Chapter 2 History of research

In the following pages an epitome is attempted of the long series of researches that have been concerned with the Tertiary igneous rocks of Mull. Other subjects, such as glacial phenomena, raised beaches, and diatomite, are sufficiently covered by references in the Bibliography at the close of the volume.

Staffa, interpreted, means the *Island of Staves,* so that it is certain that the columnar structure of its basalt attracted attention from early Norse adventurers; not until 1772, however, did its fame penetrate to the scientific world. In that year Sir Joseph Banks, Dr. Solander, Archbishop Troil, and others called at Staffa on their way to Iceland, and it is noteworthy that they did not learn of its existence till they reached the Sound of Mull. Banks' descriptions, sketches, and measurements, as published by Pennant in 1774, are of value to this day. Though he does not enter into theoretical discussions, he calls the rock "Basaltes, very much resembling the Giant's Causeway in Ireland," (1774, p. 310),<ref>Dated references in this chapter refer to Bibliography, p.</ref> and he compares some of its appearances with those of lava (1774, p. 307). In Troil's account, 1780, we find the following very significant statement: "The stratum beneath the pillars here mentioned, is evidently *tuffa,* which had been heated by fire, and seems to be interlarded, as it were, with small bits of basalt; and the red [? bed] or stratum above the pillars, in which large pieces of pillars are sometimes found irregularly thrown together, is evidently nothing else but lava."

In 1773, before Sir Joseph Banks' account of Staffa appeared, Dr. Samuel Johnson touched at the headland of Ardtun near the mouth of Loch Scridain in Mull, and he tells us how the columns of this shore were pointed out to him as no less deserving of notice than those of Staffa itself. When it is remembered that Desmarest published his paper on the volcanic origin of columnar basalt in 1774, and Hutton his *Theory* of *the Earth* in 1785, it will be realized at what an opportune time the news of Staffa and Ardtun was circulated among geologists.

In 1788, a vulcanist in the person of Abraham Mills visited both the localities mentioned above. He had no hesitation in speaking of their rocks as lavas. He also furnishes an account of the Ardtun sediments (1790, p. 79), though not their leaf-beds; and he described the thin coal-seam that crops out on the north-east side of the Ardtun peninsula (1790, p. 83).

Mills was followed by another vulcanist Faujas Saint Fond, who published in 1797 an account of his important travels through England and Scotland, He compares the columns of Staffa with others he was familiar with in Vivarais (1799, English edition, Vol. p. 47). He suggests that where they are irregular they betoken rapid cooling (1799, p. 57), an idea which is elaborated in Chapter 6 of the present Memoir. He notes how the craggy tracts of Mull are "composed of different currents of basaltic lava" (1799, p. 109). He draws attention to the red weathered tops of some of these lavas, but wrongly ascribes them to calcining (1799, p. 111). He records an emergence of fossiliferous limestone from beneath lava on the east coast (1799, p. 123). Altogether, he supplies a wonderfully-modern pioneer-account of the geology of Mull. Saint Fond also describes the lavas and conglomerates of Oban, though naturally he attempts no age-comparisons between them and the basalts of Mull.

It is interesting to find Saint Fond speculating on the explosions which might have carried up from below the many granite-boulders in Mull that we now know have been transported by ice from the mainland.

Between 1794 and 1799, Robert Jameson undertook an extensive exploration of the Scottish Isles. He had been initiated at Edinburgh into the simplicities of Wernerian doctrine, and his memoir, published in 1800, is a good representative of its kind. When he tells us of Mull, he smiles at the enthusiasm of his predecessors, and explains that their word lava means nothing else than *basalt.* At the same time he notes that the island furnishes examples of basalt veining basalt, a phenomenon unknown to foreign mineralogists. He also points out that Mull is predominantly composed of trap, with primary strata restricted to the Ross and Gribun, and with minor occurrences of sandstone and limestone, sometimes fossiliferous. He describes the Ardtun coal-seam examined by Mills, and adds an account of a more important seam outcropping on Beinn an Aoinidh (1800, pp. 214, 221). These coals are interbedded among the basalts, and are dealt with in Chapter 3 of the present Memoir. A notice of a piece of black pitchstone-porphyry (1800, p. 213) on the shore of

Loch Scridain furnishes an introduction to a subject that figures largely in Chapter 23 of this Memoir.

John Macculloch was selected in 1811 to undertake a series of geological investigations in Scotland; and in 1819 he published his famous monograph on the Western Isles. He tells us the circumstances under which the idea of writing a book, rather than a series of papers, came into his mind. He had been at work since five in the morning, and had visited and explored Staffa, and now at midnight he sat watching at the helm while his men slept at their oars, and the birds on the motionless sea; all the time, the mountains of Mull and the walls of Iona shared his vigil in the red glow of the mid-summer twilight.

Macculloch had to deal with a region that lent itself to broad generalization and he adopted the following classification: Primary, Secondary, and Overlying. For him the base of the Old Red Sandstone furnished the lower limit of the Secondary Formation; while the Tertiary lavas and intrusions were more or less unstratified representatives of the Overlying. Macculloch paid sufficient attention to fossils to recognize the existence of Lias in the Post-Old Red portion of his Secondary, but he never elaborated in this direction.

It so happens that this simple classification served Macculloch's purpose admirably in most of the islands. Difficulties, however, were encountered in comparing Mull with Kerrera and the Mainland of Lorne. Macculloch referred the Lorne traps to the same great Overlying Formation as constitutes the bulk of Mull. In this he was mistaken, for the Lorne lavas are of Old Red Sandstone age. At the same time, he came very near to realizing the distinction, for he classed the conglomerates of Kerrera, Oban, and Appin (Benderloch) with the Old Red Sandstone, although they contain pebbles of "basalt, greenstone, amygdaloids, cavernous trap, and clinkstone or compact felspar"; and from this observation he deduced the former existence of Primary traps, of which the Glencoe assemblage is "in all probability the remains" (1819, Vol. II., pp. 117, 121, 122).

