7. *The* PICRITE-TESCHENITE SILL *of* LUGAR (AYRSHIRE). By GEORGE WALTER TYRRELL, A.R.C.Sc., F.G.S., Lecturer in Mineralogy and Petrology in the University of Glasgow. (Read April 5th, 1916.)

[PLATES X & XI.]

CONTENTS.

I. INTRODUCTION.

THE association of teschenite and ultrabasic rocks (picrite and peridotite) in a single rock-body has now been established for several occurrences in the lowlands of Scotland. The Barnton occurrence, near Edinburgh, has been described by Sir Archibald Geikie,[1] by Mr. J. Henderson & Mr. J. G. Goodchild,[2] and by Mr. H. W. Monckton.[3] At Blackburn, near Bathgate, occurs a picrite, which has been described by the first-named writer as a lava,[4] but has recently been shown to be intrusive and associated with teschenite by the officers of the Geological Survey of Scotland.[5]

[1] 'Ancient Volcanoes of Great Britain' vol. i (1897) pp. 449–50.
[2] Trans. Geol. Soc. Edin. vol. vi (1893) pp. 297–300 & 301–302.
[3] Q. J. G. S. vol. l (1894) p. 39.
[4] 'Ancient Volcanoes of Great Britain' vol. i (1897) p. 419.
[5] 'Summary of Progress for 1904' Mem. Geol. Surv. 1905, pp. 118–19.

The famous picrite of Inchcolm, in the Firth of Forth, is well known from the descriptions of several observers. Dr. R. Campbell and Mr A. Stenhouse, however, in a recent detailed investigation of the island, have shown that at both the upper and lower contacts the picrite passes into teschenite.[1] On the west coast, Dr. J. D. Falconer has described a picrite-teschenite sill at Ardrossan, intrusive into the Carboniferous Limestone Series: here again the ultrabasic rock occupies the central part of the mass.[2] Recently the late R. Boyle drew attention to still another occurrence at Lugar, near Old Cumnock (Ayrshire). He described the passage of dolerite and basalt [teschenite] through doleritic picrite [theralite] to 'segregated' masses of peridotite or picrite. The ultrabasic rock occurs in the central parts of the mass, and passes gradually to less basic varieties towards both upper and lower contacts.[3] A picrite associated with teschenite has been discovered by Mr. E. M. Anderson at the Inner Nebbock, Saltcoats (Ayrshire).[4]

In the course of an investigation of the Permo-Carboniferous alkalic rocks of the West of Scotland[5] I made a detailed examination of the Lugar sill, and found in it an extraordinary complex of various rocks belonging to the analcite series. This included normal and melanocratic teschenites; a facies with abundant nepheline and ferromagnesian minerals—essentially a melanocratic theralite; and a curious rock composed mainly of analcite and nepheline, with subordinate plagioclase, titanaugite, and barkevikite in very perfect crystals. This unique rock, which it is proposed to call lugarite, has now been found in several localities in the West of Scotland. Extremely fresh hornblende-picrites and peridotites, however, form the major part of the intrusion.

The present paper embodies a complete description of this sill, and attempts an explanation of the processes whereby the different facies have been developed. A comparison with the other occurrences is also instituted. Five chemical analyses have been made in the course of the investigation, and in connexion with these and for the work in general I have to acknowledge the aid of a grant from the Government Grant Committee of the Royal Society. For the analyses I am indebted to the skill of Dr. Alexander Scott, of Glasgow University.

II. Field Relations.

The intrusion which is the subject of this paper occurs near the village of Lugar in Central Ayrshire, near the eastern border of the county. It is intruded as a sill into a crumbling white and yellow

[1] 'The Geology of Inchcolm' Trans. Geol. Soc. Edin. vol. ix, pt. 2 (1908) pp. 121–34.

[2] 'The Geology of Ardrossan' Trans. Roy. Soc. Edin. vol. xlv, pt. 1 (1907) pp. 601–10.

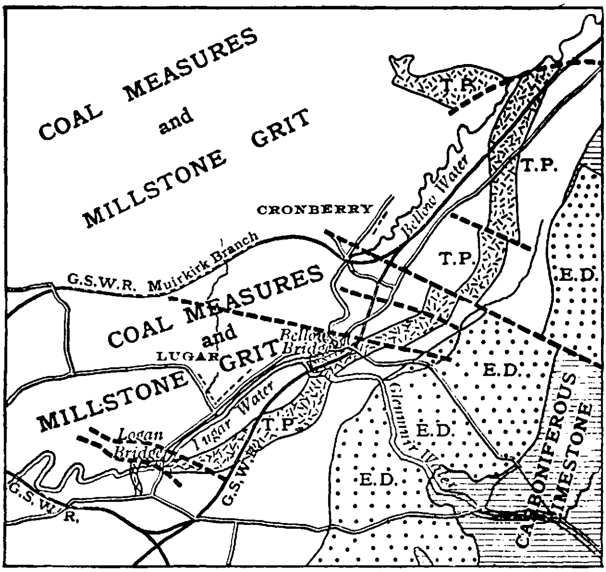
[3] Trans. Geol. Soc. Glasgow, vol. xiii (1908) pp. 202–23.

[4] 'Summary of Progress for 1911' Mem. Geol. Surv. 1912, p. 52.

[5] Geol. Mag. dec. 5, vol. ix (1912) pp. 69–80, 120–31.

sandstone belonging to the 'Millstone Grit.' When the area is re-mapped it is probable that these strata will be incorporated in the Coal Measures. The intrusive nature of the igneous rock is proved by its increasing fineness of grain towards both upper and lower contacts, and by the marginal fringes of hardened sandstone above and below the sill. Definitely transgressive contacts are not seen, although in one place a thin band of hardened sandstone is encountered about 12 feet from the upper margin of the sill. So far as can be ascertained, the intrusion keeps approximately to the same horizon. The whole series dips at about 10° north-westwards, and, from the width of the outcrop, the thickness of the

Fig. 1.—*Geological map of the Lugar district, on the scale of 1 inch to the mile, or 1 : 63,360.*



[T.P. = Teschenite-picrite; E.D. = Essexite-dolerite sill. Broken lines represent faults.]

igneous rock is estimated at 140 feet. Apart from small irregularities the outcrop forms a crescent-shaped strip about 3 miles long and a fifth of a mile wide at its widest part. It extends in a general north-easterly direction from Lugar to a mile and a half beyond the village of Cronberry. The Bellow Water with its continuation, the Lugar, cuts through both extremities of the crescentic outcrop, and gives sections at Logan Bridge on the south, and at a spot a mile north-east of Cronberry on the north. The river also cuts through a slight bulge of the outcrop at its confluence with the Glenmuir Water. The latter stream cuts a deep trench in a somewhat different direction through the intrusion at this place. The outcrop is faulted continually towards the south-east by a series of six west-north-west and east-south-east faults (see fig. 1, p. 86). At the north-eastern extremity of the outcrop the sill is cut by a west-south-west and east-north-east fault which severs it from another mass of igneous rock, extending half a mile back towards the west. This mass, however, is on a higher horizon, and has been mapped as separating the 'Millstone Grit' from the overlying Coal Measures.[1] If it be taken as part of the Lugar sill, the total length of outcrop becomes 3½ miles.

The finest sections are found just above the confluence of the Bellow and Glenmuir Waters to form the Lugar Water. Both streams have eroded deep rocky gorges through the sill, the one in a north-easterly, the other in a south-easterly direction. When the water is low, practically every foot of the thickness can be examined either in cliff-section, or in horizontal water-polished areas of rock. In these circumstances the study of the sill can be conducted with facilities unattainable in any of the other occurrences; and the conclusions as to the origin of the different facies arrived at in this case may be considered sufficiently well founded to apply to the other occurrences, in which, although the exposures are not so good, practically the same structure and disposition can be made out.

(1) The Glenmuir Section.

The Glenmuir Water, cutting through the sill in a general north-westerly and south-easterly direction at right angles to the strike, gives the most complete and typical section. The upper contact is seen at the weir, just at the confluence with the Bellow Water. Hardened whitish sandstone occurs overlying a dense basaltic facies, in a steep rocky bank on the south side of the river. The chilling influence of the contact, as shown by fineness of grain, extends down about 12 feet, and has doubtless been strengthened by the inclusion in the sill at this depth of a thin band of sandstone now metamorphosed to a hard white quartzite. The contact-rock is distinctly banded in layers, often confused, wavy, and bifurcating, which differ slightly in colour and texture. The thickness of the bands varies from several inches to very fine linear streaks but faintly indicated by a slight difference of colour. Besides the normal, greyish-black, aphanitic contact-rock, the chief varieties included in the banded material consist of fine-grained, pinkish, and greenish teschenitic rocks, and a very dense, dead-black, glossy, basaltic material, although extremely slight differences of colour and texture serve to bring out the banded structure. These varieties show no sharp contacts with each other, the transition from one to the other taking place quickly but quite gradually. These bands seem to be true schlieren, due to the flow of a slightly heterogeneous magma. In general the streaks are drawn out in bands parallel to the upper margin of the sill. In addition to the banding, the contact-facies is traversed by

[1] See the Sheets of the 1-inch Map of the Geological Survey of Scotland, Nos. 14 (1868) & 15 (1870).

numerous veins of coarse-grained teschenite with abundant analcite, similar to the rocks described below.

The upper teschenite.—From a maximum depth of 12 feet or so in the mass, the granularity of the rock increases very rapidly towards the interior. The contact-facies passes into a coarse-grained mottled rock, the prevailing tint of which is pink or dark green, according as the felsic or mafic minerals dominate the colour. In thin section the rock is seen to be a typical teschenite, composed of essential plagioclase and analcite, titanaugite, and ilmenite, with accessory orthoclase, olivine, barkevikite, and biotite. The texture is evenly granular, although the felspars sometimes tend to take on a lathy or columnar form. In another variety the augite is conspicuous as long thin black prisms, ranging up to 2 inches in length. A third variety shows very abundant analcite in large pink masses, which are frequently spherical. The rock seems to become richer in analcite as a greater depth in the sill is attained. The thickness of the teschenite cannot be measured in this section, as the contact with the underlying facies is not well seen; but it is usually between 15 and 20 feet.

