Chapter 1 General introduction

It may safely be maintained that Mull includes the most complicated igneous centre as yet accorded detailed examination anywhere in the world. This centre lies within Sheet 44 of the one-inch Map of Scotland. It is of Tertiary date, and affords the chief subject matter of the present volume.

The geographical limit of the area herein described is mainly fixed by the coast-lines of Mull and its attendant isles such as Ulva and Staffa; but eastwards it is extended to include the Loch Aline district of Morven and the Oban district of Lorne, in so far as the two fall inside Sheet 44. Thus to comprehend the accounts which follow it is essential for the reader to have a copy of Sheet 44 of the Geological Survey one-inch Map of Scotland. The remaining sheets which are to some extent involved are 43, 51 and 52. Sheet 44 is published, while the others will appear shortly.

Further introductory remarks may be grouped under three headings:

1. An explanation is offered of the Plan of the Memoir, so that a reader may be able to find his way to topics of particular interest to himself without losing sight of their significance in the general story.

2. The Petrology of the district is briefly considered as a whole, with special regard to magma-types, their associations, and their time-relations. In this connexion, the Geological Survey analyses are gathered together, so as to assist in reference and comparison.

3. An Itinerary is sketched with a view to meeting the requirements of geologists who have an opportunity of visiting the exposures for themselves.

Plan of memoir

Chapter 2 is devoted to the progress of research. The results won by the Geological Survey and associated workers have been many and varied, but they leave undiminished the respect long entertained for the discoveries of men like Macculloch, the Duke of Argyll, Forbes, Gardner, Judd and Geikie. Even their dissensions have been of assistance in pointing the way for further enquiry. The Geological Survey entered a field where a wonderful amount of knowledge had already been gained, and where there was little further to be hoped for except as a result of detailed mapping. To summarize this accumulated knowledge from a historical standpoint is the main object of Chapter 2; but a glance is also taken at progress achieved during the course of the recent survey. In the body of the text, the usual convention is adopted of attaching the initials of specific authors to various sections. One of the main contributors, Dr. Clough, died before the Memoir was written, and others have left the Geological Survey. In such cases the initials of those, to whom descriptions should in justice be attributed, have been inserted between brackets.

Apart from this account of the development of research, and a final chapter devoted to economics, the rest of the memoir is essentially a geological history. Sequence in time has been adopted as the principal guide in the presentation of events. Naturally, however, many exceptions have had to be admitted in following out this general plan, partly on account of lack of knowledge, and partly because a too strict adherence would have led to many embarassing repetitions. It should also be pointed out that every account of a particular group of rocks is concluded with a petrological discussion. In most cases the field-relations and petrology are dealt with in a single chapter; in a few instances the petrology stands in a chapter by itself.

Chapters 3 and 4 are devoted to the Tertiary sediments of the district; the former deals with field-relations, and the latter with fossils, more particularly the contents of the famous leaf-beds of Ardtun. The sediments are treated together, since, all told, they are of relatively insignificant bulk. They are taken at the beginning of the story because some of them are the earliest Tertiary rocks known in Mull. They tell of an arid climate that witnessed the upheaval and silicification of the chalk, and soon afterwards gave place to moist warm-temperate conditions. It was during this latter stage that volcanic activity awoke. The Ardtun leaves, and others from Carsaig, occur a little above the base of the volcanic pile. They have been examined by Professor Seward and Mr. Holttum, who agree with Mr. Gardner in assigning them to the Eocene.

Regarding the period at which the Mull igneous centre became extinct, all that is certain is that the whole complex was profoundly eroded before the onset of the Quaternary Ice-Age.

The nature of the sediments, and the weathering of successive lava-flows, alike bespeak a terrestrial growth of the volcanic accumulation preserved to us in Mull.

Chapters 5–10 deal with the basalt and mugearite lavas still extant in the region. It is natural to consider these lavas in advance of other igneous rocks of the district, because, as a group, they constitute the first large-scale manifestation of igneous activity. There must be many intrusions in Mull of the same general date as these early lavas, and in fact some have been identified, but the great majority of the intrusions are obviously later. One may imagine that immense masses of lava, now stripped away by erosion, were poured out at the surface during the introduction of the later intrusions. It is certain at any rate that tremendous explosions took place at the Mull centre after some of the major intrusions had consolidated in the positions in which we now find them.

Of the six chapters allotted to the lavas, the first, Chapter 5, is written as an introduction to the others, and the last, Chapter 10, is concerned with petrology. Readers at all familiar with the subject, will turn instinctively to the descriptions of the columnar lavas of Staffa and its neighbourhood, and of Macculloch's submerged, but upright, tree as illustrated in the frontispiece. Both these picturesque topics are discussed in the earlier portion of Chapter 7 devoted to the lavas of Sheet 43. Still, such fascinating details have only a subsidiary place in the general story of the lavas of Mull. One finds one's self faced with the gradual accumulation of a great mass of olivine-rich basalts (Plateau Types of (Plate 3), p. 91), attaining locally 3000 feet in thickness and followed by a comparable development of olivine-poor basalts (Central Types). The terms Plateau and Central Types are introduced for local convenience, and their petrological significance is defined in Chapter 10. During the outpouring of part at least of the Central Types, the lava-pile seems to have had the form of a gentle Kilauean dome, with a central caldera, measuring five or six miles across, and repeatedly renewed by subsidence (the south-eastern caldera of (Plate 3) and (Plate 5), pp. 91 ,165). This caldera often filled with water during periods of quiescence, and the lavas, which entered the resultant crater-lake have been apt to assume pillow-structure (Plate 4) and (Figure 18), (Figure 21), pp.133, 151).

Another feature of outstanding interest is the degree to which ' the basalt-lavas (and to a less extent the later intrusions) have undergone pneumatolytic change round about the centre of activity. A line has been laid down on (Plate 3) to surround a district 16 miles in diameter, in which the olivine of the basalt-lavas is entirely decomposed. Outside this line, a very large proportion of the olivine is still fresh. Other changes such as the development of albite and epidote have also resulted from the .pneumatolysis. For a discussion of the subject the reader should turn to Chapters 5, 8, 9, and 10, where in addition an explanation is offered of the frequent failure of trap-featuring within the pneumatolytic area.

The question of the type of eruption responsible for the Mull lavas has already been touched upon, and may now be examined somewhat more fully. One thing is certain: the lavas were poured out with a minimum of explosive activity. The conditions of their formation must have differed considerably from those giving rise to strato-volcanoes of Vesuvian type. Beyond this it is doubtful whether the comparative absence of ash, and the extreme regularity of the lava-pile, lead to any definite conclusion. Such features characterise alike the lava-plains of fissure-eruptions, and the lava-domes of certain central volcanoes (Kilauean Type). Sir Archibald Geikie has done Hebridean geology a great service in insisting upon comparison with Iceland. In Iceland, Thoroddsen<ref>Thoroddsen's results are summarised by E. B. Bailey in Iceland—a Stepping-Stone, Geol. Mag., 1919, p. 466</ref> points out that every type of volcanic activity can be recognized; and he enumerates, among others, 87 examples of fissure-eruption, and 16 of Kilauean lava-domes. The evidence which the pillow-lavas afford of a caldera in Central Mull during a considerable part of the lava-period (as one may for brevity call it) points strongly to the existence for the time being of a Kilauean lava-dome. In keeping with this interpretation, it may be mentioned that a certain small proportion of the basic intrusions concentrated in Central Mull are referable to the lava-period.

But let us consider the matter a little further. Sir Archibald Geikie has cited the profusion of dykes characteristic of Mull ((Figure 60), p. 357) as an argument in favour of the fissure-origin of the lavas of the island. He was well aware that many of the dykes—it is probably safe to say a large majority of them—are of later date than any of the lavas at present preserved. Still, he was able to demonstrate in Skye, and the same holds good in Mull, that a fair proportion are of relatively early date; and it is possible that some of them may even be as early as the lavas taken as a whole. The analogy of Iceland led Sir Archibald Geikie to infer that many of the Mull dykes are the consolidated feeders of fissure-eruptions, and that some among them have been the main source of supply of the Mull lavas still visible to-day.

The relationships of the Mull dykes will be returned to later on (pp. 10, 48). Meanwhile, the present writer may explain that he regards Mull as a volcanic centre of unusual longevity and complexity, with almost every conceivable type of eruption represented in its lavas, its agglomerates, and its intrusions; he thinks that this centre has repeatedly served as a focus of fissure-eruptions; but he is doubtful whether the lavas still spared by erosion are not, in the main, the products of a central volcano, an idea always linked with the name of Professor Judd (pp. 45, 49).

The view that fissure and central eruptions may have taken place in one and the same region within a comparatively brief period is in keeping with Thoroddsen's Icelandic observations; for on more than one occasion he refers to fissures cutting across lava-domes.

Chapter 11 supplies an account of all basic intrusions which have been assigned on local evidence to the same period as the basaltic lavas; and also of certain other dolerites and gabbros which do not readily find a place in the scheme of the Memoir.

Chapter 12 describes the granophyres of Glas Bheinn and Derrynaculen ((Plate 5), p. 165). These masses are the earliest large intrusions exposed by erosion in Mull. They seem to have risen in dyke-fashion along the fissure that bounds the caldera in which the pillow-lavas occur, until, on approaching the surface, they expanded laterally with irresistible force. At any rate, outside their outcrops, there has been developed a most wonderful series of arcuate folds concentric with the pillow-lava caldera. These folds are illustrated in (Plate 5), and (Figure 25) and (Figure 35) (pp. 174, 237), and are considered in some detail in Chapter 13, along with other features of the Tertiary tectonics of Mull. The field-evidence proves conclusively that they are of very early date, compared, that is, with most of the intrusions of the Mull centre; and it is largely on this account that a genetic connection between themselves and the Glas Bheinn and Derrynaculen Granophyres has been suggested. It may be pointed out, however, that there is some doubt whether the Glas Bheinn Granophyre, as now exposed, is not rather. earlier than the folding. The granophyre has certainly been broken up by the first paroxysmal explosions of the Mull centre, dealt with in Chapters 15 and 16, and it is not quite clear in the field whether the agglomerate resulting from these explosions is not affected by the folding. In Chapter 15 it is suggested that the balance of evidence favours the view that the agglomerate was showered down into already formed synclines; in which case the time-sequence may be interpreted thus: Glas Bheinn. Granophyre accompanied by folding and followed by explosions. If, on the other hand, it is eventually found that the agglomerate has been involved in the folding, this suggested sequence will have to be a little modified and may perhaps read: Glas Bheinn Granophyre consolidating in its upper portions and followed by a renewal of intrusion of similar magma accompanied by folding and explosion. A close association of intrusion, folding, and explosion is probable enough in view of Omori's account of the phenomena attending the upheaval of the New Mountain of Usu San in Japan.<ref>E, B, Bailey, The New Mountain of Usu San, Geol. Mag., 1912, p. 248</ref>

A break in the story must be noted at this point, for Chapter 14 intervenes between the discussion of the folds and that of the agglomerates. It deals with an interesting set of alkaline intrusions of intermediate composition grouped together for petrographical convenience, in the absence of any very satisfactory chronological data. In some instances, these intrusions are accompanied by explosion-phenomena, and it is thought that certain of them may belong to the maximum period of explosive activity which supplies the main topic of the two succeeding chapters.

It has already been explained that these two, Chapters 15 and 16, include an account of the first paroxysmal outbursts of the Mull centre following upon, or accompanying, the development of arcuate folding. Chapter 15 is devoted to the surface-agglomerates of these outbursts. Chapter 16 describes the corresponding vents; but it goes much further, and emphasizes a point, first established by Mr. Wilson, that central explosions of great importance were repeated at a much later period in the history of Mull, notably after the intrusion of the Ben Buie Gabbro of Chapter 22.

Another feature of general interest dealt with at this juncture is the evidence for the most of Mull's explosive activity being connected with acid magma. Still another is the frequency of gneissic debris in the vents surrounding the calderas of

(Figure 29) (p. 201).

Chapter 17 introduces three important felsite-intrusions ((Plate 5), p. 165). Of these, the Beinn Mheadhon Felsite is of slightly later date than the first paroxysmal eruptions, whereas the Torness Felsite is probably rather earlier, while the Creag na h'Iolaire Felsite cannot be very precisely dated. The Beinn Mheadon Felsite is the most interesting of the three, and furnishes an example of what appears to be a laccolithic swelling on a dyke, or sheet, inclined outwards from the Mull centre. It is also the largest of the many composite intrusions (p. 32) known in the district.

Chapter 18 discusses two large intrusions of augite-diorite balancing one another on either side of the north-west axis of symmetry through Loch Bà ((Plate 5), p. 165), first recognized by Mr. Wright. The augite-diorites are taken at this stage because they seem to be earlier than any of the cone-sheets of Mull; but all that is firmly established is that they are earlier than the Late Basic Cone-Sheets of Chapter 28.

Here the reader has come to a stage in the history of Mull from which it is profitable to look forward and also to look back. The igneous centre from henceforth assumes a new character marked by an intermittent intrusion of numberless cone-sheets. Considering the profusion in which cone-sheets are represented in Mull, it is very strange how seldom they are met with at other eruptive centres investigated by geologists. At the present time cone-sheets are scarcely known outside Mull, except in Ardnamurchan, and Skye; and it was in Skye that they first obtained due recognition, receiving from Dr. Harker the title inclined sheets, now gradually giving place to the synonym cone-sheets. For a definition of the term, and a discussion of its application in Mull, the reader is referred to Chapters 19, 21, and 28 of the present Memoir. To appreciate in some degree the distribution and aggregate bulk of the local cone-sheets, he must turn to the one-inch Map, Sheet 44, where cone-sheets are represented as groups rather than as individuals, and are lettered aI, bI, and tI, on a basis of composition combined, as .far as is convenient, with relative age. The form taken by cone-sheet intrusions has suggested to various workers, notably Mr. Anderson, the application of magmatic pressure near the apex of the cone (p. 11).

Looking back over the events at the Mull centre, prior to the introduction of the first cone-sheets, one may epitomize the whole as follows: At first, the outstanding event is the quiet outpouring of basalt-lava, olivine-rich to begin with, olivine-poor or olivine-free to end with. Thereafter, the story is of an acid magma that was either intruded as great subterranean masses, sometimes accompanied by marked disturbance of adjacent rocks, or else extruded at the surface by virtue of explosions.

Certain features, for instance, the development of one or two calderas, the location of granophyre intrusions, and the arcuate distribution of folds, indicate the early establishment of a ring-tendency ((Plate 5), p. 165). This ring-tendency finds much fuller expression at intervals during the succeeding period ((Plate 6), p. 307).

Ring-fractures are more widely known in igneous geology than cone-fractures. It is not intended here to anticipate the few remarks offered in Chapter 2 regarding their recognition in Mull. The reader who wishes to follow the subject farther afield may, however, turn to descriptions of Glen Coe,<ref>E. B. Bailey in Summary of Progress for 1905, Mem. Geol. Surv., 1906, p. 96; C. T. Clough, H. B. Maufe, and E. B. Bailey, The Cauldron-Subsidence of Glen Coe, Quart. Journ. Geol. Soc., vol. lxv., 1909, p. 611; The Geology of Ben Nevis and Glen Coe, Mem. Geol. Surv., 1916, Chapter 8.</ref> Ben Nevis,<ref>H. B. Maufe in Summary of Progress for 1909, Mem. Geol. Surv. 1910, p. 80; The Geology of Ben Nevis and Glen Coe, Chapter 10</ref> and Iceland <ref>T. Thoroddsen, summarized by E. B. Bailey, in Iceland—a Stepping-stone, Geol. Mag., 1919, p. 466</ref>; and also, as Mr. Wright points out, to the Irish Geological one-inch Map (Sheets 59, 60, 70, and 71) of Slieve Gullion. It was in Iceland that the word ring-fracture (Kreisbrüche) was introduced by Thoroddsen. Mr, Anderson furnishes a dynamical discussion of the phenomenon (p. 11).

A very beautiful feature in the story of the intermittent injection of cone-sheets and ring-dykes is the distribution of these intrusions with reference to twin centres situated near Beinn Chàisgidle and the head of Loch Bà, respectively (one-inch Map, Sheet 44, and (Plate 6), p. 307). These twin centres are lettered C_1 and C_2 in (Figure 58) (p. 338); and, though they seem to have functioned to some extent simultaneously, there is no doubt that activity about C_1 tended to be replaced as time went on by activity about C_2. Thus C_1 is the main centre for the Early Acid and Basic Cone-Sheets of Chapters 19 and 21, and it also seems to have had a share in controlling the earliest of the Late Basic Cone-Sheets of Chapter 28;

but presently activity shifted, and a large proportion of the Late Basic Cone-Sheets is grouped about C_2. In the same way, C_1 is the principal centre for the ring-dykes of Chapter 29, referable to the earlier part of the Late Basic Cone-Sheet period; while C2 is the centre of the Loch Bà Felsite of Chapter 32, a ring-dyke later than all the cone-sheets of Mull.

The story of magmatic change after the appearance of cone-sheets in Mull is for the most part a repetition of what occurred in the pre-cone-sheet period. There is, it is true, a well-marked tendency for the earliest cone-sheets to be of acid or intermediate composition; but the resultant Early Acid Cone-Sheets may perhaps be regarded as a magmatic heritage from pre-cone-sheet clays, and they arc, after all, of subordinate bulk. The main magmatic succession is, as Dr. Clough clearly established, from olivine-rich magma responsible for the Early Basic Cone-Sheets of Chapter 21, and the great olivine-gabbros of Chapter 22, to olivine-poor or olivine-free magmas represented by the Late Basic Cone-Sheets of Chapter 28, and the quartz-gabbros, granophyres, and felsites of Chapters 29–32. How the various petrological types of dykes described in Chapter 34 fit into this scheme has only been very partially determined; but one point is beyond question: some among them, the latest of Mull's igneous manifestations, clearly demonstrate a return of olivine-rich magma in the final stage of activity.

Chapter 19 furnishes an account of all the intermediate and acid cone-sheets of Mull (*see* one-inch Map, Sheet 44); most of them belong to an early stage of the cone-sheet period. As a body, they share with every other suite of minor intermediate and acid intrusions in the island, irrespective of age or habit, a marked tendency to composite association with basic magma. Again and again in such cases, one meets with intrusions which have intermediate or acid interiors, and relatively thin basic marginal layers; and there is no development of a chilled edge except at the exterior contacts of the two basic layers with country-rock (Chapters 27, 25, and 34; p. 32). In the present Memoir, the name composite intrusion is reserved for such intimate associations, although it has been used in a rather wider sense in the past to cover all complex acid and basic intrusions without insisting upon an absence of chilling at mutual contacts.

Chapter 20 deals with the Loch Uisg Granophyre and Gabbro. Both probably belong to some phase of the lengthy period characterized by Early Acid and Early Basic Cone-Sheets. The flat top of the granophyre, cutting across folded and highly baked lavas, is one of the most easily appreciated phenomena of Mull geology ((Figure 34), p. 231).

Chapter 21 gives an account of the Early Basic Cone-Sheets.

Chapter 22 describes the three chief olivine-gabbros of Mull ((Plate 5), p. 165). The Ben Buie Gabbro was intruded at a late stage of the Early Basic Cone-Sheet period; the Corra-bheinn Gabbro actually at the close; the Beinn Bheag Gabbro is less precisely dated. In form, the gabbros are great steep rather irregular masses. All three can be seen to break through vent-agglomerates, and yet to be themselves broken by a return of explosive activity at some date succeeding their own consolidation.

Chapters 23–27 cover almost all the sills and sheets of the district, except the cone-sheets to which reference has been so often made. It is thought that the majority of these intrusions date from some stage in the development of the Late Basic Cone-Sheets of Chapter 28; but there is very little evidence upon which to base a judgment. Apart from their unsatisfactory age-relations, the sills and sheets are in many ways noteworthy. Thus, one may allude to their relative concentration in South-West Mull, where they mark out a special field of intrusion (Chapters 23–26, (Figure 42), p. 258), with a sub-area in the neighbourhood of Loch Scridain, characterized by abundant pitchstone (Chapter 23), and singularly interesting xenoliths often carrying sapphire (Chapter 24). Sills and sheets other than those of the South-West Field are dealt with in Chapter 27.

The reader must realize that the intrusions considered above do not correspond in field-relations, or petrology (Chapters 25–27), with what Dr. Harker styles the "Great Group of Sills" in Tertiary Hebridean geology. As explained in some detail in Chapters 5 and 6, the authors of the present memoir follow Sir Archibald Geikie in interpreting most of Dr. Harker's "Great Group" as the more solid portions of lava-flows.

Chapter 28 treats of Late Basic Cone-Sheets. The time-relations of these cone-sheets to the ring-dykes of subsequent chapters are discussed in some detail, and evidence is advanced for the view that the centre of cone-sheet activity migrated during the, period of the intrusion from C_1 to C_2 ((Figure 58), p. 338).

