Chapter 14 Tertiary cone-sheets, Centres 1, 2, and 3, Ardnamurchan

The importance of cone-sheets in the igneous geology of Ardnamurchan will be realized from an inspection of the coloured Memoir-map, where, together with subordinate sills, they are indicated by the letter I. On one-inch Sheet 51 the same letter is further employed to denote certain basic inclined sheets of North-west Mull. The latter are probably connected with the Ardnamurchan igneous focus, but since they differ from the cone-sheets in direction they are described separately (Chap. 22).

The majority of the cone-sheets are individually quite thin, but they occur in vast numbers, and may collectively form extensive outcrops. For the most part they are indicated diagrammatically on the small-scale published maps, and also on the ordinary field-maps (scale 6 inches to the mile). A well-exposed shore-section south of Kilchoan mapped on a larger scale (25.344 inches to the mile) is reproduced in (Figure 23). This map and the accompanying horizontal section serve to illustrate the great abundance of the cone-sheets, their almost uniform inclination and strike at any particular locality, their transgressive relation to the bedded rocks, and their occasional offshoots along the bedding planes as sills.

The cone-sheets are chiefly composed of non-porphyritic quartz-dolerite of Talaidh type, or of porphyritic basalt. Composite cone-sheets and sills also occur here and there, with margins of quartz-dolerite and more acid centres of craignurite, granophyre, or felsite. In the chilled edges and fine-grained marginal zones of the porphyritic cone-sheets, felspar phenocrysts are frequently not developed.

Various sets of cone-sheets can be distinguished, but only portions of them are now on view owing to their partial replacement by ring-dykes, and to the fact that much of their outcrop is hidden by the sea. The visible portions suffice to show that cone-sheets were developed around each of the three Intrusion-Centres of Ardnamurchan (*see* (Plate 2), p. 71). An eastern set of massive individuals conforms to the same Centre 1 as the Northern Vents and the Early Major Intrusions. Two sets are arranged around Centre 2, an Outer Set earlier than all ring-dykes, and an Inner Set that is later than the majority of the ring-dykes of Centre 2. Lastly, a few basic inclined sheets cut the outermost and earliest ring-dyke of Centre 3, the Quartz-gabbro (A), and are inclined towards this centre. These are regarded as a partially developed set of cone-sheets.

Individual cone-sheets that make up each set were intruded successively, for they bear well-chilled margins whether in contact with country rock or with an earlier cone-sheet. Successive intrusion is also indicated by the fact that the same north-west dyke may cut and also be cut by cone-sheets (Figure 23) and (Figure 25)

The basic cone-sheets are, as a rule, conspicuously cross-jointed (*see* (Plate 4)). Rarely, they weather spheroidally. Only five instances of this were noted, for example, along the coast-section illustrated in (Figure 23). A cone-sheet showing both spheroidal weathering and cross-jointing may be cited from the southern corner of the Mingary Pier headland (Rudha gird an Iasgaich), 150 yds. south-west of the Pier. The intrusion is about 21 ft. in thickness, and consists of spheroidally weathering margins, 6 ft. thick, and a central cross-jointed portion. The junction of the different portions is well defined, and though there is no sign of an intrusive contact it seems probable that there were two injections of magma, quickly following one upon the other. A third injection is perhaps represented by an elongate mass of extremely xenolithic quartz-dolerite, full of schist fragments, which extends along the centre of the middle cross-jointed portion of the cone-sheet for 20 yds. (*see* p. 190).

The inclination of the cone-sheets varies within wide limits, though the variation within any particular set is small. Those of Centre 1 dip at low angles, on an average at about 20 degrees. In the Outer Set of Centre 2 angles of 35 to 45 degrees are met with, the lower angles being the more usual. Those of the Inner Set of Centre 2 are inclined very uniformly at an angle of 70 degrees. Those of the partially developed set of Centre 3 are inclined at 50 degrees.

Various data concerning the Ardnamurchan cone-sheets are set out in tabular form in (Table 4).

(Table 6) Data Concerning Cone-Sheets, Ardnamurchan

Order of age	Title of set	Angle of inclination	Thickness in Feet	Age relations with other intrusions
1	Set of Centre 1	143–20°	20–50	Pene-contemporaneous with Ben Hiant Intrusion, and later than Ben Hiant and Northern Vents.
2	Outer Set of Centre 2	35–45°	5–20	Later than the Major Intrusions of Centre 1, generally. Almost all earlier than all ring-dykes.
3	Inner Set of Centre 2	70°	5–30	Later than most ring-dykes of Centre 2. Earlier than all ring-dykes of Centre 3.
4	Partial Set of Centre 3	50°	3–5	Later than earliest of the ring-dykes of Centre 3, and earlier than Great Eucrite Ring-dyke.

The phenomenon of cone-sheet injection is obviously connected with localized crustal stresses, and these are considered to have been produced in the roof of a restricted magma-reservoir (p. 78 and (Figure 5), p. 57). In Ardnamurchan the regional N.E.–S.W. crustal tensions, so characteristic of the British Tertiary igneous period, and which find expression in north-west dykes and crush-lines, may have operated within the area affected by the local cone-sheet tensional stresses and contemporaneously with these stresses. This would account for a tendency to north-west trend shown by individual cone-sheets mapped by Messrs. Bailey and Simpson along the outer, eastern limit of the massive cone-sheets of Centre 1 (*see* Memoir-map). Again, in the case of the Outer Set of Centre 2 north-northeast of Camphouse, cone-sheets forming a group about half a mile wide follow a north-west course and are considerably out of line with their neighbours that run with reference to the same centre. In this connexion a further point of interest is the occurrence of north-west dykes of the same composition and age as the cone-sheets (p. 348).

The combined effect of the injection of such immense numbers of cone-sheets as are found in Ardnamurchan must have been attended with considerable central uplift. In the case of the Outer Cone-sheets of Centre 2, our knowledge seems sufficiently complete to allow us to form an estimate of the probable amount of the vertical displacement. In our calculation two assumptions are made. In the first place, it is postulated that space for each cone-sheet injection was provided by displacement of its roof, not of its floor. Further, it is only on the south-east side of the cone-sheet belt that we can form an estimate of the aggregate thicknesses of the Outer Cone-sheets. Elsewhere the belt is only partly seen, and we have to assume that cone-sheet intrusion was, in the aggregate, more or less equal around the whole belt. With these assumptions the uplift of the central area enclosed by the belt of Outer Cone-sheets may be calculated by the equation $x = y/ \cos a$ where x = total uplift due to the whole belt, y = aggregate thicknesses of cone-sheets forming the belt, and a = average angle of inclination of the cone-sheets.

Now the belt of Outer Cone-sheets on its south-east side is about 2 miles in width. Towards its inner and outer margins the number of cone-sheets diminishes. An average density of intrusion for the central three fourths of the belt is considered to be presented by the shore-section south of Kilchoan, which has been accurately mapped (Figure 23), while an average for the remaining fourth may be taken as half of this amount. The combined thicknesses of the cone-sheets in the half-mile section of (Figure 23) are approximately 950 ft. The total for the whole belt may then be estimated at about 3300 ft. Taking the average inclination of the cone-sheets to be as low as 35 degrees, we obtain 4000 ft. as an estimate of the total uplift.

It is of interest to note that doming of the country rocks around Centre 2, developed within the limits of the belt of Outer Cone-sheets, seems to have immediately preceded the injection of these cone-sheets (p. 116). The doming may, therefore, have been occasioned by the same magma-pressure as that which determined the cone fissures and injection of cone-sheet magma.

However approximate an estimate of total uplift due to cone-sheet intrusion may be, it seems at least evident that at various periods central parts of the Ardnamurchan area must have experienced considerable uplift. Such uplifts during times of increased pressure in the magma-reservoir may, however, have been compensated by later subsidences that accompanied ring-dyke intrusion when magma-pressure became reduced.

Detailed distribution

Cone-sheets of Centre 1

These easterly cone-sheets have been mapped by Messrs. Bailey and Simpson from the northern coast, between Achateny and Ockle, as far south as Loch Mudle, and by the writer farther south. The individuals are generally massive and give rise to well-defined scarps. An especially prominent example forms the summit of Beinn nan Losgann. The trend of the sheets, considered as a whole, refers them definitely to Centre 1.

West of Ben Hiant, towards Kilchoan, these early cone-sheets have not been recognized with certainty. There, cone-sheets conforming to Centre 2 are extremely abundant, but in the mapping of this very complicated belt of country some occurrences of basic cone-sheets inclined towards Centre 1 were recorded, and may belong to the early set. For example, along the shore eastwards of Mingary Castle, cone-sheets follow two directions, east-north-east and north-north-east. The east-north-east cone-sheets dip towards Centre while those running north-north-east incline towards Centre 2, but evidence of their relative ages was not obtained. Between Mingary and the summit of Glas Bheinn to the north, there is also a very complex area of cone-sheet intrusion, and it would be of interest to know if cone-sheets referable to Centre 1 could be identified there. Only those following the north-north-east direction were noted during the mapping, but older quartz-dolerite was also observed, the decipherment of which was not attempted. Farther west, on the west side of Kilchoan Bay, two massive intrusions of quartz-dolerite extending north-west may belong to Centre 1. They at any rate are of early date, as they are cut by the Outer Cone-sheets of Centre 2. One of them forms a slight headland a mile south-west of the Landing Jetty, the other a projecting point of the headland of Sròn Bheag. The latter is lettered eD on the geological maps, and can be traced for a quarter of a mile. It is accompanied on either side by granophyre intrusions that are found both in sharp and in merging contact with it. The mass is in the nature of a composite intrusion, and will be described later in detail. (P. 197).

Outer Cone-sheets of Centre 2

A belt of country very sparsely cut by cone-sheets extends from Achateny past Braehouse southwards towards Camphouse, and separates the massive cone-sheets of Centre 1 from the Outer Set of Centre 2. The Centre 1 sheets here fall outside, that is to the east of, the Centre 2 sheets. For each set, the outer limit of sheet distribution lies at about 4½ miles from the centre concerned.

Internally, the belt of Outer Cone-sheets belonging to Centre 2 is limited by the succeeding ring-dyke complexes, but in one area west of Kilchoan, next to the ring-dykes of Centre 2, the cone-sheets become sparse before this limit is reached. The outer margin of the ring-dykes thus appears, here, to be approximately at the original inner limit of the sheet belt, at a distance of 2 miles from Centre 2. As will be seen on the Memoir-map only a portion of the belt is on view, but this remnant seems sufficient to show that the belt originally completely encircled the Centre.

The Outer Cone-sheets of Centre 2 are so thin and abundant that they are represented diagrammatically on the published geological maps. They are shown individually on (Figure 23), (Figure 24), and (Figure 25). Along the shore south of Kilchoan (Figure 23), their field relations may be conveniently studied. Above high-water mark, 200 yds. west of Mingary Pier, cone-sheet fracture-planes unfilled by magma are well seen in Lower Lias limestone. The beds of limestone with partings of shale of varying thickness can be followed by the eye across the fractures, showing that there has been no displacement along them. Where the fractures are filled by magma, such displacement of the walls as is found seems to be only so much as is necessitated by the thickness of the intrusion. For example, in the horizontal section, (Figure 24), a group of three thick cone-sheets, south-west of Mingary Pier, crosses the outcrop of the Trias and appears to shift it no more than the combined thicknesses of the cone-sheets require.

In a low-water promontory north of the Pier, sills in the Moine Schists are invariably cut by the cone-sheets. No visible cone-sheet feeders for the sills are there seen, but, along the shore northwest of the Pier, sills and cone-sheets in continuity with one another are on view. There is no reason to suppose that the sills form a separate group from the cone-sheets. In composition both are quartz-dolerites, though the sills are usually of finer texture, a difference which is irrespective of thickness. Sills greatly complicate the network of Outer Cone-sheets north of Kilchoan on the south side of Glas Bheinn. Possibly also, as already mentioned, cone-sheets of Centre 1 may occur here.