There are, however, considerable variations in the thickness of this band. Along the western bank of the Glenmuir Water, above the lugarite locality (see p. 91), indurated sandstones and contact-basalts occur less than 20 feet above the picrite. Hence the theralite and teschenite intervening between the picrite and the upper contact must be attenuated, or one of them must be absent in this part of the section.

The theralite band.—Underlying the teschenite is a fine-grained, almost aphanitic, grey rock, which, under the microscope, is seen to have the composition of a theralite. The mafic minerals, olivine and titanaugite, are dominant over the plagioclase and nepheline. Barkevikite, biotite, and iron-ores are rather abundant accessories, and there is often a small amount of analcite. This rock forms a band perhaps 10 feet thick; but in the Glenmuir gorge its outcrop mainly occurs high up in a vertical cliff, although it may also be examined in small exposures on the eastern side of the stream, and in the river-bed when the water is low. In the latter it may be easily distinguished by its smooth, polished, water-worn surface, in contradistinction to the coarse-grained, pitted surfaces of the overlying teschenite and the underlying picrite. Further details of the theralite band are reserved for the description of the Bellow section, where it is much better exposed.

The picrite and peridotite.—By a gradual diminution in the amount of felspar and nepheline, the theralite passes into coarse-grained ultrabasic rocks, composed mainly of olivine and titanaugite, frequently with abundant barkevikite, some iron-ore, biotite, plagioclase, and analcite. These rocks constitute the major portion of the sill, and occupy the interior of the mass. The upper part of the ultrabasic stratum is rich in titanaugite and barkevikite, as well as olivine, and usually contains some plagioclase and analcite. This is a true picrite in the original sense of Tschermak, who applied the term to a melanocratic facies of the Moravian teschenite. In the remainder, however, plagioclase and analcite completely disappear, and olivine becomes the dominant mineral. This rock is a hornblende-peridotite, in which the alkalic tendency is still recognizable by the unusual amount of alkalies contained in the bisilicates. A tongue-like extension of the ultrabasic outcrop occupies the bed of the Glenmuir Water for some distance north-west of the railway-viaduct, the overlying facies forming the cliffs at this point. Good waterworn surfaces can be examined here when the river is low. The rock is remarkably fresh, and shows sharp and irregular variations in granularity. East of the railway-bridge, the ultrabasic stratum forms nearly the whole of a great cliff rising vertically to a height of 90 feet from the north side of the stream. Here, where it is exposed to the weather and is not being continually scoured by the water, it is much decomposed, and weathers to a loose crumbling mass, with spheroidal lumps of harder and fresher rock in places. The north-westerly inclination of the intrusion is well shown in the face of the cliff by the inclination of the joint-planes, but principally by the contrast between the jointing of the ultrabasic rock and the overlying theralitic facies. The former is traversed by a few large irregular joints; but the latter by many, both vertical and horizontal, causing a rude columnar structure. While the transition between the two is not sharp, it is sufficiently well marked to show the general dip of the intrusion towards the north-west. The ultrabasic rock is traversed by a few thin veins of a fine-grained felspathic rock (teschenite-aplite).

The lower teschenite.—A blank of about 30 feet in the section separates the last exposure of the ultrabasic stratum from the underlying facies, which consists of teschenite made up, for the greater part, of the variety containing numerous blade-like or columnar augites. This is exposed in a thick bar across the stream near the second right-angle turn above the railway-viaduct: its thickness is estimated at about 20 feet. It is important to notice that no theralite intervenes here between the picrite and the teschenite. There is little reason to suppose that it is hidden by the blank in the section, for the theralite is the most resistant rock in the complex to ordinary atmospheric weathering.

The lower contact.—The granularity of the lower teschenite declines rapidly, until it passes into the ordinary contact-basalt. The latter shows banding precisely similar to that of the upper contact, and is also traversed by veins of coarse pink teschenite. The two most prominent varieties involved in the banding, which is frequently much confused and contorted, are a fine-grained pink teschenitic rock and a dense black or grey basalt, the two rocks being intimately welded together. Immediately beneath the contact the Carboniferous sediments crop out, dipping westwards at 10°.

This gradual transition from the lower teschenite to a dense basaltic contact-facies can be followed on the eastern side of the stream. On the western side there are much more complicated relations. Here a portion in which the dense basaltic schlieren are dominant over the coarser teschenitic layers may be distinguished from one in which the reverse relation holds. The former abuts against the latter horizontally, and overlies and underlies it. There is also a more or less gradual transition between the two portions. These relations are shown diagrammatically in fig. 2. The coarse-grained teschenitic rock forms conspicuous, waterworn knobs in the bed of the stream. As the stream is crossed to the eastern side the fine-grained basaltic schlieren disappear, and the teschenite passes down normally, as above described, into its contact-facies. This can be traced to a small bar of sandstone seen at low water in the bed of the stream. The relations of the various facies at the lower contact are suggestive of considerable movement in the magma before crystallization had taken place to any extent, for the minerals show little or no alignment in the direction of the banding.

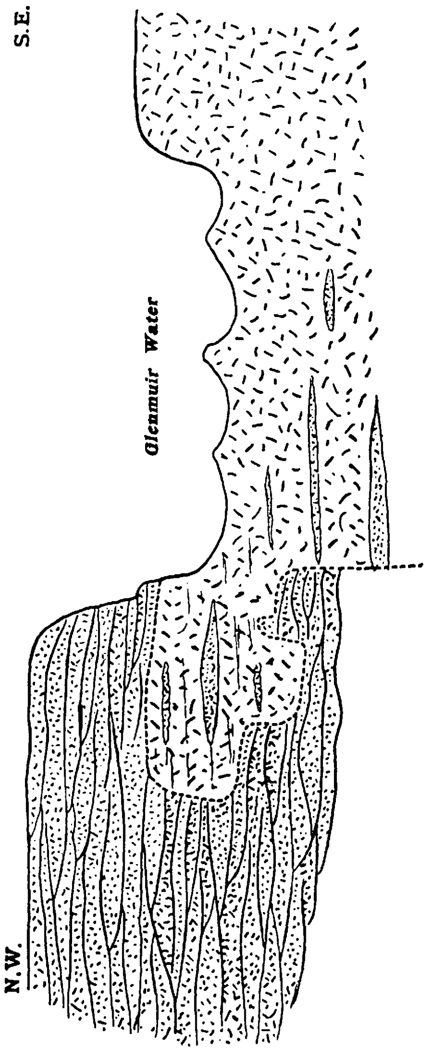


Fig. 2.—*Section across the Glenmuir Water, near the lower contact of the sill, showing the banding of the coarser and finer schlieren. (Scale: 1 inch = 8 feet.)*

The lugarite.—On the west bank of the river, under the railway-bridge and a little to the north side of it, the cliff exhibits a sharp horizontal junction between decomposed picrite and a peculiar rock overlying it. The latter shows a greyish or greenish aphanitic ground-mass, crowded with both stout and slender black prisms. Sometimes small rectangular whitish felspars are seen also. In thin section the ground-mass may be identified as analcite, crowded with needles of apatite, and containing some nepheline. In it are scattered numerous perfectly euhedral prisms of barkevikite, with subordinate titanaugite and plagioclase, also extremely well formed. This rock forms a stratiform mass about 4 feet thick overlain by the theralitic facies. The junction is quite sharp, as the two very distinct rocks can be got within an inch of each other; but the line of demarcation is, in general, not marked by any definite feature on the face of the cliff. The two rocks are intimately welded without any appearance of passage. The long prisms of barkevikite, however, project from the lugarite into the theralite. At places the junction is marked by a thin, fine, horizontal joint-plane, or by a thin layer of slightly decomposed rock. The contact with the picrite is doubtless of the same nature, but the latter is so decomposed that the junction is quite obscured. Some veins of lugarite penetrating the picrite supply further evidence on this point. These veins or small dykes range up to 4 inches in width, and are largely composed of analcite and barkevikite prisms, which are frequently arranged in stellate groups. The contact of these veins with the picrite is an intimate welding, and the barkevikite crystals project from the sides of the veins into the enclosing rock.

The lugarite is also to be found in the Bellow section in the same relative position, but rather poorly exposed. The Glenmuir exposure is only accessible when the stream is low; but south of the viaduct occur numerous fallen blocks from an inaccessible exposure in the face of the cliff. In the other direction the dip of the intrusion carries the lugarite down to the water's edge, where it is lost.

All the available evidence goes to show that this remarkable rock is intrusive in the picrite. The veins of similar material traversing the picrite transgress sharply the different varieties of the ultrabasic rock. There can be no doubt that these veins proceed from the main mass of lugarite, although the junctions have not actually been demonstrated. While the rock is clearly intrusive, it is but slightly posterior to the main phenomenon of intrusion, for the intimate welding and absence of chilled rock at the margins indicates that the ultrabasic rock was still very hot at the time of intrusion.

(2) The Bellow Section.

Although not so complete, this section supplies many details which are missing or obscure in the Glenmuir section. Just above the confluence with the Glenmuir Water, the upper contact of the sill with a soft, yellow, crumbling sandstone is well seen. The contact-facies is a brownish aphanitic rock, with some sporadic flakes of biotite. It is obviously much more decomposed than the corresponding rock in the Glenmuir section. The flow-banding also is not at all prominent.

The contact-facies passes down quickly first into a fine-grained pink and green mottled teschenite, and then into a coarser rock with a conspicuous development of large columnar augites. Although this is the dominant facies there are a few bands of fine-grained material, which are doubtless due to the flow of a slightly heterogeneous magma. Still lower down the rock becomes distinctly more felsic, and shows abundant pink and white spots of analcite. In this variety the augite-crystals are not columnar.