Chapter 29 starts with a definition of two important terms *ring-dyke* and *screen.* It then passes to the ring-dykes of Glen More and Beinn Chàisgidle ((Plate 6), p. 307). This is the first region from which a numerous suite of concentric ring-dykes has been described. It is also a region of great complexity, for the ring-dykes are in many cases much cut up by cone-sheets. Accordingly an unusually full treatment is offered based upon (Figure 52) and (Figure 53) (pp. 308, 312), which reproduce with slight reduction the field-maps of two selected parts of the district. An interesting feature established for the ring-dykes is their occasional upward splitting, due to the magma concerned having found more than one ring-fissure available at the time of its intrusion. Another feature, and one of prime importance, is the clear, evidence of gravitational differentation in *situ* afforded in several instances by these intrusions. Chapter 30 is devoted to this aspect of the subject ((Figure 54), (Figure 55), (Figure 56), pp. 322–326). It is not surprising that the ring-dykes concerned should show such a tendency, for they are often more than 100 yards wide, and exposed on valley sides for over 1000 feet in a vertical sense, while their margins are unchilled, and their texture indicative of slow cooling; moreover, their magma is of quartz-gabbro composition, and, as such, is particularly prone to allow of a migration of an acid residuum during the progress of crystallization.

Chapter 31 deals with the. Glen Cannel Granophyre ((Plate 6), p. 307),a great central intrusion with a dome-shaped roof largely stripped from it by erosion. In places the granophyre has been cut through for a thousand feet, but no floor is exposed. The granophyre has been intruded at the more north-westerly of the twin-centres of activity.

Chapter 32 discusses three very important ring-dykes, one of them clearly intruded with reference to the same north-westerly centre. These intrusions, the Knock and Bienn a' Ghràig Granophyres, and the Loch Bà Felsite ((Plate 6), p. 307), furnished Mr. Wright with a first insight into the ring-structure of Mull. Later Mr. Richey completed the mapping of the Loch Bà Felsite, as shown in (Figure 58) (p. 338), and found in it the most perfect example of a ring-dyke known to science. All three are of relatively late date in the igneous history of Mull, in fact the Loch Rh Felsite may be claimed as the latest of all Mull intrusions except some of the northwest dykes of Chapter 34. The Loch Bà Felsite almost certainly surrounds a cauldron-subsidence, and during its uprise its magma seems locally to have exploded. The two associated granophyres also furnish much material for thought. Nowhere in Mull is the form of major intrusions displayed to better advantage, and nowhere can one realize so graphically the part played by a screen of country. rock, than in the hills overlooking Loch na Keal. It is particularly noteworthy that a great intrusion, like the Beinn a' Ghràig Granophyre, can replace a large mass consisting of consolidated lavas and cone-sheets without upsetting the arrangement of the adjoining country-rock. Since there is evidence that in Beinn Fhada, at any rate, the roof of the intrusion has not been forced up, it seems fairly clear that the floor has sunk down, either *en masse,*<ref>Cf. C. T. Clough, H. B. Maufe, and E. B. Bailey, The Cauldron-Subsidence of Glen Coe, Quart, Journ. Geol. Soc., vol. lxv., 1909, p. 669</ref>or piecemeal <ref>Cf. R. A. Daly, The Mechanics of Igneous Intrusion, 3rd paper, Am. Journ. Sci., Ser. 4, vol. xxvi., 1908, p. 17</ref>

Chapter 33 is mainly of petrological interest and discusses certain hybrid complexes found at the margin of the Beinn a' Ghràig Granophyre.

Chapter 34 supplies an account of all the normal dykes of Mull ((Figure 60), p. 357). It is pointed out that these dykes are of many different ages some of them are the latest products of igneous activity represented in the district; while others are of relatively early date, and quite possibly include examples contemporaneous with the lavas of Chapters 5–10. Most of the Mull dykes form part of a north-westerly swarm, rather more than 10 miles wide and well over 100 miles in length. The existence of the Mull Swarm seems to have been first definitely realized by Mr. Made, largely as a result of his experience in Sheet 36 of the one-inch Map (cf. . (Figure 60)). The swarm can be interpreted in exactly the same manner as the analagous Etive Dyke-Swarm<ref>C. T. Clough, H. B. Maufe, and E. B. Bailey, *op. cit.,* p. 674</ref> of Old Red Sandstone Age. Individual dykes of the Mull Swarm are regarded as a response to regional tension, or at any rate a relief of pressure, which opened, or helped to open, fissures directed north-west and south-east. The tension was in the great majority of cases relieved for the time being by very moderate movement, and accordingly individual dykes are narrow. The tension was, however, renewed again and again, and this accounts for the extraordinary number of the dykes and their wide disparity of age. Naturally, in the opening of a fissure, advantage would be taken of any particular structural weakness which the district presented; and one can claim that it was the frequent subterranean weakness of the Mull centre, with the magma of its pipes (annular or, otherwise) often in a molten condition and perhaps under excess of pressure, that determined the location, though not the direction of the Mull Swarm.

In Chapters 5–10, attention is drawn to the widespread pneumatolysis of the lavas found about the Mull centre. In later chapters it is pointed out that pneumatolytic changes can often be detected affecting the intrusions of the same central district. In fact, few of the more central intrusions of Mull, except such massive examples as the Ben Buie Gabbro, have retained their olivine fresh. Even the latest of the dykes of Chapter 34 have suffered markedly in this respect, though not through quite so extensive an area as that shown for the lavas in (Plate 3) (p. 91). Thus one can recognize the presence of the subterranean molten plug of our theory not only in the localization of the dykes, but also in their alteration.

Another feature of interest dealt with in Chapter 34 is the occasional evidence of explosions having occurred along the course of Tertiary dykes of the district. Naturally, this evidence greatly strengthens Sir Archibald Geikie's comparison between the Tertiary dykes of the Hebrides and those which have been responsible for fissure-eruptions during historic times in Iceland.

Chapter 35 treats of certain camptonite-dykes in and near Mull. It is uncertain whether these intrusions are of Tertiary or New Red Sandstone Age.

Chapter 36 turns from the igneous history of Mull, and directs attention to what many regard as the most striking lesson the district has to offer, namely the profound erosion which it has suffered during Tertiary times. Various episodes and features of this erosion are passed in review. One of the latest of them, reached not long before the onset of glacial conditions, has left clear traces of marine attack at levels lying between 100 and 160 feet above present high water.

Chapter 37 passes on to the Glacial and subsequent history of the area. It is shown that, during the maximum glaciation, Mull maintained a sanctuary uninvaded by mainland-ice ((Figure 64) and (Figure 65), pp. 393, 395); that, during the valley-glaciation, several glaciers reached down into the sea of the period until after the elevation of adjacent 100-foot and 75-foot beaches; that, during the period of the Post-Glacial submergence responsible for the 25-foot raised beach of the district, Mull lay half included in the South-West Highlands, where this last-mentioned beach is very prominently developed, and half in the North-West Highlands, where it is much less clearly marked; and, finally, that men with Azilian culture occupied one of the caves of this 25-foot beach, when probably the sea had scarcely forsaken it.

Chapter 38 deals with the economic aspect of the region. Its most interesting feature is a series of lignite-analyses by Dr. W. Pollard.

An Appendix supplies a general Bibliography.

E.B.B. (as Editor).

Dynamics of cone-sheets and ring-dykes

A dynamical theory of the formation of cone-sheets and ring-dykes may be developed on the following lines. One may disregard the probable existence of a broad lava-cone and other irregularities, and suppose that, speaking very generally, the surface of the ground, at the periods at which these features were developed, was horizontal. Underneath this horizontal surface, at a depth of several miles, was a magma reservoir Its shape may have been roughly that of a paraboloid of revolution.

One may suppose that at first the magma had a specific gravity equal to that of the surrounding rocks, and that it was under a pressure just high enough to have raised it to surface-level if there had been an outlet. Overlooking the fact that the rocks themselves were not quite homogeneous, one may further suppose that they were under the same horizontal and vertical pressures at every point as would obtain in a liquid with the same surface and the same specific gravity.. While such was the case no fractures could arise.

Cone-sheets

If, however, these conditions were modified by an increase of pressure in the magma-basin, the pressure-system in the crust would have superimposed on it a system of tensions, acting across surfaces which near the basin were roughly conical. The fine firm lines in (Figure 1) are intended to show the intersection of these surfaces with the plane of the diagram. A superimposed system of pressures would also act across surfaces which cut the former orthogonally and are indicated in section by the fine broken lines. The superimposed tensions, together with the increased pressure of the magma, might cause a series of fractures to develop, along which the magma would intrude. The opening fractures would follow the fine firm lines of (Figure 1), and thus may Have originated the cone-sheets of Mull. It will be seen from the diagram that if the surface were denuded to a certain depth, the cone-sheets exposed might be expected to be steeper in the central parts of the area of intrusion. This is actually the case.

Ring-dykes

If the conditions were reversed, and the pressure of the magma fell below that which was at first assumed, the originally "hydrostatic" pressure in the crust would be modified in a different way. Superimposed pressures would act across the surfaces whose trace is shown by the fine firm lines of (Figure 1), and superimposed tensions across those which are indicated by the broken lines. It seems likely that, in this case, surfaces of fracture would originate inclined at an angle to the surfaces across which there were maximum superimposed tensions, as in the case of normal faults.<ref>E. M. Anderson, The Dynamics of Faulting, Trans. Geol. Soc. Edin., vol. viii., 1905, p. 387</ref> The angle may have been about 20° or 30° Such surfaces of fracture correspond not to tension-cracks, but in theory at least, more nearly to planes of maximum shearing-stress. They deviate from the directions across which this stress is an absolute maximum, owing to certain considerations of friction. An attempt to show the trace of such surfaces, taking the angle mentioned as about 25°, has been made in the diagram. It can easily be seen that the theory explains the tendency to an outward slope, which is perhaps- a feature of ring-dykes. If the fractures formed curves that were closed in cross-section, the rock inside them might tend to become detached, and to sink down into the magma. The gap between the subsiding mass and the stationary walls would widen with the subsidence, and this perhaps explains, in part, the greater width of ring-dykes when compared with cone-sheets. It is uncertain whether, in the majority of cases, the ring-fractures continued upwards to the surface of the ground. When they did so, they must have given rise to circular depressions. Such a subsidence of the surface is known to have happened at Glencoe, and it appears to have happened in Mull in the case of the supposed south-eastern caldera.

The calculations necessary to fix the course of the surfaces of maximum and minimum tension on any particular assumption (as to the shape of the underground cavity, etc), are extremely elaborate. They have not been fully carried out, but there can be no doubt that the general result will be roughly as shown in the diagram. The case is similar in certain respects, though not very closely, to that treated by Hertz,<ref>H. R. Hertz, On the Contact of Rigid Elastic Solids, and on Hardness, Miscellaneous Papers. 1896, p. 163</ref> who dealt with the stresses set up by the impinging of curved surfaces in elastic solids, or by French,<ref>J. W. French Percussion Figures in Isotropic Solids, Nature, vol. civ., 1919–20, p. 312</ref> who showed that pressure exerted by a small steel ball on glass can lead to the formation of cone-fractures. E.M.A.

Mull petrology

In the body of the Memoir, the grouping of the petrological material is in large measure determined by the field-relations of the various rocks described. In the present chapter, a general survey of Mull petrology is attempted, in which special attention is paid to the composition of the Mull magma at various stages of its history. In this task, we are able to base our views on an exceptionally complete series of analyses. To Mr. E. G. Radley we are indebted for thirty-three rock-analyses from the Mull district, and to Mr. F. R. Ennos for five. Moreover, we have been able to draw upon published analyses of Mull types collected in other parts of the British Tertiary province, and in this connexion we quote freely from Dr. Harker's Memoirs for the Geological Survey, including ten analyses by Dr. W. Pollard.

In dealing with analysed material, we have carefully distinguished between what is typical, and what is exceptional. We have recognized certain compositional characteristics as belonging to what we term magma-types, illustrated in (Figure 2), (Figure 3), (Figure 4) and (Table 1), (Table 2), (Table 3), (Table 4), (Table 5), (Table 6), and (Table 7). The conception of magma-type is based upon composition alone. In this, it differs from the conception of rock-type which takes into account texture as well as composition. Thus a basalt and a gabbro may belong to one magma-type though admittedly representatives of different rock-types. The reader is warned, however, that the compositional definition of a magma-type is just as vague as that of a rock-type. All one can do is to state an average composition around which actual rocks seem to group themselves.

In the following pages, we have selected certain Mull magma-types for special discussion. A very large proportion of Mull rocks range themselves approximately in a magma-series graphically expressed in (Figure 2). Every stage in this series is copiously represented. Two other magma-types, selected as highly typical, are illustrated in (Figure 3). In addition, the extreme of alkaline variation reached by the Mull magma is shown in (Figure 4); in this last case the magma-types are of very little importance from the point of view of bulk.

After introducing the reader to the scope of magmatic variation illustrated in Mull, attention will be directed to certain intrusions which through differentiation *in situ* have produced a very large proportion of the magma-types illustrated in (Figure 2). Following upon this a general discussion of Mull differentiation is attempted in the light of observed magmatic sequences. Admittedly the treatment is speculative, but it is thought that it will help the reader to an appreciation of many of the observed facts of Mull petrology.

The account of magma-types and differentiation outlined above is illustrated by tables of analyses (1–8). These include most of the complete analyses of Mull material. There are other analyses, of minerals, xenoliths, and sediment, and these are grouped in (Table 9) by themselves. They are printed in this chapter merely for convenience of reference.

Normal Mull Magma-Series of Figure 2

Plateau Magma-Type of (Figure 2)

This magma-type provides the bulk of the Plateau Basalt Lavas (Chapter 10), most of the Early Basic Cone-Sheets (Chapter 21), and many dykes including examples belonging to the latest phase (Chapter 34).

The magma-type is known with either a basaltic or doleritic crystallization (attaining to gabbroic in certain massive cone-sheets).

Its essential minerals are olivine, augite, zoned basic plagioclase and iron ore, with a certain amount of interstitial remainder; analcite and natrolite are often present in this remainder where the olivine of the rock is fresh, but elsewhere serpentine seems to take their place. An approach to Non-Porphyritic Central Magma Type is marked in some doleritic representatives by a little residual quartz (Chapter 21).

A purple colour is characteristic of the augite of the rocks here considered. It is found in the augite of all the analysed specimens quoted in Table I., except E, which last, apart from its magnesia-content, corresponds with the basic end of the Mull Non-Porphyritic Central Magma. Though well-nigh universal, the purple tint of the augite is more marked in some examples than in others; and it is difficult to connect this difference with the bulk-analyses of -the rocks. Thus in A, B, I., and C (Table 1), the purple colour is very pronounced; in II. and III., it is less conspicuous; and, in E, it is wanting.

A marked feature of the crystal-development is that the augite does not occur as phenocrysts, nor does it build minute perfect prisms such as occur commonly in the ground-mass of British Carboniferous and Continental Tertiary basalts of similar basicity. These two related characteristics of the augite of the basalts of the British Teriary province were long ago pointed out by - Professor Hull<ref>E. Hull, On the Microscopic Structure of the Limerick Carboniferous Trap-Rocks (Melaphyres), Geol. Mag., 1873, p. 160</ref> and Sir Jethro Teall<ref>J.J.H. Teall, British Petrography,' 1888, pp. 187, 246, 247</ref> Our Mull experience agrees with Professor Hull's generalization, so far as basalts of Plateau Type are concerned, though small, phenocrysts of augite are not uncommon in basalts of Central Types. It is noteworthy, however, that the ophitic augites of the Mull Plateau Type often completed their growth well within the crystallization-period of the associated felspar (p. 138).

Dr. Flett has grouped the analcite (or natrolite) bearing doleritic varieties of the Mull Plateau Type under the title *crinanite* (type-specimen A, (Table 1)).

The analyses quoted in (Table 1) are taken from various West Highland localities, but in every case the rocks analysed can be matched in Mull, and may in this sense be regarded as representative of the Mull Plateau Magma-Type. The main chemical features of the type are summarized in (Figure 2); but it may be pointed out, in addition, that high TiO_2, about 2.5 per cent. is characteristic, and that a considerable range of MgO, from about 7–10 per cent. may occur without affecting the alkali-content.

As explained in Chapter 34, there is, very occasionally, a definite approach to camptonite among undoubted Tertiary representatives of Mull Plateau Magma-Type. This emphasizes the importance of the comparison Dr. Flett has drawn between the crinanite type of dolerites and the camptonites.<ref>For analyses *see* E. G. Radley quoted by J. S. Flett in Geology of the Country near Oban and Dalmally, Mem. Geol. Surv., 1908, p. 126.</ref>The camptonites show a slight. fall in SiO_2 and Al_2O_3, and an increase in CaO and K_2O. Two analysed Scottish camptonites, quoted by Dr. Flett, have 1.41 and 1.93 per cent., respectively, of K_2O. It must be borne in mind that, whether of Tertiary age or no, the camptonites of Scotland are of relatively insignificant bulk (Chapter 35). Associated more extreme types, such as monchiquites and nepheline-ouachitites, are rarer still.<ref>J. S. Flett, in Geology of Colon say and Oronsay with part of the Ross of Mull, Mem. Geol. Surv.,1911, pp. 41–46, 90, 91.</ref>

Attention may be directed in this connexion to definitely alkaline segregation-veins developed in a small proportion of the Plateau Type of basalt-lava (Chapter 10).

Non-Porpyyritic Central Magma-Type of (Figure 2)

This magma-type first appeared in the south-west part of the Mull district where it furnished wonderfully columnar lavas of Staffa Type (Chapters 7 and 10). It recurred in greater volume, and variety, as an important constituent of the Central Group of lavas (Chapters 5 and 10). It supplied many of the sills (Chapters 23–27), most of the Late Basic Cone-Sheets (Chapter 38), several of the ring-dykes (Chapter 29), and a large proportion of the normal dykes (Chapter 34).

The magma-type is known as a partially denitrified glass. (Two silica-determinations by Mr. E. G. Radley quoted in Chapter 28 for variolites of Cruachan Dearg Type give 50.66 and 53.65 per cent), and with every grade of crystallization from this onwards to gabroic. The names which naturally apply to the various products of crystallization are compact or fine-grained basalt (lavas), variolites (pillow-lavas and minor intrusions), tholeiite (defined in Chapter 25 – minor intrusions), quartz-dolerite (cone-sheets and ring-dykes), and quartz-gabbro (ring-dykes).

The essential minerals are augite, plagioclase felspar, and magnetite, with an acid residuum in which crystallization reveals quartz and alkali-felspar. Towards the basic end, olivine appears as a minor constituent.

In non-variolitic lavas of the suite, the augite manifests a very strong tendency to granular crystallization in the ground-mass, and sometimes furnishes a. few small phenocrysts. In intrusions, It favours a columnar or branching (cervicorn) form ((Figure 50), p. 302), which gives place, however, to an ophitic habit in relatively basic representatives, and in the earlier crystal-groupings of even the more acid rocks. The colour of the augite is usually brownish, but is often tinged with purple especially in olivine-bearing varieties.

A feature of the more acid and more crystallized members of the group is the obvious freedom of migration of the acid residuum, and the extent to which chemical action has proceeded between this residuum and the early-formed crystals. The conditions of Central Mull were clearly favourable to such chemical exchange both before and after complete consolidation, and it is fairly certain that auto-pneumatolysis and general pneumatolysis have often co-operated in accelerating the process.

The analyses of (Table 2) are, with the exception of A, all taken from Mull localities. The Giant's Causeway basalt (A) is included because it is a good example of the Staffa Type (Chapter 10). The main features of the thagma-type as a whole are sufficiently summarized in (Figure 2); in addition, it may be noted that, as compared with the Plateau Magma-Type, there is a distinct, though not universal, fall in TiO_2.

Intermediate to Sub-Acid Magma-Type of (Figure 2)

This magma-type is represented more particularly among the augite-diorites (Chapter 18), Early Intermediate and Acid Cone-Sheets (Chapter 19), and Loch Scridain sills (Chapter 23).

Its consolidation in these various occurrences ranges from glassy to dioritic. The products may be styled glassy andesite—pitchstone—and stony andesite (in both cases sills), craignurite (defined Chapter 19 – cone-sheets), and augite-diorite (large masses).

The essential minerals are augite, plagioclase, and magnetite, with a very considerable residuum of glass or devitrification-products consisting lareely of alkali-felspar and quartz. Olivine is almost always absent. Augite is brownish, and typically columnar or acicular; but may also be ophitic or cervicorn. Enstatite-augite is an essential of the inninmorites (andesite-type defined in Chapter 25), and a common accessory of many craignurites. Hypersthene is often met with in the leidleites (andesite-type defined in Chapter 25).

More or less variolitic structure is often met with among the andesites.

The early minerals of the whole group usually show marked interaction with the acid base, except where this latter has consolidated as a glass. The effect is especially marked where there has been relative migration of crystals and residuum (Chapter 30).

The main chemical characteristics of the magma-type are summarized in (Figure 2). Comparison of the analyses of (Table 3) leaves it uncertain what chemical peculiarity determines the distinction of leidleite from inninmorite.

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A very interesting point is the extent to which the more glassy representatives retain their magmatic water. This feature is discussed later on with additional partial analyses ((Table 11), p. 263). The fall of TiO_2, which began to manifest itself in the Non-Porphyritic Central Magma-Types, is now pronounced.

The acid magma-type supplied the early granophyres (Chapter 12), the rhyolites and explosion-phenomena of Chapters 15 and 16, three important felsite-intrusions (Chapter 17), cone-sheets (Chapter 19), the Loch Uisg Granophyre (Chapter 20), a fair number of sills (Chapter 25), many ring-dykes (Chapters 29 and 32), the Glen Cannel Granophyre (Chapter 31), and a fair number of dykes (Chapter 34).