West of Kilchoan above Ormsaigbeg the hill-slopes are featured by regularly running cone-sheets that are rather gently inclined. Porphyritic types become frequent here, towards the inner limit of the belt, and are the dominant type farther west, south of Beinn nan Codhan. Along the coastal cliffs westwards of Sròn Bheag, which are mainly formed of Jurassic limestone and sandstone, a plexus of dark sheets (cone-sheets and sills) traverses these white-weathering beds. The cliffs are conspicuous from the seaward side, and attracted the attention of Macculloch (p. 65), and later of Sir A. Geikie,<ref>Sir A. Geikie, The Ancient Volcanoes of Great Britain, vol, ii., 1897, fig. 248, p. 155,</ref> both of whom have illustrated them by drawings.

Westwards of Beinn nan Codhan, and north-west of An Acairseid, two highly baked screen-like masses of Lower Lias shales and Tertiary basalt lava partly separate the main mass of the Hypersthene-gabbro Ring-dyke from an outer arm that forms the ridge of Garbhlach Mhor. The strike of the cone sheets has here swung round to the north-west. Cone-sheets and country rock are so highly altered that their separation in the field is a difficult matter, but the brown-weathering surfaces of the cone-sheets and the greyer hues of the Lias shales and Tertiary basalt lava serve to distinguish them.

Northwards of Garbhlach Mhòr to Sanna Point the Outer Cone-sheet Complex lies out to sea except for a single cone-sheet cutting the Hypersthene-gabbro at the Point of Ardnamurchan, which may perhaps be regarded as a late representative of the Outer Set (*see* p. 183). East of Sanna Point, the cone-sheet complex again comes ashore, but is so highly baked by the adjoining Hypersthene-gabbro that the direction of its component sheets can only be determined with difficulty. That we are here dealing with a cone-sheet complex referable to Centre 2 is, however, evident, for contiguous sheets are frequently separated by lenticles of the country rocks (Jurassic sandstone and limestone). Farther east, bordering the northern coast to the north of the Great Eucrite Ring-dyke of Centre 3, the cone-sheet complex is once more well seen, though adjacent to the Great Eucrite its component intrusions are as difficult to recognize individually as near Sanna Point. The cone-sheet belt is exposed continuously, in part at least, from this district round to the eastern side of the complex. An encircling belt of Outer Cone-sheets is therefore demonstrable except for the gap to the west where exposure is interrupted by the sea.

Inner Cone-sheets of Centre 2

These cone-sheets will be seen on the geological maps to form a belt less than a mile wide traversing many of the Ring-dykes of Centre 2. The belt extends round a quarter of a circle only, being truncated to north and east by ring-dykes of later date. The outer limit of the belt on the south side is separated by a zone of older rock free of cone-sheets (the Hypersthene-gabbro) from the Outer Cone-sheets above described. Partly on this account the Inner Cone-sheets are held to constitute a separate set. In age also the two sets must differ, for the Outer Cone-sheets are contact altered close to the outer margin of the outermost ring-dyke (the Hypersthene-gabbro), whereas this intrusion near its inner edge is freely cut by the Inner Cone-sheets. Other points of difference between the two sets are the greater steepness of the Inner Cone-sheets, and their reference to a centre near Aodann slightly different to that of the Outer Set. The difference in inclination is a remarkable feature. The high dip of 65–70 degrees of the Inner Cone-sheets is met with across the whole belt, while within half a mile to the south the Outer Cone-sheets are inclined at much lower angles. Mr. E. M. Anderson<ref>E. M. Anderson *in* Tertiary Mull Memoir, 1924, p. xi.</ref> has formulated a theory of cone-sheet intrusion which accounts for interior cone-sheets being steep because of their position more directly above an intrusion-centre, but in the present case some additional factor would seem to be involved.

Partial set of cone-sheets of Centre 3

North of Kilchoan, a few thin inclined sheets, chiefly of porphyritic basalt, traverse the outermost of the Ring-dykes of Centre 3 (Faskadale Quartz-gabbro), and isolated masses of basalt lava and agglomerate that occur within this ring-dyke complex. Their inclination is fairly constantly at an angle of 50 degrees, and is towards Centre 3. The breadth of the belt is three quarters of a mile, but individually the sheets have not been found to continue very far. They may be regarded as cone-sheets, but they constitute a very partially developed set.

Just south of the Ring-dykes of Centre 3, at the western extremity of Glas Bheinn, the Outer Cone-sheets of Centre 2 are abundant, and are non-porphyritic. A single porphyritic cone-sheet inclined towards Centre 3 was observed here cutting a nonporphyritic individual inclined towards Centre 2. West of this, on Glebe Hill, porphyritic types become more numerous, but some at any rate run tangentially to Centre 2, and it is evident that at this point porphyritic cone-sheets are becoming prevalent among the Outer Set.

A stray cone-sheet possibly belonging to the partial set traverses the Faskadale Quartz-gabbro Ring-dyke alongside a stream about half a mile north-east of Beinn na Seilg summit. It is composed of non-porphyritic basic rock, and is inclined towards Centre 3.

Age relations

Two lines of evidence are of service in determining the relative ages of the cone-sheets. In the first place, their distribution as described in the previous section shows that they occur as distinct sets. Secondly, the relation of the various sets to other intrusions, or groups of intrusions, fixes their relative positions in the igneous sequence. The more direct method of determining age, the traversing of one set of cone-sheets by members of another set, has not been found of much service in Ardnamurchan. It is difficult of application, owing to the similar composition of the sheets concerned at such crossing places, the great complexity of the cone-sheet assemblages, and the numerical insignificance of intrusions seen to cut one another, as compared with the sets to which they are referred. Age relations of the four sets to various other intrusions have been already stated in (Table 6), p. 176, the evidence for which is given in detail below.

Cone-sheets of Centre 1

These cone-sheets are demonstrably later than the Northern Vents. It is, however, noteworthy that quartz-dolerite fragments occur in the agglomerates, so that cone-sheet intrusion may also have preceded vent-formation, at some lower crustal level than that now exposed (*see* p. 131).

Their pene-contemporaneity with the Ben Hiant Intrusion has been already discussed (p. 166).

Outer Cone-sheets of Centre 2

The prior age of this set to all ring-dykes follows from the evidence given below. The outer margin of the whole ring-dyke complex, against which the Outer Cone-sheets abut, will be described in clockwise direction, taking each ring-dyke concerned in the following order:(1) Hypersthene-gabbro; (2) Great Eucrite; and (3) Quartz-gabbro of Faskadale. Of these, the Hypersthene-gabbro is perhaps the earliest of the Ring-dykes of Centre 2, while the other two intrusions are among the outermost and earlier members of the Ring-dykes of Centre 3 (*see* (Plate 5), p. 201).

1. Contact alteration of cone-sheets near to the Hypersthene-gabbro must be dated at any rate not later than this intrusion, the fine-grained outer margin of which is itself not contact altered. The effect is most pronounced in the case of the chilled edges of cone-sheets, which, when granulitized, lose their black, vitreous appearance and become stony. A good locality for observing this effect is on the hill-slope west-south-west of Kilchoan Free Church, near a track leading from Ormsaigbeg up to the twin lochs south-east of Beinn na Seilg. In this vicinity other evidence of age

is the net-veining of cone-sheets and gabbro-margin alike with acid magma, marking a final stage in the crystallization of the ring-dyke. Farther west, where the outer margin of the gabbro meets the coast, south-west of Beinn nan Codhan, a good contact is seen against Lower Lias shales that are cut by a complex of cone-sheets and sills. Along this shore, just east of An Acairseid, the gabbro is intruded by three or four thin non-porphyritic cone-sheets, but on the other hand it truncates a great number of more massive, porphyritic individuals that traverse the adjoining Lower Lias shales. There is therefore no doubt that the Hypersthene-gabbro is later than the porphyritic cone-sheets that are referred to the Outer Set of Centre 2. Along the north margin of the Hypersthene-gabbro, highly contact-altered quartz-dolerite forms the headland east of Sanna Point, and includes lenticular patches of sediments (Jurassic sandstone and limestone). As already mentioned (p. 180), it is also possible to detect a few sheet-junctions in the quartz-dolerite, showing that the mass is a complex of cone-sheets, a continuation of the Outer Set. The contact alteration of the quartz-dolerite is evidently due to the Hypersthene-gabbro, which is in welded contact with it in a low sea-cliff west of the headland. On the other hand, on the north shore of Sanna Bay, the gabbro is cut by a thin basic cone-sheet inclined towards Centre 2, and farther east by a thick inclined-sheet of granophyre with similar dip and strike (*see* Memoir-map). Though the Outer Cone-sheets as a group are earlier than the Hypersthene-gabbro, there are about half a dozen cone-sheets, all except the granophyre quite thin, which cut its outer portion.

2. The Great Eucrite is in contact with the Outer Cone-sheets for 2 miles on its north side, and has so completely granulitized them that their margins are very difficult to trace (p. i80). The effect decreases northwards away from the Eucrite, but, even along the northern coast east of Rudha Carrach, flakes of secondary biotite may be detected in the cone-sheets with a lens.
3. Along the east and south-east sides of the ring-dyke complex, the Faskadale Quartz-gabbro comes into intrusive contact with many cone-sheets. Characteristic evidence of age is afforded by its highly-baked wall, composed in part of cone-sheets, which extends north and south parallel to the Allt Faskadale river. An actual contact of unaltered gabbro with granulitized cone-sheet rock is exposed where the gabbro reaches the coast, on the east side of Faskadale Bay (*see* p. 284). E.B.B.

Perhaps most striking of all is the evidence found on Glas Bheinn, north of Kilchoan. The outer margin of the Quartz-gabbro there transgresses the belt of Outer Cone-sheets for a distance of a mile, and runs almost at right angles to the direction of the cone-sheets. The north and south sides of the hill present a remarkable contrast. To the south, there are rugged rocky slopes formed of the cone-sheet complex, with a conspicuous massive cone-sheet extending obliquely up to the summit. To the north, smooth lower slopes are composed of quartz-gabbro, while a rocky, jagged crest is formed of an intensely baked complex of cone-sheets and country rocks.

Inner cone-sheets of Centre 2

These cone-sheets traverse practically all the Ring-dykes of Centre 2 excepting the Eucrite of Beinn nan Ord and the Quartz-gabbros of Loch Caorach and Beinn na Seilg (see (Figure 37)). No contacts showing truncation of the cone-sheets by the margins of the Eucrite and Quartz-gabbros have been found, but the fact that two inwardly projecting lobes of the Eucrite, at the north end of Beinn na Seilg and east of the north end of Beinn nan Ord, cross the strike of the cone-sheets and are not cut by a single individual, seems sufficiently to prove that the cone-sheets antedate the Eucrite. The Quartz-gabbros of Loch Caorach and Beinn na Seilg are apparently slightly later than the Eucrite, and are consequently to be regarded as later than the Inner Cone-sheets. Acid veining of a cone-sheet on the southern summit of Beinn na Seilg is perhaps due to the adjoining Quartz-gabbro.

The westward continuation of the Faskadale Quartz-gabbro north-north-east of Beinn na Seilg is intrusive in the Beinn nan Ord Eucrite, and also contact alters porphyritic cone-sheets of the Inner Set and an older Quartz-gabbro traversed by them ((Figure 28), p. 219).

Partial set of Cone-sheets of Centre 3

The Faskadale Quartz-gabbro north of Kilchoan is sparsely traversed by these cone-sheets, as is also the capping of basalt lava and agglomerate south-west of Meall an Tarmachain. In the latter locality the cone-sheets are contact altered next to the Great Eucrite, and the set would therefore seem to antedate this intrusion.