This analcitic facies is in sharp contact with the dark, fine-grained, theralitic stratum beneath. The stream has cleared this contact rather thoroughly, owing to the differential resistance of the rocks to erosion. It slides down a polished waterworn surface of theralite, which is bordered on one side by a low cliff of the coarser and softer teschenite. Hence the contact can be particularly well examined. The theralite is here seen to be shot through or permeated with irregular masses, patches, nests, strings, and anastomosing veins of a pinkish, coarse-grained, felsic rock, resembling the overlying teschenite. These patches and veins do not appear to be intrusive. They have no sharply-defined contacts with the theralitic facies, but the minerals interlock at the margins, welding the two rocks into an intimate union. There is no sign of chilling at the margin of the patches, the normal granularity being maintained up to their edges. There can hardly be any doubt that the theralitic rock and these felsic veins and patches crystallized practically at the same time. The theralitic rock immediately beneath the band of analcitic teschenite is full of these veins and patches, which are also found at lower horizons (although in greatly diminished quantity), until they finally disappear long before the picrite is reached. The overlying analcitic teschenite is not a continuous band, but is developed irregularly, sometimes dying out altogether, in such wise that the augitic facies comes into contact with the theralite.

By the gradual disappearance of the felsic minerals, the theralite passes into picrite, although at one or two places lugarite appears to separate the two rocks. Owing to the conformation of the Bellow gorge, the ultrabasic outcrop has a tongue-shaped lobe directed westwards, which occupies the bed of the stream, while the overlying facies form the sides of the valley. The ultrabasic rocks have precisely the same characters as in the Glenmuir section. At and beyond Bellow Bridge the outcrop widens, but the overlying theralitic and teschenitic facies may still be traced in the steep wooded slopes west of the bridge. At the first right-angle bend of the stream above Bellow Bridge the picrite is intersected by many small crush-planes filled with 'beefy' calcite. At the second bend a large fault-plane is well exposed in the bed of the stream. This, with its fellows, has determined the course of the stream for some distance. It is a fissure about a foot wide, filled with calcite and a yellow flinty material. The rock on both sides of the major fault belongs to the ultrabasic stratum. It is much crushed, splintered, and traversed by numerous thin, anastomosing veins of calcite. Sedimentary rock, however, is exposed on the inner side of the bend, and consists of black shale upturned steeply at the fault. High up in the bank on the west side of the stream, highly analcitic teschenite is exposed, passing quickly into a dense black contact-facies containing sparse flakes of biotite. At the outer edge of the first right-angle bend above Bellow Bridge occurs a black-and-white mottled rock belonging to the lower band of teschenite. At the fault the continuous section of igneous rock ends, and the stream cuts into the sedimentaries. Hence the lower contact is not here visible.

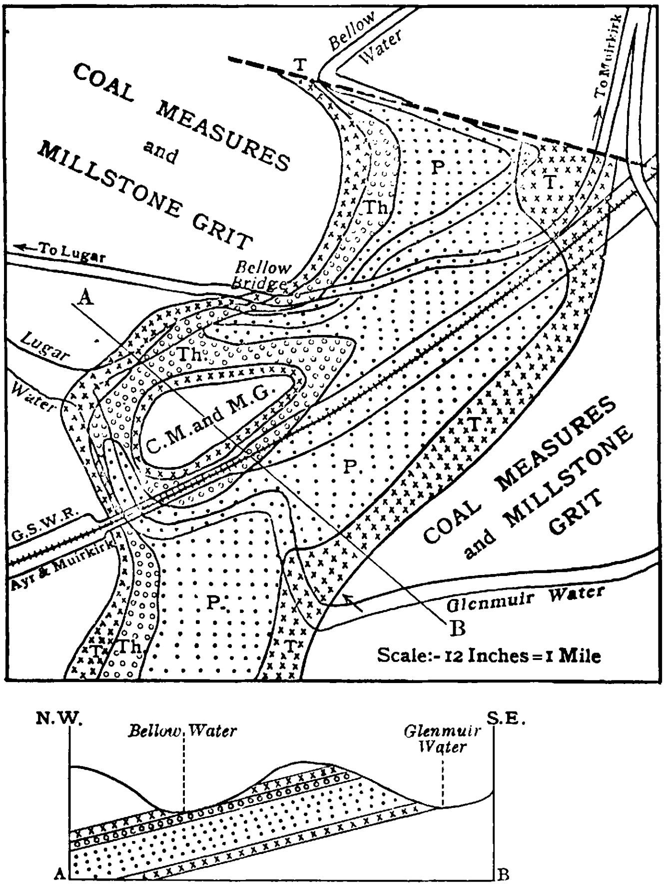
(3) Other Exposures.

Between the Bellow and Glenmuir Waters, near their confluence, rises a knoll of high ground. The Ayr-Muirkirk railway crosses the Glenmuir Water here, and is carried through the knoll in a shallow cutting. As one ascends from either stream, exposures of the theralitic facies and the teschenite are encountered, capped by a small outlier of the 'Millstone Grit' (see map & section, fig. 3, p. 94). The railway-cutting shows nothing but decomposed crumbling picrite.

At the extreme north-eastern end of the sill, a mile and a half north-east of Cronberry, a small exposure is seen in the Bellow Water, here known as the Gass Water. At the south-western end of the section a fine-grained marginal facies of pink teschenite (doubtless the top of the sill) is observed, followed by grey theralite and decomposed picrite towards the north-east. The lower teschenite is not seen; but, so far as it goes, the sequence here is identical with that in the typical exposures. Another section is seen in the Lugar Water at Logan Bridge, at the extreme south-western end of the outcrop. Here the intrusion is quite thin, measuring not more than 15 or 20 feet in thickness, and is wedging out westwards among the sandstones. Both contacts, bordered by hardened white sandstones, are seen. The marginal facies is a decomposed brownish aphanitic rock showing a few flakes of biotite. The interior consists of decomposed teschenite, but there is no trace of the other facies.

A mass of theralite probably connected with the Lugar sill, but with a distinct dyke habit, crosses the Lugar Water in a north to south direction, about 250 yards west of Logan Bridge. The contacts are not seen; but, on the northern bank of the river, the rock forms a small knoll with vertical sides, and has the aspect of a dyke. In appearance and microscopic structure it is identical with the dominant phase of the theralite stratum in the Lugar sill.

Fig. 3.—*Geological map and section of a part of the Lugar Sill.*



[P = Picrite and peridotite; T = Teschenite; Th. = Theralite.]

(4) Summary.

It is now possible to attempt a general view of the Lugar sill, and of the structure and disposition of the various facies of which it is composed. This mass, 140 feet thick, was intruded into cold rocks, as testified by the chilled contacts at both upper and lower margins. The upper and lower contact-basalts are identical in composition. The chilling influence of the contact is manifest in fineness of grain to a maximum thickness of 10 feet, after which the rock passes rapidly into a coarse teschenite at both margins.

A movement of the magma has given rise to distinct schlieren, distinguishable by slight differences of colour and texture, at both contacts. The same explanation can hardly be applied, however, to the remarkable differences obtaining in the interior of the sill. Including the contact-basalts and the normal teschenites continuous with them, the rock of the interior is divided into at least three different bands by some process of differentiation or by successive intrusion. First there is a band of ultrabasic rock—picrites and peridotites of coarse texture and remarkable freshness—occupying the major part of the interior, and indeed of the whole mass, and resting on the lower teschenite. The picrite forms the upper part of the ultrabasic stratum and the peridotite the lower. Above the picrite comes a band about 10 to 15 feet thick, of a fine-grained, basic, nepheline-rock belonging to the theralite family, which may be considered as continuous with the picrite and passing into it somewhat rapidly. Between the theralite and the normal teschenite overlying it generally intervenes a thin and variable layer of highly analcitic rock, patches, streaks, and veins of which, or a rock allied thereto, permeate the theralite in its immediate vicinity. Fig. 4 (p. 96) embodies a vertical section of the sill showing the approximate thickness of the various facies, and the map (fig. 3, p. 94) illustrates the surface-distribution of the facies in a limited area at the confluence of the Bellow and Glenmuir Waters.

The differentiation will be dealt with in greater detail, after the discussion of the microscopical and chemical evidence.

III. Petrography.

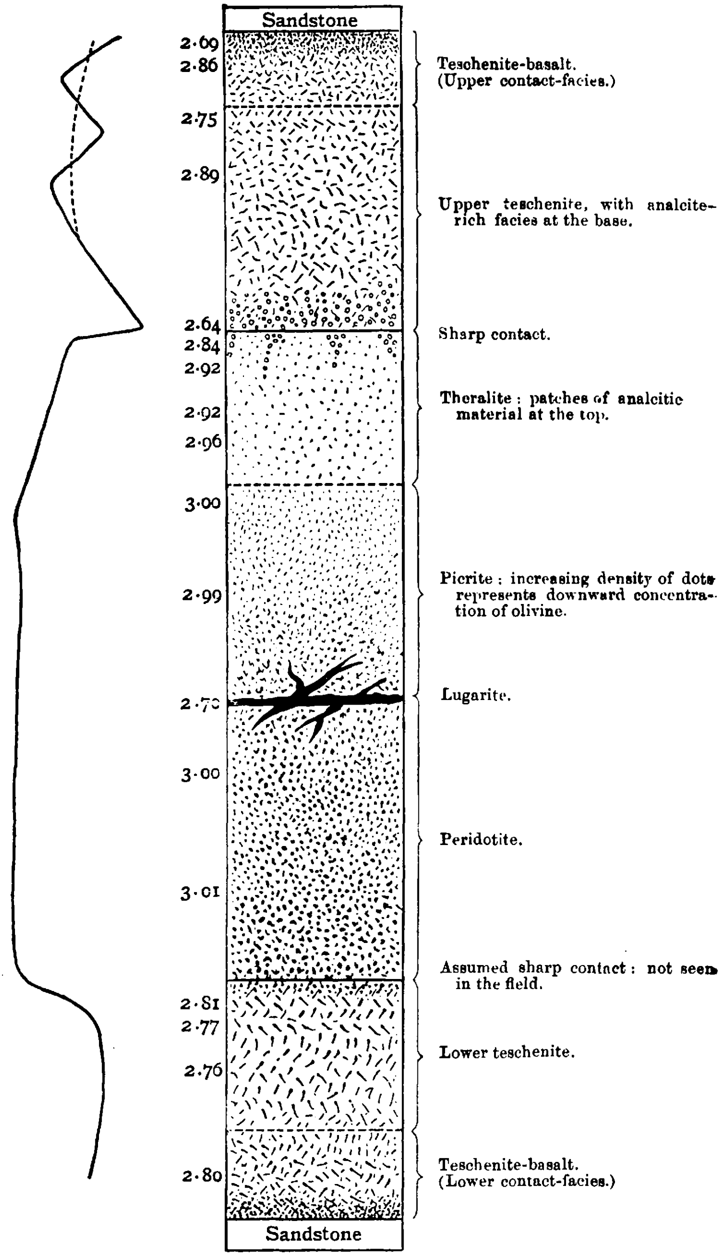
(1) The Contact-Rocks. (Pl. X, fig. 1; Pl. XI, fig. 4.)