At the time he wrote his account of the Western Isles, Macculloch was very reticent in regard to the origin of trap. His leaning towards some species of igneous theory is however clearly indicated: he advanced the hypothesis that stratified traps might have resulted from melting *in situ* of sediments (1819, Vol. I., pp. 357–360, 378), and pointed out that the recurrent traps and conglomerates of Canna are very suggestive of submarine volcanic action (1819, Vol. I., pp. 419–458); he also produced evidence to suggest that traps, like lavas, are in many cases augite-, rather than hornblende-, bearing (1819, Vol. I., p. 381); and he cites instances of vesicular traps to confound those who claimed that traps, in contrast to lavas, are always amygdaloidal (1819, Vol. I., p. 458).

Perhaps his clearest statement of approximately this date is to be found in his *Geological Classification of Rocks,* 1821, p. 594, a book which he regarded as a supplement to his *Western Isles.* Macculloch points out here that differences of opinion exist regarding the classification of the products of recent and extinct volcanoes. " But it will be found that the chief confusion has arisen from prejudices respecting the trap rocks, which some of these observers have thought to attribute to an aqueous origin. That more correct theory of the trap rocks, which now begins so generally to prevail, will hereafter remove many of these obscurities."

It is curious to find Macculloch speaking of obscurities, since his own obscurities are proverbial. But, as Sir Archibald Geikie puts it, "so laborious a collection of facts, and so courageous a resolution to avoid theorising upon them, gave to his volumes an almost unique character. His descriptions were at once adopted as part of the familiar literature of geology. His sections and sketches were reproduced in endless treatises and text-books."

Space forbids more than brief mention of other contributions by Macculloch to our knowledge of Mull geology.

1. He shows by maps and sections the main distributional and structural relationships of Gneiss, Secondaries, and Trap, in both Mull and Morven (1819, vol. iii., pp. 27, 63).

2. Like Jameson, he found the trap of Mull ' traversed by great veins of basalt, which also cross the strata beneath' (1819, vol. i., p. 567). This was in keeping with his experience elsewhere (pp. 238, 384, 385, 394); in fact, he tells us that further work would probably show, within the Overlying Formation of the Hebrides, great masses of trap of two dates feeding earlier and later veins. There is not much in this conception comparable with the idea of successive lava-streams, which so readily presented itself to Saint Fond, and even to Macculloch himself in the special case of Canna, but still it marks

an important stage in the realization of a time-scale for the Hebridean complexes.

3. He figured and described the tree which appears as the frontispiece of this Memoir. He recognized the tree as coniferous and regarded it as occurring in a vein of conglomerate, apparently thinking that both tree and conglomerate might be occupying a fissure in a trap older than themselves (1819, vol. i., pp. 197, 568). It is interesting to recall that the exact locality of Macculloch's tree was for many years lost sight of until it was brought to the Duke of Argyll's notice by Mr. Bell of Tavool.

4. He drew attention to the poor development of trap-featuring in parts of Mull (1819, vol. i., pp. 570, 576). This subject is debated in Chapter 5 of the present Memoir.

5. In his map of Mull, he partially separated the Beinn a' Ghràig Granophyre from the general trap. At the same time he regarded the junction of trap and granophyre on the slopes overlooking Loch na Keal as affording evidence of transition from the one rock-type to the other (1819, vol. i., pp. 577, 578).

6. He noticed a metamorphosed xenolith on the north shore of Loch Scridain as a mass of the primary strata' entangled in trap (1819, vol. i., p. 569). The Loch Scridain Xenoliths furnish the subject matter of Chapter 24 of the present Memoir.

7. Finally, he recognized that the Overlying Trap must be extremely old before its ' exterior strata could have been shaped into distinct mountains by the abrasion of their edges or the loss of extensive portions; before the separation of Staffa from Mull, for example, could have taken place (1819, vol. i., p. 575).

Macculloch's *Western, Isles* was quickly followed, probably in 1820, by Ami Boué's *Essai,* which remains to this day our only text-book of Scottish geology. It was complete up to date, and was enriched by many new observations, coupled with a frank recognition of volcanic phenomena as such. Boue's wide experience in Central Scotland leads to a suggestion (1829, p. 146) that the Lorne lavas are of Old Red Sandstone Age; but further on in the book (1820, p. 227) he concludes, with considerable hesitation, that the lavas of the Western Isles and Lorne, are probably all of them later that the *Gryphea*-limestone, and that some, perhaps all, are like their neighbours of Antrim, later than the Chalk. This question of time-classification was destined to remain open for many years to come.

One of Ami Boué's most interesting observations relates to the boles, or iron-clays, to use Macculloch's name for them. Boué noted boles among the lavas of Mull and elsewhere in the Hebrides (1820, pp. 237, 246); he compared them with red clays beneath the lavas of Mezen and Cantal, and, interpreting them as fine ashes, drew the pregnant and quite novel deduction that some of the Hebridean basalts flowed from subaerial vents.

Boué pays considerable attention to the basaltic veins of the Hebrides (1820, p. 272). He does not follow Hutton in regarding them as injected from below, but rather as fed from the super-incumbent lavas. In this he agrees closely with Macculloch.