Composite Cone-Sheets And Sills

These intrusions recur at intervals throughout the cone-sheet complexes of Centres 1 and 2. More striking examples from the British Tertiary province are already well known from Skye<ref>A. Harker, The Tertiary Igneous Rocks of Skye, Mem. Geol. Surv.,1904, pp. 197–234.</ref> and Mul1,<ref>E. B. Bailey in Tertiary Mull Memoir, 1924, p. 223.</ref> and the Ardnamurchan occurrences need be only briefly described. They consist of basic, usually narrow, margins with more acid, thicker centres. The margins are of quartz-dolerite, the centres of craignurite, felsite, or granophyre. The contact between basic and acid portions may be either sharp or merging, or the two portions may be separated by a zone of intermediate composition which contains much altered and partly resorbed basic xenoliths. There is no doubt that the acid centres were intruded later, though not much later, than the basic margins. The basic margins are chilled externally against the country rock, but there is no chilling observable in the interiors of the composite sheets.

A good example of a composite sill is within easy reach of Kilchoan along the foreshore 60 yds. south of Mingary Pier (Figure 23). Its lower portion is well seen, but its upper half has been cut out by a thick cone-sheet of later date and aberrant direction. A marginal basic, intermediate xenolithic and part of a central acid zone are on view. The basic margin, 1.5 to 2 ft. thick, is in sharp contact with the intermediate zone. In the lower part of the latter, the xenoliths are frequently elongate, with rounded outlines and sharply defined margins. Higher up they become much smaller, and the rock is more acid. The central zone of felsite or granophyre is free of obvious xenoliths. Above the big aberrant cone-sheet, at the base of which this central portion ends, the lower part of the sill is again exposed. The junction between the intermediate and basic zones is here sharp at one place, but becomes ill-defined within a yard or so.

Another good example of a composite sill is seen along the west side of Kilchoan Bay, just under a mile south-west of the Landing Jetty (*see* (Figure 3)).

A composite cone-sheet with an unusually massive acid centre about 100 ft. thick, outcrops along the shore 600 yds. northwest of Mingary Pier (Figure 23). No intermediate xenolithic portion is present.

Sometimes granophyre or craignurite occur alone, unaccompanied by a basic margin. As examples one may cite the granophyre cone-sheet north of Plocaig, and the craignurite sill on which Mingary Castle is built (Figure 25). J.E.R.

Petrology

The cone-sheets of Ardnamurchan, as of Mull, form a particularly interesting petrographical study, for they express definite and well-marked phases in the igneous history of the intrusive complex. In petrographical types they range over a wide scale from basic to acid, but sub-basic to intermediate types are most frequently encountered and certainly form the bulk of the cone-sheet intrusions.

In Mull the cone-sheets of successive intrusive periods, and coordinated to the different intrusive centres, showed remarkable constancy in their petrographical characters. The early sheets were mainly acid, followed by a great suite of olivine-dolerites. Later, with a shift of centre, came equally abundant quartz-dolerites. As has been discussed in the earlier part of this chapter (p. 182), in Ardnamurchan the greater number of cone-sheets were intruded before the larger plutonic masses reached their present position, and they are thus, relatively speaking, as early as, or earlier than, the bulk of the cone-sheets of Mull.

Amongst the cone-sheets of Ardnamurchan, non-porphyritic, variolitic, and porphyritic types are all represented. The majority of the porphyritic cone-sheets are more centrally situated and are, generally speaking, younger than their non-porphyritic associates. The cone-sheets thus present a sequence that corresponds to a definite time-change in magmatic composition.

The non-porphyritic types mainly have affinities with the quartz-dolerites, and with rare exceptions occur beyond the limits of the plutonic intrusions. Sheets that cut the plutonics, and are definitely of later date, are mostly porphyritic dolerite with felspar phenocrysts. Comparable porphyritic basic cone-sheets occur in Mull. We have in Ardnamurchan, however, an apparent difference in the order of intrusion of the cone-sheets when compared with Mull; for whereas in Mull the quartz-dolerites and variolites were generally later than the porphyritic varieties, in Ardnamurchan quartz-dolerite appears to be the prevalent early type.

Basic Cone-Sheets beyond the limits of the Plutonic Complex of Centres 2 And 3

Amongst these cone-sheets, variolitic, non-porphyritic, and porphyritic rocks are represented, and for purposes of description this order will be followed.

The Variolites

The variolites of Ardnamurchan form a group subordinate to the general quartz-dolerite cone-sheets, and like the variolitic sheets of Cruachan Dearg in Mull<ref>H. H. Thomas and E. B. Bailey *in* Tertiary Mull Memoir, 1924, pp. 304–305.</ref> are fine-textured more or less tachylitic sheets of no great thickness.

As exemplified by a sheet referable to Centre 2, and exposed on the shore 100 yds. east of Rudha Groulin (S21444) [NM 4692 7102], they consist of slender prismatic to acicular crystals of titaniferous augite and elongated narrow crystals of oligoclase-andesine felspar in a glassy partly devitrified matrix. The augite crystals, which reach 3 or 4 mm. in length, are traversed and occasionally linked together by numerous narrow plates and rods of magnetite, which are usually normal to, or make a wide angle with, the long axes of the pyroxenes.

The devitrification of the glassy base has largely resulted in the formation of feathery aggregates of felspar and quartz, the latter mineral frequently being segregated into small but easily recognized patches.

In this form the rocks compare closely, both structurally and mineralogically, with the variolitic late basic cone-sheets of Mull, and their chemical composition must be quite similar. As might be expected, they are comparable in many respects with the variolitic rocks associated with the Ben Hiant Intrusion (p. 171) and like them are compositionally related to the quartz-dolerites of Talaidh type which form the great Ben Hiant Intrusion and the bulk of the cone-sheets.

In another cone-sheet, referable to Centre 1, elongated felspars dominate the crystalline structure of the rock, while the augite and magnetite are more or less confined to the hyaline matrix (S24468) [NM 5609 6299]. In such rocks the texture is generally finer than in the true variolites, the augite may assume a branching and cervicorn development, and magnetite builds a fine-textured rectangular lattice, as well as occurring abundantly as small isometric grains. Such rocks are related to the pitchstones of leidleitic affinities, or are transitional between the true variolites and the variolitic and tholeiitic varieties of the quartz-dolerites of Talaidh type.

The non-porphyritic cone-sheets

The majority of the nonporphyritic cone-sheets, mostly referable to Centre 2, but some related to Centre 1 (p. 178), are quartz-dolerites of a type that was particularly prevalent amongst the Late Basic Cone-sheets of Mull, and to which the name Talaidh Type was applied on account of their development in the region of Beinn Talaidh in that island.

They are generally fine-grained rocks, rich in iron-ore, which are dark brownish-grey in colour and are usually devoid of olivine. They are composed of a moderately basic plagioclase felspar, augite, titano-magnetite, alkali-felspar of a preponderating albitic character, and quartz. The outstanding feature of these rocks is not to be found so much in their mineral composition as in their structure. There has been an early separation of the larger and more basic constituents from an acid residuum that remained fluid till the last, and which was capable of migration and segregation into well-defined but unevenly distributed areas. The rocks, therefore, consist of an open mesh-work of indefinitely bounded elongated crystals of labradorite-andesine felspar, which embraces crystals of augite and has its interspaces filled with a copious fine-grained mesostasis of alkali-felspar and quartz (S21439) [NM 5490 6431], (S21441) [NM 5180 6303]. Augite and attendant titano-magnetite are usually the earliest products of consolidation. The augite thus generally avoids an ophitic structure and has a hypidiomorphic-columnar habit, building somewhat stumpy crystals bounded by prism and pinacoid faces and elongated parallel to the *c* axis. It is a normal aluminous variety of a brownish colour, and seldom shows the lilac tinge attributable to a high content of titanium. Magnetite, or titano-magnetite, occurs chiefly in association with the augite, intergrown with the peripheral portions of the augite crystals, but iron-ore also builds isolated crystals and in some instances appears to be ilmenite.

The mesostasis is a fine-grained crystalline mass, usually turbid with secondary products, with an acicular to granular type of crystallization of its constituents. The main elements are alkali-felspar and quartz, but acicular augite is of frequent occurrence. The felspar is mainly albite, but potash-felspar is also present and this may be distinguished in fine graphic intergrowth with quartz. Quartz also is segregated into small isolated areas representing the ultimate excess of silica. Apatite, as has been found to be the case withfmost of the rocks that have an acid mesostasis, is concentrated in this partial magma, and in some instances becomes an abundant constituent.

The analysed specimens are both from thick representatives of the Outer Set connected with Centre 2, and are of Talaidh type. One sheet (S23296) [NM 4928 6260] is a moderately fine-textured rock that shows an almost simultaneous crystallization of augite and felspar, so that the augite exhibits both a columnar and a subophitic habit. In this respect the rock shows a slight leaning towards the coarser varieties of quartz-dolerite in which an ophitic structure is more general. The other sheet (S22819) [NM 4949 6392], probably on account of its thickness, is a still coarser variety of the Talaidh type in which the augite exhibits a subophitic habit. The mesostasis is abundant and has the characteristic variable distribution.

A review of the analyses given on p. 82, and a comparison with those of the Talaidh cone-sheets of Mull,<ref>H. H. Thomas and E. B. Bailey in Tertiary Mull Memoir, 1924, p. 17.</ref> show that the type as a whole is very constant in its chemical composition and is one that must mark a quite definite stage in the process of differentiation. It is interesting to note, as pointed out in connexion with the Ben Hiant Intrusion, that the cone-sheets have practically the same chemical composition as the Ben Hiant mass. The size of the Ben Hiant mass and its intrusion as a unit prove that a magma of Talaidh composition was, on occasion, produced and intruded in bulk. At the same time, microscopic examination of these rocks shows that such a magma during the process of solidification would, and did, give rise to an acid partial magma that was capable of self-expression, provided mechanical separation of liquid from solid fractions could be effected. That such a separation actually took place in certain instances is more than conjecture, and the results of this process are discussed elsewhere (p. 95).

Of the cone-sheets related without question to Centre 1, in addition to those referable to the Talaidh type (S24470) [NM 5502 6706], there are others, usually non-porphyritic, which are either variants of, or depart more or less widely from, this type. Slight variants of the Talaidh type are furnished by sheets of moderately fine-grained quartz-dolerite. One of these (S24469) [NM 5550 6871], cutting Moine Schists to the north of Loch Mudle, has small hypidiomorphic-columnar crystals of augite and laths of labradorite felspar in an apatite-rich residuum of alkali-felspar and quartz. Its main difference from the Talaidh type lies in the occurrence among its constituents of small flakes of biotite and brownish-green hornblende, both of which appear to be original and not due to subsequent thermal alteration.

A certain number of sheets occurring in a zone to the southeast of Ben Hiant, and seen as discontinuous outcrops, are subacid in composition and moderately coarse in texture. As represented by a typical specimen (S21438) [NM 5507 6259], they are microporphyritic, containing small crystals of labradorite-andesine felspar which reach a sixteenth to an eighth of an inch in length. The bulk of the rock, however, is a mass of elongated blade-like crystals of decomposed augite and elongated, irregularly bounded, crystals of oligoclase-andesine with interstitial slightly turbid feathery aggregates of alkali-felspar and quartz. Quartz also is segregated into small clear patches. These rocks certainly show affinities to the quartz-dolerites and may be regarded, perhaps, as acid representives of the Talaidh type.

Of the widely variant types we may cite a sheet that occurs at the bridge over Allt Tòrr na Mòine, half a mile east-north-east of Bourblaige (S24467) [NM 5571 6269]. It is a grey compact splintery rock with small porphyritic felspars that reach a few millimetres in length. The microporphyritic constituents are a moderately basic plagioclase and relatively infrequent augite pseudomorphed by calcite. These occur in a matrix that has an acicular to feathery type of crystallization and is full of blade-like and skeleton crystals of augite. The residuum was presumably glassy and the feathery crystalline aggregate of quartz and alkali-felspar which constitutes the base is probably in part due to devitrification. The rock is closely allied to the pitchstones, and although its somewhat decomposed condition makes its precise classification a matter of difficulty its microstructure is reminiscent of the inninmorite-pitchstones of Mull.<ref>H.