The rocks of the upper and lower contacts are identical in all respects, and will therefore be described together in this section. They consist, for the greater part, of a hard, dense, basaltic rock, usually black or dark grey. In several specimens bands or schlieren differing in many subtle gradations of colour and texture are seen. Thin veins of coarse flesh-coloured teschenite, indifferently traversing all the schlieren, are rather numerous.

Microscopically the rock is holocrystalline, on the whole very fine-grained, and shows numerous sharp variations in texture and composition. The minerals observed are plagioclase, augite, biotite, analcite, magnetite, and occasionally olivine. The chemical analysis (p. 104) shows that a considerable amount of orthoclase must be present. A thin section of a rock obtained at the lower contact in Glenmuir Water gives a good general idea of the aspect of both contact-facies, and will accordingly be described in detail. There are several distinct types of rock in the slide (Pl. XI, fig. 4).

(a) Starting from one side of the section there is first a schlieren composed of an even-grained aggregate of plagioclase-laths, subhedral prismoids of purplish augite, numerous small ragged plates of reddish biotite enclosing all

Fig. 34.—*Vertical section of the Lugar Sill, on the scale of 22·5 feet to the inch.*



[Figures on the left-hand side represent the specific gravities of the rocks collected approximately at the points indicated. The curve shows the variation of specific gravity with depth in the sill: the zigzags at the top are due to the alternation of schlieren of different densities. The broken-line curve shows the effect of averaging these variations. The division of the sill into three sharply-defined parts is well marked.]

other constituents but analcite, and minute uniformly-scattered cubes of magnetite, all embedded in a limpid, colourless, isotropic base which has the cleavage and low refraction of analcite. The latter is occasionally segregated into small areas comparatively free from the other constituents. A few small patches of serpentinized material occur, which may represent olivine. The extinction of the felspar is between 20° and 30°, but the fine grain forbids exact measurement; it is probably to be referred to acid labradorite. The following is a rough estimate of the mineral percentage :—plagioclase (Ab_1An_1) 45, augite 40, biotite 5, magnetite 5, analcite 5.

(*b*) Adjacent to the above, with a sharp boundary between the two, is a band composed of the same minerals, but distinctly finer in grain. The proportion of augite has increased at the expense of plagioclase and analcite.

(*c*) The next band is still denser. The minerals are the same as above, but are so crowded together as practically to exclude the isotropic base. Magnetite is more abundant, and is sprinkled very uniformly over the field.

(*d*) A coarse vein of teschenitic material separates (*c*) from (*d*), which is the densest of all the bands occurring in the slides. It consists of a crowded mass of minute microlites of augite and plagioclase, with very numerous, small, irregular, poikilitic plates of biotite, all dusted over with magnetite. There are sparse microphenocrysts of plagioclase and purple augite. The felspar has dwindled, and the rock approximates in composition to the monchiquites. The colourless isotropic base is still to be recognized with a powerful objective, and can be definitely identified as analcite, where, in places, it is comparatively free from augite and magnetite.

Apart from the coarse teschenitic veins the four schlieren described above are the principal textural varieties to be found in the slide. But within each of them occur slighter variations in texture and composition, and no fewer than eight distinct varieties of rock occur within the limits of a thin section half an inch long.

These rocks are basaltic in aspect, and in accordance with their occurrence as the contact-facies of a teschenite, they may be called teschenite-basalts. The term analcite-basalt is unsuitable, as it has been used for definite lava-form rocks. Moreover, this rock is practically devoid of olivine, which is abundant in the great majority of analcite-basalts. Some of the schlieren approximate to monchiquites, and others to biotite-basalts.

The contact-facies gradually merges into teschenite by increasing granularity and enlarged proportion of analcite. The following will serve to give an idea of the intermediate fine-grained teschenitic rock. The thin section is from a specimen obtained immediately above the lower contact-facies in the Glenmuir Water. Microscopically the rock is somewhat similar to the coarser schlieren of the contact-facies, but is not banded and is not so rich in ferromagnesian minerals. It consists of numerous, small, euhedral to subhedral prisms of pale augite, with stout plagioclase-laths, some serpentinized olivine, and leucoxenic ilmenite, in a ground-mass of dusty analcite. Associated with the ilmenite are numerous minute scraps of biotite. A few turbid areas have the shape, low double refraction, and general aspect of nepheline as it is more recognizably developed in rocks to be described hereafter. Apatite needles are abundant in the areas of analcite. The rock may be described as a fine-grained teschenite, or if it be desired to emphasize its origin as a contact-facies it may be called teschenite-dolerite.

(2) Teschenite. (Pl. X, fig. 2.)

The differences between the teschenites proper of the upper and those of the lower margins respectively are so slight, that the rocks may be described most conveniently in the same section. The teschenites are rather variable, both in macroscopic appearance and in thin section. Variation occurs in granularity and fabric, but the mineral composition is approximately constant, or, at least, variations in the minerals present or their relative abundance do not carry any of the rocks outside the teschenite group. The dominant type, perhaps, is one which has an effect of very coarse grain, due to the abundance of large, irregular, black prisms or blades of augite ranging up to an inch in length, embedded in an even-grained, apparently-uniform ground-mass consisting of pinkish felspar and analcite. It is noteworthy that the teschenites of the upper margin carry a pink analcite, whereas at the lower margin the analcite is white. The former, therefore, are mottled in black, green (olivine, serpentinous and chloritic alteration-products), and pink; the latter in black, green, and white. The dominant type with columnar augites (Galston type)[1] is interbanded in the upper teschenite with a much finer-grained rock devoid of the pseudo-porphyritic augite. Towards the junction with the underlying theralite the pink analcite becomes increasingly abundant, and forms the dominant macroscopic element in a thin irregular band immediately overlying the theralite. In the lower band of teschenite a fine-grained type occurs, carrying numerous, small, acicular prisms of augite in a white ground-mass of felspar and analcite, with much hornblende and biotite, and a little nepheline (Cathcart type).

In thin section the teschenites consist essentially of labradorite, titanaugite, analcite, olivine, and iron-ores, named in order of abundance. As accessories occur biotite, orthoclase, apatite, nepheline, and barkevikitic amphibole. The last-named invariably occurs as a peripheral alteration-product of the titanaugite. The secondary products are serpentine, chlorite, and leucoxene. The texture is medium- to coarse-grained, and the fabric an interlocking mesh of labradorite and titanaugite in sub-ophitic relations, the large polygonal or irregular interspaces being filled with analcite.

The plagioclase forms broad laths, thoroughly euhedral, and highly zonal. It is a medium to acid labradorite (Ab_2An_3–Ab_1An_1). The crystals are frequently somewhat albitized, and, adjacent to large analcite areas, have been irregularly corroded and replaced by analcite. The cleavage-cracks and the interior of a crystal are occasionally occupied by serpentinous material, which has migrated from adjacent decomposing olivine.

The pyroxene is a feebly-coloured titanaugite, which, in the dominant type, occurs as large, blade-like, or columnar crystals. These, however, although elongated in one direction, are very

[1] G. W. Tyrrell, Geol. Mag. dec. 5, vol. ix (1912) p. 74.

irregular in shape, owing to their indentation by the terminations of felspar-laths. In some of the rocks, notably the finer-grained varieties, the titanaugite is perfectly euhedral, and is moulded by felspar. The colour is a pale purplish brown, and is very variable and patchy. The most common appearance is of a darker tint towards the margins, but bands alternatively of lighter and darker colour may occur. This zoning coincides with a similar zoning observable between crossed nicols, and frequently also with an hour-glass structure. It is, therefore, connected with slight chemical and optical variations in the crystals. There is occasionally a distinct pleochroism from purplish brown to a pale sepia. A notable feature is that practically all the crystals are hollow. In the prismatic sections elongated cavities occur along the centre-lines, and are filled with calcite, serpentinous alteration-products, and occasionally even analcite. The cavities are more or less equi-dimensional in the basal sections. They are frequently lined with a highly pleochroic biotite, which extends in ragged indefinite patches throughout the interior of the crystal, and is evidently an alteration-product. The latter frequently has an astonishing pleochroism in shades of brilliant blue, red, and peach-bloom tint, but it is sometimes scarcely more than a discoloration of the augite, so indefinite are its boundaries. The more individualized mica has a more normal pleochroism, but its darker shades have a peculiar 'beetroot' tint. Serpentinous material also occurs within the augite, but its relations show that it has migrated from adjacent olivine, entering the crystal through the cleavage and other cracks. The augite often thus presents a honeycombed appearance in the interior of the crystals, the exterior being almost invariably sound, and free from inclusions and honeycombing.