In 1850, one of the most important finds of Scottish geology was announced by the Duke of Argyll. Leaves, in a beautiful state of preservation, had been discovered a few years previously at Ardtun by Mr M'Quarrie, of Bunessan, who brought them to the notice of the Duke of Argyll. The Duke, realizing their scientific importance, made a thorough investigation of the beds in which they occur, and entrusted his material to Professor Edward Forbes for determination. Professor Forbes declared the leaves Tertiary, and tentatively ascribed them to the Miocene. Later work by Mr. Gardner (1887), and after a long interval by Professor Seward and Mr. Holltum, has modified Professor Forbes' suggestion by substituting Eocene for Miocene; for further information regarding the history of research on this extremely important subject, the reader may consult Chapters 3 and 4 of the present Memoir. Suffice it here to say that the Duke of Argyll drew the following deductions from the Ardtun leaves, and from chalk-flint which he recognized in an associated conglomerate:

The Ardtun lavas above the sedimentary layer are undoubtedly of Tertiary date, comparable with those of the Antrim coast and the products of a subaerial volcano.

Strangely enough, at the same time as the Duke of Argyll demonstrated the existence of Tertiary lavas at Ardtun, he suggested a Jurassic date for the mass of Hebridean lavas, including most of those constituting Mull. In this, he was influenced by Professor Forbes, who claimed that some of the Skye basalts, correctly interpreted by Macculloch as, injections into Secondary sediments, might in reality be interbedded lavas.

Sir Archibald Geikie in his early days followed the lead given by the Duke of Argyll and Professor Forbes. In the map accompanying his paper on the *Chronology of the Trap-Rocks of Scotland* (1861, p. 654), he groups Hebridean and Lorne lavas alike as Jurassic, with the exception of the Ardtun exposures. In his *Scenery of Scotland* (1865), he shows the Hebridean lavas as doubtfully Jurassic, and the Lorne lavas as of Old Red Sandstone Age. Two years later, 1867, he has righted matters completely: he claims the Mull lavas, with their occasional interbedded coals, as Tertiary; notices a fresh occurrence of flint-conglomerate among them near Carsaig; and points out that the Ardtun lavas lie near the base of the series, which, all told. amounts to more than 3000 feet in thickness, and consists of basalt below and pale lavas above (pale weathering basalts and mugearites, Chapter 8 of present Memoir). He also draws attention to alteration of the lavas of Ben More near the syenite (granophyre) of the district.

Throughout his writings Sir Archibald Geikie has laid particular stress on the importance and extent of the north-west dykes accompanying the Hebridean lavas. In his British Association address of 1867, he argues that many of them may have acted as feeders of lava-streams (1868, p. 53).

In 1871, Professor Zirkel greatly advanced our petrological knowledge of Mull, more particularly by describing olivine-gabbro which he had collected in the complicated central region of the island. It is at this stage that the microscope was adopted as an auxiliary of the hammer by Hebridean geologists.

In 1872, Scrope, in the second edition of his *Volcanoes,* pointed out that the double-tier type of jointing, so clearly seen in Staffa, is exactly comparable with what he had long ago recorded in the case of columnar lavas of Auvergne. He attributed the upper irregular columns to heat-radiation from the lava-top, and the lower regular columns to heat-conduction from the lava-base. Scrope's point is more clearly stated by Professor Judd (1874, p. 225) than it is in the original, and it is to Judd that we are indebted for the reference.

Professor Judd would always be remembered by students of Mull's Tertiary rocks, were it only for his zoning of the local Jurassic, and his discovery of the unconformable Upper Cretaceous of Gribun and Morven. In addition to this, his paper of 1874 records the first serious attack made on the region of central complication, and it also establishes as a general proposition that the Tertiary eruptions were terrestial.

Before entering upon detail, the reader may be reminded that Professor Judd reached the general conclusion that Mull, Ardnamurchan, Rum, and Skye are the basal wrecks of great central volcanoes. His history of Mull itself included the following stages:

1. Major Acid Phase: the centre supplied abundant acid lavas and accompanying intrusions.

2. Pause: erosion reduced the acid volcano to a wreck.

3. Major Basic Phase: the centre revived, furnishing floods of basic lava and accompanying intrusions; the mobile basalt-flows spread far beyond the, remnant of their acid predecessors.

4. Extinction, decay, and erosion of central volcano.

5. Puy Phase: minor sporadic outbursts of acid and basic material found their way to the surface at scattered foci.

The above propositions contain much that is erroneous; but they all have a basis in observation, and should be borne in mind in reading the critical summary given below.

Professor Judd's maps and sections show several very important features hitherto left more or less unrecorded:

1. Difference of character of Mull Tertiary lavas as centre of activity is approached. We recognize this difference by enclosing Judd's peculiar central lavas within a line termed the Limit of Pneumatolysis ((Plate 3), p. 91). Judd called his peculiar lavas felstones.' In this and several other respects, Judd's statement of the case was wrong; but our discussion

of his 1890 paper will show that it contained the germ of a great truth.

2. Agglomerates and Breccias of Central Mull, often with gneiss-fragments. Judd's work in this direction is in danger of being discredited through his local mistakes. In Ben More, he misinterpreted some lavas particularly rich in zeolites as basaltic agglomerates (1874, pp. 240, 247), and others with a fissile structure as stratified tuffs. At the same time many of his agglomerate-outcrops are correct, and his insistance upon their importance is a great advance upon the passing references of previous observers.

3. Profusion of Acid and Basic Intrusions in Central Mull, the latter occurring more particularly in a horseshoe outcrop open towards the north-west, and reaching the surface in innumerable branches inclined towards the centre of the complex.

It is well to understand that Judd at this stage mainly relied, in matters petrological, upon his reading of Zirkel's recent paper. He grouped his rocks into two great series; Acid, ranging in texture from 'granite' to 'felstone', and Basic ranging from gabbro to basalt and tachylyte. His determination of 'felstone' was mostly based upon field-appearances, and, as already hinted, we find him continually misinterpreting altered basalt as 'felstone'. Add to this the preconception that a simple succession from Acid to Basic, or *vice versa,* was involved, and the *rationale* of many of his theories is supplied:

1. Naturally he failed to determine an age-relationship between his basalts and 'felstones' on any consideration of superposition. He wrongly interpreted this difficulty by supposing that the basalts abut against the eroded edges of the 'felstones'.