H. Thomas and E. B. Bailey in Tertiary Mull Memoir, 1924, pp. 282–284.</ref>

Passing now to non-porphyritic sheets referable to Centre 2, we find a number of departures from the usual Talaidh type of quartz-dolerite.

A thick sheet exposed on the shore at Rudha Groulin (S21443) [NM 4685 7101], while having the structures and general composition of the normal quartz-dolerites, has the somewhat unusual occurrence of a colourless rhombic pyroxene (enstatite) as small ill-shaped crystals, in addition to hypidiomorphic-columnar augite. There has been a slight development of biotite as the result of contact alteration by the later plutonic rocks.

What may be regarded as a variable and basic representative of Talaidh type is represented by a sheet exposed on the shore of Rudha Aird an Iasgaich, south-west of Kilchoan (p. 175). The sheet is about 21 ft. in thickness. The outer 6 ft. on both sides consists of a coarse-textured, spheroidally-weathering rock, with well-chilled margins, while the central 9 ft. exhibits vertical jointing; in the centre of this latter portion is a lenticular xenolithic mass, some 20 yds. long, which contains abundant xenoliths of schist and other rocks closely packed in a quartz-dolerite matrix. The upper surface of the sheet is in contact with calcareous Liassic shales that have suffered considerable contact alteration.

While the margins of the sheet against the Liassic strata above and below are well chilled, there is no internal chilling, and the sheet is presumably a composite intrusion.

The coarse marginal zones (S22231) [NM 4928 6260] may be described as of quartz-gabbro composed of a brownish subophitic augite, moderately well-formed interlocking crystals of zoned labradorite, magnetite, and an interstitial acid mesostasis of alkali-felspar and quartz. The mesostasis is collected into relatively large areas and exhibits a fine-textured to skeletal type of crystallization. Where it is in contact with felspar it has produced resorption and acidification, and against augite has effected the formation of brown hornblende at the expense of the pyroxene. That the rock has been subjected to stress and movement during consolidation is shown by the frequently bent and curved cleavage planes in the augite and felspar crystals, similarly observed in some of the quartz-dolerites of Mull<ref>H. H. Thomas and E. B. Bailey in Tertiary Mull Memoir, 1924,. pp. 324–327.</ref> and elsewhere.

The vertically jointed interior of the sheet (S22232) [NM 4928 6260], though generally fine-textured, is variable, and in the same section it is possible to pass from a moderately coarse quartz-dolerite with subophitic augite to a finer-grained rock of Talaidh type. The rock has an almost xenolithic appearance, as if it had been churned up during its consolidation. As in the outer zones, curved augite crystals are often encountered and there has been a local precipitation of augite that is hard to account for except on a xenolithic hypothesis. The rock contains a small amount of brown hornblende intergrown with the augite and forming small isolated patches in the mesostatic material.

The central xenolithic lenticular mass (S22233) [NM 4928 6260] is presumably a later injection, for it is difficult to account for its highly xenolithic character and central position in any other way. It is a much more acid rock than the rest of the mass, and has undoubtedly still further acidified itself by the assimilation of acid gneiss, quartzite, and other xenolithic matter. The matrix in which the xenoliths lie is an acid type of quartz-dolerite characterized by small columnar to idiomorphic augites, irregular laths of labradorite, moderately large crystals of magnetite, and a copious acid mesostasis. In the neighbourhood of the siliceous xenoliths the rock is acidified, the mesostatic matter is more abundant, augite is more definitely idiomorphic, and at the actual contacts with the xenoliths there has been an excessive precipitation of augite in closely packed more or less idiomorphic crystals. The augite appears to be an ordinary aluminous variety with a moderately wide axial angle.

The xenoliths themselves have been much corroded and penetrated by magmatic matter. Quartz grains have suffered partial solution with the subsequent formation of tridymite fringes on the undissolved portion, and tridymite has also separated from the silicified melt. This mineral, as is usually the case, has reverted to quartz, and, where fringing incompletely dissolved grains, has the same crystallographic orientation as the original quartz.

It is not usual for individual cone-sheets to have produced any marked contact alteration of the rocks with which they come in contact, though the cumulative effect of many sheets is often apparent. In the case, however, of this particular sheet, partly owing to its thickness and partly because the Liassic deposits readily respond to thermal agencies, quite interesting metamorphic effects are to be observed at its contact. The calcareous Liassic shale (S22234) [NM 4928 6260] has been indurated and has developed a suite of calc-silicates, amongst which are garnet, monoclinic pyroxene, idocrase, tremolite, and prehnite.

The garnet is colourless, well-shaped, and averages about 1 mm. in diameter. The pyroxene is an aluminous variety. It occurs in elongated blade-like crystals of a greenish tint, and is usually edged with aegirine, due probably to the amount of alkali in the original rock. Tremolite is detectable chiefly by its habit, but a few small patches have escaped the general replacement by calcite, while prehnite builds small rectangular crystals with the usual moderately high birefringence. In addition there is a mineral developed somewhat irregularly, with low birefringence and apparently straight extinction, which is most probably scapolite, but its determination is doubtful. Sphene occurs in brownish granules and patches that reach o•l mm. in size.

A few moderately coarse-textured non-porphyritic sheets occurring on the southern side of the ring-dyke complex are referable to quartz-dolerite. They show affinities with the tholeiites and are characterized by subophitic yellowish slightly pleochroic augite, and elongated felspars that occasionally show a stellate grouping. Generally they are olivine-free (S21844) [NM 4757 6329], but in some cases olivine may have been an original constituent (S21847) [NM 4710 6382]. A certain amount of mesostatic matter, usually chloritized, is present, and quartz appears to have been an original product of consolidation.

The porphyritic cone-sheets

All the sheets here considered carry phenocrysts of plagioclase felspar. As has been stated already, they show a tendency to group themselves near to the plutonic centres. The majority belong to Centre 2, but some may with certainty be co-ordinated with Centre 3.

Relatively few of the porphyritic sheets occur beyond the limits of the ring-dyke complex, and most of them are more or less close to the boundary of the Hypersthene-gabbro Ring-dyke of Centre 2. They have, therefore, in most instances suffered the effects of thermal metamorphism, usually in the form of granulitization of the matrix and the development of biotite from iron-ores and chlorite. Their major structures, however; are retained, and we are enabled to state that these porphyritic rocks are classable as ordinary porphyritic basalts and dolerites. There appears to be no essential difference between the porphyritic sheets that are respectively referable to the various centres, and they find their equivalents in the porphyritic types of Early Basic Cone-sheets and small-felspar basalts of Mull.

A representative of the porphyritic cone-sheets referable to Centre 2 (S22236) [NM 4899 6288], which occurs on the shore near Mingary pier, and is far enough away from the plutonics of Centre 2 to have escaped metamorphism, may be described as a porphyritic basalt or dolerite. It contains small crystals of a moderately basic labradorite in a matrix of felspar laths, grains of magnetite, and a brownish micro-ophitic augite that reproduces in a measure the well-known ophimottled ' structure. A group of sheets from the neighbourhood of Maol Buidhe, also beyond the range of contact metamorphism, are of the same general character, their chief variation being in the texture of the matrix rather than in their mineral composition. The matrix may be either definitely ophitic (S21837) [NM 4599 6230] or finely hypidiomorphic-granular (S21836) [NM 4599 6230].

A well-chilled sheet (S22369) [NM 4859 6475] that cuts the Glas Bheinn Porphyritic Dolerite exhibits the usual character of bearing small unzoned porphyritic labradorite felspars in its fine-textured chilled edges. The dolerite in contact shows signs of shattering and both rocks have suffered thermal alteration by later ring-dyke intrusions.

Sheets still beyond the boundary of the ring-dykes, but sufficiently close to be thermally altered, occur between Kilchoan and Beinn na Seilg. Some of these were hypidiomorphic - granular basalts (S22246) [NM 4787 6435], (S22679) [NM 4670 6387] with olivine, others (S21820) [NM 4698 6386] were porphyritic olivine-bearing basalts with a subophitic matrix. All have suffered granulitization, and otherwise show changes that will be discussed in detail when dealing with the metamorphic effects of the ring-dykes.

Basic Cone-Sheets cutting members of the Plutonic Complex of Centres 2 And 3

The majority of these sheets are porphyritic in character, some referable to normal basalts and dolerites, others to quartz-dolerites.

Amongst those that cut the Hypersthene-gabbro, a typical sheet near the summit of Beinn na Seilg (S21564) [NM 4597 6412] has porphyritic zoned labradorite-andesine felspars that range up to 3 mm. in length, and occasional porphyritic crystals of augite, in a matrix of irregularly bounded laths of zoned plagioclase with interstitial magnetite and augite. Slight thermal alteration has modified the texture of the matrix to a small extent only.

The edges of such sheets (S22277) [NM 4711 6385] are well chilled against the gabbro, which may show slight signs of shattering at the contact. The chilled edge usually carries unzoned porphyritic crystals of labradorite and sometimes of augite in a fine-textured magnetite-rich basaltic matrix.

Amongst the sheets that cut the old Quartz-gabbro of Garbh-dhail (c of (Plate 5)), both basalts and quartz-dolerites are represented; the majority are porphyritic, and almost all show the effects of contact metamorphism due to the later members of the ring-dyke complex. In the basaltic varieties the porphyritic crystals reach 3 or 4 mm. in length, and the matrix is either hypidiomorphic-granular (S21572) [NM 4564 6491], or the augite is granular to subophitic (S21819) [NM 4446 6468]. The quartz-dolerites have porphyritic zoned labradorite felspars in a matrix of interlacing laths of labradorite-oligoclase, magnetite, and columnar to subophitic augite, with an acid residuum containing free quartz. Such sheets (S22681) [NM 4617 6467], (S24445) [NM 4617 6467], occurring to the north-east of Beinn na Seilg, are older than, and have been metamorphosed by, the Quartz-gabbro of Centre 3 (A of P1. V) (p. 184). They have had their original augite granulitized, and biotite developed at the expense of chlorite; while the chloritized residuum with free quartz has given rise to aggregates of biotite and small well-formed crystals of rhombic pyroxene (hypersthene).

A porphyritic basaltic sheet (S22311) [NM 4574 6544] that cuts the basalt lavas and agglomerates on the inner margin of the Old Gabbro of Lochan an Aodainn (b of (Plate 5)) carries porphyritic labradorite and augite, often in glomero-porphyritic groups, in a fine-textured microlithic to granular matrix rich in magnetite and apatite. In the nature of its porphyritic constituents it is similar to certain basaltic sheets that cut the Hypersthene-gabbro, and which are described above.

A representative of certain sheets that cut the basalt and agglomerate capping of Meall an Tarmachain (S21854) [NM 4857 6608], and which are dispositionally related to Centre 3, is especially interesting on account of its metamorphism proving conclusively that this group of sheets, although related to Centre 3, is earlier than the Great Eucrite of that centre. It is a porphyritic quartz-dolerite with porphyritic crystals of zoned labradorite, which reach a quarter of an inch in length, in a matrix of felspar laths, magnetite, moderately large subophitic augites, and an interstitial quartz-bearing acid mesostasis. The metamorphism has produced the usual turbid schillerization of the felspars, partial granulitization and schillerization of the augite, and the development of granular rhombic pyroxene and biotite in the siliceous mesostasis.