A red hornblende belonging to barkevikite occurs as an alteration-product upon the margins of the augite-crystals, especially in the fine-grained rocks of the lower contact, where the augite is euhedral. The boundary between the two minerals is always exceedingly indefinite. A rock from the lower band of teschenite above Bellow Bridge is so rich in hornblende that it deserves the designation hornblende-teschenite. This rock is fine-grained and contains nepheline, thereby approximating to the Cathcart type.[1]

A thin band of ægirine-augite or ægirine frequently occurs on the margin of an augite-crystal, especially where it is adjacent to an area of analcite. Small crystals of ægirine are occasionally enclosed in the analcite.

Analcite fills up large and small polygonal spaces between the felspars and augite; but, where corrosion and analcitization of the felspar has occurred, irregular or rounded spaces are formed. It is mostly fresh, showing the cubic cleavage, and occasionally some anomalous birefringence. The commonest alteration is to an extremely-fine, irresolvable, brown dust; but, with a further degree

[1] G. W. Tyrrell, Geol. Mag. dec 5, vol. ix (1912) p. 74.

of weathering, calcite begins to appear. Beautiful rosettes of a serpentinous mineral are frequently developed in, and apparently at the expense of, the analcite. These enclose flakes of biotite and also the other minerals usually found within the analcite areas. Occasionally the analcite is completely replaced by the fibrous serpentine. These rosettes have been mentioned by Mr. E. B. Bailey in describing the Glasgow teschenites, and he indicates the need for some special explanation of this phenomenon. He suggests that it may possibly originate from 'juvenile' reactions.[1]

The analcite corrodes and replaces the felspars enclosing the cavities in which it has crystallized. The attack has usually spread from the cleavage and other cracks, and the process can be followed from mere incipient analcitization, resulting in a widening of the cleavage-fissures, to complete replacement of the crystal. The latter, however, frequently retains its form; equally often the felspar forms shapeless, irregular masses entirely enclosed in analcite. The final appearance is of a patch of clear or dusty analcite lying in the midst of a large area of partly or wholly analcitized felspars, mixed with serpentinous, chloritic, and other alteration-products.[2] These reactions clearly belong to a juvenile stage in the history of the magma, and may be referred to that late period when the rock was stewing in a hot alkaline solution which ultimately crystallized as analcite.[3] Further evidence as to the original nature of the analcite is afforded by the numerous inclusions of biotite, pyroxenes, apatite, and felspars that it contains; by its association with soda-orthoclase; and by its evident reaction on the adjacent felspars and augite, resulting in the latter case in the formation of a thin layer of a green soda-pyroxene. Pyroxenes which have been entirely enclosed in the analcite have suffered this change to a much greater extent, leading in some cases to complete replacement.

It is remarkable that, while a susceptible mineral such as analcite often remains entirely or comparatively fresh, the other constituents of the teschenites have undergone so much alteration. This leads to the conclusion that the alteration is not so much due to ordinary weathering as to the presence, during the crystallization of the rock, of a hot, intensely-active, alkaline, and water-rich mother-liquor, which crystallized as analcite after effecting much corrosion among the earlier-formed constituents.

Because of the corrosion and replacement effected by the analcite among the earlier constituents of this and other rocks, there is a disposition to regard it as 'secondary' in a certain sense of that term. But it is as definitely a primary consolidation-product of the teschenite magma, inasmuch as its crystallization took place before the cessation of cooling of the rock, as is the allotriomorphic quartz of a granite. Both represent a final magmatic residuum, which

[1] 'The Geology of the Glasgow District' Mem. Geol. Surv. Scotland, 1911, p. 132.

[2] 'The Geology of the Neighbourhood of Edinburgh' *ibid.* 1910, p. 296.

[3] E. B. Bailey & G. W. Grabham, Geol. Mag. dec. 5, vol. vi (1909) p. 256.

crystallized in the interspaces left among the earlier constituents. Analcite, however, is more active chemically than silica, and, before its consolidation, finds time to attack and partly to replace some of the other constituents. Thus the analcite is not derived from the alteration of the felspar, as held by some petrographers, but the alteration of the felspars is due to the analcite.

Olivine is a constant though never abundant constituent in all varieties of the Lugar teschenites. It is invariably replaced by serpentine, which has crept or spread from the original crystal until the form of the latter has been completely obliterated. The serpentinization may be due to juvenile reactions, as suggested by Mr. Bailey; but it may also be due, as the migration of the serpentine into the surrounding minerals certainly is, to ordinary weathering. Olivine is most abundant in the coarse teschenites of the Galston type, and almost entirely absent from the nepheline-bearing Cathcart type mentioned above.

A constant constituent of the Lugar teschenites is ilmenite in peculiar skeletal forms, and invariably associated with a red highly-pleochroic biotite. These ilmenite-biotite groups are most strongly developed in the Cathcart types. The ilmenite presents a variety of skeletal forms, the commonest, perhaps, being an irregularly-shaped, coarsely-reticulate mass. Another form shows a herring-bone structure, with a central axis from which spring rows of thick, parallel, clubbed rods. Biotite fills up the spaces in the skeletal growth. The ilmenite, as a rule, is anterior in crystallization to the pyroxene, and is also frequently enclosed in felspar. Its decomposition gives rise to a greyish mass of leucoxene, which is often reticulated with three sets of black bars intersecting at angles of 120°.

Biotite occurs in three forms; one, in independent flakes, highly pleochroic from pale straw-yellow to dark reddish brown, is of early consolidation, and is found enclosed in the felspars and analcite. A second form is that described above as occurring in ilmenite-biotite aggregates. The third, which is especially prominent in a Cathcart type from the lower band, is (as described above) an alteration-product of the titanaugite. It occurs as irregular flecks in the interior of the pyroxenes, and also as large, well-formed flakes on their margins. The outer edges of the flakes are quite euhedral, but the interior boundaries with the augite are ragged and indefinite. The biotite is frequently interleaved with chlorite. It often lines a cavity filled with analcite, and serves partly to define the crystallographic form of that mineral.

Orthoclase is a frequent but variable accessory in the teschenites. As the penultimate constituent to crystallize, it is associated and varies in quantity with the analcite. It is generally much altered, and partly or wholly replaced by analcite. Traces of moiré and perthitic structures seem to indicate that it is probably a soda-bearing variety.

A little altered and turbid nepheline, only recognizable by the shape of the pseudomorphs, is to be seen in some of the rocks, notably in the Cathcart type from the lower band of teschenite. It is altered to a highly-polarizing, scaly, micaceous substance. Apatite is abundant, and is enclosed in all the other constituents of the rocks.

The above description covers rocks belonging to the Glasgow, Galston, and Cathcart types. In addition to these are one or two abnormal rocks which may be regarded as highly felsic and mafic varieties of the teschenites. The former occurs as a phase of the variable analcite-rich layer which intervenes between the teschenite proper and the underlying theralite. The orthoclase is approximately equal in amount to the plagioclase, and the rock is clearly leucocratic. Teschenitic rocks comparatively rich in orthoclase are mentioned in Dr. Flett's account[1] of the teschenites of the Edinburgh district. These rocks might be called analcite-monzonites, analogous with the nepheline and leucite-monzonites.

The melanocratic variety also occurs near the junction of the teschenite and the theralite, where the analcite-band is absent. Its mineral composition is defined in Table I, col. v (p. 103). It shows a decided predominance of mafic minerals, and the whole aspect of the rock is ultrabasic. Olivine becomes an essential constituent; augite with hornblende borders is abundant, as well as biotite. Ilmenite, for some unexplained reason, dwindles in this as in all the more basic and ultrabasic rocks of the series. Analcite has decreased considerably in quantity; and, concomitantly, the felspar generally is very fresh. The latter was one of the last minerals to crystallize, fills up the irregular interspaces between the mafic constituents, and shows radiating cracks due to the expansion of serpentinized olivine.

The position of this rock is rather perplexing. It may be interpreted merely as a local, very basic, schlieren; or as due to a small and localized gravity-stratification in the upper teschenite. Its mineral composition shows that it cannot be regarded as a transition-facies from the teschenite to the theralite. The theralites are entirely different, both mineralogically and texturally. A melanocratic teschenite has been described by Prof. W. J. Sollas from New Zealand.[2] That rock, however, is rich in titaniferous magnetite and poor in olivine, thereby differing in these respects from the Lugar rock.

Quantitative Mineral Composition of the Teschenites.

These rocks lend themselves well to micrometric analysis by the Rosiwal method. The chemical compositions calculated from the mineral analyses agree well with the actual chemical composition, as determined by the usual methods of analysis, with the general exception of potash (see Table II, p. 104). This is due to the

[1] 'The Geology of the Neighbourhood of Edinburgh' Mem. Geol. Surv. Scotland, 1910, p. 294.

[2] 'Rocks of the Cape Colville Peninsula, Auckland (New Zealand)' vol. ii (1906) p. 156.

difficulty of identifying and measuring potash-felspar, when occurring in small quantities in rocks of this kind. Table I illustrates the mineral composition of a number of the Lugar teschenites.

TABLE I.

	I.	II.	III.	IV.	V.
Plagioclase (Ab_1An_1)	23·2	27·9	28·9	34·5	6·6
Orthoclase	10·2	5·6	...	2·9	...
Analcite	16·1	19·9	13·8	15·5	12·2
Titanaugite	28·1	27·2	39·9	27·3	24·0
Hornblende	...	...	...	...	18·1
Olivine (serpentine)	10·6	7·5	4·6	12·9	32·5
Biotite	3·4	1·5	2·9	2·1	3·7
Titaniferous iron-ore	7·1	9·3	9·9	3·7	1·9
Apatite	1·3	1·1	...	1·1	1·0

I. Fine-grained banded teschenite, near the upper contact, Bellow Water.
II. Teschenite, rich in analcite, upper band of teschenite, Bellow Water.
III. Teschenite, lower band, between peridotite and No. IV, Glenmuir Water.
IV. Teschenite, near the lower contact, Glenmuir Water.
V. Melanocratic teschenite, in the upper band, Bellow Water.