The range of texture is complete from glass to coarsely granophyric. Thus there are rhyolites, or acid pitchstones, felsites, fine granophyres, and coarse granophyres. Much of the Loch Bà Ring-Dyke of Chapter 32 is rhyolite, while the Knock, Beinn a' Ghràig, and Glen Cannel Granophyres of Chapters 31 and 32 afford excellent examples of coarse granophyre.

The predominant minerals are alkali-felspar and quartz; and a tendency to granophyric structure is very pronounced. In most of the analysed specimens of (Table 4), there is an appreciable proportion of soda-lime felspar, but this fails in the Beinn a' Ghràig (Anal. IV) and Glen Cannel Granophyres. Augite is the common ferromagmesian mineral, and is generally some shade of pale brown, but in the Beinn a' Ghràig and Glen Cannel Granophyres it is a green pleochroic aegerine-augite. The brown-type of augite is not infrequently accompanied by enstatite-augite. Pyrogenetic hornblende occurs along with augite in the Glas Bheinn Granophyre (Chapter 12); but hornblende- or biotite-granophyres are very rare in Mull, except as a product of contamination (Chapter 33). Dr. Harker<ref>A. Harker, 'Tertiary Igneous Rocks of Skye, Mem. Geol. Surv.,1904, p. 153.</ref> has pointed out that, among the major acid intrusions of the British Tertiary province, biotite is the characteristic ferro-magnesian mineral of the more acid types (75 to 77 per cent. SiO_2), whereas hornblende and augite are more abundant in the less acid types (70 to 72 per cent. SiO_2); and that the quartz and felspar of these less acid types show a special tendency to granophyric intergrowth. The Mull occurrences fall into place in this generalization.

The chemical characteristics summarized in (Figure 2) include a strongly marked tendency to predominance of K_2O over Na_2O. A low content of MgO is also striking. Reference to the analyses of (Table 4) shows that the drop of TiO_2, noted above in connexion with increasing SiO_2, is still continued. Thus, whereas, in the Plateau Type (Table 1) with about 45 per cent. SiO_2, it is common to find 2.5 per cent. TiO_2, in the Acid Type with over 70 per cent. SiO_2, there is generally only about 0.5 per cent. TiO_2.

Other magma-types

Allivalite–Eucrite Magma-Series of (Figure 3)

This magma-series, so far as Mull is concerned, has only been recognized in bulk in Ben Buie where it furnishes the Ben Buie Eucrite, or Gabbro as the rock is generally styled in the course of the Memoir (Chapter 22). Anal. 1, (Table 5), is from Ben Buie. For comparison Anal. B is borrowed from Dr. Harker's description of a eucrite from Rum, which differs somewhat from the Ben Buie rock in containing a fair proportion of hypersthene. Anal. A represents Dr. Harker's typical allivalite from Rum. There are several small masses of such allivalite in association with the Ben Buie Eucrite, and the greater part of the intrusion is definitely more allivalite in composition than the analysed specimen I.

If one compares the mineral development of the Ben Buie Magma with that of the Plateau Magma, one notes a marked falling off of iron-ores and alkali-residuum (alkaline zoning of felspars, interstitial analcite, etc), and a disappearance of the purple tinge from the augite. At the more basic end of the series there is also a decided relative reduction in the amount of augite.

In a chemical comparison of the two magmas, the most striking features are a great fall in TiO_2, total iron, and alkalies, and a corresponding rise in MgO; there is also a distinct upward tendency in AlO3 and CaO.

Porphyritic Central Magma-Type of (Figure 3)

In Mull's history the appearance of this type on a tolerably large scale follows closely upon that of the Plateau Type on two widely separated occasions. Thus, lavas of the Porphyritic Central Type succeed lavas of Plateau Type (Chapter 10), and at a much later time cone-sheets of Porphyritic Central Type succeed cone-sheets of Plateau Type (Chapters 21 and 28). On both these occasions there is a marked association of Porphyritic and Non-Porphyritic Central Types with perhaps a tendency for the Porphyritic to antedate the Non-Porphyritic. Among the sills (Chapters 25 and 26), there is possibly a similar association to be noted. The Porphyritic Central Type is also represented among the dolerites and gabbros of Chapter 11 and the dykes of Chapter 34.

The magma-type is always porphyritic in its finer crystallizations, with small or large phenocrysts of basic plagioclase felspar. The base may be partially vitreous, and often variolitic in chilled portions of pillow-lavas and minor intrusions; elsewhere it is anything from basaltic to gabbroic in texture. In the gabbros the porphyritic tendencies of the felspar may be lost sight of, or at any rate much obscured.

The essential minerals are basic plagioclase, augite, and iron-ore; olivine is often a minor constituent.

The outstanding feature of the type is the abundant early separation of basic plagioclase felspar. In quenched specimens, including many with variolitic tendencies, basic felspar may figure as the only phenocryst. In more thoroughly basaltic types, it is often associated with olivine and augite in small amounts. Where augite occurs as phenocrysts, its colour is brownish and the crystallization of the augite of the ground is typically granular; in such cases, olivine is often absent. With increase of olivine, the augite is apt to assume the purple tint and ophitic habit so characteristic of the Plateau Type.

In a chemical comparison with the Plateau-Magma Type (Figure 2) and (Table 1), one notes a slight general increase in SiO_2, accompanied by a marked increase in Al_2O_3 and CaO. Alkalies remain approximately steady, while TiO_2, Fe, and

MgO are all reduced.

In comparison with the Non-Porphyritic Central Magma-Type ((Figure 2) and (Table 2)), there is substantial agreement as regards MgO. The Porphyritic Type is, however, sometimes poorer in SiO_2, and is distinguished throughout by its abundant Al_2O_3 and, except towards the acid end, by its marked preponderance in CaO. Other differences are a reduction in K_2O, TiO_2, and Fe.

In comparison with the Eucritic Magma Type (Figure 3) and (Table 5), the Porphyritic-Central Type has a less extended range on the basic side. With equal silica, the porphyritic type is richer in TiO_2, Al_2O_3, CaO, K_2O, and Na_2O; iron remains roughly constant; and MgO has fallen heavily.

The chemical peculiarity of the Porphyritic Central Magma-Type viewed in relation to all other associated magma-types is the relatively great concentration of Al_2O_3 and CaO; this peculiarity finds mineralogical expression in an abundance of basic felspar.

Mugearite Magma-Type of Figure 4

This magma-type is very subordinate in Mull, except in the form of lavas among the Plateau Basalts, where it occurs more particularly at a high level in the Ben More succession (Chapters 5 and 10).

The crystallization of the Mull mugearite-lavas is trachytic.

The essential minerals recognized are oligoclase, olivine, augite, and magnetite. Orthoclase is probably an important constituent, but has not been identified.

The mugearites of Mull are only represented by Anal. I., (Table 7), which lies. at about the acid extreme of the group. The limiting silica-percentages have not yet been chosen for mugearite, but it seems probable that they will agree approximately with 49 and 56 suggested on (Figure 4).

Compared with rocks of Non-Porphyritic Central Type, the mugearites are rich in alumina and alkalies and poor in lime and magnesia. These features find mineralogical expression in a notable relative reduction of basic felspar and augite.

Syenite, Trachyte, and Bostonite Magma-Type of (Figure 3)

There is much uncertainty regarding the exact period, or periods, at which this magma-type manifested its presence at the Mull centre. Various occurrences are grouped together in Chapter 14. They range in crystallization from trachytic to fine-grained syenitic. Traehytic' and bostonitic tuffs are also known (Chapters 14 and 16).

The outstanding minerals are the alkali-felspars which make up almost all the rock in the bostonites—not analysed. In the syenite (Anal. II., (Table 7)), aegerine-augite is the main ferromagnesian mineral, with a little aegerine, enstatite-augite (pseudomorphed), and amphiboles; the latter are, mostly referable to arfvedsonite, but varieties allied to riebeckite and barkevikite are also met with. In the Ardnacross Trachyte (Anal. III), biotite predominates, but it is accompanied by aegerine-augite, and some decomposed amphibole. In the Bràigh a' Choire Mhòir Trachyte (Anal. III), aegerine-augite and an ally of riebeckite are present in about equal proportions. In both these trachytes, there is reason to suspect the presence of nepheline.

If one compare this magma-type with the Intermediate to Sub. acid Magma-Type of (Figure 2), one notes a great increase of Al_2O_3, Na_2O, and K_2O, and a fall in MgO and CaO. Comparison between (Table 3) and (Table 7) shows furthermore a marked fall in the TiO_2 of the alkali-rocks.

The chemical characteristics of the Intermediate Alkaline Magma-Type finds mineralogical expression in an abundance of alkali-felspar, and also in the alkali-content of the associated ferro -magnesian minerals.

Differentiation—Column; Glen More Ring-Dyke

In Chapter 30, a detailed account is given of certain ring-dykes which furnish examples of gravitational differentiation on d large scale. The type-sections are provided by the Glen More Ring-Dyke, two exposures of which have supplied the material for (Figure 54), (Figure 55), (Figure 56) (pp. 322–6), and the analyses of (Table 8). It is obvious that these analyses fit with wonderful precision the values given in (Figure 2) for the Normal Magma-Series of Mull. It should be clearly understood that the curves of (Figure 2) were drawn to meet the requirements of Tables 1–4 and that they had taken their present form before any comparison was made between them and (Table 8).

The agreement between the curves of (Figure 2) and the analyses of (Table 8), is, of course, not complete. Some of the differences appear to be mere irregularities, as for instance, the relatively high lime and low iron of Anal. II. Others, though smaller, seem to be of a more reliable nature. Thus:

- MgO decreases somewhat more steeply from the basic to the intermediate range of (Table 8) than in (Figure 2).
- Na_2O is slightly higher throughout, the difference amounting to about 1 per cent, at intermediate compositions.
- K_2O is slightly higher at intermediate and subacid compositions. At the latter, the excess may reach almost 1 per cent.

Another difference between the rocks of (Table 8) and those of the normal magma-series of (Table 2), (Table 3) and (Table 4) is shown in the relative concentration of P_2O_5 at intermediate compositions in (Table 8). In (Table 2), (Table 3) and (Table 4), there is a tendency for P_2O_5 to decrease fairly regularly from the basic end of the series to the acid. The condition of affairs as regards P_2O_5 in (Table 8) is probably not accidental (p.), but it would be idle to discuss in the present state our knowledge why it is not reproduced in Tables 2–4.

Most petrologists will probaly agree that the same general conditions as determined the differentiation illustrated in (Table 8) are sufficient to account for the development of the greater part of the magma-series illustrated in (Figure 2). These conditions, as explained in Chapter 30, are the early crystallization of olivine, augite, and basic felspar, leaving behind a partial magma of alkali-felspar and quartz endowed with high fluidity and low temperature of consolidation; the migration of the acid residuum, impelled by gravity, has led to differentiation, though it is possible to show that the process has been in some measure hindered by chemical exchange between solid and liquid.

It would not be proper to conclude this section without noting the essential agreement between ourselves and Dr. Bowen<ref>N. L. Bowen, The Later Stages of the Evolution of the Igneous Rocks, Journ. Geol., 1915, vol. xxiii., Supplement, pp. 1–91; and The Reaction Principle in Petrogenesis,' Journ. Geol., vol. xxx., 1922, pp. 177–198.<ref> as regards the efficacy of differentiation through crystallization and also the importance of such reactions as are apt to occur between early crystals and residual magma in the course of the process.

Further comments on Mull differentiation

In the preceding section a sketch was offered of the main process of differentiation which is regarded as responsible for the greater part of the magma-series illustrated in (Figure 2). A few words may be added concerning the place of the Plateau Magma-Type in this scheme.

There are two reasons, both inconclusive, for assuming the Plateau Magma-Type as the parental stock from which the others have been derived:

1. It is of great bulk and early manifestation.

2. It is possible to arrange most of the Mull magmatic time-sequence into two great cycles, each beginning with the Plateau Magma-Type.

The second of these two statements may be elaborated as follows:

Cycle I

Starts with the Plateau Basalt Lavas and leads through the Central Lavas (of both Porphyritic and Non-Porphyritic Magma-Types) to manifestations of intermediate and acid magma. These latter include the early granophyres of Chapter 12, the main explosions of Chapters 15–16, the felsites of Chapter 17, the Early Acid Cone-Sheets of Chapter 19, and the Loch Uisg Granophyre of Chapter 20.

Cycle II

Starts with the bulk of the Early Basic Cone-Sheets of Plateau Magma-Type (Chapter 21), and continues, after the eucritic episode of Ben Buie (Chapter 22), with Porphyritic. Early Basic Cone-Sheets of Porphyritic Central Magma-Type (Chapter 22), and Late Basic Cone-Sheets of predominantly Non-Porphyritic Central Magma-Type (Chapter 28). During the Late Basic Cone-Sheet period an extensive series of ring-dykes (Chapters 29–32) was intruded ranging from Non-Porphyritic Central to Acid Magma-Type; among these, the acid predominates towards the close.

In commenting upon the above time-scale, it must be pointed out that locally, in the Staffa district, the Mull lavas begin with Non-Porphyritic Central. Magma-Type. These particular lavas have been neglected in the statement given above because they are of relatively small volume. In addition to this, the Early Acid Cone-Sheets do not seem to be wholly earlier than their Early Basic Associates so that there appears to have been an overlap of the two cycles. It may be added for the sake of completeness, though it does not affect the argument, that a recurrence of Plateau Type of Magma is evidenced at the close of Cycle II by certain very late basic dykes (Chapter 34) cutting the Loch Bà Felsite of (Chapter 32).

If it be admitted that the Plateau Magma-Type holds a parental position in Mull petrology, a difficulty is at once manifest. In its most typical representatives, analcite and natrolite, rather than quartz, seem to be the last products of consolidation. How then was the passage brought about from the Plateau Magma-Type to the unstable Non-Porphyritic Central Type?

A possible answer is that diopside, spine], and silica might result during crystallization as an alternative to aluminous augite, or that a magnesian olivine, magnetite, and silica might develop instead of a ferriferous olivine; but Mull does not seem to supply evidence bearing upon such matters. Possibly the change from the one magma-type to the other was due in part to assimilation, as Professor Daly<ref>R. A. Daly, Igneous Rocks and their Origin, 1914.</ref> has argued in comparable cases. There is again no direct evidence bearing upon this point; all that can be said is that if assimilation has been of importance in modifying the Mull Magma it must have been accomplished at a high temperature under conditions admitting of complete admixture of melted sediment and original magma. There is no inherent impossibility in. this conception. At Tràigh Bhàn na Sgurra, a thin sill of Non-Porphyritic Central Magma-Type has melted the gneiss forming its roof through a thickness amounting locally to 4 or 5 feet (p. 266); and, in many other sills of the same class, more or less completely fused xenoliths of sedimentary origin occur surrounded by crystalline products of interaction (Chapter 24; for instances of assimilation, see Chapter 33). Under the more extreme temperature conditions that prevailed in the probably deeper-seated reservoir that supplied the plateau-lavas, it is easy to imagine modification of magma by a limited but complete absorption of country-rock.

If it is tempting to see in the transition from Plateau Magma-Type to Non-Porphyritic Central Magma-Type a suggestion of an absorption of siliceous country-rock, it is equally tempting to suppose that the Porphyritic Central Type of (Figure 3) might have been initiated through an absorption of argillaceous schists or gneisses. The growth of anorthite through interaction of basic magma and argillaceous xenoliths is dealt with in some detail in Chapter 24.

The place of the Eucritic Magma-Type of (Figure 3) in the differentiation-scheme of Mull is too hypothetical to deserve discussion.

The Mugearite Magma-Type of (Figure 4) can be derived from the Plateau Magma-Type by elimination, through crystallization, of a considerable proportion of olivine, augite, and basic felspar. It has already been pointed out that the augite of the Plateau Magma-Type, though commonly ophitic, often concludes its crystallization at a relatively early date. Examples are cited (p. 138) where augite-felspar complexes lie embedded in a felspar-olivine base.

The Trachytic Magma-Type of (Figure 4) has much in common with the felspathic segregations of the Plateau Type of basalt-lavas (p. 138), and basalt-dykes (pp. 361, 369).

Explanation of magma-sequence

In general Complex

If we accept the Central, Intermediate, and Acid Magma-Types as derivatives of the Plateau Magma-Type, there still remains the problem why they manifested themselves during the two great cycles of activity in the order stated, from basic to acid.

Dr. Bowen would probably suggest, as he has done in similar cases,<ref>N. L. Bowen, The Later Stages of the Evolution of the Igneous Rocks, Journ. Geol., vol. xxiii., 1915, Supplement, p. 81.</ref> that the sequence of magma-types has been controlled by the progresssive variation in composition of the residual magma left liquid towards the summit of a great. reservoir during long-continued crystallization. This view has much in common with Dr. Harker's<ref>A. Harker, Natural History of Igneous Rocks,' 1909, p. 329.</ref> suggestion that " the earliest erupted volcanic rock will represent more or less the undivided magma of the province." In interpreting the Mull record we adopt the ideas expressed above with two reservations:

1. We accept the Plateau Magma-Type as parental, neglecting the Staffa-Type for reasons already explained.

2. We think that the main reservoir was charged on three occasions, rather than one, with parental magma. Thus we account for what we style the two major cycles of activity, and also the final recurrence of the Plateau Magma-Type as represented among the dykes that cut the Loch Bà Felsite.

While we employ the theory of progressive differentiation in accounting for the Mull magmatic cycle, the reader should remember that there is an alternative suggestion applied by Mr. Barrow<ref>G. Barrow, Discussion of Garabal Hill, Quart. Journ. Geol. Soc., vol. xlviii., 1892, p. 121.</ref> in regard to the Pre-Tertiary plutonic intrusions in the Highlands, and by Dr. Harker<ref>A. Harker, Natural History of Igneous Rocks, 1909, p. 330.</ref> in dealing with the Tertiary plutonic rocks of Skye. According to this interpretation, the order of decreasing basicity among the plutonic intrusions is determined by remelting front the base upwards of a density-stratified, and completely consolidated, magma. These two authors were concerned with instances where ultrabasic rocks have functioned as liquids rather than as mere crystalline precipitates, and it is probably impossible to avoid some species of remelt-hypothesis to meet the difficulty thus encountered. In another direction, a special type of remelt-hypothesis, which we shall now attempt to elaborate, is of assistance in co-ordinating certain peculiarities of composite minor intrusions.

Composite intrusions

As already explained, the term composite intrusion is employed in this Memoir in a more restricted sense than in the past. There are three conditions, in our definition:

1. Composite intrusions are composed of parts of recognizably different composition.

2. As a complex they chill exteriorly against country-rock.

3. The component parts do not chill against one another—if they do the intrusion is multiple, not composite.

Such composite intrusions are exceedingly numerous in Mull (p. 8). Probably quarter at least of the acid to intermediate minor intrusions of the 'island are composite. Their habitual arrangement in such cases is acid interior with relatively thin basic marginal layers, chilled exteriorly. Always the acid has followed the basic; and Professor Judd and Dr. Harker have given such good descriptions of composite intrusions showing this character in the Hebrides generally that there can be no doubt of the definiteness of the phenomenon.

To account for the magmatic sequence in such cases Dr. Bowen<ref>N. L. Bowen, The Later Stages of the Evolution of the Igneous Rocks, Journ. Geol., vol. xxiii., 1915, Supplement, pp. 13, 14.</ref> invokes the same principle of progressive, differentiation as is outlined in the previous section. He pictures a fissure as having served for the passage of magma during so considerable a period that the composition of the upper part of the reservoir of supply has been radically altered by progressive crystallization. We are inclined to think that this hypothesis demands too long a period of infilling for the very numerous minor intrusions concerned. In fact we agree with Dr. Harker<ref>A. Harker, Natural History of Igneous Rocks, 1909, p. 344</ref> that the differentiation of the magmas involved was already effected before the date of their intrusion.