Sills and other sheet-like masses

A number of sheet-like masses, occurring mostly in the bedded strata beyond the limits of the ring-dyke complex, will here be considered. Some of these are possibly true sills, but others are most probably aberrant representatives, or extensions, of cone-sheets. The basic examples call for no special comment, for with one exception they are of types well represented amongst the cone-sheets. They are chiefly non-porphyritic rocks referable to varieties of the Talaidh type of quartz-dolerite (S21434) [NM 4914 6289], which sometimes present a pronounced variolitic structure (S21435) [NM 4968 6301]. The most important and perhaps the most interesting example is the thick subacid sheet well exposed on the shore beneath Mingary Castle (p. 185). It is a compact greenish-grey, finely-speckled rock with decided granophyric affinities (S22430) [NM 5103 6316]. Like most of the subacid sheets, as also the acid portions of the composite intrusions, it is rich in soda-felspar. It consists of elongated crystals of augite, pseudomorphed in chlorite or partly replaced by brownish hornblende, and elongate crystals of oligoclase, in a matrix of alkali-felspar and quartz. The matrix has a feathery to acicular type of crystallization, with, here and there, definite micrographic intergrowths of potash-felspar and quartz. Generally, the felspar of the matrix appears to be albitic. Magnetite as grains is commonly associated with the augite, and pyrites occurs in small isolated patches. The rock is similar to the acid craignurites of Mull<ref>H. H. Thomas and E. B. Bailey *in* Tertiary Mull Memoir, 1924, pp. 226, 227.</ref>and may be classified as a granophyre of craignurite affinity. Another sub-acid sheet, exposed on the shore 750 yds. west by south of Mingary Castle (S21437) [NM 4959 6296], is of similar type, except that the acicular type of crystallization characteristic of the craignurites is less pronounced. The rock has a more bostonitic structure with a tendency for the felspars to assume a less elongate form. There is a good deal of micrographic matter in the base, and the rock may be described as a somewhat basic soda-granophyre.

A large intrusion (S21843) [NM 4768 6339] striking with the cone-sheets, but cut by them and having vertical junctions with the Lower Lias shales, occurs on the western side of Kilchoan Bay, 300 yds. southwest of the jetty. It is a fine-textured grey speckled rock that, under the microscope, presents a very mixed appearance. It consists of relatively basic clots of augite, albitized labradorite felspar, and magnetite in a feathery felspathic matrix of albite-oligoclase, orthoclase and quartz with subordinate acicular augite. The basic portions are rich in augite that shows serpentinous decomposition and the approximately uniaxial character typical of the enstatite-augites. The pyroxene usually has a subidiomorphic habit, but it may also take on a subophitic relationship to the plagioclase, when it frequently shows the effects of pressure and movement by the curving of its cleavage-planes.

This association of enstatite-augite with labradorite in glomeroporphyritic groups was, in Mull, not an unfamiliar feature of certain of the more acid craignurites, and the rock under description would find its place in this group.

A unique occurrence of an extremely basic sheet of plateau basalt type occurs within the lavas of the Ardslignish outlier, and is lettered eD on the Memoir-map. It forms a thick columnar sheet, trending in a north-westerly direction, and is cut by a north-west dyke. Judged by the inclination of the columns, the sheet dips at 30° to the south-west. A specimen collected one and a half miles north of Ardslignish farm (S24477) [NM 5633 6343] is a dark-grey finely crystalline olivine-dolerite. It is composed of abundant olivine, almost wholly fresh, a deeply tinted titaniferous augite, strongly zoned basic labradorite felspar, titano-magnetite, and interstitial turbid analcite. The olivine, a colourless variety, has a marked tendency towards idiomorphism. It occurs in somewhat rounded grains, isolated crystals and glomero-porphyritic groups, and has preceded the crystallization of all other constituents. The felspar forms a coarse mesh-work of moderately large elongate crystals and is ophitically embraced by the titaniferous augite. The iron-ore is associated more particularly with the augite and has given rise to a little biotite in its immediate vicinity. Analcite is not an abundant constituent, but occupies well-defined areas that represented ultimate intercrystal spaces.

A number of north-westerly directed sheets cut the eastern extremity of the Glas Bheinn Porphyritic Dolerite (p. 143), and are also encountered cutting the Lower Lias limestones to the east of Beinn na h'Urchrach, on the north side of Ben Hiant. They all appear to be quartz-dolerites of which some exhibit a subvariolitic structure reminiscent of the subvariolitic rocks of the Ben Hiant Intrusion (p. 172). These variolitic varieties (S22431) [NM 5355 6392], (S22703) [NM 5221 6518] are rich in titaniferous augite and titano-magnetite, the former in elongate blade-like crystals and cervicorn groups, the latter as plates and grains intimately associated with the augite. The matrix presents an acicular and skeletal type of crystallization indicative of relatively rapid solidification.

Other sheets of this group, less basic in composition and paler in colour, may be described as subvariolitic varieties of the Talaidh type (S21436) [NM 5354 6382]. They have semi-columnar crystals and stellate groups of augite and felspar in a feathery matrix; but, with a more pronounced colimnar and cervicorn habit of the augite, they become normal representatives of the type (S22705) [NM 5243 6468].

Metamorphism by cone-sheets and sills

As has already been stated, the metamorphism effected by individual cone-sheets is not particularly well marked, and even in the case of the thicker sheets is confined to the actual contact. The cumulative metamorphic effect of numerous contiguous sheets is, however, of a more pronounced character and may be impressed on the country rock over a relatively wide area. It is in the various sedimentary series, as might be expected, that the metamorphic changes brought about by cone-sheets are most in evidence, and the Liassic sediments seem particularly responsive. The igneous masses where cut by cone-sheets suffer little change even at the contacts, and it is chiefly in xenoliths of the country rock, where assimilative processes as well as contact metamorphism are active, that any radical changes are effected.

The conversion of Liassic limy shale into calc-silicate rock has already been dealt with (p. 190), but another type of interesting contact rock also results from the metamorphism of certain Upper Lias shales. Along the shore on the western side of Kilchoan Bay, the black shales in contact with the cone-sheets are frequently indurated, have lost their fissility, and become more granular. A microscopic examination shows that they have been converted into a turbid mass of highly birefringent prehnite, enclosing small prisms of idocrase and occasional small colourless garnets, and rendered turbid by dusty carbonaceous matter (S21845) [NM 4693 6258]. In certain parts the amount of unaltered finely-divided clastic quartz is considerable and clearly demonstrates the original clastic character of the rock.

Composite and acid intrusions

The majority of the acid and intermediate cone-sheets, and those more acid sills associated with the cone-sheet complex, have a marked tendency to exhibit a composite character, and as in Mull do not appear to be confined to any particular period of intrusion, although most are included in the Outer Set of Centre 2. They almost invariably have basic edges which show a merging junction with an acid interior. In some cases there is perfect petrological gradation from one rock to the other, but in other instances the later acid intrusion has hybridized with the already intruded basic rock to a varying degree, and produced xenolithic and other abnormal features.

The rock types represented are mainly varieties of the Talaidh type of quartz-dolerite associated with granophyres that are more than usually rich in soda-felspar. There does not appear to be that prevalence of tholeiitic margins as was a feature of the composite sheets of Mull.<ref>H. H. Thomas and E. B. Bailey *in* Tertiary Mull Memoir, 1924, p. 228</ref>

One of the best examples of a composite sheet may be studied On the shore, to the south of Mingary Pier (S22227) [NM 4937 6262], (S22228) [NM 4940 6267], (S22229) [NM 4940 6267], (S22230) [NM 4940 6267], (S21855) [NM 4938 6268], (S21856) [NM 4938 6268]. The basic edge (S22228) [NM 4940 6267], which has a thickness of 1.5 ft., is best described as a subvariolitic quartz-dolerite of Talaidh type. Its augite, which is titaniferous, occurs in elongated and occasionally curved crystals that are crossed by plates of magnetite after the manner of the variolites; also, there is a good development of augite presentingthat cervicorn structure which was found to be characteristic of the augite in many of the Late Basic Cone-sheets of Mull<ref>H. H. Thomas and E. B. Bailey in Tertiary Mull Memoir, 1924, p. 302.</ref>The felspars are elongated and about andesine in composition, while the matrix is largely chloritic. The intermediate portions (S22229) [NM 4940 6267], and the more basic portion of the acid interior (S21855) [NM 4938 6268], are of albite-granophyre that has been basified by the resorption of earlier basic material. The rock consists of a few large resorbed crystals of a relatively basic plagioclase set in a fine-textured matrix of oligoclase, alkali-felspar, and abundant free quartz. The central portion (S21856) [NM 4938 6268] is a granophyre rich in soda-felspar. It contains large turbid crystals of albite in a definitely micrographic matrix of alkali-felspar and quartz, which includes a moderately large proportion of albite. The lower intermediate part of the intrusion (S22230) [NM 4940 6267], and the outer portion of the acid interior, carry more basic xenoliths, which may in a measure be regarded as cognate. These xenoliths are of a non-variolitic fine-textured quartz-dolerite of Talaidh type, and are similar in composition to portions of the basic margins.

Another composite sheet, that has well-defined basic margins about 1.5 ft. in thickness and an acid interior measuring some 6 ft. across, occurs about one third of a mile north-east of Sròn Bheag, and a quarter of a mile north-east of the Sròn Bheag intrusion described below (p. 197). The margins (S21823) [NM 4684 6251], as in the composite sheet mentioned above, are of a variolitic quartz-dolerite that consists of elongated frequently-curved crystals of titaniferous augite, similarly elongated crystals of oligoclase-andesine felspar and irregularly distributed patches of magnetite in a fine-textured matrix of augite, plagioclase, and residual quartz. The pyroxene of the matrix shows to perfection the cervicorn structure so frequently adopted by augite in rocks of this character and composition.

The more acid central portion (S21822) [NM 4684 6251] is also a quartz-dolerite of Talaidh type, but a much more acid variety. The more siliceous character is indicated by a much paler tint in the hand-specimen, and microscopically by a superabundance of alkali-felspar and quartz in its composition. The rock contains moderately large turbid crystals of albite-oligoclase felspar, and crystals and clots of hypidiomorphic augite, in a subvariolitic matrix of narrow elongated crystals of decomposed pyroxene and sheaf-like aggregates of oligoclase, with a residual base of alkali-felspar and quartz.

The ultimate products of consolidation would appear to have a composition similar to that of the soda-granophyres and felsites that frequently form the central portions of the thicker composite intrusions. The central portion of this sheet is locally xenolithic and basified by partial or complete resorption of the earlier basic material.

In some instances the acid central components are of a felsite that approaches pitchstone in character and are rocks that suggest an originally glassy texture. One such mass (S21442) [NM 5175 6343], apart from a few crystals of plagioclase that may well be xenolithic, consists of mutually interfering areas of alkali-felspar and quartz, replete with trichites. It has a structure that is due presumably to devitrification, and shows a tendency towards the development of spherulitic, radial, and sectorial growths of quartz and felspar.

An acid cone-sheet (S21811) [NM 4506 7023], unaccompanied by basic margins, is intruded into the Hypersthene-gabbro to the north of Plocaig. It is a fine-textured rock containing isolated crystals of augite which appear to be xenolithic, and which are rendered almost opaque by the separation of magnetite. The only other constituent of any size is a plagioclase felspar that occurs as crystals of one or two millimetres in length, and consists of acid labradorite zoned to oligoclase. The matrix is a feathery mass of alkali-felspar and quartz in which both soda-felspar and orthoclase are represented, and which contains abundant small pseudomorphs after acicular augite. The ultimate products of consolidation are orthoclase and quartz in extremely fine micrographic intergrowth. The rock is a somewhat basic granophyre that has further basified itself by the resorption of basic matter of Talaidh type. In the structure of its matrix it somewhat resembles the more acid varieties of the craignurites of Mull,<ref>H. H. Thomas and E. B. Bailey in Tertiary Mull Memoir, 1924, p. 127.