2. He realized a very striking phenomenon of Central Mull, namely the repeated cutting of other rocks, including some important acid intrusions, by basic sheets; and on this he founded his law of basic follows acid. As stated above, however, Prof. Judd always admitted a minor final stage of sporadic eruptions in which there might be a recrudescence of acid magma (1874, p. 272).

We have already outlined some of the theoretical consequences of his too general deduction that basic follows acid. It is, however, worth while pointing out that it did not prevent him from realizing the following very important facts:

1. The 'granites' arc often clearly intrusive into the 'felstones.'

2. The Beinn a' Ghràig 'Granite' is an intrusion with caps of 'felstone' lava (1874, p. 246).

3. Mull is a region of marked central subsidence (1874, p. 256).

Away from the district of complication, Professor Judd gave a very good account of the picturesque 'S Airde Beinn plug in the country west of Tobermory. In fact, it furnished him with a type-example of puy-eruption.

In conclusion, it may be recalled that Judd's conception of Mull as a great central volcano is at the present time regaining adherents (See Chapter 1 of the present Memoir); and further, that no one, not even Sir Archibald Geikie or Macculloch, has emphasized more successfully than Judd the vast erosion that has succeeded the extinction of Hebridean vulcanicity.

In 1880, Sir Archibald Geikie published a most valuable account of impressions gained the previous year during a traverse of the lava-fields of western America, already ascribed by Richthofen to fissure-eruptions. Geikie claimed that the Hebridean plateaux must be relics of a Brito-Icelandic lava-field fed from fissures, the dyke-contents of which are now revealed by erosion. We shall postpone comment on this conception until we consider Sir Archibald Geikie's classic of 1888 based upon explorations in large measure inspired by his visit to America.

Meanwhile, in 1883, Professors Judd and Cole described several occurrences of basalt-glass in the Western Isles: they demonstrated by analysis that true basalt-glass does occur, though they significantly remark that it is generally restricted to narrow selvages; and they quoted two analyses by Sir Jethro Teall giving 46.68 and 47.46 per cent, of SiO_2 for glasses collected by themselves in Mull.

In 1886 Judd continued his account of the basalt-glasses by publishing a comprehensive survey of all varieties of crystallization of basic magma from basalt to gabbro. The paper is especially noteworthy for its announcement of the conception of petrographical provinces (1886, p. 54), with special reference to the Brito-Icelandic province of Post-Cretaceous date.

There can be little doubt that, in accounting for dissimilarities of microstructure in rocks of more or less similar texture, Judd laid too great stress on contrasts of tranquillity and flow, and too little on differences of chemical composition. Thus it is now recognized that what we term the Plateau Type of basalt is particularly prone to *ophitic,* and the Central Non-Porphyritic Type to *granular,* crystallization of the contained augite. In another connexion, Judd's assumption that iron avoids crystallizing as magnetite under plutonic conditions (1886, p. 79) leads one to suppose that he was comparing iron-poor gabbros, or eucrites, such as figure in the Cuillins and Ben Buie, with iron-rich basalts and dolerites (cf. (Table 1), (Table 5), (Table 6), pp. 15, 23, 24 of present Memoir). In conclusion, it may be pointed out that many interesting subjects such as the action of surrounding magma upon crystals, and the action of steam and other gases at the surface are broached in this important paper; while schillerization, already referred by Judd in 1885 to solvent action under pressure, is dealt with once again. In this latter connexion it is noteworthy that salite-structure is in our own accounts that follow often attributed to action of residual acid magma on early-formed augite.

In 1888, Professor Cole returned to the subject of tachylyte, and described a well-known occurrence at Ardtun where a basalt-sill occurs with glassy selvages. His analysis shows 53.03 per cent. SiO_2, but it is so high in Al_2O_3 that it seems to stand in need of confirmation.

The same year, Professor Kendall gave an extensive synopsis of investigations of chilled edges of dykes in Mull. He found more or less definite tachylytic selvages in many cases; but, at the same time, he pointed out that the degree of marginal chilling of an intrusion is sometimes materially affected by the conductivity of the country-rock.

The great feature of 1888, however, was the appearance of Sir Archibald Geikie's comprehensive account of British Tertiary volcanic action. In this work, Geikie constantly acknowledges discoveries by colleagues on the Geological Survey, notably Dr. C. T. Clough's observations on the dykes of Cowal; he also points out that during two visits to Mull he received much assistance from Mr. H. M. Cadell, while in matters petrological he was largely guided by Dr. F. Hatch.

Tertiary dykes are described with particular care, and one realizes how truly Geikie tells us that they are to his mind "by far the most wonderful feature in the history of volcanic action in Britain." When he mentions Arran, Mull, Eigg, and Skye as furnishing illustrative districts for gregareous north-west dykes (1888, p. 33) he comes very near formulating the conception of a Dyke-Swarm discussed already in Chapter 1. In his treatment of the dynamics of dykes and fissure-eruptions, he makes constant references to a paper by Professor Hopkins (1888, pp. 71, 74, 110).

Geikie clearly showed that the major intrusions of Mull are later than such lavas as have escaped erosion; but he was of opinion that they had been in large measure located by "the larger or more closely clustered vents of the plateau-period" (1888, p. 183); and he was ready to believe that possibly they might themselves have supplied lava-streams now denuded away. As regards the great bulk of the lavas of the region, he was certain that they had resulted from scattered vents along the course of dyke-fissures. In referring the reader back to the discussion of this subject in Chapter 1, it is well to emphasize two elements of the problem disclosed by recent work:

1. The pillows structure of many of the lavas found within the central region of Mull suggests a central crater-lake.

2. The satellitic grouping of the Mull Swarm of dykes makes it clear that the Mull Centre was already marked out *before* the Mull Swarm had developed to any appreciable extent.