The first four columns show that the mineral composition of the Lugar teschenite is fairly constant. Labradorite averages about 28 per cent., analcite 15 per cent., titanaugite 30 per cent., olivine 8 per cent., biotite 2 per cent., iron-ore 7 per cent., and apatite 1 per cent. Orthoclase is a variable constituent, reaching 10·2 per cent. in No. I, and declining to nothing in No. III. It is probable that a little nepheline occurs in some of the types, but it is hard to detect and harder still to measure. It is probably included with the analcite and orthoclase in the analyses. The fifth analysis is clearly that of a highly mafic variety, with a large increase in the proportion of olivine, and the incoming of 18 per cent. of hornblende, causing a concomitant drop in the proportions of plagioclase and analcite. In respect of the proportions of light and dark constituents (felsic and mafic, or leucocratic and melanocratic), it will be seen that there is a substantial equality in the first four rocks, that is, they are mafelsic. The fifth rock is domafic.[1]

The Chemical Composition of the Teschenites.

Two full chemical analyses of the Lugar teschenites were made for me by Dr. A. Scott; one of the upper contact-basalt, the other of a normal teschenite from the upper band. These are supplemented by analyses calculated from the mineral compositions given in Table I. The minerals of variable composition here are titanaugite, hornblende, biotite, and olivine. It was,

[1] For an explanation of these terms, see G. W. Tyrrell, 'The Bekinkinite of Barshaw (Renfrewshire) & the Associated Rocks' Geol. Mag. dec. 6, vol. ii (1915) p. 366.

therefore, necessary to know their exact chemical composition in this series of rocks before the quantitative mineral analyses could be utilized. Accordingly, Dr. Scott made analyses of the barkevikite in the lugarite of Lugar, and of the titanaugite in the porphyritic essexite of Crawfordjohn (Lanarkshire), minerals which are optically identical with those of the same species in the Lugar rocks, and occur in rocks belonging to the same petrographic province. For biotite, which occurs in small quantity, an analysis of a biotite from the monchiquite of Horberig, Oberbergen, Kaiserstuhl,[1] was used. From a consideration of the complete series of Lugar chemical analyses it is clear that the olivine also varies somewhat in composition. In the peridotites and picrites it is richer in the forsterite molecule than in the theralites and teschenites. The average composition of the olivine in the different rocks was calculated as follows:—

	Forsterite.	Fayalite.
Peridotite and picrite	4	1
Theralite	3	1
Teschenite	2	1

In the same way the iron-ore was calculated to have the composition

Ilmenite : Magnetite : : 3 : 4; or

Fe_2O_3, 39·4; FeO, 38·0; TiO_2, 22·6.

The chemical analyses by Dr. Scott, and the calculated Rosiwal micrometric analyses are collected together in Table II, with an analysis of teschenite from Mons Hill (Midlothian).

TABLE II.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2	44·50	45·26	45·55	44·98	43·41	46·84	42·06	46·06
TiO_2	2·43	3·01	2·91	3·29	4·02	2·06	2·10	2·56
Al_2O_3	15·23	15·74	14·89	15·85	14·89	16·32	8·70	15·94
Fe_2O_3	2·81	2·33	4·06	4·83	5·63	2·65	3·07	2·94
FeO	6·88	7·12	8·23	8·11	9·02	7·30	13·84	7·44
MnO	0·26	0·22	tr.	...	...	...	0·07	0·31
MgO	4·91	5·23	8·03	6·35	7·01	8·53	16·45	4·14
CaO	12·08	8·86	6·98	7·24	8·47	7·93	6·97	7·04
Na_2O	3·94	5·01	5·07	5·78	5·63	5·55	4·59	4·95
K_2O	2·41	2·51	1·94	1·05	0·19	0·63	0·28	2·76
H_2O+	3·09	2·94	1·41	1·67	1·21	1·33	1·15	4·22
H_2O-	0·72	0·68						0·55
P_2O_5	0·24	0·90	0·94	0·84	0·55	0·84	0·75	0·84
BaO(SrO)	...	p.n.d.	...	...	...	...	...	0·10
CO_2	1·16	tr.	...	...	...	...	...	0·11
F	...	...	0·05	0·04	...	0·04	0·04	...
FeS_2	...	...	...	...	...	...	...	0·36
Totals	100·71	99·81	100·06	100·03	100·03	100·02	100·07	100·32

[1] H. Rosenbusch, 'Elemente der Gesteinslehre' 1910, p. 300.

I. Teschenite-basalt, upper contact of Lugar sill, Glenmuir Water, Lugar. Chemical analysis by Dr. A. Scott.
II. Banded teschenite, upper teschenite layer of Lugar sill, Bellow Water, Lugar. Chemical analysis by Dr. A. Scott.
III. Banded teschenite, same as II, calculated from Rosiwal analysis No. 1 of Table I.
IV. Teschenite, rich in analcite, upper teschenite layer, Bellow Water, Lugar. Calculated from Rosiwal analysis No. II of Table I.
V. Teschenite, from lower teschenite layer, Glenmuir Water, Lugar. Calculated from Rosiwal analysis No. III of Table I.
VI. Teschenite, from lower teschenite layer, Glenmuir Water, Lugar. Calculated from Rosiwal analysis No. IV of Table I.
VII. Melanocratic teschenite, from upper teschenite layer, Bellow Water, Lugar. Calculated from Rosiwal analysis No. V of Table I.
VIII. Teschenite, Mons Hill, Dalmeny (Midlothian). Analysis by E. G. Radley, 'Geology of the Neighbourhood of Edinburgh' Mem. Geol. Surv. Scotland, 1910, p. 299.

The teschenitic character of these analyses is at once evident. For a silica percentage averaging 45, and high ferrous iron and lime, the alkalies run to about 7 per cent. The magnesia is comparatively low, indicating the poverty of the rocks in olivine. Combined water, due to the analcite present, is of course high. The analyses obtained by calculation from the Rosiwal analyses are remarkably in accord with the chemical analyses. The greatest discrepancies are in magnesia, potash, and water. The latter may be explained by the fact that no account of the alteration of the rocks was taken in the calculation. The excess of magnesia may perhaps be explained by the complete alteration of the olivine to serpentine in the analysed rocks. The serpentine was analysed as serpentine, but calculated as olivine. The deficiency in potash is due, as explained above, to the difficulty of detecting and measuring orthoclase in these rocks. The analysis of the Mons Hill teschenite shows the essential identity of the Midlothian occurrences with those of Western Scotland.

The richness of some of the Scottish teschenites in potash points to the fact that some of the analcite-rocks are probably to be referred to the monzonite series. With increasing abundance of orthoclase teschenites pass into analcite-monzonites, analogous to nepheline- and leucite-monzonite (sommaite).

The abundance of lime in the teschenite-basalt (I) as compared with the normal teschenite, is due partly to calcite, and partly to a slight enrichment of the contact-rock in augite. The abundance of olivine in the melanocratic type (VII) is shown by a great excess of ferrous iron and magnesia in the calculated analysis.

(3) Theralite. (Pl. X, figs. 3 & 4.)

Three phases of the theralite may be distinguished. A black or dark-grey, compact, doleritic rock forms the main mass of the stratum. The lower part, however, carries abundant hornblende, and is slightly coarser in grain; while, near the junction with teschenite, the rock is veined and shot with patches of a medium-grained, light-grey, analcitic variety.

Microscopically, the theralites consist of essential plagioclase, titanaugite, olivine, nepheline, and ilmenite, with accessory hornblende, biotite, analcite, orthoclase, and apatite. The texture is very fine-grained, and hence the rock might be termed nepheline-dolerite or doleritic theralite. In the principal variety the fabric shows innumerable small, prismoid grains of augite embedded poikilitically in a ground-mass of felspar and nepheline, the whole forming a base in which pseudoporphyritic olivine, augite, and ilmenite is set. The hornblende-bearing variety has the same fabric, only a new pseudoporphyritic element, hornblende, being added. The light-grey veins, however, contain no granular augite, and their abundant analcite gives them a fabric similar to that of the teschenites.

In the principal variety the felspar forms broad, anhedral plates, and seems to have been the last constituent to crystallize, even the nepheline being euhedral towards it. It is extremely zonal, and is crowded with grains of augite. Its composition is consequently difficult of determination, but the evidence points to the usual acid labradorite (Ab_1An_1), with marginal transitions to oligoclase. The plagioclase is liable to decomposition, especially in the central portions of the crystals, and passes into an irregular felted mass of scaly mica.

The augite occurs in two forms: as innumerable prismoid grains embedded in felspar and nepheline; and as larger, pseudoporphyritic, euhedral crystals of a much darker tint than the grains. The colour is a pale purple or lilac, generally darker towards the margins of the crystals. The mineral is often strongly pleochroic, from purplish to pale yellow. It alters, just as in the teschenites, with the production of biotite.

Olivine occurs in large pseudoporphyritic crystals, euhedral originally, but now the angles are largely rounded off, and therefore nearly spherical grains are not uncommon. It is very fresh with, at most, a slight peripheral serpentinous alteration. All the fissures are much blackened by separated magnetite.

Nepheline forms small subhedral to anhedral masses, and appears to be idiomorphic towards the felspar. It is usually altered to a turbid, streaky, micaceous aggregate, the scales of which are arranged parallel to the crystallographic axis of the mineral. It is occasionally quite fresh, and its identification can be made absolutely certain by the usual tests.

Ilmenite occurs in skeletal masses associated with biotite, but not so abundantly as in the teschenites. Biotite also occurs as small independent flakes embedded in felspar or nepheline, or as an alteration-product of augite.

Analcite occurs very sparingly in the principal variety of theralite, but is much more abundant in the veins towards the top of the stratum. Apatite is very abundant, enclosed in all constituents.

A red soda-hornblende, belonging to the barkevikite group, becomes an important constituent in the lower part of the theralite stratum. It usually forms extremely irregular plates, embayed by the earlier constituents, and occasionally enclosing them. It is pleochroic, with colour-extremes of pale straw-yellow and clear red-brown.