The conception of prior differentiation. lends itself to two alternative explanations of the observed magmatic sequence, basic to acid. Some may hold that the sequence is controlled by the remelting of a completely consolidated stratified magma (see previous section). Our difficulty in accepting this hypothesis is that the phenomenon to be explained is too regular. The impression we have gained is that acid and basic magma must have been available in very many cases at one and the same time, and that it is some inherent physical difference that has given precedence to the basic magma in the invasion of cold fissures. Our own suggestion as regards magma-sequence in composite intrusions is a variant of the remelt-hypothesis, in that it involves remelting of a special type as a preliminary condition. Stated fully it as is follows:

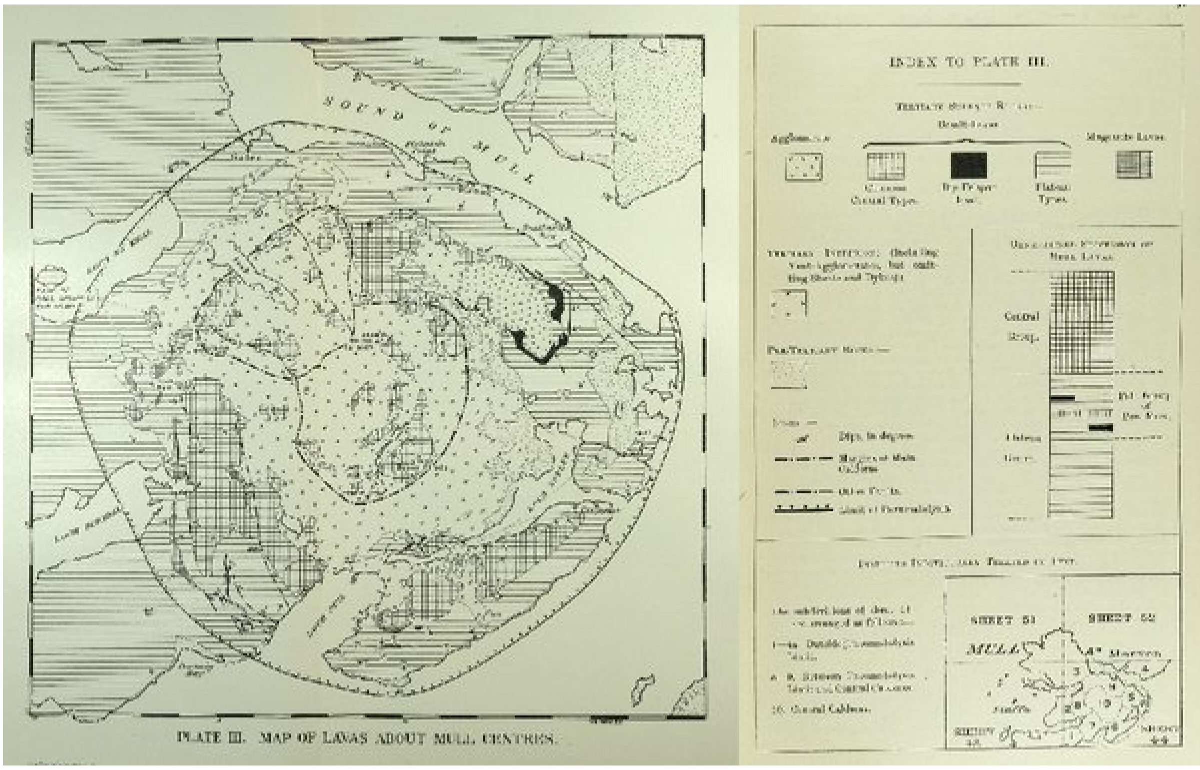
1. Magmatic differentiation, though controlled by sinking of crystals, may, under certain circumstances, give rise to liquid differentiates through remelting of fallen crystals at lower levels. The necessary condition is that the magma-basin is kept hot below, while it is cooling above. A concentration of heavy remelted matter at relatively low levels, would, in itself, tend to cheek thermal convection-currents; while upward diffusion would merely lead to further precipitation of solid phases at high levels where support is lacking.

2. A fissure communicating with a reservoir in which the liquid contents are stratified, may often cut the wall of the reservoir obliquely, and thus offer itself as a channel of intrusion for both acid and basic magma. It may he expected in such a case that hot basic magma would proceed much more readily along a cold fissure than relatively cool acid magma. Once basic magma has prepared the way, acid magma can easily follow; field-experience teaches that acid magma under hot subterranean conditions is extremely mobile; whereas under the conditions which generally attend the progress of lava-flows it is notoriously viscous.

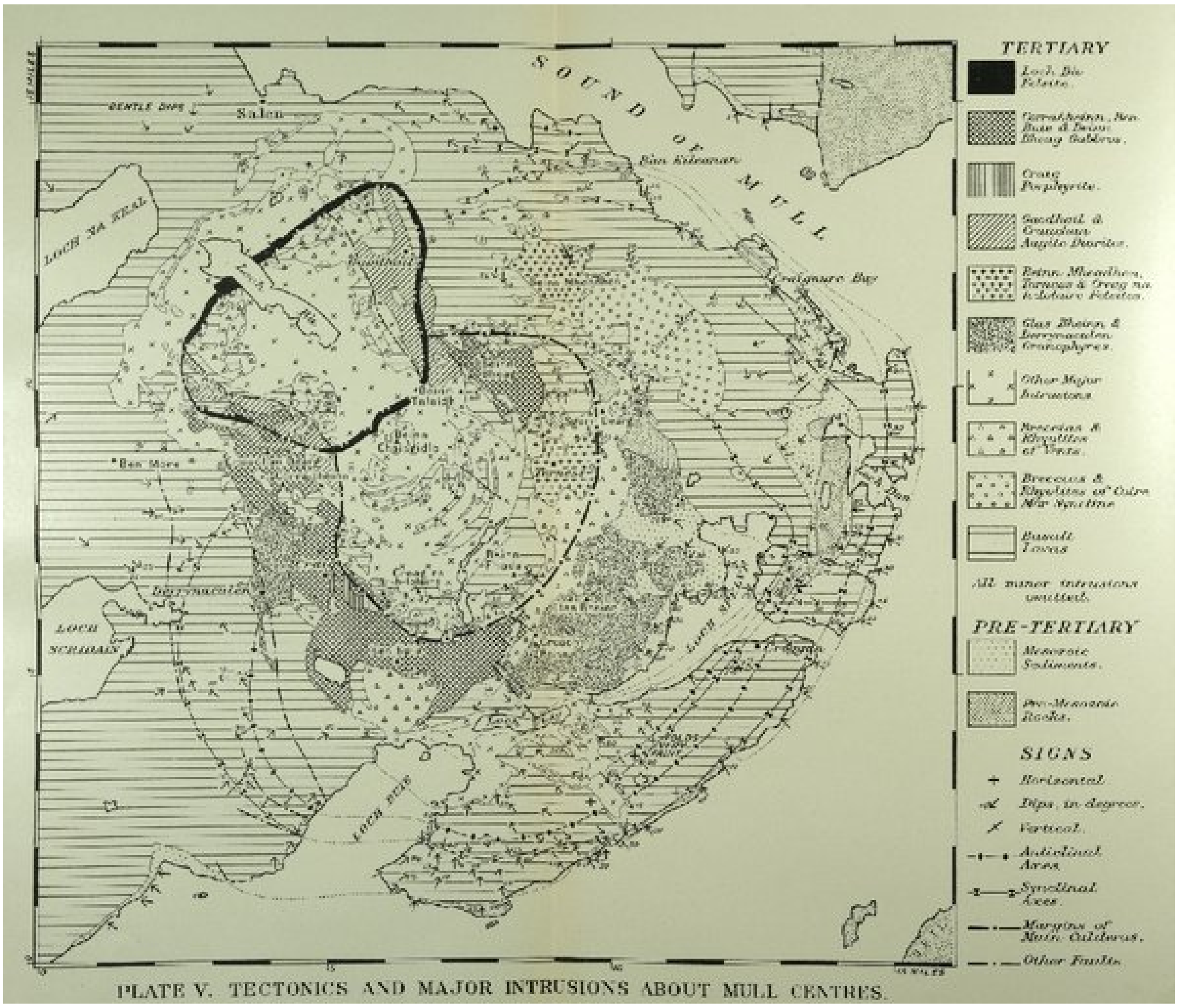
Other topics

Additional subjects of petrological interest include: Pneumatolysis (Chapters 5, 10, 34, etc); Hybridization (Chapter 33); Xenoliths of the Loch Scridain Sills (Chapter 24); and Devitrification of Pitchstone (Chapter 23).

(Table 9) gathers together analyses, other than bulk-analyses of igneous rocks, made from material collected in the Mull district. These analyses are mostly of minerals, and, taken with those already to be found in Dr. Harker's Geological Survey Memoirs on Skye and the Small Isles, they furnish a fairly complete record of chemical research in regard to Hebridean minerals of Tertiary date. For analyses of the Mull coals, or lignites, the reader is referred to Chapter 38 dealing with the economic side of the subject. H.H.T., E.B.B.



(Plate 3) Map showing the distribution of lava-types and the limit of pneumatolysis



(Plate 5) Map showing calderas, major intrusions, and folds

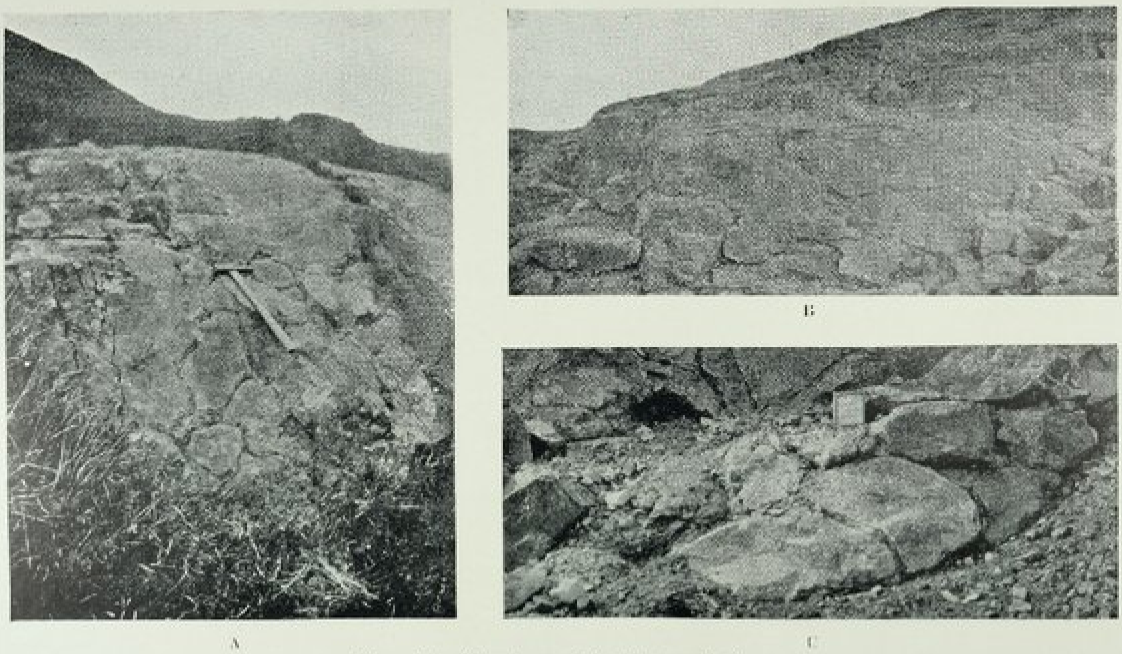


PLATE IV.—Pillow-Lavas of South-Eastern Caldera.

(Plate 4) Pillow-lavas of central Mull

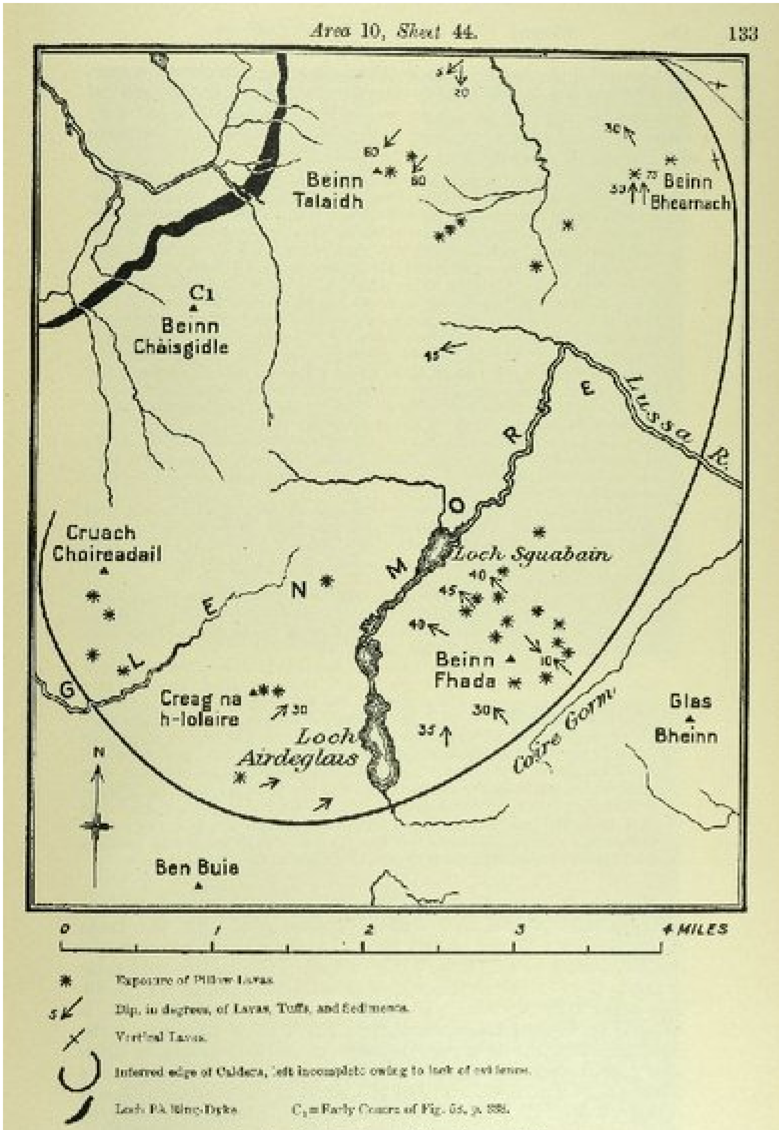
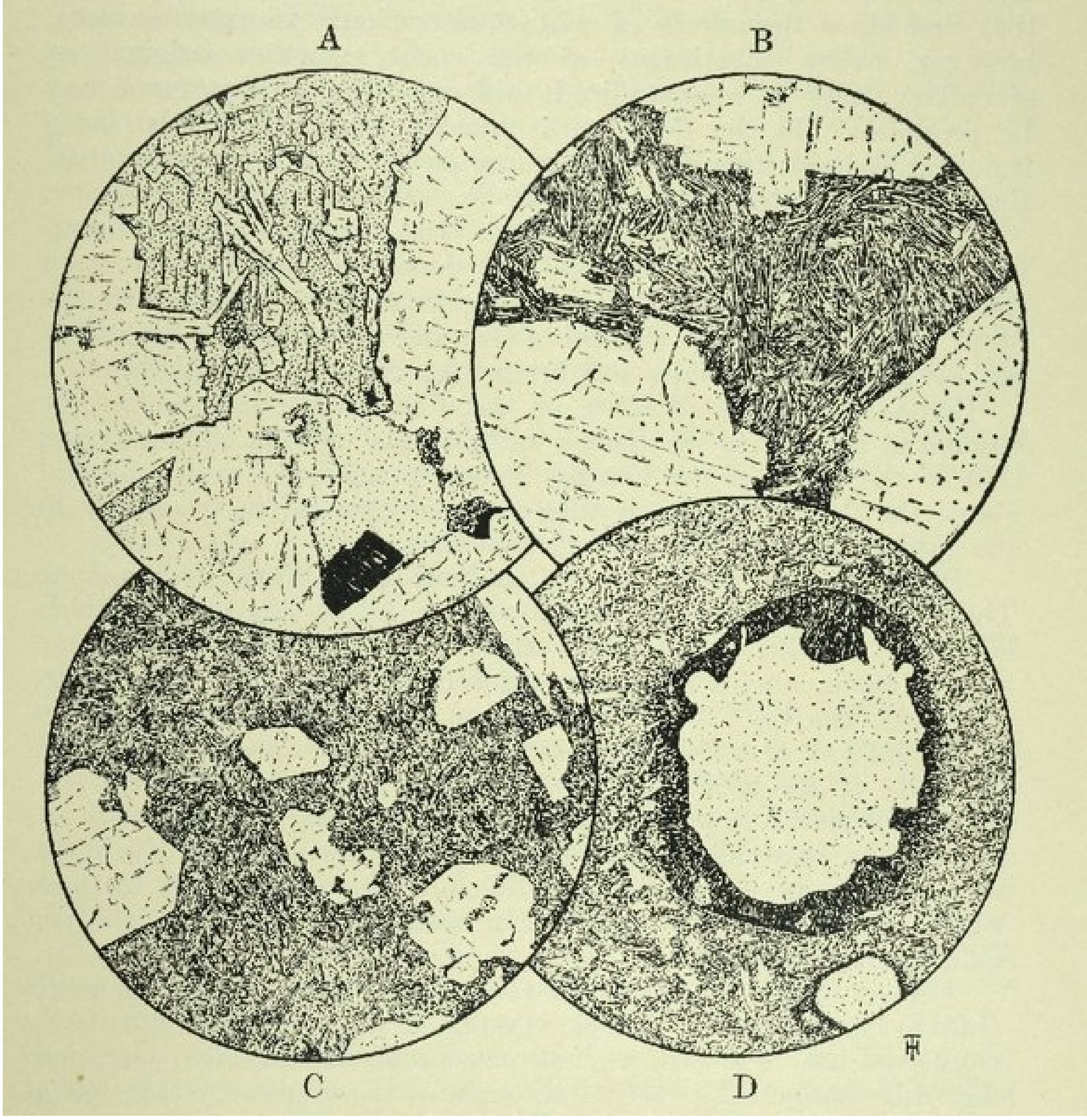


FIG. 18.—Distribution of Pillow-Lavas, Mull.
Quoted from 'Summary of Progress for 1914,' p. 40.

(Figure 18) Distribution of Pillow-Lavas, Mull. Quoted from Summary of Progress for 1914, p. 40.



(Figure 21) A -C Pillow-Lava, Cruach Choireadail. D Beinn Fhada. A. (S17184) [NM 5932 2982] x 17. Interior of Pillow. Moderately coarse doleritic rock with the augite and felspar in ophitic relationship. B. (S17185) [NM 5940 3000] x 17. Exterior of Pillow. The felspar occurs in two generations as porphyritic crystals of bytownite-anorthite, and as slender laths, which, with elongated crystals of augite, impart a variolitic structure to the matrix (compare with (Figure 23a, p. 163). C. (S17186) [NM 5924 3011] x 17. Chilled Margin of Pillow. Porphyritic basic plagioclase, near anorthite in composition, in a fine-textured matrix. The ground-mass is composed of small, elongated crystals of felspar, augite and iron-ore, with a chloritized residuum probably representing glass (compare with Fig 23A, p. 163). D. (S18039) [NM 6437 2936] x 17. Beinn Fhada. Portion of the exterior of a pillow showing the characteristic invasion of vesicular cavities by mesostatic residual material which has subsequently frothed up in situ.

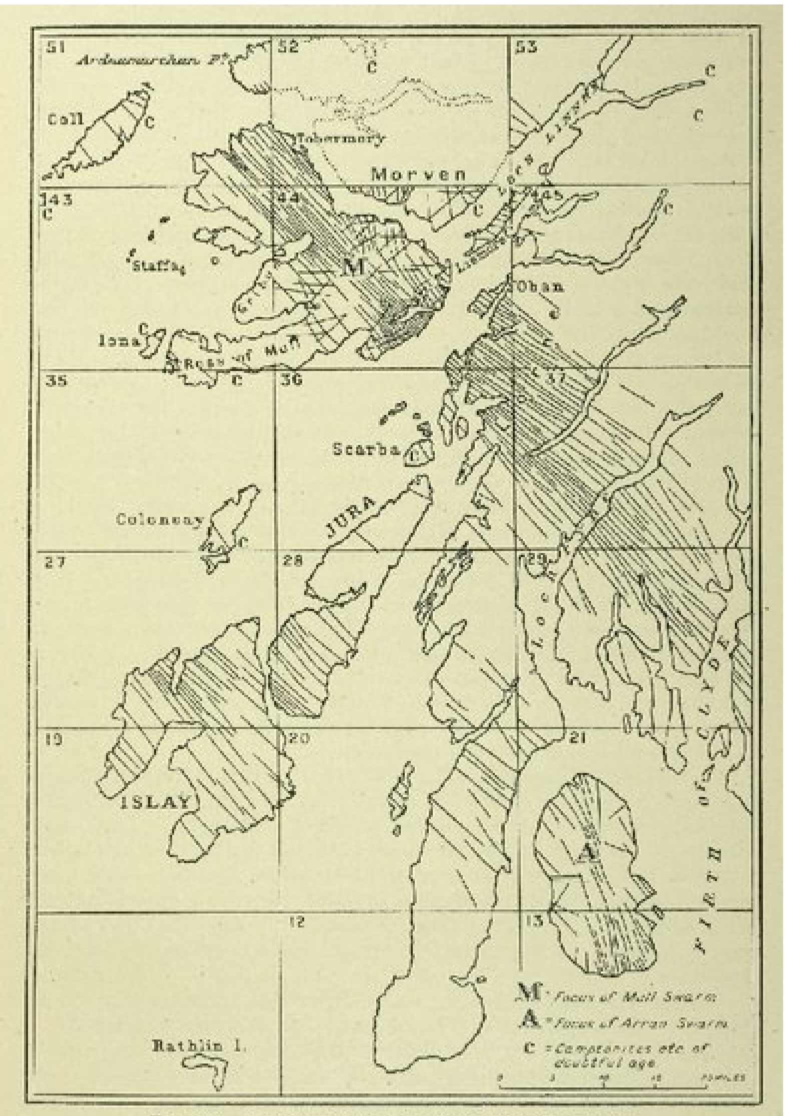
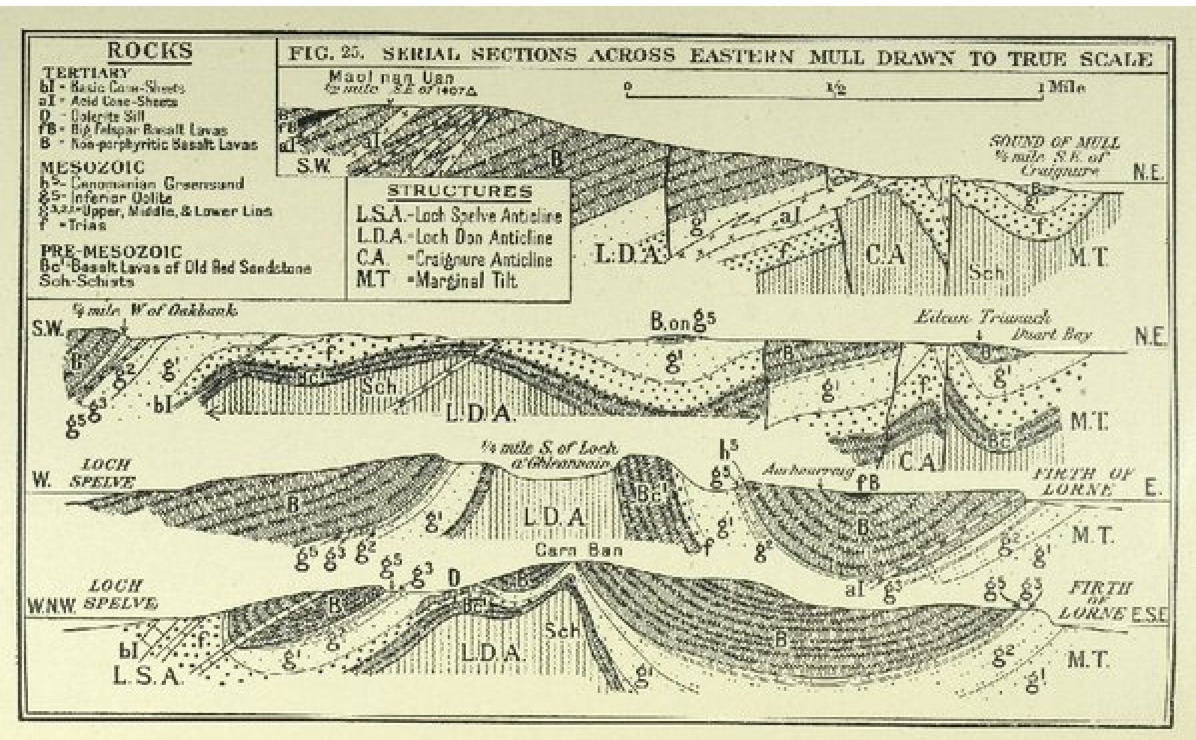


Fig. 60.—Tertiary Dykes of the South-West Highlands.
Only about one dyke in every ten or fifteen is shown. The mainland portion of Sheet 52 of the one-inch Map of Scotland has still to be surveyed.