Sir Archibald Geikie's comparison of the Hebridean gabbros with Gilbert's laccoliths (1888, p. 143) is not helpful in Mull; but his account of the acid intrusions near the mouth of Loch Bà is excellent, and marks a considerable advance upon Judd and Macculloch. He not only traces the course of the Beinn a' Ghràig and Knock Granophyres (he takes no notice of the separating screen of Chapter 32), but he also recognizes the Loch Bà Felsite as an individual dyke continuing for miles (1888, pp. 152–157). He gives a sketch (1888, (Figure 43)), showing in masterly fashion the granophyre with a conspicuous capping of lava, and the course taken by the associated feLsite across hill and dale. He did not realize any arcuate tendency in the outcrops of either granophyre or felsite; but he confirmed Judd's observations of intrusive contacts between granophyre and lavas—the latter now correctly interpreted as altered basalts,—and he emphasized the extraordinary absence of all signs of disturbance.

Sir Archibald Geikie successfully demonstrated that the acid intrusions of Mull are later than the basic lavas; but when he claims comparatively simple basic to acid sequence among the intrusions themselves, he overstates his case very much as Professor Judd had already done, only in the reverse direction. As a matter of fact, the earliest major intrusions of Mull are acid (Chapter 12), and in spite of all the complications of the district it so happens that it is much more obvious in the field that basic intrusions follow acid, than vice versa; but Geikie covers such instances of this relationship as he noticed by referring them to a late recurrence of basalt-veins and dykes (1888, pp. 145, 158). As explained in Chapter 1, the magma-sequence in Mull, in the most generalized view possible, cannot be accommodated in less than two cycles from basic to acid, and even then one has to admit a basic recrudescence at the end of the second cycle.

Two very useful features of Sir Archibald Geikie's 1888 account of the Mull lavas are his further definition of the Pale Group of Ben More and his description of the gradual changes one meets with as one approaches the plutonic masses: in the Pale Group he notes the occurrence of fissile lavas, the muge arites of the present Memoir; and among the altered basalts he records an incapacity to weather either spheroidally or to a loam, and comments on a development of epidote both in amygdales and in interlacing veins (1888, p. 138).

The introduction of the term granophyre into Hebridean geology furnishes an interesting petrological feature of the paper.

In 1889, Professor Judd published a reply to Sir Archibald Geikie, and instituted a comparison between Mull and the Hawaian. volcanoes.

In 1890, Professor Judd returns in earnest to the subject of the 'felstones'. In some respects the results of his further study are disappointing. His discrimination between lavas and intrusions remains inadequate, and his reading of the lava-sequence is still inverted. His petrology, too, is often inaccurate. To show how difficult all this makes it to do justice to his results, the reader is warned that the two analyses Judd furnishes of early propylite-lavas from Mull must be interpreted as analyses of intrusions later than any lavas preserved in the island; and that when he speaks of hornblende-propylites he means, so far as Mull is concerned, intermediate or acid intrusions with pseudomorphs after acicular or columnar augite. Attention is directed to these blemishes mainly to clear the ground for recognition of an important generalization which emerges from the confused statement of his observations. He found throughout his 'felstone'-area, now called the propylite 'area, widespread changes which he attributed to solfataric action; these changes result in a decomposition of felspars and ferromagnesian minerals, and a development of epidote, chlorite, magnetite, etc. He also recognized definite contac t-a Iteration of much more restricted geological scope, and often characterized by crystallization of granular aggregates of augite and magnetite, and of scales of biotite. A considerable portion of the present Memoir is concerned with the elaboration of Judd's dual conception of metamorphism outlined above. It has stood the test of minute enquiry, and the only important detail that we should like to criticize at the present juncture is the over-emphasis Judd lays upon the presence of sulphides in his propylitic area. Our experience is that sulphides are rare in this position.

Later publications by Professor Judd and Sir Archibald Geikie have added very little that is new in regard to Mull geology. Professor Judd, however, has been shown to be wrong in his interpretation of a well-exposed gabbro-granophyre junction in Skye; and this has reacted unfavourably upon the general reception of his views. One feels, in going over the old controversy, that Sir Archibald Geikie proved himself much more capable than Judd of Escaping from the influence of initial mistakes. Both authors had great ideas to present to us; but in Judd's case, the great ideas were too often shrouded behind errors, which others could easily detect, and he himself seemed unable to disperse.

In 1895, Dr. Heddle wrote an account of a tachylyte-selvage which is quoted from on p. 265 of the present Memoir.

In 1899, Dr. Currie reported upon a particularly interesting amygdale-assemblage characteristic of some of the lavas of Maol nan Damh, Ben More, and contrasted it with what he was familiar with in 'Torosay', meaning thereby the western portion of Gribun Peninsula. Currie comments on the abundance of scolecite, epidote, and a green mineral which he calls celadonite, though it is later spoken of by Dr. M'Lintock and ourselves, without critical determination, as chlorite. To account for an abundant development of this peculiar amygdale-assemblage, Mr. Currie invokes pneumatolysis very much as Judd had done before him.

In 1901, the posthumous appearance of Dr. Heddle's volumes on the *Mineralogy of Scotland,* edited by Mr. J. G. Goodchild, brought together a number of scattered observations regarding the amygdale-minerals, etc., of the Mull archipelago. We supply (p. 425) a species-index of this work, so far as it is concerned with the subject-matter of the present Memoir, and this enables us to omit from our Bibliography many of the detailed references it contains. Ten of the analyses of (Table 9) (p. 34) are to be found in Heddle's pages, and the brief account of the amygdale-assemblages of the Mull plateau-region (p. 140) is based almost altogether on his statements.