The quantitative mineral composition of the main varieties of theralite is set out in Table III, cols. i & ii (p. 109). It will be seen that the mass of the rock is decidedly mafic, much more so than the rocks which have been described as theralite. In addition to the mafic composition, it is characterized by a poikilitic fabric. The light-grey veins, however, are much coarser in grain, are devoid of granular augite and the poikilitic fabric, and show approximate equality between the felsic and the mafic constituents. Containing, as it does, some orthoclase and analcite, this variety closely resembles the true theralites, which are, in general, mafelsic in composition. A mineralogical feature that deserves special mention is the beautiful lilac colour of the augite.

(4) Lugarite. (Pl. XI, fig. 1.)

This rock is found intercalated near the transition between the theralite and the underlying picrite. It has a maximum thickness of 4 feet, and is intimately welded to both the contiguous rocks. It also occurs as irregular, anastomosing veins ramifying through the picrite, and varying in thickness from 1 to 5 inches.

In hand-specimens it presents a striking and beautiful appearance; so much so that it is a matter for comment that the rock has apparently never been noticed before. Boulders of it occur in the bed of the Lugar for a mile or two below the outcrop. It is phanerocrystalline and apparently coarse-grained, consisting of an abundant, continuous, greyish-green ground-mass (analcite, nepheline, and alteration-products) crowded with shining black prisms of barkevikite ranging up to 3 inches in length. The rock of the main exposure also shows equally abundant, more or less equidimensional, black crystals of titanaugite. Occasionally, whitish rectangular felspars may be recognized. Weathered blocks are still more striking in appearance, as the ground-mass becomes white, contrasting effectively with the black prisms embedded in it.

Microscopically, lugarite is a very beautiful rock, owing to the brilliant colours of its mafic constituents and their perfect euhedrism. The rock consists essentially of an abundant cloudy greyish base, partly isotropic, and partly cryptocrystalline because of an extremely-fine dusty alteration-product, clearing occasionally to areas of identifiable analcite. This base is crowded with perfectly euhedral crystals of deep purple titanaugite, red barkevikite ranging up to 3 inches in length, ragged masses of ilmenite passing over to leucoxene, corroded felspars, and innumerable prisms and needles of apatite.

Titanaugite forms well-shaped crystals ranging up to a quarter of an inch in diameter. Its pleochroism is very intense, the scheme being as follows:—

X............ clear pale brownish yellow.
Y............ deep maroon or reddish purple.
Z............ brownish violet.

The hour-glass and kindred zonal structures are prominent, and the exterior zone is always the more deeply coloured and pleochroic. A green coloration frequently appears on the extreme margin. Occasionally, an augite encloses the termination of a felspar-crystal; and in rare cases it is interdigitated with barkevikite, the junction between the two minerals being indefinite, but the exterior margins euhedral. A few crystals are honeycombed by irregular cavities filled with colourless isotropic material, presumably analcite. The titanaugite of this rock is identical in its optical characters with that of the ijolite-dolerite (nepheline-dolerite) of the Lobauer Berg, Saxony.

The barkevikite forms perfect crystals, and is of a deep reddish-brown colour. The pleochroism is intense, with the following scheme:—

X	pale yellow.
Y	deep chestnut-red.
Z	deep brown-red with a tinge of violet.

The maximum extinction-angle in prismatic sections is about 11°. The simple twin parallel to 010 is prominent. The mineral is, therefore, referable to the barkevikite group.[1] It occasionally moulds the pyroxene, and is then evidently an alteration-product; but the great majority of the crystals are entirely independent of pyroxene. On the other hand, the smaller crystals are frequently enclosed in the felspar.

The felspar, where uncorroded, forms well-shaped rectangular laths, and is an extremely zonal plagioclase. Where the extinctions can be measured they indicate a labradorite of composition Ab_1An_2. On the margins, however, nearly straight extinctions are obtained, indicating a transition to oligoclase. The felspar is nearly always corroded, and all stages in its replacement by dusty analcite and isotropic alteration-products can be followed. The replacement begins along the cleavage and other cracks, and advances until large irregular areas in the interior of the crystal are replaced; while, at the same time, the alteration proceeds from the exterior of the crystal in such a way that the felspar remnants are often crescentic in shape, and appear as if large pieces had been scooped or gouged from their sides. The final stage is a complete replacement of the crystal; or, at most, small crescentic fragments of felspar are left. Frequently, however, the crystal form is preserved, and is differentiated from the rest of the ground-mass by a slightly paler tint.

Olivine occurs very sparsely as rounded inclusions in the hornblende or augite; and biotite in small flakes, or as an alteration-product of augite. Both minerals may be completely lacking in a slide.

Ilmenite occurs in rather well-shaped hexagonal crystals, and is in process of alteration to leucoxene, giving rise to a marked striation (in black on grey) of three sets of lines in directions intersecting at 120°. It appears to have crystallized in this rock before the hornblende or the pyroxene.

[1] A. Scott, 'Barkevikite from Lugar' Min. Mag. vol. xvii (1914) pp. 138–42.

Apatite in needles and small crystals is extremely abundant, and occurs embedded in all constituents save ilmenite. The longer needles and prisms show the usual cross-fracture, and are frequently bifid at the terminations.

It is difficult to study the ground-mass, because of its turbidity: it is composed mostly of alteration-products, a fine brown dust, brightly-polarizing zeolites, and 'ghosts' of analcitized felspars; but occasionally it clears to an area of recognizable analcite. Under a high-power objective the fine brown dust resolves itself into clear highly-refracting granules, embedded in a colourless isotropic substance which has a refractive index distinctly lower than that of Canada balsam, and, on the thin edges of the section, a cubic cleavage. It is fairly clear, therefore, that the bulk of the ground-mass is a cloudy analcite. Faint, streaky, paler patches, with an occasional approach to hexagonal or rectangular outlines, are probably to be referred to nepheline. This mineral occurs much more recognizably in a lugarite-like rock in association with the bekinkinite of Barshaw, near Paisley.[1]

Two varieties of lugarite are distinguished. In one, titanaugite and barkevikite are developed in about equal proportions (Table III, col. iii). The distribution of these minerals is, however, very patchy. Some slides contain titanaugite or barkevikite only; others contain both. The veins that penetrate the picrite have barkevikite only (Table III, col. iv), the prisms of which are frequently arranged in a rude stellar fashion.

Quantitative Mineral Composition of Theralite and Lugarite.

These were estimated by the Rosiwal method, and gave fairly concordant results, which are recorded in Table III, below.

TABLE III.

	I.	II.	III.	IV.
Plagioclase[2]	23·3	16·4	10·5	14·6
Analcite	...	...	} 42·5	} 49·0
Nepheline	12·6	16·6	}	}
Titanaugite	36·1	35·9	21·7	...
Barkevikite	...	12·2	17·2	29·5
Olivine	18·6	8·7	...	...
Biotite	3·6	6·7	...	...
Ilmenite	4·2	2·5	5·0	2·7
Apatite	1·6	1·0	3·1	4·2

I. Theralite, Bellow Water, Lugar.
II. Hornblende-theralite, Bellow Water, Lugar.
III. Lugarite, main mass, Glenmuir Water, Lugar.
IV. Lugarite, veins in picrite, Glenmuir Water, Lugar.

[1] G. W. Tyrrell, Geol. Mag. dec. 6, vol. ii (1915) p. 308.
[2] Ab_1An_1 in theralites; Ab_1An_2 in lugarites.

A little orthoclase has certainly been overlooked in the lugarites and probably in the theralites. Also, in the lugarites the analcite total contains some nepheline. From the chemical analyses it appears that apatite has been considerably over-estimated in the lugarites.

Chemical Composition of Theralite and Lugarite.

No chemical analysis was made of the theralite proper. The rock analysed proved to be nearer to picrite than to theralite, and its composition is set out in Table VI, col. i (p. 114). The lugarite was analysed by Dr. Scott: its chemical composition is unique, reflecting the unique mineral composition of the rock. The chemical compositions, as calculated from the mineral compositions recorded in Table III, are collected here for purposes of comparison, and serve, as do the others already tabulated, to demonstrate the efficiency of the Rosiwal method in suitable cases as an auxiliary to actual chemical analysis.

TABLE IV.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
SiO_2	42·47	42·75	44·42	46·29	45·56	47·35	43·70	52·73	56·75
TiO_2	2·59	2·68	1·63	2·37	2·53	1·46	0·89	...	0·30
Al_2O_3	14·20	15·19	13·33	17·47	15·92	18·02	19·77	20·05	20·69
Fe_2O_3	3·25	3·50	9·14	2·24	4·04	3·07	3·35	3·43	3·52
FeO	8·73	8·44	6·35	7·07	6·75	5·65	3·47	0·99	0·59
MnO	...	0·05	...	0·28	0·07	0·11	tr.	...	tr.
MgO	12·92	9·47	5·74	2·10	3·02	0·82	3·94	0·17	0·11
CaO	8·26	8·83	10·60	5·82	8·10	7·82	10·30	3·35	0·37
Na_2O	5·33	6·50	5·60	8·69	8·82	9·76	9·78	7·94	11·45
K_2O	0·92	1·37	1·81	1·47	0·04	0·06	2·87	4·77	2·90
H_2O+ / H_2O-	0·10	0·21	1·75	5·12 / 0·69	3·53	4·09	0·89	4·85 / 0·69	3·18 / 0·04
P_2O_5	1·18	0·91	0·35	0·70	1·61	1·78	1·34	tr.	...
BaO(SrO)	...	...	...	0·09	...	...	...	0·11	none
CO_2	...	...	...	none	...	...	...	0·93	...
F	0·06	0·04	...	p.n.d.	0·12	0·16	...	...	Cl ·28
S	...	...	0·18	...	...	...	...	...	tr.
Totals	100·01	99·94	100·90	100·40	100·11	100·15	100·30	100·01	100·18

I. Theralite, Bellow Water, Lugar. Calculated from Rosiwal analysis, Table III, No. I (p. 109).

II. Hornblende-theralite, Bellow Water, Lugar. Calculated from Rosiwal analysis, Table III, No. II.

III. Theralite, Flurhubl, Duppau (Bohemia). F. Bauer, Tscherm. Min. u. Petr. Mitth. vol. xxii (1903) p. 281.

IV. Lugarite, main mass, Glenmuir Water, Lugar. Chemical analysis by Dr. A. Scott.

V. Lugarite, main mass, Glenmuir Water, Lugar. Calculated from Rosiwal analysis, Table III, No. III.

VI. Lugarite, veins in picrite, Glenmuir Water, Lugar. Calculated from Rosiwal analysis, Table III, No. IV.

VII. Ijolite, Iivaara, Kuusamo (Finland). Anal. N. Sahlbom. Quoted from J. P. Iddings, 'Igneous Rocks' vol. ii (1913) p. 306.