(Figure 60) Tertiary Dykes of the South-West Highlands.



(Figure 25). Serial sections across Eastern Mull drawn to true scale. Rocks, Tertiary: bI = Basic Cone-Sheets aI = Acid Cone-Sheets D = Dolerite Sill fB = Big Felspar Basalt Lavas B = Non-porphyritic Basalt Lavas. Mesozoic: h^5 = Ceitomanian Greensand g^5 = Interior Oolite $g^{3,2,1}$ = Upper, Middle.& Lower Lias f = Trias. Pre-Mesozoic: Bc^1=Basalt Lavas of Old Red Sandstone; Sch=Schists. Structures: L.S.A.=Loch Spelve Anticline. L.D.A.=Loch Don Anticline. C.A. =Craignure Anticline M.T. =Marginal Tilt.

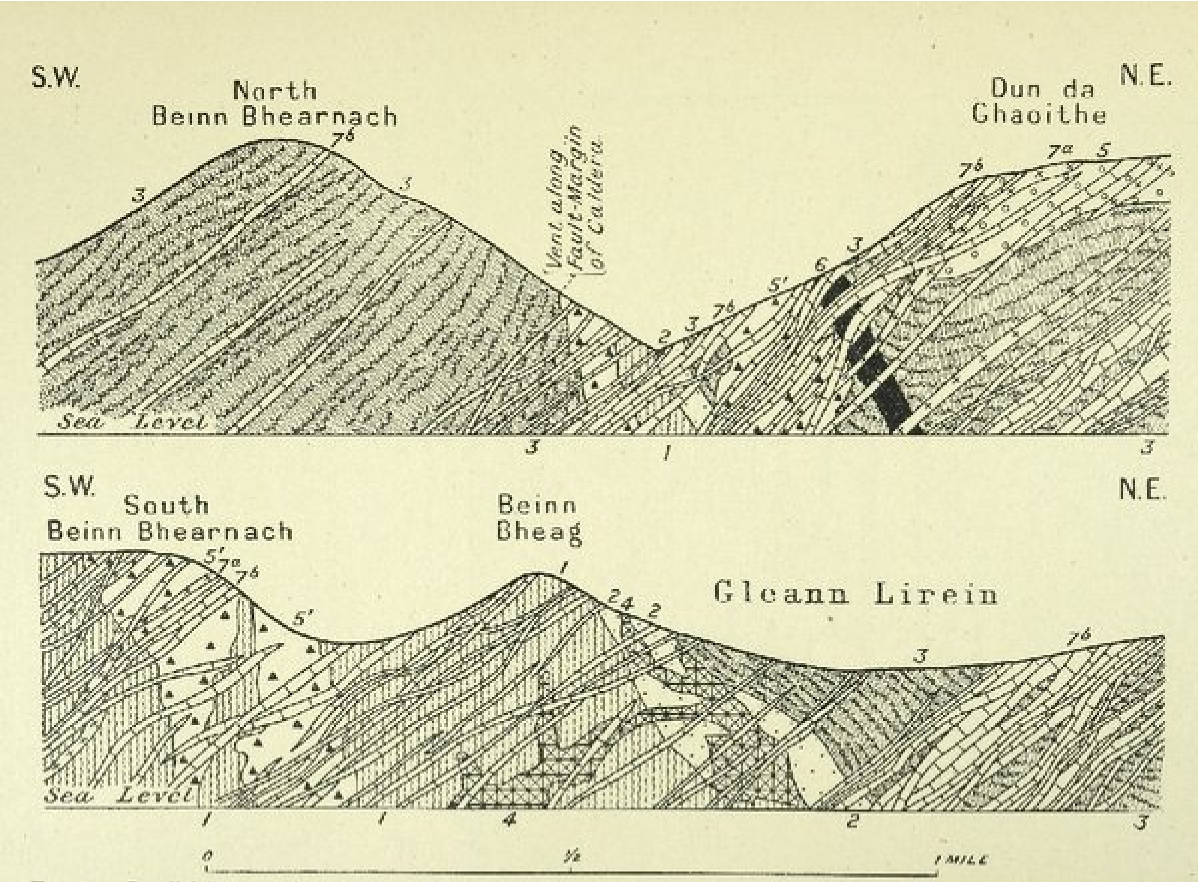
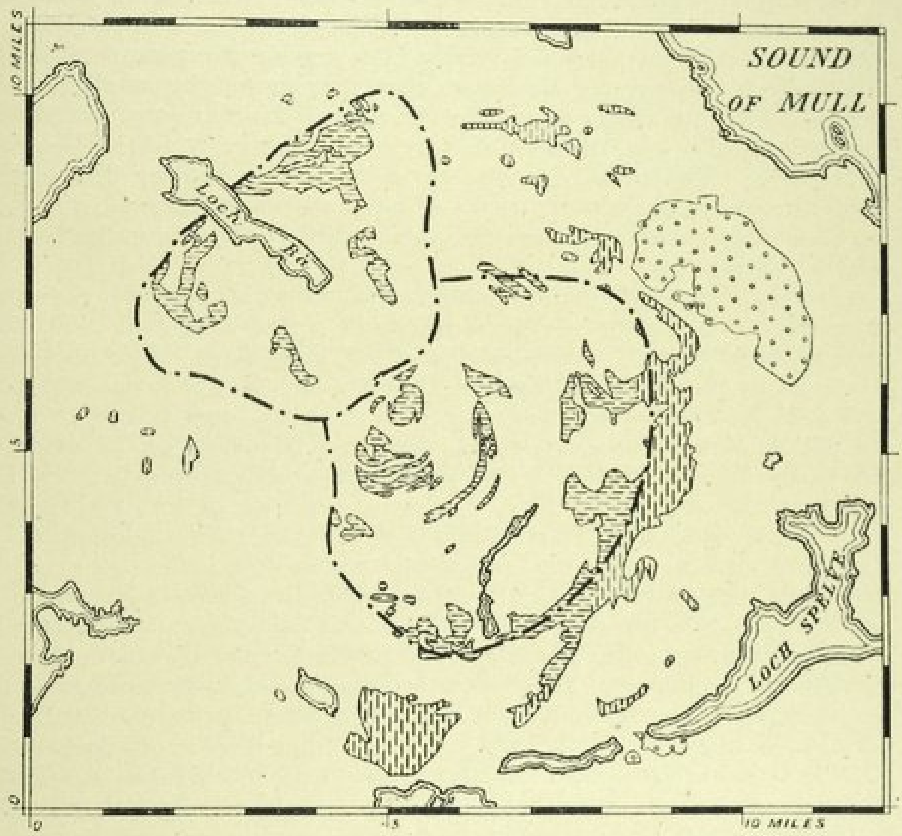


FIG. 35. Parallel Sections showing Early Basic Cone-Sheets cutting Loch Spelve Anticline, North-West and South-East of Sgùrr Dearg. 1 Moine Gneiss. 2 Mesozoic Sediments. 3 Basalt-Lavas. 4 Big-Felspar Gabbro. 5 Surface-Agglomerate. 5' Vent-Agglomerate. 6 Beinn Mheadhon Felsite. 7a Early Acid Cone-Sheets. 7b Early Basic Cone-Sheets.

(Figure 35) Parallel Sections showing Early Basic Cone-Sheets cutting Loch Spelve Anticline, North-West and South-East of Sgùrr Dearg. 1 Moine Gneiss. 2 Mesozoic Sediments. 3 Basalt-Lavas. 4 Big-Felspar Gabbro. 5 Surface-Agglomerate. 5' Vent-Agglomerate. 6 Beinn Mheadhon Felsite. 7a Early Acid Cone-Sheets. 7b Early Basic Cone-Sheets.



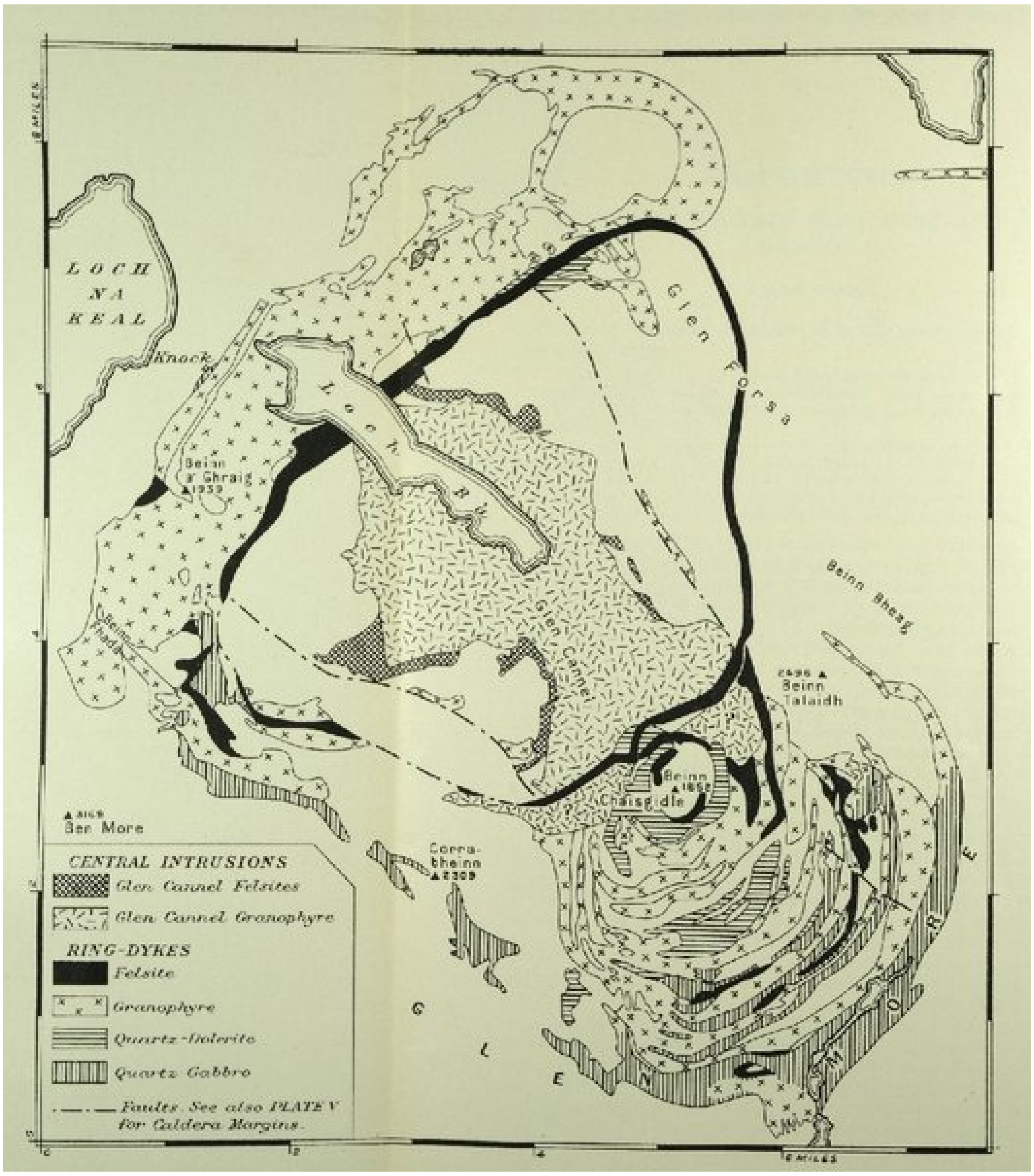
Agglomerates and associated Rhyolites in Vents. { Where agglomerate does not contain gneiss-fragments. Where agglomerate does contain gneiss-fragments.

Agglomerates and associated Rhyolites in Coire Mòr Syncline; agglomerates contain gneiss-fragments.

Margins of Main Calderas.

Fig. 29.—Distribution of Gneiss-Fragments in Mull Agglomerates.

(Figure 29) Distribution of gneiss-fragments in Mull Agglomerates.



(Plate 6) Map showing ring-dykes

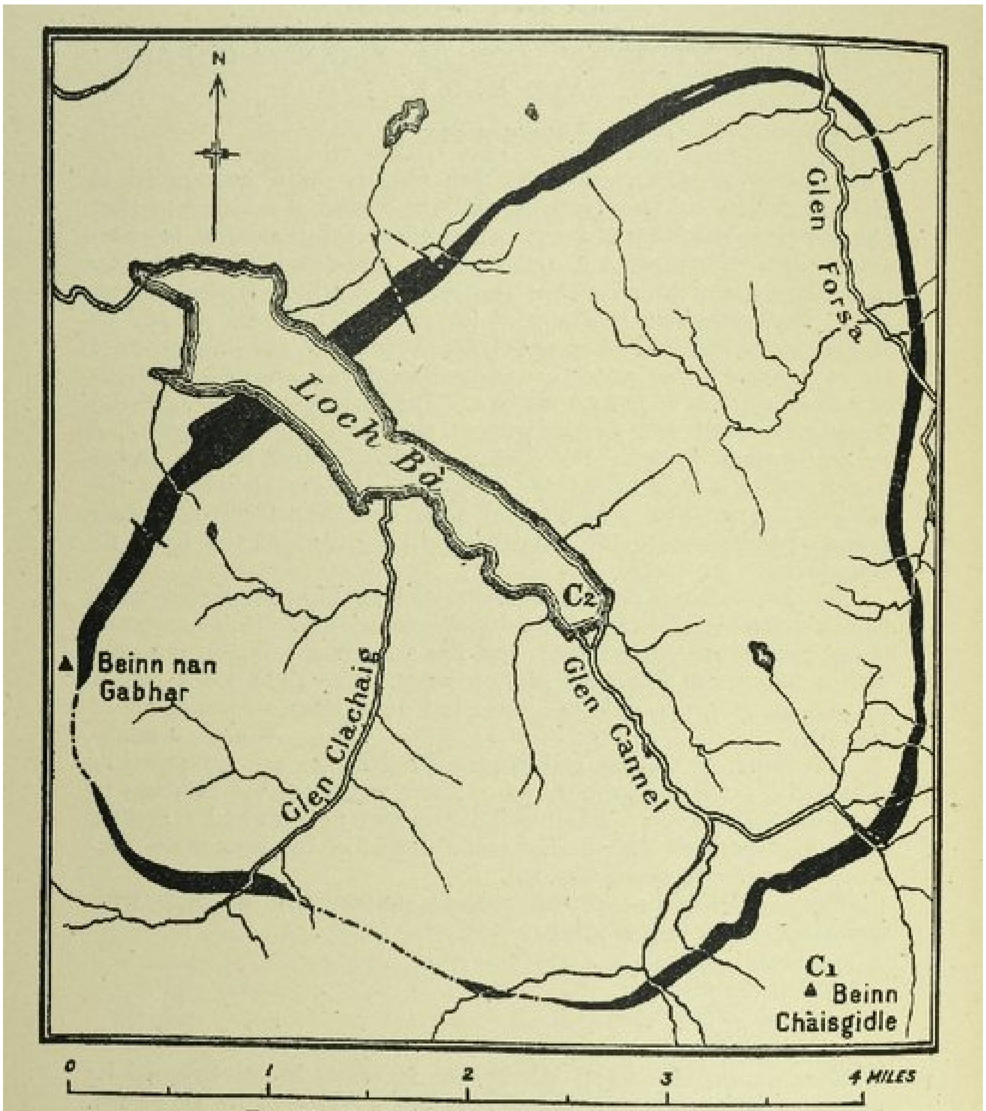
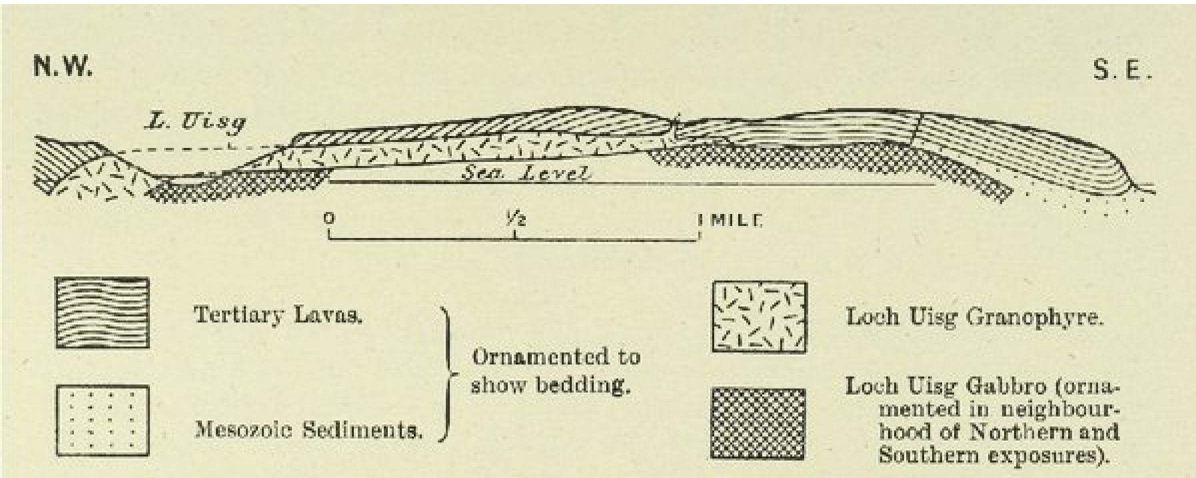
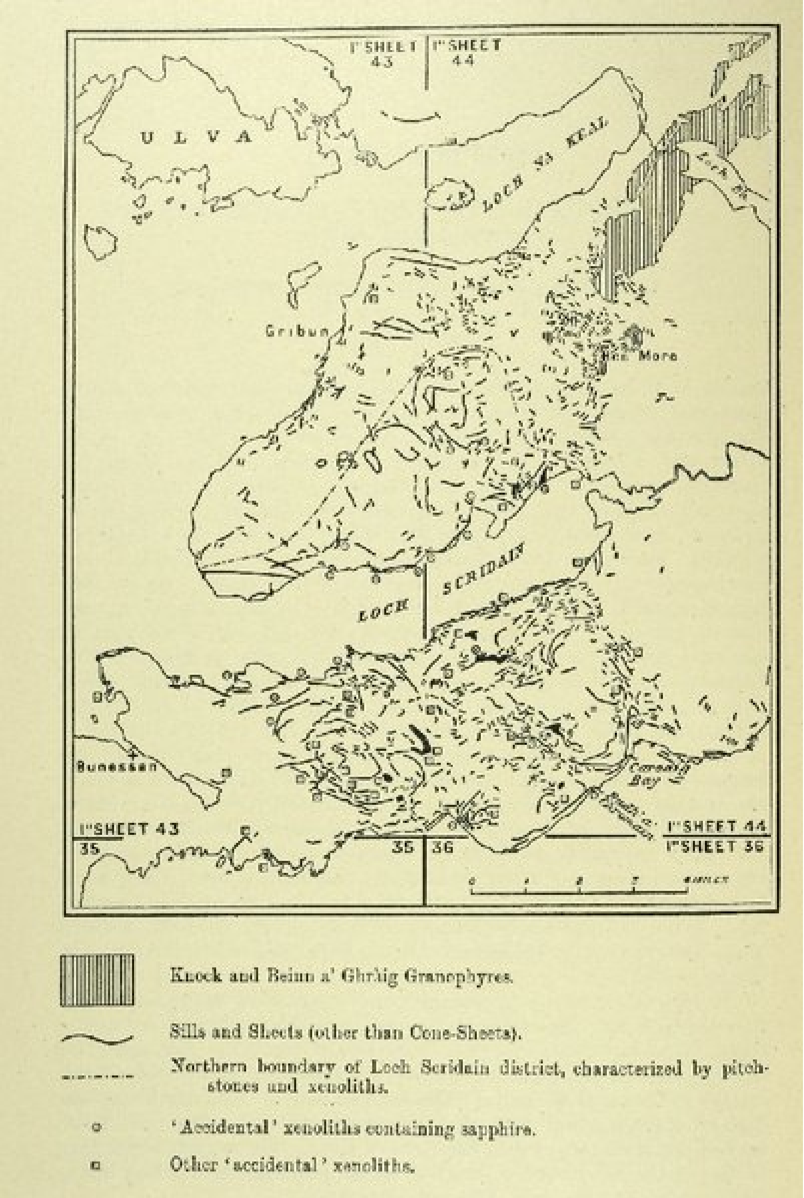


FIG. 58.—Loch Bà Felsitic Ring-Dyke along Fault.
C1 and C2 show two chief centres of ring-dykes and cone-sheets.
Quoted from *Summary of Progress for* 1914, p. 36.