In 1915, Dr. M'Lintock carried Mr. Currie's work a step further. He identified albite, previously mistaken for heulandite; and he showed that the Maol nan Damh amygdale-assemblage undergoes marked change in the vicinity of the Beinn a' Ghràig Granophyre. Among the new minerals set up, garnet and hornblende are conspicuous. Dr. M'Lintock's research into these matters has been so thorough that we have drawn freely upon his accounts in preparing Chapter 10 of the present Memoir. Only in one matter of detail, do we differ. Dr. M'Lintock thinks that the Maol nan Damh amygdale-assemblage was developed through auto-pneumatolysis of the lavas containing it, whereas we shall give reasons later for following Mr. Currie and Professor Judd in ascribing it to pneumatolysis, or solfataric action, belonging rather to the volcano than to its individual lavas. At the same time, auto-pneumatolysis is a pronounced feature in some departments of Mull geology; and its separation from general pneumatolysis is in many cases a matter in which no final opinion can be expressed.

Dr. M'Lintock worked alongside members of the Geological Survey and acknowledges help from Mr. J. E. Richey in the field, supplemented by chemical analyses by Mr. E. G. Radley. Before sketching the history of the recent survey upon which the present Memoir is based, it is but proper to acknowledge the assistance derived from Dr. A. Harker's *Tertiary Igneous Rocks of Skye* published by the Geological Survey in 1904. There are two main features in which the Skye Memoir has contributed to lighten the task of those who have laboured in Mull; the first of these is the recognition of Inclined Sheets, or Cone-Sheets, as we now style them; the second is the clear and accurate statement of petrology, which we have found in large measure as applicable to Mull as it is to Skye.

Geological Survey

The mapping of Mull was commenced for the Geological Survey in 1902, when the small corner of the island projecting into Sheet 36 of the one-inch Map was examined. Further work was postponed until 1907, from which date yearly progress was made until the outbreak of war, 1914. In 1920 the survey of the whole island was completed. The corresponding *Summaries of Progress* contain a brief contemporary record of this work, accompanied by chemical analyses. Moreover, initials of authors are inserted in the body of the present Memoir, so that all that is required here is a very brief statement in regard to certain selected pivotal dates.

Cone-sheets

The fact that Mull reproduces the Inclined Sheet system of the Cuillins was realized by Mr. Wright and myself when we accompanied Dr. Harker to Skye in 1909 (1910, pp. 31, 34). That the basic cone-sheets (inclined sheets) of Mull could be separated into an earlier suite preceding the Corra-bheinn Gabbro and a later suite following the same was subsequently clearly shown by Dr. Clough (1913, p. 44).

Magma-sequence

Dr. Clough recognized in the early basic Cone-Sheets and the Ben Buie and Corra-bheinn Gabbros an olivine-rich assemblage followed by an olivine-poor or olivine-free assemblage, represented by Late Basic Cone-Sheets and Coir' an t-Sailein Gabbro, the latter merging into granophyre (1913, pp. 44, 45). In regard to an earlier stage of the igneous centre, he suspected that what we now term the Porphyritic Central Types of lava succeed the Plateau Types (1912, p. 34).

Ring-dykes

On analogy with Glen Coe and Ben Nevis, Mr. Wright introduced the idea of ring-structures in the Loch Bà district, where he was the first to emphasize the importance of screens in igneous tectonics (1910, pp. 32, 33; 1911, pp. 31–35). Mr. Richey completed the tracing of the Loch Bà Felsite, showing beyond question that it is a ring-dyke (1914, p. 4 9; 1915, p. 36); and the writer demonstrated that ring-dykes are a dominant feature of the Glen More district (1914, p. 51).

Axis of symmetry

Mr. Wright realized a north-west axis of symmetry in Mull geology (1911, p. 38). Mr. Richey found that two centres of ring-dykes lie on this axis, and Mr. Wilson, in preparing a one-inch reduction showing outcrops of cone-sheets, found the same to hold good in relation to these intrusions (1915, p. 36).

Gravitational differentiation

The writer advanced the idea that gravitational differentiation is exhibited by the contents of certain ring-dykes observed by Dr. Clough and himself (1914, p.51). At first the interpretation adopted was one of gravitational separation in a liquid emulsion, but after consultation with Dr. Thomas and Mr. Hallimond this has been exchanged for gravitational separation of early crystals and residual magma.

Pillow-lavas

Pillow-lavas were independently recognized in Central Mull by Dr. Clough and the writer in 1913 (1914, pp. 47, 50). When they were found to be common, they were interpreted as a record of a crater-lake (1915, pp. 39, 40).

Vent-agglomerates

It was early realized by the writer that Judd's agglomerates have two contrasted relationships: in the one case they are more or less conformable to the lavas; in the other, they are very transgressive and come into contact with disintegregating gneiss and Tertiary plutonic rocks (1910, p. 30). At first it was thought that the transgressive breccia was a superficial accumulation, but this view was already much weakened when Dr. Clough found breccia both earlier and later than the Corra-bheinn Gabbro (1914, p. 51); and was finally replaced by a vent-interpretation when Mr. Wilson got the same relationship on a large scale in the case of the Ben Buie Gabbro (1915, p. 38).

Arcuate folding

The strong folding of south-east Mull was the first feature of interest to attract the writer's attention (1908, pp. 67, 68). Its acuate character made it the subject of a series of maps (1910, p. 28; 1913, p. 46; in collaboration with Mr. Wilson 1914, p. 44). Its interpretation as a result of the intrusion of granophyres along the old caldera edge was suggested (1915, p. 41).