</ref> but this structure is probably in part dependent on its basification rather than upon its original composition. At the contact, the Hypersthene-gabbro (S22267) [NM 4533 7011], (S22268) [NM 4533 7011] shows signs of crushing and is traversed by veins from the acid sheet which have assimilated gabbro material. The effect has been a general basification of the sheet and the precipitation of a greenish augite at and near its junction with the gabbro and xenoliths. The gabbro itself seems to have suffered no appreciable contact alteration.

Sròn Bheag Composite Intrusion

Inthis composite dyke-like mass striking hybridization has taken place between the component members. A basic interior, consisting of quartz-dolerite, forms the most prominent feature of the headland of Sròn Bheag, at the south-western extremity of Kilchoan Bay, and is lettered eD on the geological maps. It is some 200 to 300 ft. broad, and is seen to extend steeply or vertically up the face of the sea-cliff. It can be traced inland for a distance of about a quarter of a mile. The quartz-dolerite is accompanied on either side by similarly orientated intrusions of felsite or granophyre of bostonitic affinity, 50 to 100 ft. in width. These acid masses are well seen on the shore and in the sea-cliff, but have not been traced far inland. The upper part of the more easterly mass, however, appears to extend as a sill among the Inferior Oolite sediments that form the country rock.

The junctions between the felsitic masses and the quartz-. dolerite are in some places relatively sharp, but more frequently the rocks merge into each other. Such indefinite contacts are well seen on the south-westerly side of the quartz-dolerite, and here, also, acid veins that profusely cut the quartz-dolerite are best developed. The basic rock is traversed by bands of breccia which have been invaded by felsitic matter and which may well be due to the explosive action of the acid magma. These merging junctions between the basic and acid masses of Sròn Bheag

suggest that this complex is akin to the composite intrusions, but differs from the great majority in that the later acid magma has intruded itself along the margins, and not in the centre, of the earlier basic intrusion.

The basic and acid intrusions of the Sròn Bheag composite mass are alike traversed by quartz-dolerite cone-sheets that belong to the Outer Set of Centre 2, and thus the complex as a whole is of early date. The possibility that it may belong to the cone-sheet complex of Centre 1 has already been considered (p. ivy), but it is also possible that its north-westerly orientation may have been induced by regional, rather than local, tensional stresses.

The basic, and here central, portion of the intrusion (S21825A) [NM 4657 6228], (S21828) [NM 4651 6226] was originally, before modification by the incoming acid magma, a moderately, basic quartz-dolerite of Talaidh type. It appears to have consisted of elongated columnar augites, charged with magnetite or otherwise associated with iron-ore, and elongated crystals of albitized labradorite, in the usual matrix of plagioclase felspar and quartz, with subordinate orthoclase. As now encountered it is modified to a great extent by acid material that has penetrated it in all directions from the subsequently intruded granophyre or bostonite. The augite is pseudomorphed in chlorite, and abundant 'ox-red biotite has developed throughout the rock between the felspars, and in association with the augite and iron-ores. The plagioclase felspars are frequently reduced to the condition of albite-oligoclase, and fibrous bastite pseudomorphs suggest that a rhombic pyroxene was one of the products of hybridization. Acid veins penetrate the more basic material and cut the rock up into isolated and relatively basic areas.

The acid portion of the intrusion was presumably bostonitic in character for phenocrysts of perthite (S21827) [NM 4652 6227] are of common occurrence. Their average size is about three or four millimetres, but they may reach a centimetre in extreme cases. The rock as a whole is light-grey in colour, but has a very mixed aspect. The perthitic phenocrysts occur in a mosaic of mutually interfering squarish crystals of oligoclase, albite-perthite, and anorthoclase; more or less isolated, and occasionally pseudomorphed grains of augite; and abundant patches of red biotite with interstitial quartz and occasional small areas of micropegmatite.

The rock may be regarded as a thoroughly basified and contaminated soda-granophyre or bostonite. The contained augite is either largely a product of imperfect assimilation or clearly xenolithic (S21829) [NM 4652 6227], while the biotite has resulted from the complete interaction of acid and basic material, involving in the latter an enrichment in silica and alkalis.

As the more basic portion of the mass is approached, the acid margins (S21826) [NM 4654 6226] take on a darker tint and are studded with small bright phenocrysts of albitized labradorite, with albitic peripheries, and albite. There has been a local development of hypidiomorphic pale-greenish augite as large thick-set crystals, and fairly abundant biotite. The basic material is included as clots, against which there is a strong development of augite and biotite. The fine basic portions have the microstructure of a quartz-dolerite of Talaidh type, but they have been completely changed by metamorphism and hybridization. These portions show a vesicular structure, and it is worthy of mention that Dr. Harker<ref>The Tertiary Igneous Rocks of Skye,' Mem. Geol. Surv., 1904, pp. 175,</ref> and others have noted the development of vesicles in rocks of a modified nature, and have attributed such to the liberation of gas or steam resulting from the interaction of an acid magma upon a basic rock recently consolidated.

In the more basic areas, the felspar occurs as narrow irregularly bounded laths of acid labradorite with albitic fringes. Augite is granular and abundant, as also is scattered magnetite, while actinolitic and chloritic patches and grains probably represent a rhombic pyroxene. There is also a general distribution of fox-red biotite, in moderately large plates, which becomes more particularly abundant in the more siliceous and alkaline areas.

The vesicular cavities mentioned above are usually lined with augite, but either augite and plagioclase, or biotite, may occupy the central regions.

We see clearly that the more or less normal quartz-dolerite of the central mass (S21825A) [NM 4657 6228] has been completely granulitized and contaminated by the acid magma, which in its turn has been modified by the assimilation of basic material. This mass as a whole constitutes, perhaps, the most instructive example of hybridization met with in Ardnamurchan and is directly comparable to instances cited by Dr. Harker from the Island of Skye. H.H.T.

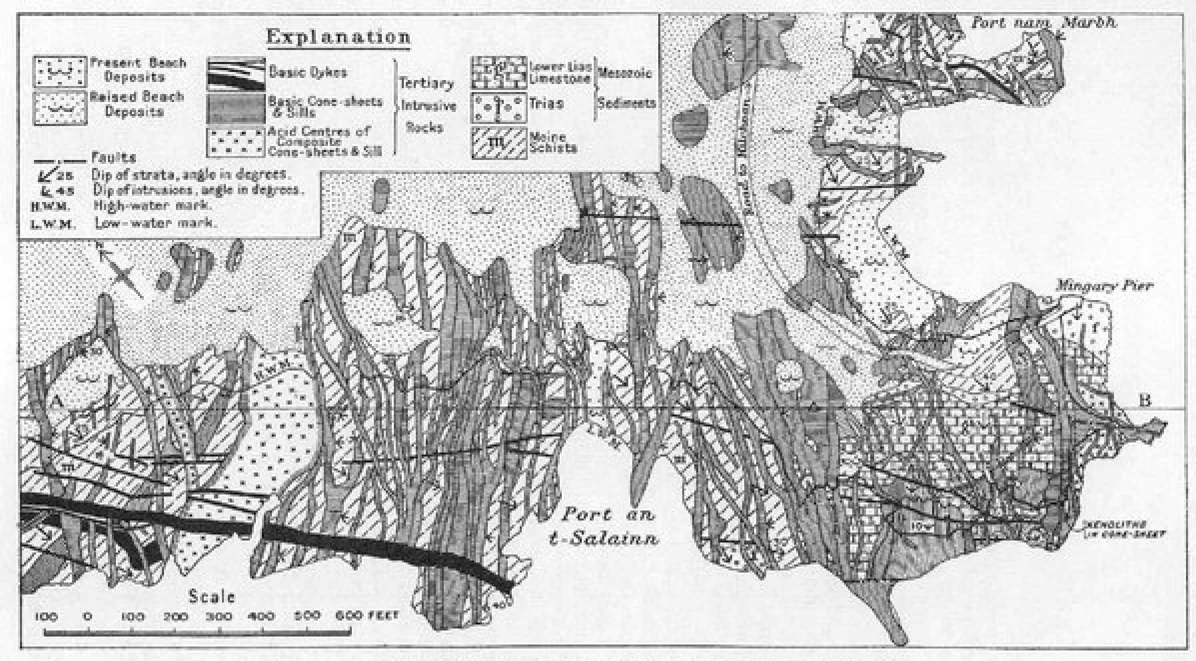
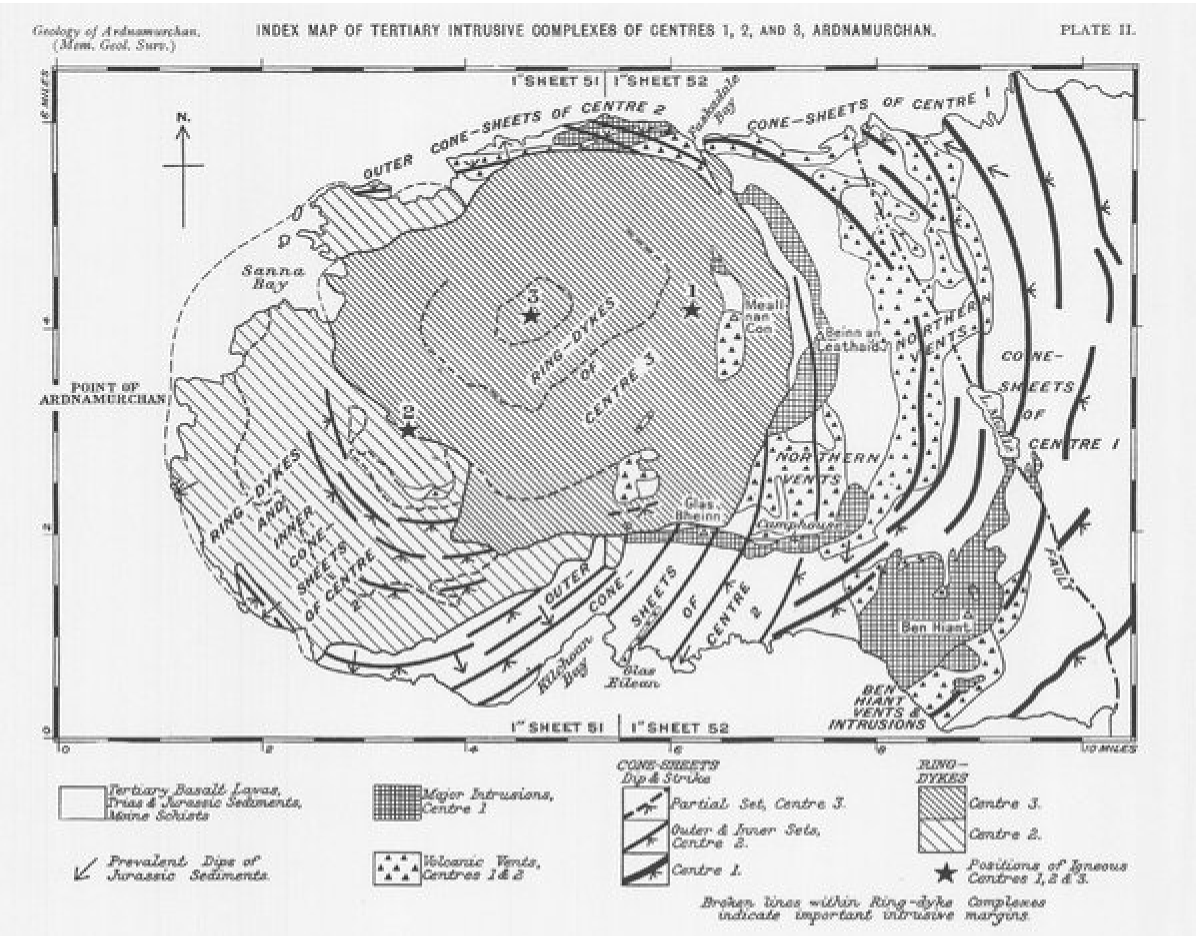


FIG. 23.—Map of Outer Cone-sheets of Centre 2, shore south of Kilchoan.