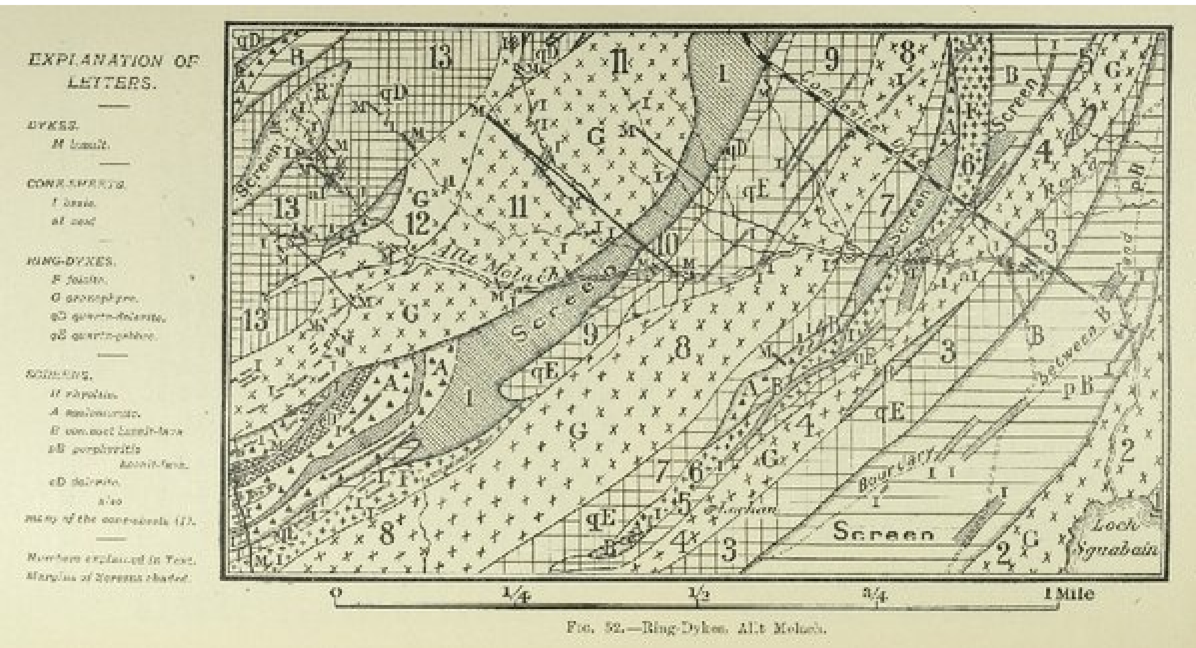
(Figure 58) Loch Bà Felsitic Ring-Dyke along Fault. C1 and C2 show two chief centres of ring-dykes and cone-sheets. Quoted from Summary of Progress for 1914, p. 86.



(Figure 34) Section showing Loch Uisg Granophyre cutting folded lavas.



(Figure 42) Map of South-West Mull, showing distribution of Sills and Sheets other than Cone-Sheets.



(Figure 52) Ring Dykes, Allt Melach.

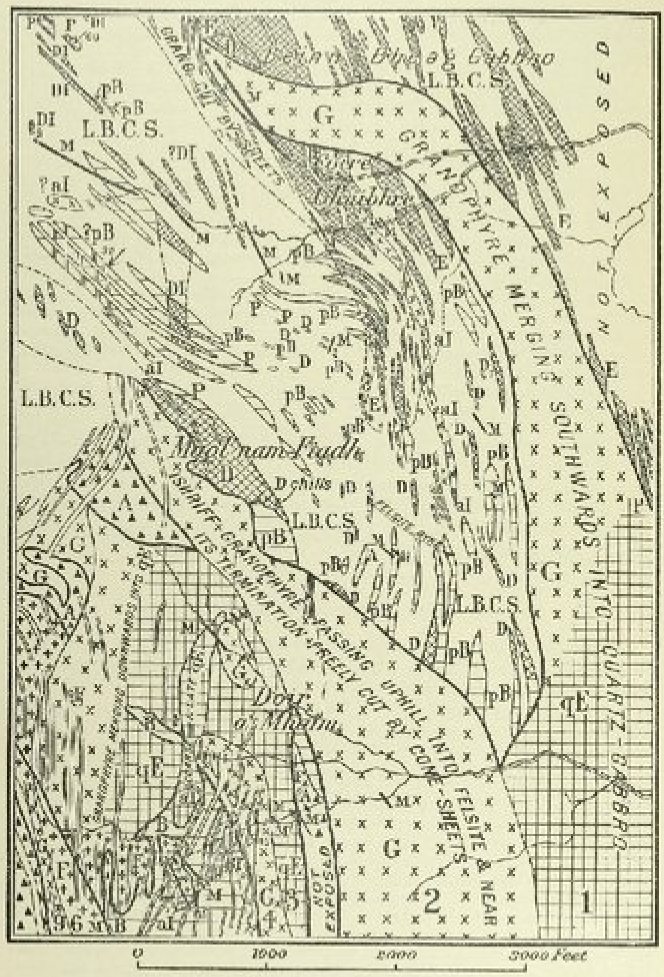


Fig. 53.—Ring-Dykes, Maol nam Fiadh.

Dykes: M basalt,

Cone-Sheets: DI dolerite; aI acid; L.B.C.S. Late Basic Cone-Sheets (shown without ornament).

Ring-Dykes: F felsite; G granophyre; qE quartz gabbro.

Screens: A agglomerate; B compact basalt lava; pB porphyritic basalt-lava; P pillow-lava; D dolerite; E gabbro; also many of the cone-sheets.

Numbers as in Fig. 52, see Text.

(Figure 53) Ring-Dykes, Maol nam. Fiadh. Dykes: M basalt, Cone-Sheets: DI dolerite; aI acid; L.B.C.S. Late Basic Cone-Sheets (shown without ornament). Ring-Dykes: F felsite; G granophyre; qE quartz-gabbro. Screens: A agglomerate; B compact basalt-lava; pB porphyritic basalt-lava; P pillow-lava; D dolerite; E gabbro; also many of the cone-sheets. Numbers as in Figure 52, see Text.

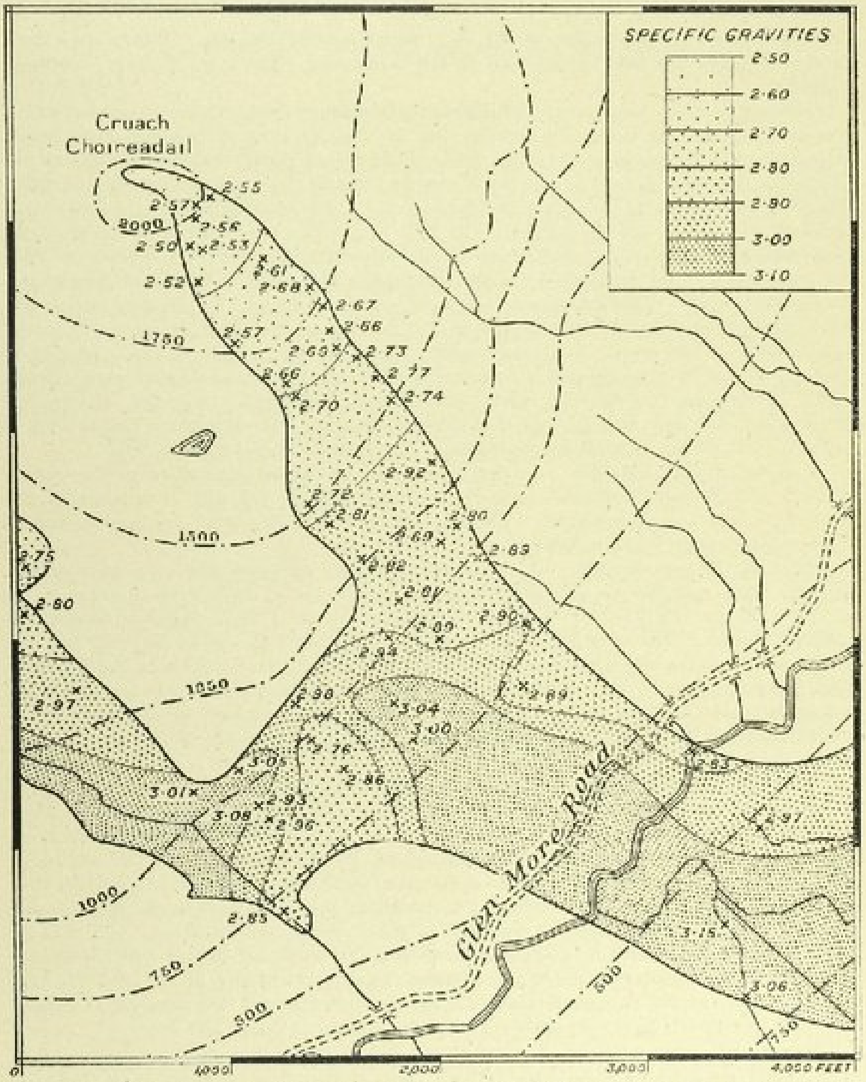


FIG. 54.—Map showing Density-Stratification in differentiated Ring-Dyke, Cruach Choireadail, Glen More (Locality 1). The extreme products exposed are olivine-bearing quartz-gabbro and granophyre.

(Figure 54) Map showing Density-Stratification in differentiated Ring-Dyke, Cruach Choireadail, Glen More (Locality 1). The extreme products exposed are olivine-bearing quartz-gabbro and granophyre.

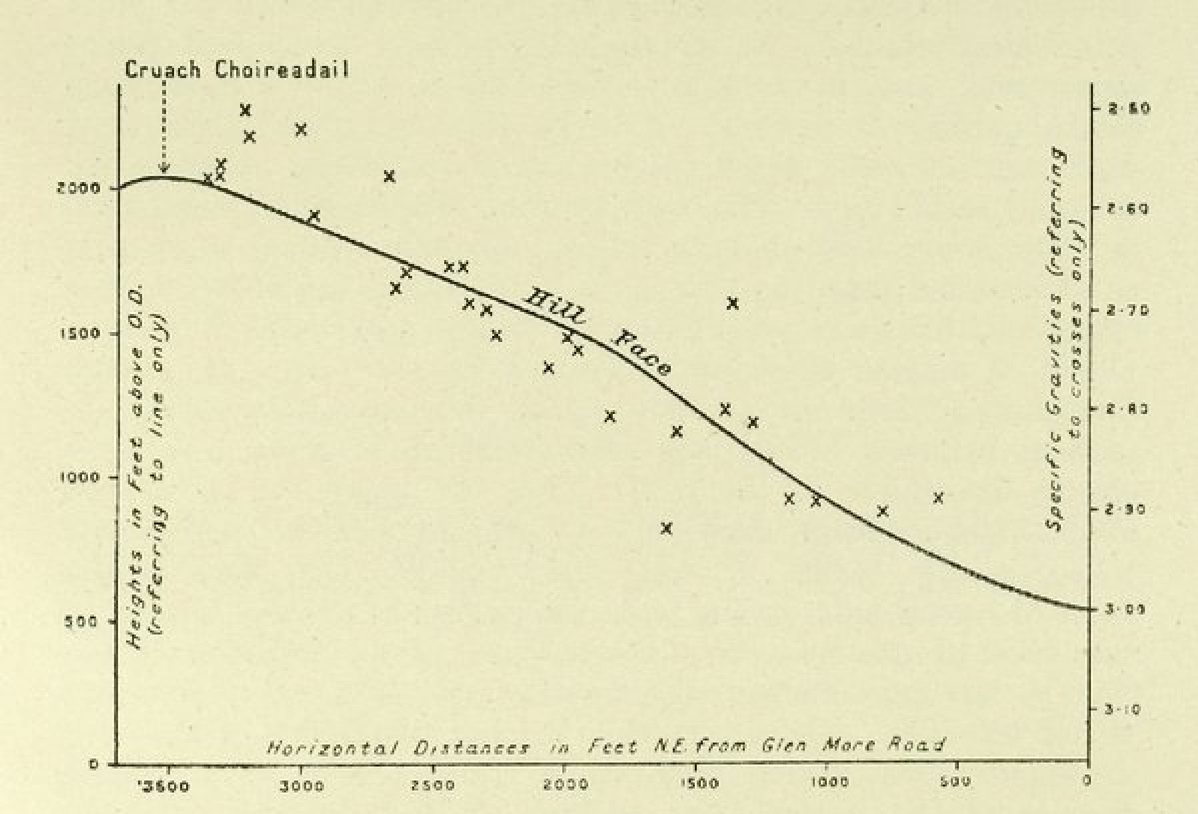


FIG. 55.

(Figure 55) Graph showing relation of Specific Gravity to Altitude in gravitationally differentiated Ring-Dyke, Cruach Choireadail, Glen More.

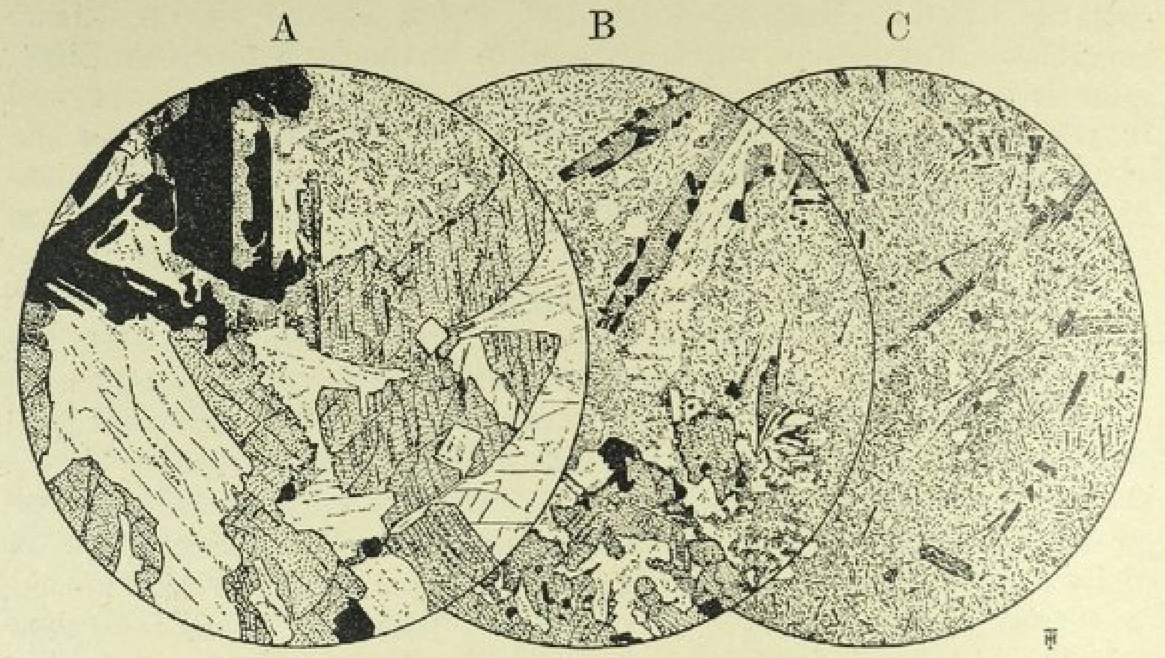


FIG. 56.—The Glen More Differentiated Ring-Dyke.

(Figure 56) The Glen More Differentiated Ring-Dyke. A. [(S17636) [NM 5968 2968]] ×15. Lower Basic Portion. Quartz-gabbro. The rock is composed of labradorite, ophitic augite and large plates of ilmenite, with a variable amount of finely crystalline acid mesostasis (top). Where in contact with the acid residuum, the augite shows signs of resorption. Movement of the mass after partial consolidation has frequently resulted in the bending and breaking of crystals—note the curved cleavage-traces in the large crystal of augite.Fig. 56 B. [(S17632) [NM 5965 3014]] ×15. Intermediate Portion. The figure shows a rock in which there is an increased proportion of acid mesostatic matter with characteristic acicular crystallization of its components. It has developed columnar crystals of augite (top) with their usual association of magnetite, and it encloses small patches of more doleritic material (bottom) which show signs of resorption and of being

out of equilibrium with their surroundings. C. [(S17626) [NM 5952 3042]] x 15. Higher Acid Portion. Acicular type of crystallization is a characteristic feature. The rock is composed of elongated crystals of greenish hornblende, pseudomorphous after augite, in a feathery base of alkali-felspar and quartz, frequently in micrographic relationship to each other.

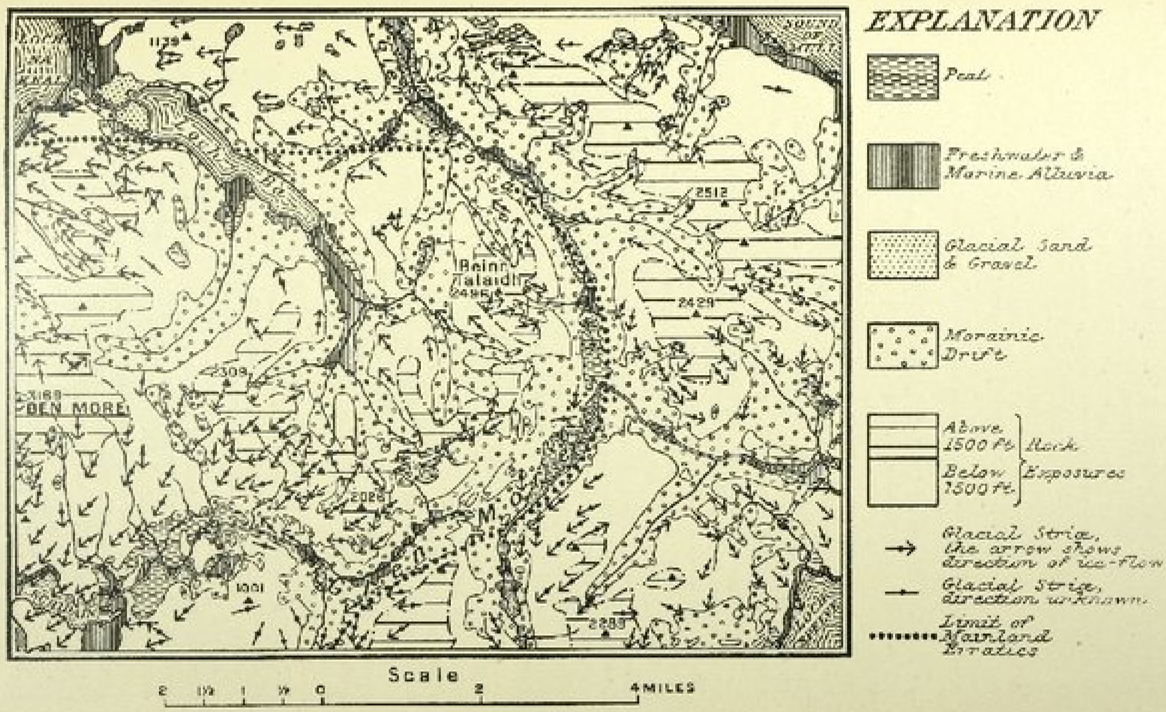


FIG. 64.

Map showing Superficial Deposits and Glaciation of Central Mull within limits indicated by note at left hand top corner of one-inch Map, Sheet 44.

(Figure 64) Map showing Superficial Deposits and. Glaciation of Central Mull within limits indicated by note at left hand top corner of one-inch Map, Sheet 44.