Dykes

As explained in Chapter 1, Mr. Maufe had arrived at his conception of the dyke-swarm before he visited Mull. The theoretical interpretation adopted for Mull is the same as that previously advanced by the writer for the Etive Swarm of Old Red Sandstone age.

Loch Scridain pitchstones

Pitchstones, their sheath-and-core structure, and their association with olivine-free dolerites in southern Mull were reported on by Mr. Lightfoot (1911, p. 30). They have been made the subject of a special paper by Mr. E. M. Anderson and Mr. E. G. Radley (1917), in which the role played by water as an inhibitor of crystallization is discussed. The same paper includes preliminary definitions of two new rock-types, leidleite and inninmorite, by Dr. Thomas and myself. An essential constituent of inninmorite is a uniaxial augite described in detail by Mr. Hallimond (1914).

Loch Scridian xenoliths

These xenoliths, as already noted attracted the attention of Macculloch. Later on, Compton and Rose recorded occurrences of graphite (1821, p. 374, and 1851, p. 102). Little more was done until Mr. Cunningham Craig, Dr. Clough, and Dr. Flett described a very interesting xenolithic sill (with cordierite, etc) at Traigh Blan na Sgurra (1911, *Geology of Colonsay etc.,* p. 92). Mr. Anderson described other xenoliths (1912, p. 34), and eventually he sent in material in which Dr. Thomas recognized sapphire (1913, pp. 48, 66). A little later, Mr. Wilson and Mr. Tait discovered the Rudh' a' Chromain locality for this mineral (1913, pp. 48, 66). Many other interesting xenolith-localities are now known, mainly as a result of work by Mr. Anderson and Dr. Clough. The whole subject has been investigated by Dr. Thomas, who has published a detailed account (1922).<ref>The same conclusion is expressed by Sir Archibald Geikie in regard to the Eskdale Dyke of Southern Scotland; Ancient Volcanoes of Great Britain,' 1897, Vol. II., p. 134.</ref>

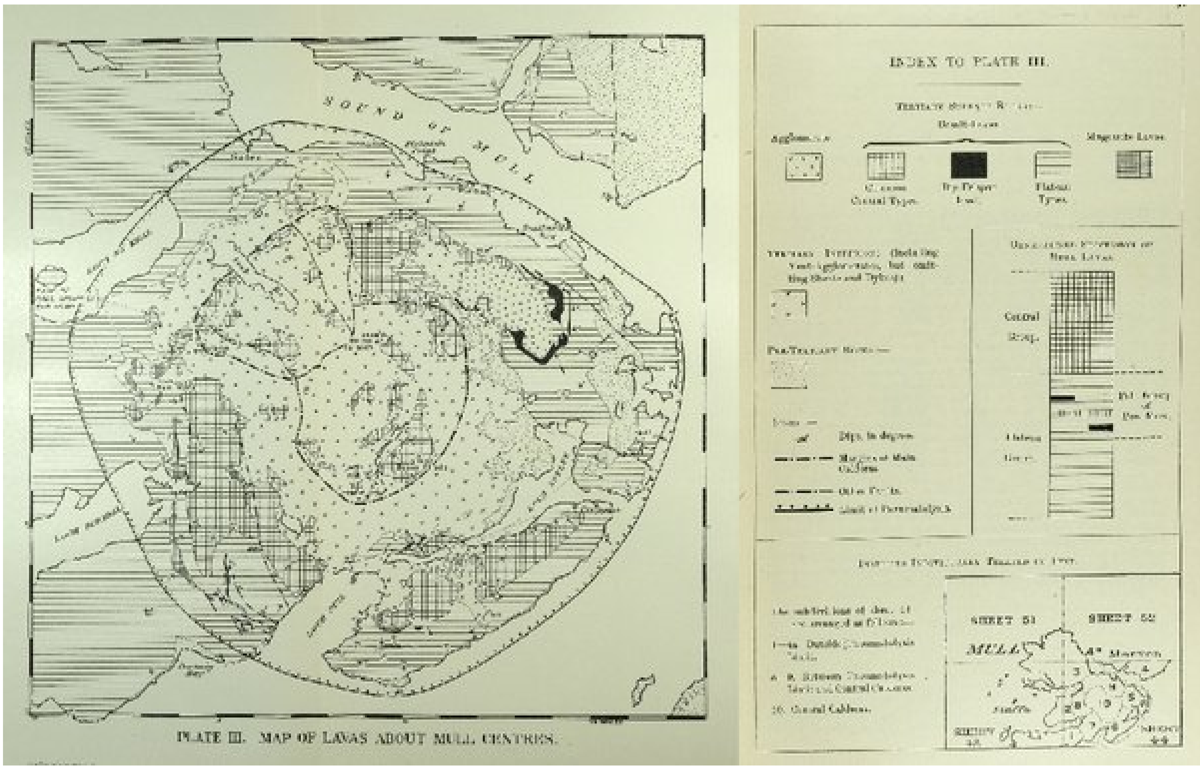
Tertiary desert

The view that the Tertiary period in Mull was ushered in under desert conditions first occurred to the present writer in 1920 (1921, p. 36; 1924).

Petrology

For a brief summary of the petrological section of Chapter 1 by Dr. Thomas and myself, *see* 1923, p. 113.

E.B.B.