(Figure 23) Map of Outer Cone-sheets of Centre 2, shore south of Kilchoan.



(Plate 2) Index map of Teriary intrusive complexes of Centre 1, 2, and 3 Ardnamurchan.

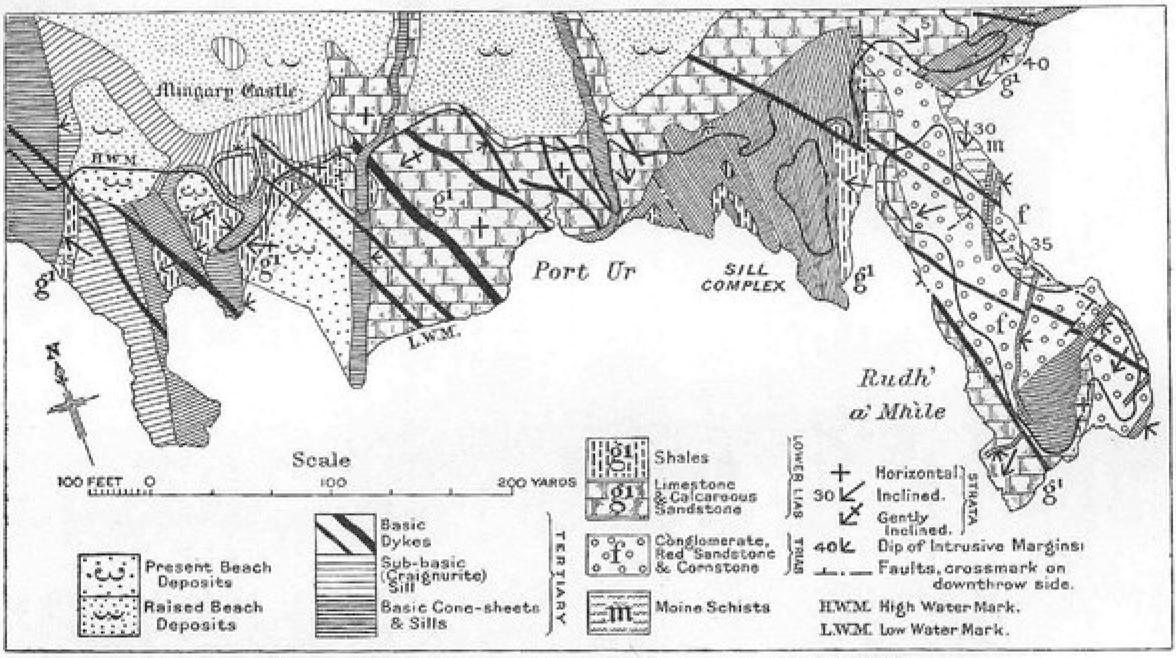


FIG. 25.—*Map of shore near Mingary Castle, east-south-east of Kilchoan.*

(Figure 25) Map of shore near Mingary Castle, east-south-east of Kilchoan.

Geology of Ardnamurchan.
(Mem. Geol. Surv.)

PLATE IV.

Quartz-dolerite Cone-sheets along Shore south of Kilchoan, Ardnamurchan.
(For Explanation, *see* p. viii.)

(Plate 4) Quartz-dolerite cone-sheets along shore south of Kilchoan, Ardnamurchan. The cone-sheets are inclined away from the camera, and show well-developed cross-jointing. (See (Figure 23), p. 174.) Geological Survey Photograph, No. [C2826](C2826).

TABLE IV

PORPHYRITIC CENTRAL MAGMA-TYPE (*see* Fig. 7)

	EUCRITE, GABBRO, AND BASALT.								
	I.	A.	II.	III.	B.	IV.	V.	VI.	
SiO_2 ..	47·26	47·28	47·75	48·28	48·34	49·60	49·78	50·12	SiO_2
Al_2O_3 ..	22·80	21·11	19·46	20·38	20·10	15·06	18·82	15·98	Al_2O_3
Fe_2O_3 ..	2·21	3·52	2·31	1·78	1·97	5·29	5·58	4·91	Fe_2O_3
FeO ..	5·41	3·91	6·28	6·70	6·62	5·00	4·85	6·31	FeO
MgO ..	7·76	8·06	7·50	7·93	5·49	4·44	4·15	4·43	MgO
CaO ..	10·93	13·42	11·32	11·80	13·16	9·69	10·40	10·86	CaO
Na_2O ..	1·72	1·52	2·46	1·75	1·66	2·62	3·04	3·60	Na_2O
K_2O ..	0·29	0·29	0·24	0·14	0·98	0·70	0·56	0·70	K_2O
$H_2O > 105°$	0·90	0·53	0·50	0·76	0·44	1·29	1·35	0·53	$H_2O > 105°$
$H_2O < 105°$	0·11	0·13	0·18	0·09	0·02	2·65		0·46	$H_2O < 105°$
TiO_2 ..	0·38	0·28	0·43	0·23	0·95	2·38	1·34	1·76	TiO_2
P_2O_5 ..	0·06	trace	0·62	0·02	0·04	0·29	trace	0·08	P_2O_5
MnO ..	0·31	0·15	0·17	0·28	0·32	0·19	0·28	0·18	MnO
CO_2 ..	0·10	—	trace	0·03	0·11	0·44	—	0·21	CO_2
FeS_2 ..	0·00	—	0·16	0·04	0·00	0·00	0·00	0·05	FeS_2
Fe_7S_8 ..	0·00	—	trace	0·00	—	—	—	—	Fe_7S_8
SO_3 ..	—	—	trace	—	—	0·40	0·00	trace	SO_3
Cr_2O_3 ..	—	—	0·05	—	—	0·02	0·00	0·04	Cr_2O_3
(Co, Ni)O ..	0·00	—	—	0·00	0·00	0·00	—	—	(Co, Ni)O
BaO ..	0·00	—	—	0·00	0·10	trace	0·03	0·04	BaO
Li_2O ..	0·00	—	trace	0·00	0·00	trace	—	trace	Li_2O
C	—	—	—	—	—	—	traces	—	C
Organic matter ..	—	—	—	—	—	trace	—	—	Organic matter
	100·24	100·20	99·83	100·21	100·30	100·06	100·18	100·26	

I. (21250; Lab. No. 735.) Biotite-eucrite. Ring-dyke, Centre 3, Ardnamurchan. Bank of stream, 1 mile E. 33° S. of Achnaha. *Anal.* E. G. Radley.

A. (8194; Lab. No. 19.) Olivine-gabbro. Major Intrusion. Coir' a' Mhadaidh, Cuillins, Skye. Quoted from A. Harker, 'Tertiary Igneous Rocks of Skye,' *Mem. Geol. Surv.*, 1904, p. 103. *Anal.* W. Pollard.

II. (22821; Lab. No. 790.) Hypersthene-gabbro. Ring-dyke, Centre 2, Ardnamurchan. In side of hollow ¼ mile W. 33° S. of Trigonometrical Station at 1123 ft., Beinn na Seilg, and 1000 yds. E. 27° N. of

(Table 4) Porphyritic Central Magma-Type (see (Figure 7)).

TABLE VI

Data concerning Cone-sheets, Ardnamurchan

Order of Age.	Title of Set.	Angle of Inclination.	Thickness in Feet.	Age Relations with Other Intrusions.
1	Set of Centre 1	10–20°	20–50	Pene-contemporaneous with Ben Hiant Intrusion, and later than Ben Hiant and Northern Vents.
2	Outer Set of Centre 2	35–45°	5–20	Later than the Major Intrusions of Centre 1, generally. Almost all earlier than all ring-dykes.
3	Inner Set of Centre 2	70°	5–30	Later than most ring-dykes of Centre 2. Earlier than all ring-dykes of Centre 3.
4	Partial Set of Centre 3	50°	3–5	Later than earliest of the ring-dykes of Centre 3, and earlier than Great Eucrite Ring-dyke.

(Table 6) Data concerning cone-sheets, Ardnamurchan.

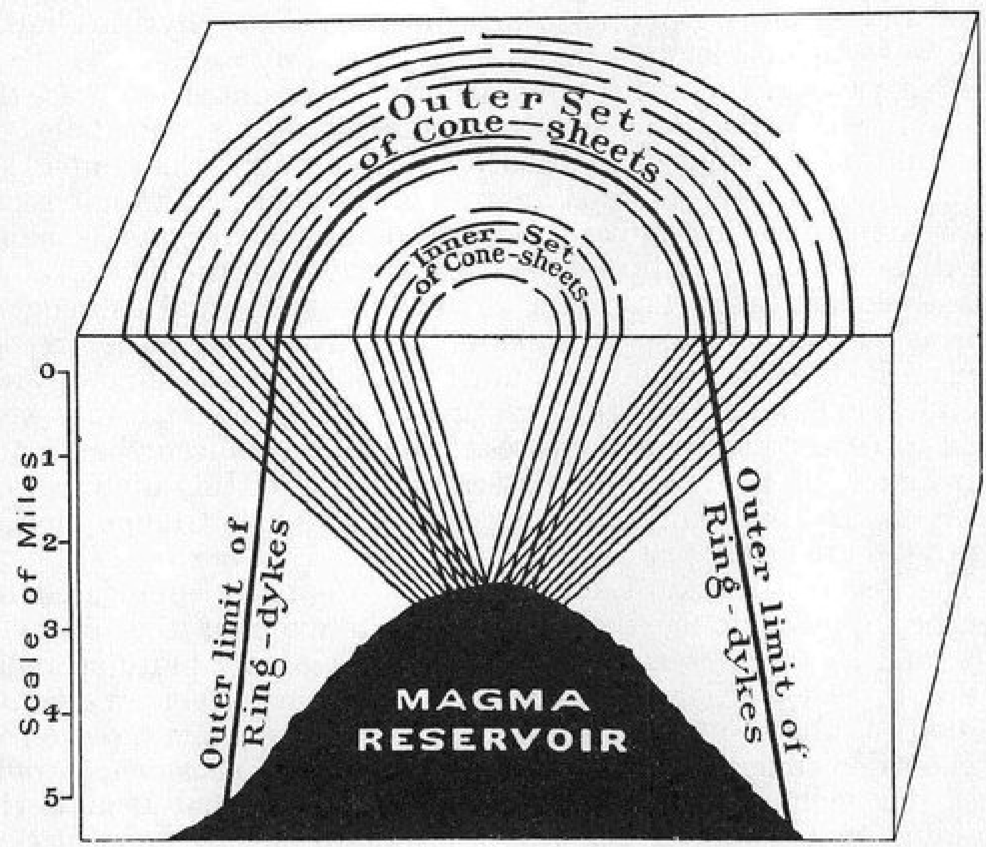


Fig. 5.—*Stereogram representing diagrammatically the Cone-sheet Complexes of Centre 2, Ardnamurchan, with reference to their inferred magma-reservoir.*