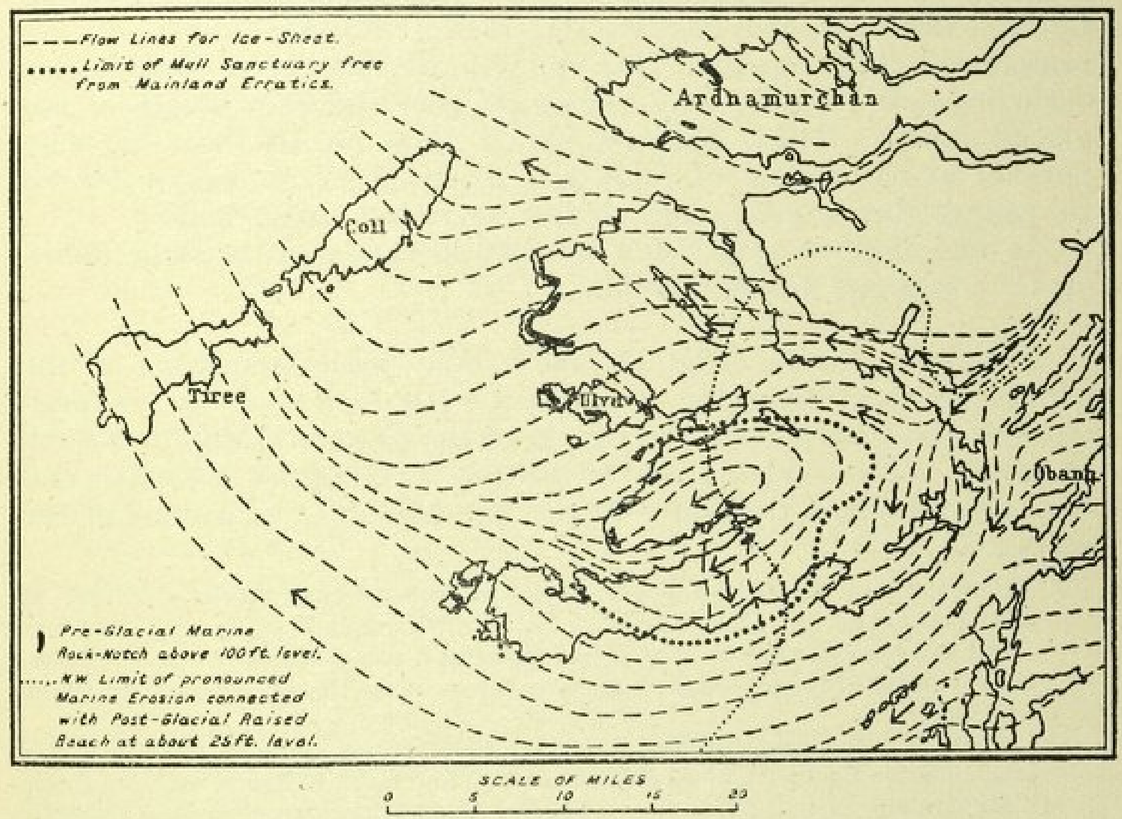
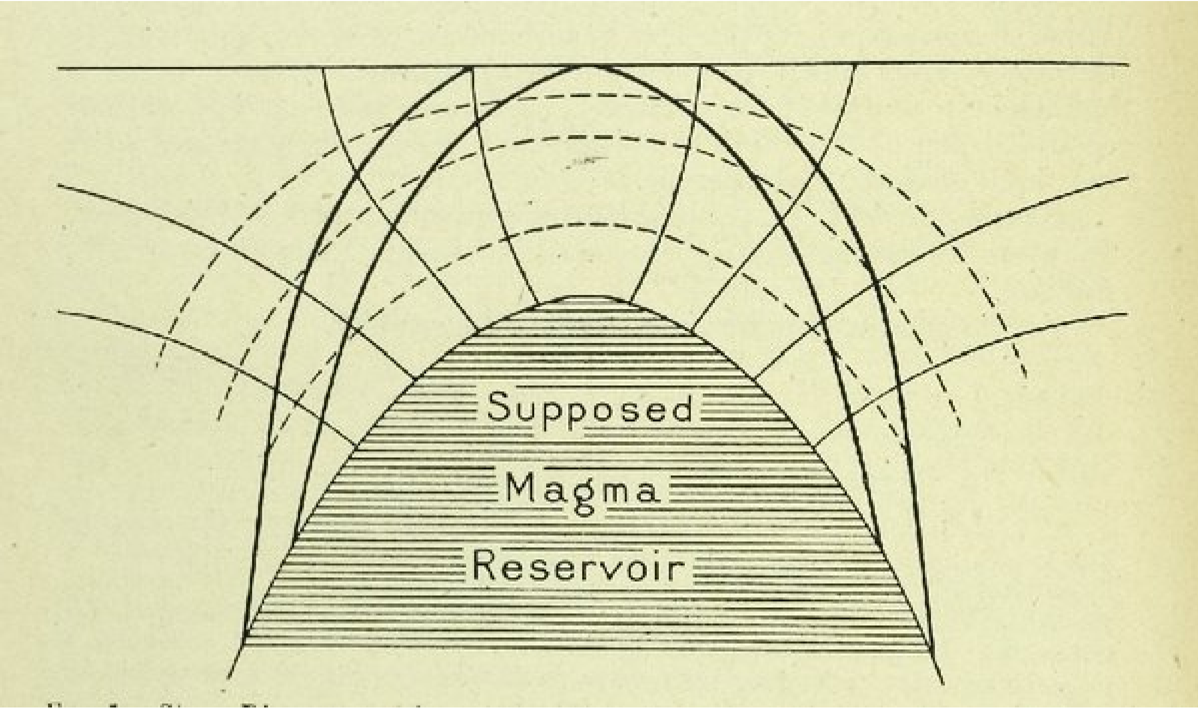
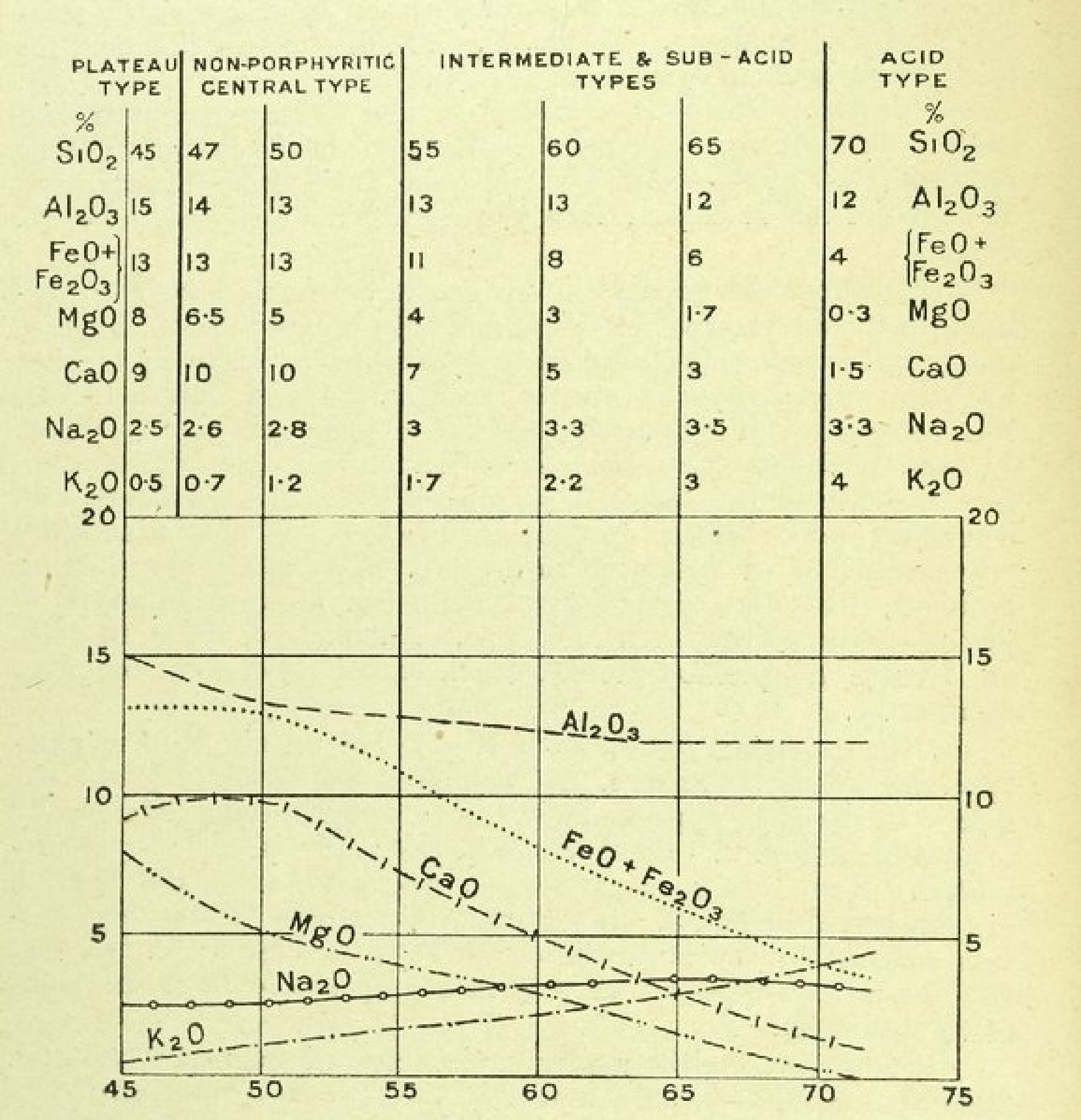


FIG. 65.

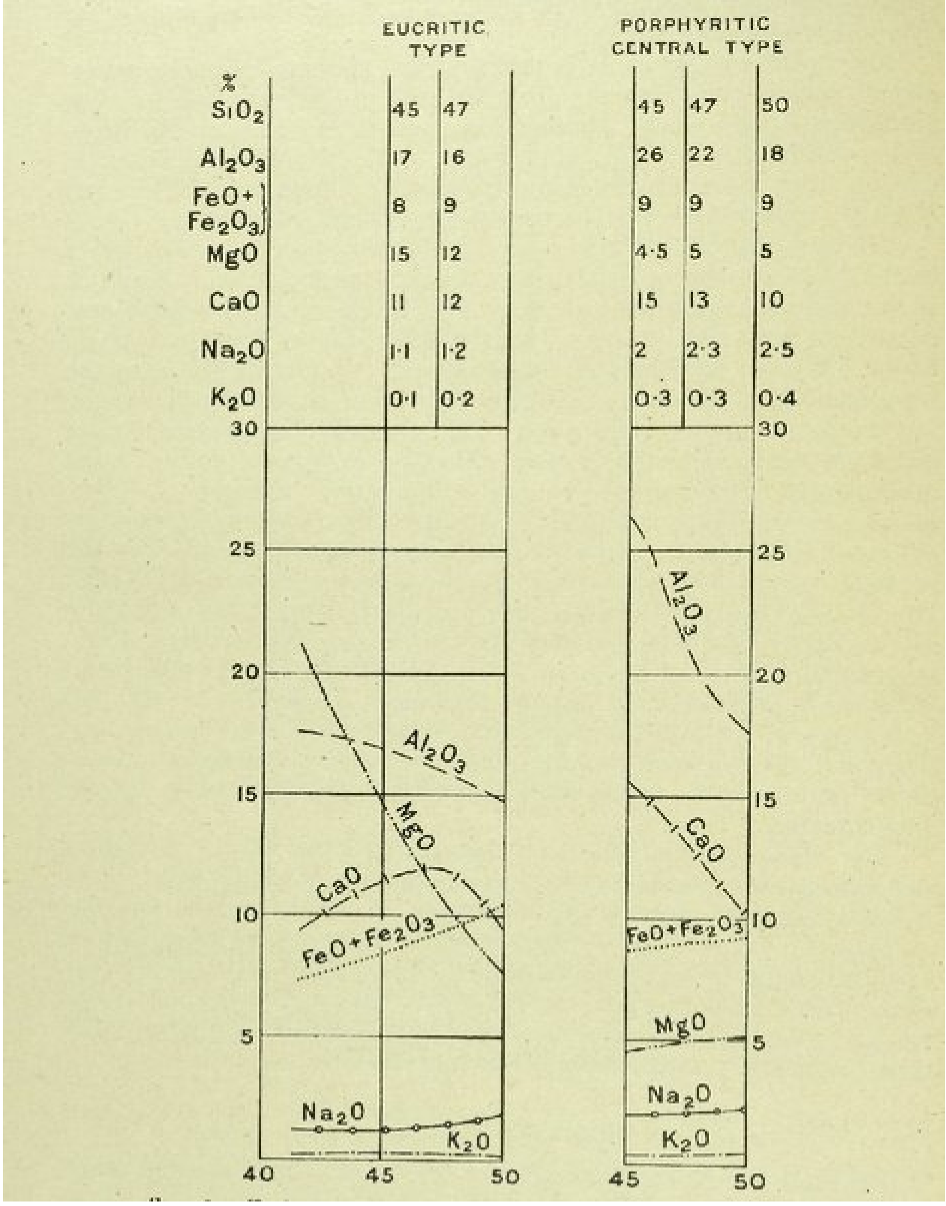
(Figure 65) General Glaciation of District, and some Raised-Beach phenomena.



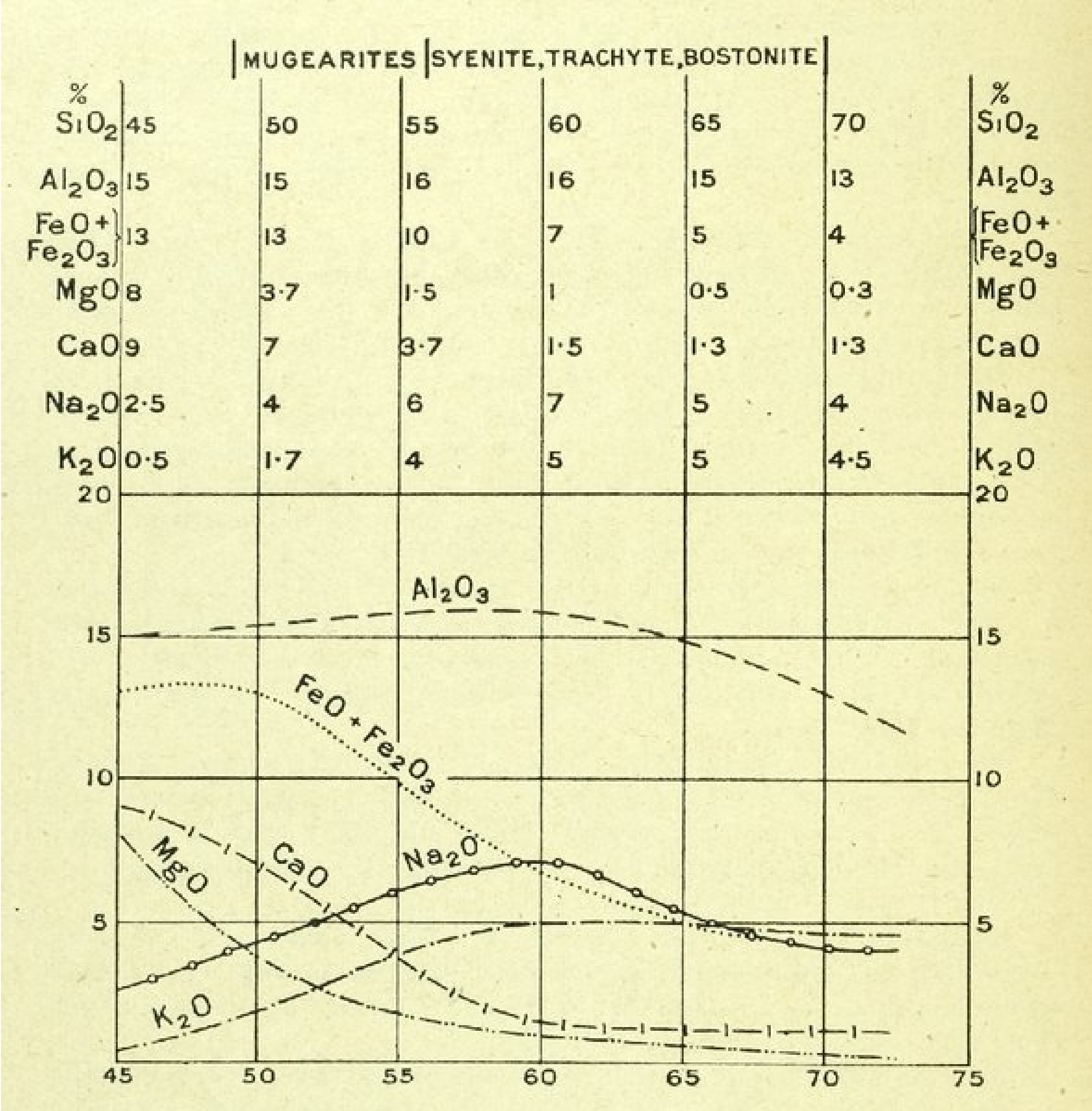
(Figure 1) Stress-diagram to show supposed mode of formation of cone-sheets and ring-dykes. For explanation of lines, see text.



(Figure 2) Variation-diagram: Normal Mull Magma-Series.



(Figure 3) Variation-diagrams: Allivalite-Euerite Magma-Series; and Porphyritic Central Magma-Type.



(Figure 4) Variation-diagram: Mull Alkaline Magma-Series.

TABLE I. : PLATEAU MAGMA-TYPE OF FIG. 2.

	A	B	I.	II.	III.	C	D	E	
SiO_2	43·94	45·24	45·37	45·48	45·52	46·46	46·61	47·64	SiO_2
TiO_2	2·45	2·26	2·87	3·48	2·85	2·07	1·81	1.27	TiO_2
Al_2O_3	14·03	15·63	15·16	15·66	14·30	15·48	15·32	14·15	Al_2O_3
Cr_2O_3	tr.	tr.	...	...	...	0·02	tr.	0·01	Cr_2O_3
V_2O_3	...	...	...	...	...	0·05	...	0·06	V_2O_3
Fe_2O_3	1·95	5·56	3·38	3·64	3·43	3·63	3·49	5·18	Fe_2O_3
FeO	11·65	7·19	11·58	10·56	9·00	10·23	7·71	7·96	FeO
MnO	0·32	0·23	0·31	0·20	0·19	0·48	0·13	0 33	MnO
(Co,Ni)O	nt. fd.	tr.	nt. fd.	...	...	0·02	tr.	tr.	(Co,Ni)O
MgO	10·46	7·82	6·72	6·99	10·65	6·80	8·66	7·38	MgO
CaO	8·99	9·38	8·11	8·24	9·54	9·05	10·08	11·71	CaO
(Ba,Sr)O	nt. fd.	...	nt. fd.	..	...	0·02	...	nt. fd.	(Ba,Sr)O
Na_2O	2·68	2·01	2·90	2·68	2·21	3·01	2·43	2·38	Na_2O
K_2O	0·33	0 72	0.44	0·49	0·42	0·68	0·67	0·71	K_2O
Li_2O	nt. fd.	...	nt. fd.	nt. fd.	nt. fd.	? tr.	...	...	Li_2O
$H_2O + 105°$	2·31	2·21	1·96	1·52	1·53	1·43	2·07	1.44	$H_2O + 105°$
H_2O at 105°	0·85	1·12	1·18	0·93	0·70	0·89	1·10	0·19	H_2O at 105°
P_2O_5	0·20	0·20	0·29	0·26	0·23	0·30	tr.	0·09	P_2O_5
CO_2	0·16	0·49	...	0·21	0·15	nt. fd.	tr.	...	CO_2
FeS_2	0·04	...	...	...	...	...	...	...	FeS_2
Fe_7S_8	0·06	...	...	...	...	...	...	...	Fe_7S_8
½S	...	...	...	...	...	0·08	...	...	½S
S	...	...	...	nt. fd.	nt. fd.	...	...	0·03	S
	100·42	100 06	100·27	100·34	100·72	100·70	100·08	100·53	...
Spec. grav.	...	2·85	2·95	2·93	2·99	...	2·87	...	...

(Table 1) Plateau Magma-Type of Figure 2

TABLE II.—NON-PORPHYRITIC CENTRAL MAGMA-TYPE OF FIG. 2.

	Tholeiite Salen Type	Basalt Staffa Type			Basalt Compact Central Type		Tholeiite Brunton Type		Quartz-Dolerite and Tholeiite Talaidh Type		
	I.	II.	III.	A	IV.	V.	VI.	VII.	VIII.	IX.	
SiO_2	47·35	47·80	49·76	52·13	50·54	53·78	51·53	51·63	52·16	53·97	SiO_2
TiO_2	1·75	....	0·94	....	2·80	2·28	1·57	2·00	3·25	1·24	TiO_2
Al_2O_3	13·90	14·80	14·42	14·87	12·86	12·69	11·05	11·77	11·95	14·65	Al_2O_3
Fe_2O_3	5·87	....	3·95	....	4·13	3·44	2·73	3·23	4·86	3·62	Fe_2O_3
FeO	8·96	13·08	7·77	11·40	8·75	8·94	10·98	10·47	9·92	6·32	FeO
MnO	0·23	0·09	0·20	0·32	0·32	0·53	0·45	0·35	0·18	0·30	MnO
(Co, Ni)O	nt. fd.	....	nt. fd.	....	0·06	nt. fd.	nt. fd.	0·04	....	nt. fd.	(Co, Ni)O
MgO	5·97	6·84	5·30	6·46	4·63	2·58	5·21	5·02	3·77	4·49	MgO
CaO	10·65	12·89	10·22	10·56	8·71	6·36	9·68	9·34	7·14	7·98	CaO
BaO	....	....	0·04	....	nt. fd.	0·09	nt. fd.	0·03	....	0·04	BaO
Na_2O	2·73	2·48	2·49	2·60	2·89	2·74	3·48	2·90	2·36	2·54	Na_2O
K_2O	0·54	0·86	1·83	0·69	1·43	2·27	0·86	0·91	1·74	1·52	K_2O
Li_2O	....	....	tr.	....	nt. fd.	nt. fd.	tr.	nt. fd.	....	tr.	Li_2O
$H_2O - 105°$	1·16	1·41	1·03	1·19	2·25	2·19	1·26	1·40	1·95	0·94	H_2O ; 105°
H_2O at 105°	1·04		2·04		0·17	1·19	0·71	0·68	0·56	1·92	H_2O at 105°
P_2O_5	0·24	....	0·21	....	0·34	0·55	0·22	0·29	0·24	0·27	P_2O_5
CO_2	0·32	....	0·06	....	0·33	0·08	0·08	0·11	0·18	0·51	CO_2
FeS_2	....	....	0·04	....	nt. fd.	0·42	0·26	0·08	....	0·09	FeS_2
S	0·23	....	....	....	....	....	....	....	0·18	....	S
	100·91	100·25	100·30	100,22	100·24	100·13	100·07	100·27	100·44	100·40	
Spec. grav.	2·96	....	2·72	....	2·90	2·68	2·93	2·95	2·91	2·83	

(Table 2) Non-Porphyritic Central Magma-Type of Figure 2

TABLE III.—INTERMEDIATE TO SUBACID MAGMA-TYPE OF FIG. 2.

