a progressive increase in basicity from the top to the base of the intrusion and a definite density stratification. Such conditions are clearly brought about by differentiation by crystallization taking place in the body of the intrusion, and the gravitative separation of early-formed basic minerals such as olivine, iron-ores, basic plagioclase and augite.

Some sills occasionally exhibit one or more bands of acid or alkaline material arranged parallel to the surfaces of the sheet, and representing the ultimate liquid residuum. It is presumed that such bands occupy regions of tension caused by contraction of the main mass during its solidification. Examples may be cited from the Permian intrusions of South-west Scotland, and also from the Tertiary picrite-dolerite sill of the Shiant Isles.

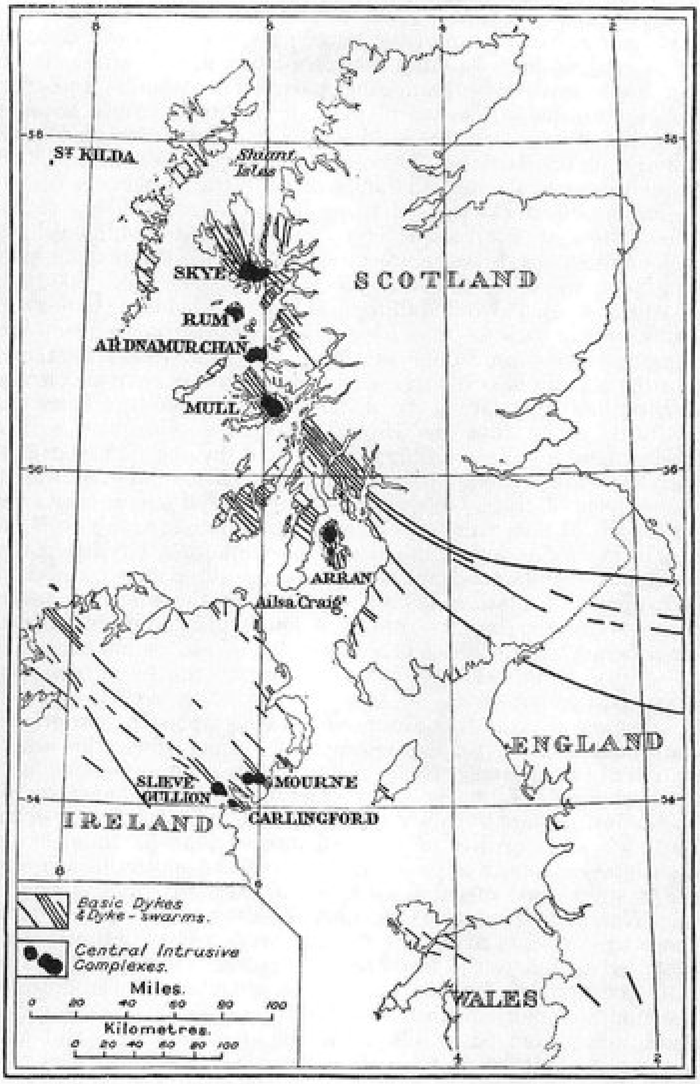

FIG. 4.—*Map showing distribution of Tertiary north-west basic dykes in relation to Tertiary central intrusive complexes of the British Isles.*
NOTE: number of dykes is greatly reduced.

(Figure 4) Map showing distribution of Tertiary north-west basic dykes in relation to Tertiary central intrusive complexes of the British Isles. Note: number of dykes is greatly reduced.

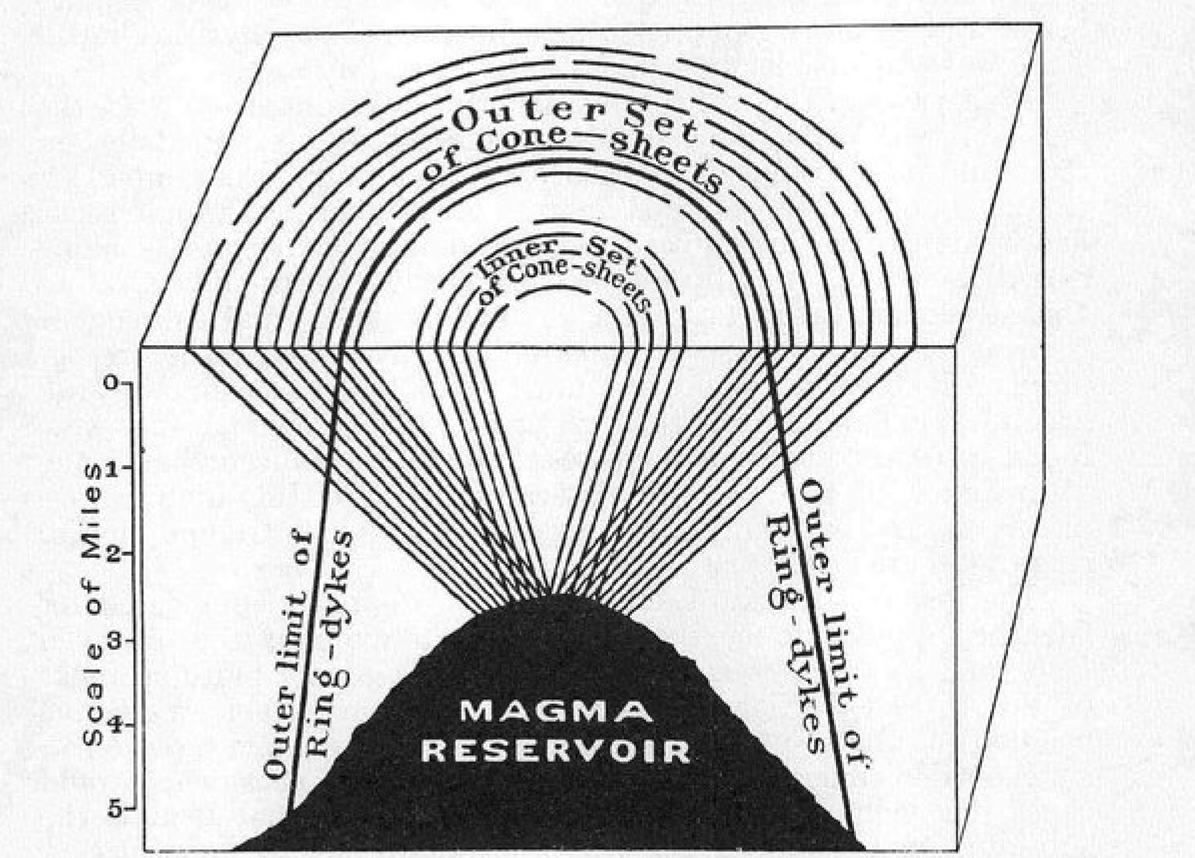

FIG. 5.—*Stereogram representing diagrammatically the Cone-sheet Complexes of Centre 2, Ardnamurchan, with reference to their inferred magma-reservoir.*

(Figure 5) Stereogram representing diagrammatically the Cone-sheet Complexes of Centre 2, Ardnamurchan, with reference to their inferred magma-reservoir.