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

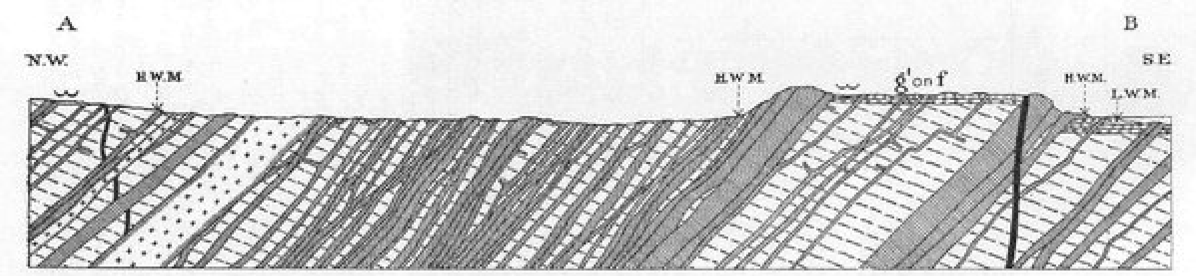
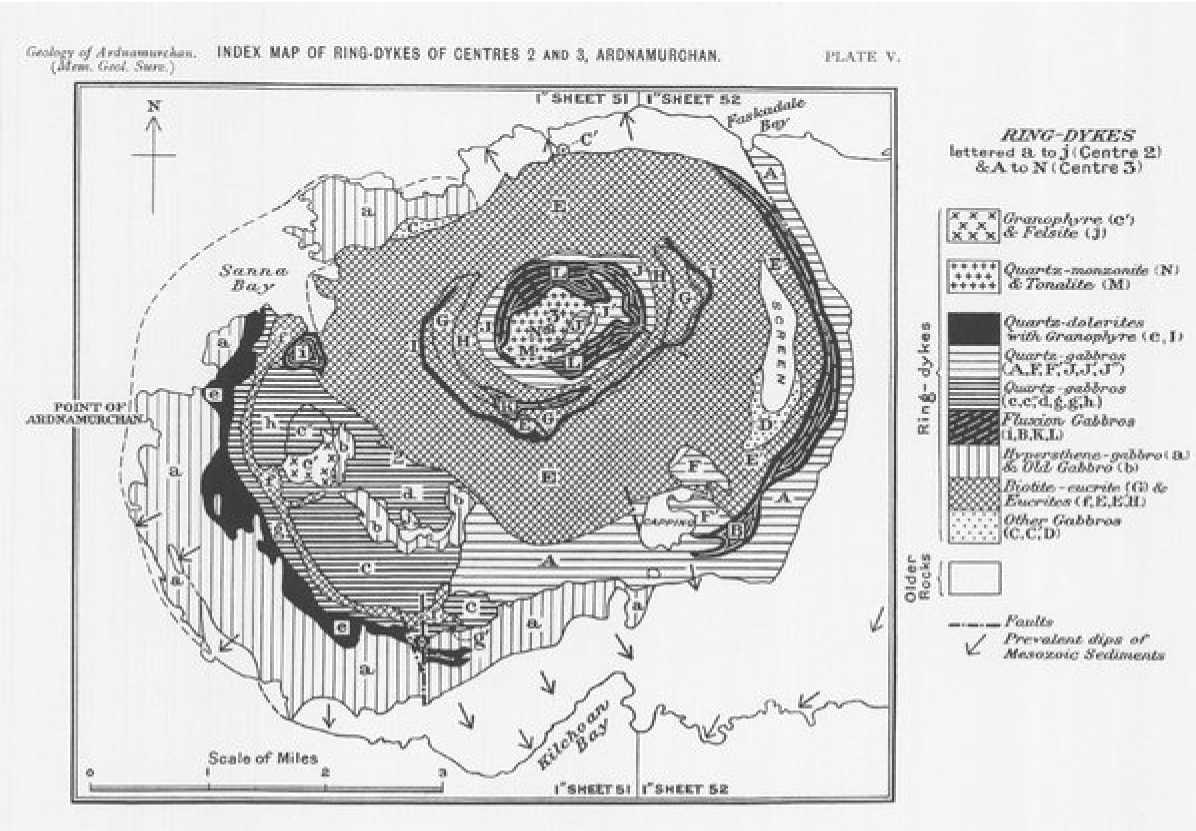


FIG. 24.—Section along line A–B of Fig. 23.

(Figure 24) Section along line A-B of (Figure 23) (Map of Outer Cone-sheets of Centre 2, shore south of Kilchoan).



(Plate 5) Geology of Ardnamurchan. Index Map of ring-dykes of Centres 2 and 3, Ardnamurchan. (Mem. Geol. Surv.)

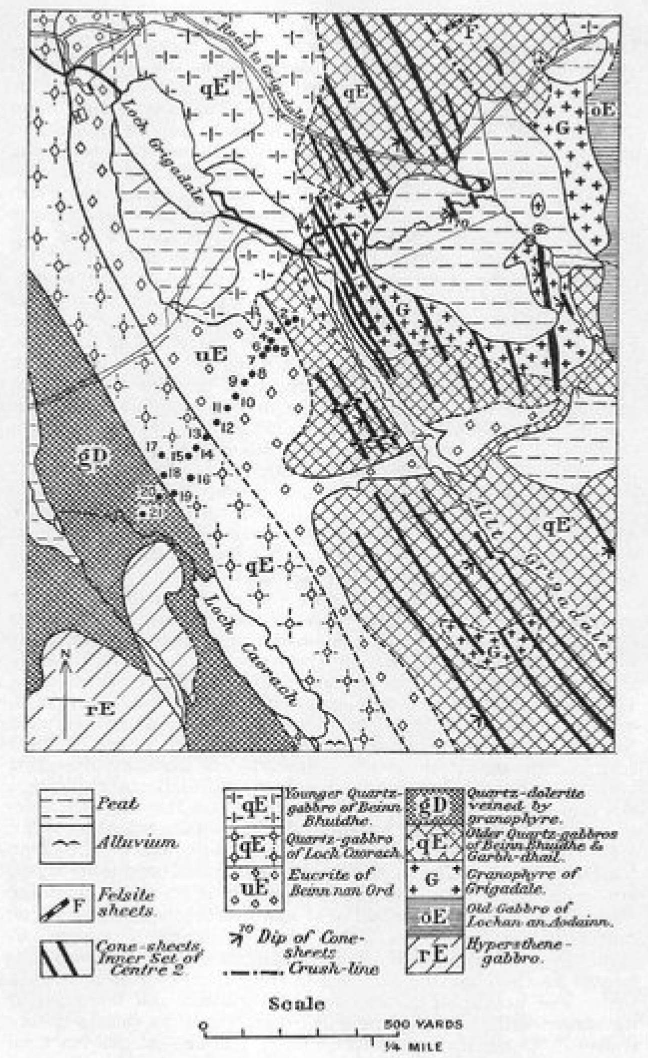


FIG. 37.—*Map of portion of Ring-dyke Complex of Centre 2, north of Beinn nan Ord.*

NOTE.—Localities of a serial collection of rock-specimens are indicated by black dots numbered 1–21 (*see* pp. 268–270, 274, 275).

(Figure 37) Map of portion of Ring-dyke Complex of Centre 2, north of Beinn nan Ord. Note. Localities of a serial collection of rock-specimens are indicated by black dots numbered 1–21 (see pp. 268–270, 274, 275).

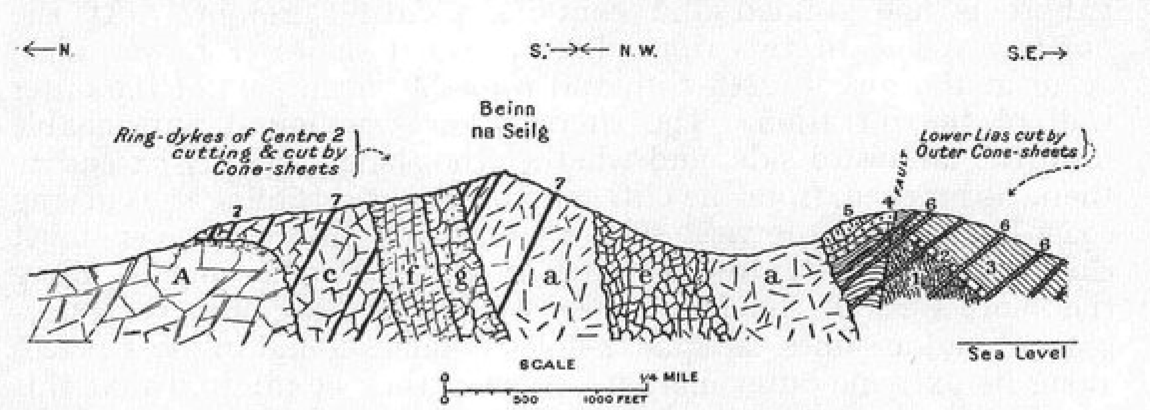


FIG. 28.—*Section across south-west part of Ardnamurchan Igneous Complex.*
1, *Highland Schists.* 2, *Trias.* 3, *Lias.* 4, *Inferior Oolite (limestone and sandstone).* 5, *Tertiary basalt lavas.* 6, *Outer, and* 7, *Inner, Cone-sheets of Centre* 2. *Ring-dykes* a, c, e, f, g, and A *as lettered on Plate V., p.* 201.

(Figure 28) Section across south-west part of Ardnamurchan Igneous Complex. 1, Highland Schists. 2, Trias. 3, Lias. 4, Inferior Oolite (limestone and sandstone). 5, Tertiary basalt lavas. 6, Outer, and 7, Inner, Cone-sheets of Centre 2. Ring-dykes a, c, e, f, g, and A as lettered on (Plate 5)., p. 201.

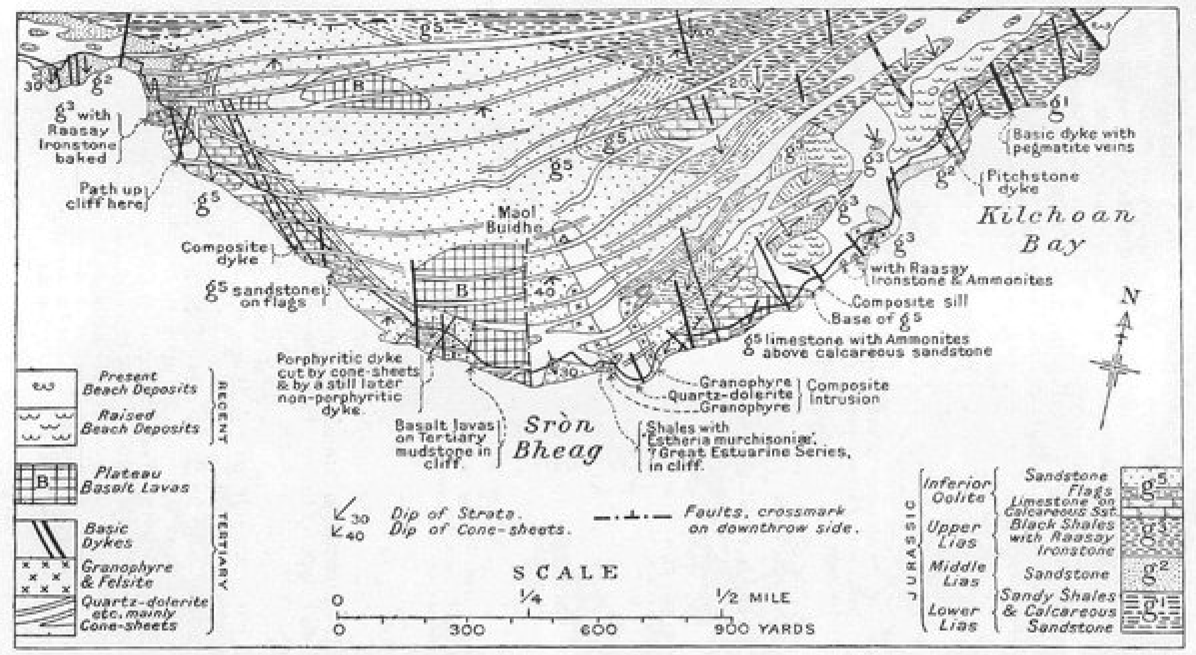


FIG. 3.—*Map of Mesozoic strata and Tertiary basalt lavas cut by Tertiary minor intrusions, west of Kilchoan Bay.*
NOTE.—Tertiary cone-sheets are mainly represented diagrammatically.

(Figure 3) Map of Mesozoic strata and Tertiary basalt lavas cut by Tertiary minor intrusions, west of Kilchoan Bay. Note. Tertiary cone-sheets are mainly represented diagrammatically.