	Craignurite (basic) I.	Leidleite II.	III.	Inninmorite IV.	V.	Craignurite (acid) VI.	
SiO_2	55·82	59·21	61·69	62·37	64·13	66·27	SiO_2
TiO_2	1·62	1·06	1·00	1·06	1·19	0·87	TiO_2
Al_2O_3	11·47	14·06	14·43	12·04	13·15	11·92	Al_2O_3
Fe_2O_3	3·68	2·66	1·23	1·87	1·08	3·09	Fe_2O_3
FeO	7·66	4·87	5·86	5·81	6·31	3·18	FeO
MnO	0·40	0·24	0·30	0·24	0·27	0·31	MnO
(Co,Ni)O	0·04	nt. fd.	nt. fd.	nt. fd.	nt. fd.	nt. fd.	(Co,Ni)O
MgO	4·08	3·71	2·81	0·97	1·08	1·44	MgO
CaO	7·88	5·95	4·97	3·51	3·62	3·30	CaO
BaO	0·03	0·03	0·04	0·07	0·09	nt. fd.	BaO
Na_2O	2·58	2·06	3·20	3·47	3·64	2·89	Na_2O
K_2O	2·00	2·83	1·72	2·34	2·32	4·03	K_2O
Li_2O	tr.	nt. fd.	nt. fd.	nt fd.	nt. fd.	tr.	Li_2O
$H_2O+105°$	1·88	1·49	2·32	5·54	2·71	1·51	$H_2O+105°$
H_2O at 105°	0·66	2·06	0·25	0·44	0·36	0·78	H_2O at 105°
P_2O_5	0·23	0·20	0·24	0·30	0·31	0·17	P_2O_5
Co_2	0·08	...	...	...	...	0·53	Co_2
FeS_2	0·09	nt. fd.	nt. fd.	nt. fd.	nt. fd.	nt. fd.	FeS_2
Cl	...	nt. fd.	0·02	...	...	...	Cl
	100·18	100·43	100·08	100·03	100·26	100·29	
Spec. grav.	2·88	2·61	2·64	2·50	2·57	2·65	

(Table 3) Intermediate to Subacid Magma-Type of Figure 2

TABLE IV.—ACID MAGMA-TYPE OF FIG. 2.

	I.	II.	III.	IV.	V.	
SiO_2 . . .	70·70	71·30	72·66	73·12	73·32	SiO_2
TiO_2 . . .	1·27	0·58	0·34	0·39	0·51	TiO_2
Al_2O_3 . . .	11·78	11·24	12·00	12·44	12·25	Al_2O_3
Fe_2O_3 . . .	1·32	1·80	2·03	2·09	2·77	Fe_2O_3
FeO . . .	3·45	2·84	2·04	1·65	2·20	FeO
MnO . . .	0·07	0·31	0·18	0·17	0·12	MnO
(Co,Ni)O . .	...	nt. fd.	nt. fd.	nt. fd.	nt. fd.	(Co,Ni)O
MgO . . .	0·53	0·61	0·07	0·14	0·11	MgO
CaO . . .	1·30	1·56	1·25	0·88	1·65	CaO
BaO . . .	...	0·07	0·12	nt. fd.	0·09	BaO
Na_2O . . .	2·48	3·44	3·26	3·90	3·92	Na_2O
K_2O . . .	4·71	4·66	5·26	4·67	2·34	K_2O
Li_2O . . .	...	? tr.	nt. fd.	nt. fd.	nt. fd.	Li_2O
$H_2O + 105°$ . .	1·14	1·04	0·47	0·24	0·35	$H_2O + 105°$
H_2O at 105° .	0·50	0·39	0·22	0·25	0·35	H_2O at 105°
P_2O_5 . . .	0·26	0·22	0·04	0·09	0·10	P_2O_5
CO_2 . . .	0·51	...	0·24	0·05	0·06	CO_2
FeS_2 . . .	...	nt. fd.	nt. fd.	nt. fd.	nt. fd.	FeS_2
S . . .	0·08	...	...	...	...	S
	100·10	100·06	100·18	100·08	100·14	
Spec. grav. .	2·58	2·53	2·61	2·57	2·66	

(Table 4) Acid Magma-type of Figure 2

TABLE V.—ALLIVALITE—EUCRITE MAGMA SERIES OF FIG. 3.

	Allivalite	Eucrite		
	A	I.	B	
SiO_2	42·20	46·66	48·05	SiO_2
TiO_2	0·09	0·47	0·49	TiO_2
Al_2O_3 . . .	17·56	16·71	15·35	Al_2O_3
Cr_2O_3 . . .	0·06	...	0·14	Cr_2O_3
Fe_2O_3 . . .	1·20	2·69	1·86	Fe_2O_3
FeO	6·33	5·87	7·53	FeO
MnO	0·18	0·12	0·28	MnO
(Co, Ni)O . . .	0·13	...	0·11	(Co, Ni)O
CuO	0·04	...	0·05	CuO
MgO	20·38	12·36	12·53	MgO
CaO	9·61	12·57.	11·02	CaO
Na_2O	1·11	1·16	1·26	Na_2O
K_2O	0·11	0·27	0·19	K_2O
Li_2O	...	nt. fd.	...	Li_2O
$H_2O + 105°$ . .	1·13	1·24	0·45	$H_2O + 105°$
H_2O at 105° .	0·06	0·13	0·15	H_2O at 105°
P_2O_5	...	0·13	...	P_2O_5
CO_2	tr.	0·18	0·44	CO_2
S	0·02	nt. fd.	0·20	S
	100·21	100·56	100·10	
Spec. grav.	2·96	2·97	2·95	

(Table 5) Allivalite-Eucrite Magma Series of Figure 3

TABLE VI.—PORPHYRITIC CENTRAL MAGMA-TYPE OF FIG. 3.

	Dolerite	Gabbro			Basalt			
	I.	A	B	II.	III.	IV.	V.	
SiO_2 .	45·54	46·39	47·28	48·34	47·24	47·49	48·51	SiO_2
TiO_2 .	1·06	0·26	0·28	0·95	1·46	0·93	1·46	TiO_2
Al_2O_3 .	23·39	26·34	21·11	20·10	18·55	21·46	19·44	Al_2O_3
Cr_2O_3 .	...	tr.	...	...	...	...	...	Cr_2O_3
Fe_2O_3 .	1·98	2·02	3·52	1·97	6·02	1·72	5·66	Fe_2O_3
FeO .	6·98	3·15	3·91	6·62	4·06	4·80	4·00	FeO
MnO .	0·27	0·14	0·15	0·32	0·31	0·15	0·23	MnO
(Co,Ni)O	...	...	...	nt. fd.	0·05	0·04	0·04	(Co,Ni)O
MgO .	4·60	4·82	8·06	5·49	5·24	4·59	5·12	MgO
CaO .	11·82	15·29	13·42	13·16	11·72	13·24	12·03	CaO
BaO .	...	...	...	0·10	nt. fd	nt. fd.	nt. fd.	BaO
Na_2O .	2·50	1·63	1·52	1·66	2·42	2·17	2·53	Na_2O
K_2O .	0·44	0·20	0·29	0·98	0·15	0·42	0·25	K_2O
Li_2O .	...	...	...	nt. fd.	nt. fd.	nt. fd.	nt. fd.	Li_2O
$H_2O + 105°$	0·72	0·48	0·53	0·44	2·24	2·54	0·48	$H_2O + 105°$
H_2O at 105°	0·62	0·10	0·13	0·02	0·21	0·17	0·04	H_2O at 105°
P_2O_5 .	0·13	tr.	tr.	0·04	0·26	0·43	0·16	P_2O_5
CO_2 .	...	...	...	0·11	0·19	0·08	0·09	CO_2
FeS_2 .	...	...	...	nt. fd.	nt. fd.	nt. fd.	nt. fd.	FeS_2
	100·05	100·82	100·20	100·30	100·12	100·23	100·04	
Spec. grav.	2·85	2·85	2·90	2·93	2·85	2·82	2·93	

(Table 6) Porphyritic Central Magma-Type of Figure 3

TABLE VII.—ALKALINE MAGMA-SERIES OF FIG. 4.

	Mugearite				Syenite	Trachyte		
	A	B	C	I.	II.	III.	IV.	
SiO_2	49·24	49·92	50·70	55·76	58·81	60·13	63·12	SiO_2
TiO_2	1·84	2·04	1·89	1·78	0·76	0·73	0·51	TiO_2
Al_2O_3	15·84	12·83	14·60	16·55	14·81	16·53	15·44	Al_2O_3
Cr_2O_3	tr.	tr.	..	...	...	...	...	Cr_2O_3
V_2O_3	...	0·04	...	...	...	...	...	V_2O_3
Fe_2O_3	6·09	6·96	5·23	3·10	4·58	2·86	1·73	Fe_2O_3
FeO	7·18	6·21	7·68	6·02	4·21	2·55	3·53	FeO
MnO	0·29	0·52	0·42	0·22	0·27	0·46	0·27	MnO
(Co,Ni)O	tr.	0·03	tr.	nt. fd.	nt. fd.	nt. fd.	nt. fd.	(Co,Ni)O
MgO	3·02	3·78	4·15	1·08	0·80	1·20	0·62	MgO
CaO	5·26	7·25	7·20	3·23	2·33	1·61	1·31	CaO
BaO	0·09	0·09	0·08	0·07	0·03	0·11	nt. fd.	BaO
SrO	tr.	tr.	tr.	...	...	...	...	SrO
Na_2O	5·21	3·72	3·71	6·28	5·60	8·06	5·81	Na_2O
K_2O	2·10	1·73	1·33	3·87	4·96	3·99	5·36	K_2O
Li_2O	...	tr.	? tr.	tr.	nt. fd.	tr.	nt. fd.	Li_2O
$H_2O + 105°$	1·61	1·05	1·15	0·95	0·82	0·97	0·44	$H_2O + 105°$
H_2O at 105°	1·08	3·58	2·08	0·80	2·00	0·55	0·14	H_2O at 105°
P_2O_5	1·47	0·45	0·49	0·40	0·20	0·57	0·25	P_2O_5
CO_2	...	nt. fd.	nt. fd.	0·03	...	...	1·89	CO_2
FeS_2	...	...	...	nt. fd.	nt. fd.	nt. fd.	nt. fd.	FeS_2
S	0·03	? tr.	nt. fd.	...	...	...	...	S
F	0·18	...	...	...	...	...	...	F
	100·46*	100·20	100·71	100·14	100·18	100·32	100·42	
Spec. grav	2·79	...	...	2·67	2·64	2·51	2·89	

(Table 7) Alkaline Magma-Series of Figure 4

TABLE IX.

	Phenocrysts		Amygdale—Minerals: Outside Pneumatolysis Limit								Inside Pneumatolysis Limit			Inside Contact-Zone		Mud-Stone	Xenoliths and enclosed Spinel			
	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIIa.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	
SiO_2	49·72	50·89	53·74	53·41	52·36	53·29	45·91	46·51	46·62	46·75	46·21	46·10	45·6	38·60	37·66	30·26	49·74	38·67	0·77	SiO_2
TiO_2	0·85											nt. fd.		0·12	0·12	1·32	1·19	0·90	0·50	TiO_2
Al_2O_3	0·90	31·04	0·82	1·76	1·71		0·11	2·40	3·90	24·82	27·00	25·65	26·0	23·51	21·21	27·34	31·59	37·27	65·81	Al_2O_3
Fe_2O_3	1·72							1·14	0·61					6·07	1·47	1·57	1·53	2·78	4·20	Fe_2O_3
FeO	27·77						2·07	1·85	1·08			0·55		0·22	9·34	17·18	4·34	5·07	24·00	FeO
MnO	0·08						2·27					nt. fd.		0·29	0·53	0·13	0·13	0·17	0·15	MnO
(Co, Ni)O	nt. fd.											nt. fd.		nt. fd.	nt. fd.	0·04	nt. fd.	nt. fd.	nt. fd.	(Co, Ni)O
MgO	12·09						0·06	0·47				0·32		0·40	0·45	0·34	0·66	2·35	0·57	MgO
CaO	3·89	12·63	31·19	31·03	31·48	33·41	40·39	33·40	35·05	13·90	13·45	14·17	14·2	22·79	33·36	0·74	0·88	4·85	0·56	CaO
BaO																nt. fd.	nt. fd.			BaO
Na_2O	0·23	3·56	9·34	8·11	8·04	8·89	0·32	0·26	0·30	0·39		tr.		tr.	1·17	1·08	3·74	3·63		Na_2O
K_2O	0·12	tr.	nt. fd.	2·43	2·47		1·16	1·15	0·57			0·03		0·03	0·73	2·05	1·72	3·01		K_2O
Li_2O	tr.											nt. fd.		tr.	nt. fd.	nt. fd.	tr.	nt. fd.		Li_2O
$H_2O + 105°$	1·37	0·52	2·38	2·66	4·07	4·16	4·17	12·61	12·11	13·64	13·78	13·78	13·8	0·29	0·29	7·20	3·44	1·08	0·14	$H_2O + 105°$
H_2O at 105°	0·08		0·6									0·13		0·09	nt. fd.	1·44	0·61	0·22	nt. fd.	H_2O at 105°
P_2O_5																0·24	0·36			P_2O_5
CO_2																	0·04			CO_2
FeS_2																nt. fd.	nt. fd.			FeS_2
	100·13	99·65	99·67	101·05	100·67	100·06	100·76	100·10	99·81	99·80	100·44	100·13	100·0	100·21	100·19	100·04	100·21	100·35	100·39	
Spec. grav.	3·44	2·78	...	...	...	...	2·605	...	2·423	...		2·265		3·488	3·61		2·65	2·91	3·807	

I. Uniaxial Augite. II. Labradorite. III.–VI. Pectolite. VII. Xonotlite. VIII, IX. Tobermorite.[1] X.–XII. Scolecite. XIII. Pink Epidote. XIV. Garnet. XV. Basal Mudstone (altered). XVI. Uncontaminated argillaceous xenolith. XVII. Contaminated argillaceous xenolith. XVIII. Dark-green Spinel.

[1] In British Museum Students' Index Tobermorite is listed as a synonym of Cyrolite.

(Table 9) Analyses other than bulk anayses of igneous rocks, made from material collected collected in the Mull District.

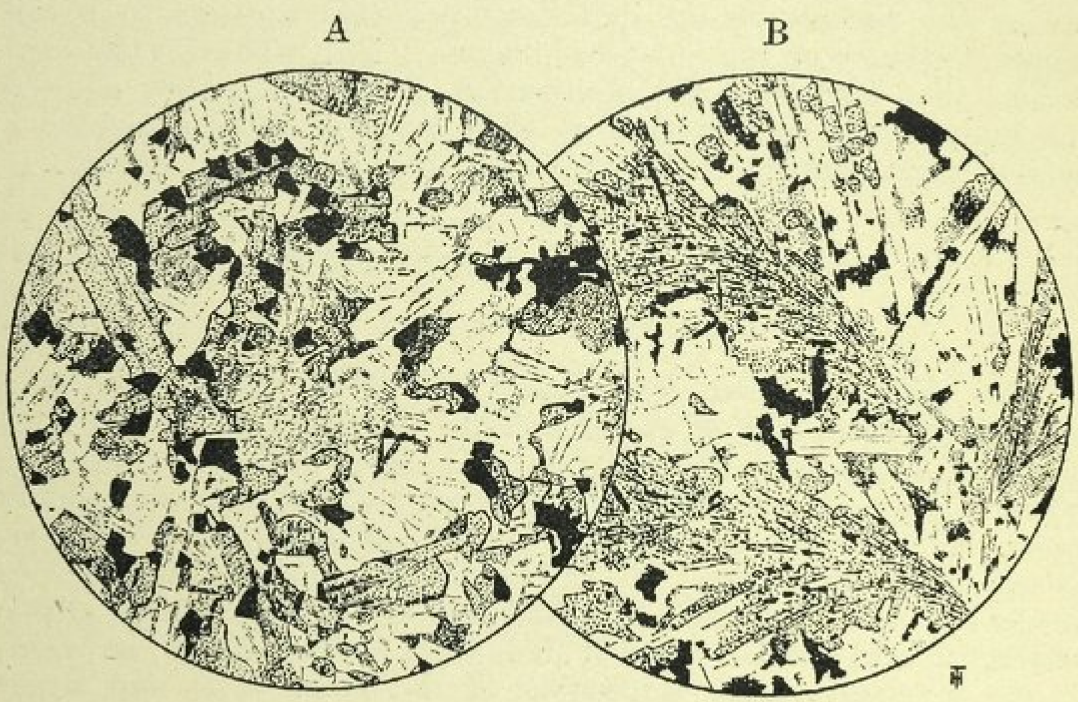


Fig. 50.—The Talaidh Type of Late Basic Cone-Sheets.

(Figure 50) The Talaidh Type of Late Basic Cone-Sheets. A. [(S14867) [NM 5354 2242]] x 17. Quartz-doleiite. The section shows columnar augite associated with titaniferous magnetite, a colourless moderately basic and albitized plagioclase, and a mesostasis of alkali-felspar and quartz. B. [(S14810) [NM 6060 3814]] x 17. Quartz-dolerite. Mineralogically similar to the above, but with a highly characteristic cervicorn development of its augite (p. 303).

TABLE XI.—Water of Augite-Andesites.

	Ia	Ib	IIa	IIb	IIIa	IIIb	IV.	V.	
SiO_2 . .	61·69	59·21					62·37	64·13	SiO_2
$H_2O+105°$.	2·36	1·54	2·38	1·56	2·44	0·93	5·54	2·71	$H_2O+105°$
H_2O at 105°	0·25	2·05	0·45	1·34	0·38	1·64	0·44	0·36	H_2Oat 105°
Cl . .	0·02	nt. fd.							Cl
Spec. grav. .	2·64	2·61	2·82	2·77	2·89	2·71	2·50	2·57	

(Table 11) Water of augite-andesites

	Cruach Choireadail, Fig. 54, p. 322.				Coir' an t-Sailein.		
	I.	II.	III.	IV.	V.	VI.	
SiO_2 . .	49·90	51·32	56·22	68·12	50·04	57·18	SiO_2
TiO_2 . .	2·56	0·98	2·74	1·26	2·56	3·25	TiO_2
Al_2O_3 . .	12·70	13·96	12·45	13·08	13·32	10·75	Al_2O_3
Fe_2O_3 . .	4·20	2·48	3·09	1·02	4·71	4·96	Fe_2O_3
FeO . .	7·88	7·10	7·58	3·26	8·07	6·24	FeO
MnO . .	0·36	0·34	0·43	0·39	0·33	0·32	MnO
(Co, Ni)O .	nt. fd.	nt. fd.	nt. fd.	nt. fd.	nt. fd.	nt. fd.	(Co, Ni)O
MgO . .	5·88	5·78	2·78	0·71	5·01	2·15	MgO
CaO . .	10·39	11·51	5·93	1·81	10·02	5·73	CaO
BaO . .	nt. fd,	nt. fd.	0·04	0·04	nt. fd.	0·06	BaO
Na_2O . .	2·86	3·50	3·82	4·15	3·28	4·62	Na_2O
K_2O . .	0·95	1·16	2·67	4·47	1·08	2·67	K_2O
iL_2O . .	nt. fd.	nt. fd.	nt. fd.	nt. fd.	tr.	tr.	Li_2O
$H_2O + 105°$.	1·65	1·27	1·35	1·16	1·45	1·31	$H_2O + 105°$
H_2O at 105°	0·67	0·36	0·44	0·40	0·27	0·33	H_2O at 105°
P_2O_5 . .	0·20	0·24	0·50	0·22	0·28	0·46	P_2O_5
CO_2 . .	0·09	0·09	0·05	0·06	0·08	0·08	CO_2
FeS_2 . .	nt. fd.	nt. fd.	nt. fd.	nt. fd.	nt. fd.	nt. fd.	FeS_2
	100·29	100·09	100·09	100·15	100·50	100·11	
Spec. grav. .	2·95	2·91	2·77	2·55	2·97	2·71	

I.–IV. Ascending Sequence, Cruach Choireadail.

(Table 8) Differentiation — Column of Glen More Ring-Dyke as exposed In Cruach Choireadail and Coir' An T-Sailein, 2½ miles apart