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

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
$\frac{1}{2}S$	...	...	...	...	...	0·08	...	...	$\frac{1}{2}S$
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 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

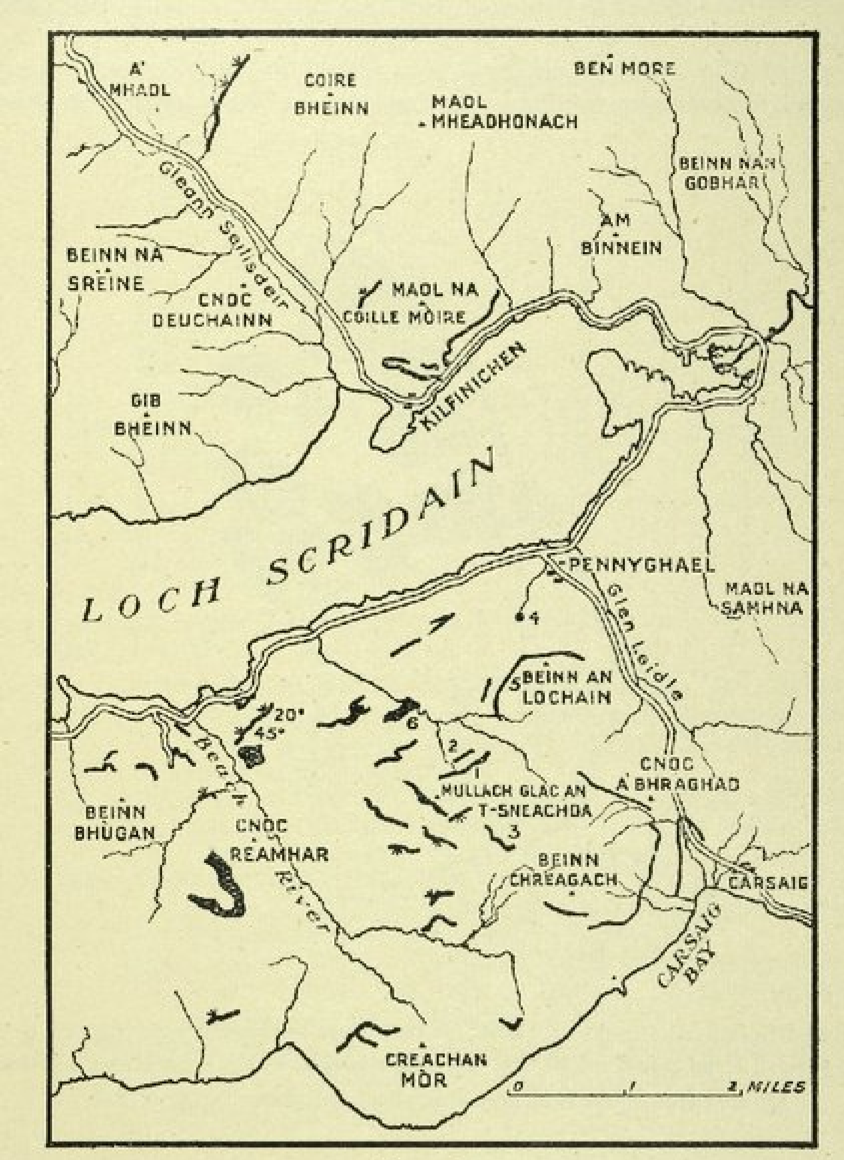


FIG. 43.

(Figure 43) Map of some of the occurrences of Pitchstone in Loch Scridain district. Quoted from Quart. Journ. Geol. Soc., vol. lxai., 1916, p. 206.

TABLE IX.

	Phenocrysts		Amygdale—Minerals: Outside Pneumatolysis Limit								Amygdale—Minerals: Inside Pneumatolysis Limit			Amygdale—Minerals: 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	50·80	53·74	53·41	52·36	53·29	48·91	45·51	46·62	46·78	46·21	45·10	45·5	38·82	37·66	39·56	40·74	38·67	0·77	SiO_2
TiO_2	0·85	—	—	—	—	—	—	—	—	—	—	nt. fd.	—	0·12	0·72	1·52	1·19	0·90	0·60	TiO_2
Al_2O_3	0·90	31·04	0·82	1·76	1·71	—	0·11	2·40	3·90	24·82	27·09	25·65	26·0	23·34	21·24	27·34	31·09	37·27	65·91	Al_2O_3
Fe_2O_3	1·72	—	—	—	—	—	—	1·14	0·60	—	—	—	—	0·87	1·67	1·57	1·53	2·78	4·25	Fe_2O_3
FeO	27·77	—	—	—	—	—	2·07	1·85	1·08	—	—	0·55	—	0·22	0·34	17·18	4·34	5·07	24·02	FeO
MnO	0·98	—	—	—	—	—	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	12·60	—	—	—	—	—	0·56	0·47	—	—	—	0·32	—	0·49	0·45	0·34	0·66	2·35	3·37	MgO
CaO	3·89	12·53	31·19	31·60	31·48	33·41	40·39	33·40	35·08	13·90	13·43	14·17	14·2	22·79	33·36	0·74	0·88	4·85	0·36	CaO
BaO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	nt. fd.	nt. fd.	—	—	BaO
Na_2O	0·23	3·56	9·94	8·11	6·04	8·80	0·22	0·36	0·80	0·99	—	tr.	—	tr.	1·17	1·08	2·74	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	7·72	3·01	—	K_2O
Li_2O	tr.	—	—	—	—	—	—	—	—	—	—	nt. fd.	—	tr.	nt. fd.	nt. fd.	tr.	nt. fd.	—	Li_2O
H_2O +105°	1·37	0·32	2·38	2·66	4·07	4·16	4·17	12·61	12·11	13·64	13·78	13·78	13·8	0·89	0·20	7·20	3·44	1·05	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	0·86	—	—	P_2O_5
CO_2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0·04	—	—	CO_2
FeS_2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	nt. fd.	nt. fd.	—	—	FeS_2
	100·13	99·05	99·67	101·05	100·67	100·06	100·76	100·10	99·87	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	—		2·285		3·488	3·61		2·65	2·21	3·897	

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 Gyrolite.

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