VIII. Heronite, Heron Bay, Lake Superior. Anal. H. W. Charlton. Coleman, Journ. Geol. Chicago, vol. vii (1899) p. 435.

IX. Analcite-tinguaite, Pickard's Point, Essex County (Mass.). Anal. H. S. Washington. Amer. Journ. Sci. ser. 4, vol. vi (1898) p. 182.

The correctness of the reference of the first two rocks in Table IV to the theralites, and the general accuracy of the Rosiwal analyses, is shown by the accordance of the calculated analyses with the analysis of Rosenbusch's type theralite from Duppau (Bohemia). The excess of magnesia and the slight deficiency in lime of the Lugar theralites are due to their more highly mafic character; but the alkalies, alumina, and silica correspond remarkably well with those of the Duppau rock.

Turning to the lugarite, the calculated Rosiwal analyses correspond well with the chemical analyses, except in lime, potash, and phosphorus pentoxide. The excess of lime and phosphorus pentoxide is partly due to the over-estimation of apatite, and partly to the overlooking of orthoclase and its measurement as labradorite. The deficiency of about 1 per cent. in potash is, of course, due directly to the latter cause. The lugarite analyses are characterized by a very large content of alkalies along with a comparatively-low silica percentage, and by their persodic character. They fall into the hitherto unoccupied and unnamed persodic subrang of lujavrase (II.7.1.5) of the American Quantitative Classification.[1]

Systematically, these rocks may be described as ijolites in which the place of nepheline is partly taken by analcite, and in which barkevikite occurs as well as, and sometimes to the exclusion of, augite. One of the analyses of ijolite from Iivaara (Finland), corresponds fairly well with that of lugarite (Table IV, No. VII). It is, however, richer in lime and alkalies than the Lugar rock, and contains much less combined water, since nepheline and not analcite is the principal felsic mineral.

The only other rocks hitherto described with an analcite-content of the same order as that of lugarite are the heronite[2] of Heron Bay, Lake Superior, with 47 per cent. of analcite; and the analcite-tinguaite of Pickard's Point, Essex County (Mass.) with 37·4 per cent. of analcite. The chemical analyses of these rocks are set out for comparison in Table IV. Heronite differs from lugarite in containing a large amount (28·2 per cent.) of orthoclase, which is reflected in the large potash-content of the analysis, although the soda-content compares well with that of lugarite. The analcite-tinguaite of Pickard's Point contains ægirine and anorthoclase phenocrysts in a ground-mass composed of nepheline and analcite, is richer in alkalies than lugarite, and is devoid of lime-soda felspar.

(5) Picrite and Peridotite. (Pl. XI, figs. 2 & 3.)

The ultrabasic rock which makes up more than half of the Lugar sill is characteristically felspar-free, and is a typical hornblende-peridotite. Some varieties, however, occurring towards the top of

[1] G. W. Tyrrell, Geol. Mag. dec. 6, vol. ii (1915) p. 361.

[2] This rock is now regarded as a decomposed tinguaite; see A. E. Barlow, 'Nepheline & Alkali-Syenites of Port Coldwell [Ont.]' Guide-book No. 8 Geol. Surv. Canada, 1913, p. 17.

the mass, contain some felspar and analcite, and are richer in the metasilicates. These are true picrites in the original sense of Tschermak. In hand specimens the peridotite is a fresh, medium to coarse-grained, blackish-green, heavy rock, in which olivine may occasionally be distinguished, and especially hornblende in large, lustre-mottled plates. The rock is variable in granularity, and may be devoid of poikilitic hornblende. The picrites are distinctly finer-grained, and show white or pink specks of felspar and analcite.

Microscopically, the peridotite consists of olivine, titanaugite, hornblende, biotite, and iron-ores in the proportions shown in Table V, col. iii (p. 113). The olivine, which may form 60 to 70 per cent. of the rock, occurs in more or less rounded, subhedral grains, ranging up to half an inch in diameter. It is occasionally quite fresh, but is usually in all stages of alteration to blue, green, yellow, and colourless varieties of serpentine. The coloured serpentines are almost entirely devoid of separated magnetite; but the unaltered olivine and the colourless variety of serpentine contain irregular streaks of magnetite, indicating that the colour of the serpentine depends on whether the iron-oxide is thrown out of combination or not during the process of alteration. The next most abundant constituent is augite, which occurs in polysomatic clusters of small euhedral grains wedged in between the olivines, and where the latter mineral is altered, embedded in serpentine. The granular habit of the augite is distinctive of this type of peridotite, which is accordingly distinguished as the Lugar type. The earliest described picrite or peridotite of the teschenite series, that of Inchcolm, contains titanaugite in large plates which mould and poikilitically enclose olivine.

A red-brown hornblende, belonging, like the amphiboles of the preceding rocks, to the barkevikite group, occurs in large, irregular, poikilitic plates, enclosing small olivines, and groups of granular augite-crystals. It usually forms about 10 per cent. of the rock.

The remaining constituents, biotite and iron-ores, form only about 4 per cent. of the rock. The two minerals are, as usual, closely associated. The rock is almost devoid of apatite: this mineral appears to be associated with analcite, and increases in abundance along with that mineral.

The picrites which occur towards the top of the ultrabasic stratum are divisible into two varieties. One, almost devoid of recognizable felspar, contains much analcite, and very abundant augite. It approximates to the lugarite type, and represents the modification of the peridotite at the contact with lugarite. In thin section this rock consists of numerous, euhedral, purple augites, embedded in a turbid cryptocrystalline or isotropic ground-mass containing zeolites, occasional clear analcite, and 'ghosts' of felspars, identical with the ground-mass of lugarite. Barkevikite occurs in ragged plates exhibiting the poikilitic habit and intergrown with ilmenite. Olivine is comparatively sparse, and is completely serpentinized.

The other variety is an extremely fresh rock, with abundant olivine and some fresh plagioclase. It occurs between the peridotite and theralite in the great cliff of the Glenmuir Water. It differs from the rock described above in the much greater abundance of olivine, in less analcite and turbid decomposition-products, and in the presence of plates of fresh felspar enveloping olivine and augite, and showing the usual expansion-fissures.

Quantitative Mineral Composition of the Picrites and Peridotites.

Table V records the results of the Rosiwal measurement of three of the ultrabasic rocks of the Lugar sill.

TABLE V.

	I.	II.	III.
Plagioclase ($Ab_1An_1-Ab_1An_2$)	...	5·7	...
Analcite	13·4	8·8	...
Titanaugite	56·6	26·1	20·5
Barkevikite	12·7	8·6	10·0
Olivine	11·1	49·1	65·2
Biotite	...	0·4	2·0
Titaniferous iron-ore	5·1	1·0	2·3
Apatite	1·1	0·3	...

I. Augite-picrite, upper part of ultrabasic stratum, Glenmuir Water.
II. Olivine-picrite, same position and locality.
III. Hornblende-peridotite, main mass of ultrabasic stratum, Glenmuir Water.

It will be seen that the picrites are domafic, and the peridotite permafic. The analcite totals contain a little unidentifiable turbid matter. The diminution in the amount of apatite is a curious feature of the ultrabasic rocks. In the Lugar series, and in the rocks of the Ayrshire petrographical province generally, apatite seems to vary in abundance along with the felsic minerals, especially analcite. A similar but less marked decline in the amount of titaniferous iron-ore also occurs. The order in which the analyses are given is that of increasing depth in the ultramafic stratum. The rapid increase in the amount of olivine illustrates the packing of the olivine-crystals in the lower part of the stratum by settling under the influence of gravity. Along with this there is a decrease in the amount of augite; but barkevikite, a mineral of later consolidation in these rocks, remains practically constant.

Chemical Composition of the Picrites and Peridotites.

Chemical analyses of the augitic type of picrite and of peridotite were made for me by Dr. A. Scott; and these are supplemented by analyses calculated from the quantitative mineral compositions recorded in Table V, above.

TABLE VI.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	44·47	41·21	42·62	40·35	39·93	42·06	40·32
TiO_2	2·73	3·88	1·58	2·12	1·74	1·93	2·66
Al_2O_3	7·59	8·43	6·41	3·75	2·75	12·18	9·46
Fe_2O_3	6·25	5·22	2·06	3·53	2·49	2·67	4·75
FeO	9·57	11·54	11·27	9·86	13·80	7·89	7·48
MnO	0·49	0·05	0·03	0·20	0·04	...	0·25
MgO	11·93	11·72	25·81	25·69	32·88	11·47	18·12
CaO	10·24	10·10	5·51	4·64	4·16	11·29	10·55
Na_2O	4·27	5·52	3·44	3·14	1·73	5·10	2·62
K_2O	1·46	0·03	0·05	0·80	0·15	1·07	1·10
H_2O+	0·73	1·14 (both)	0·76 (both)	5·28	0·08 (both)	3·08 (both)	0·57
H_2O-	0·48			0·83			1·25
P_2O_5	0·54	1·25	0·49	0·25	0·28	0·34	0·68
BaO, SrO	p.n.d.	...	...	0·06	...	...	...
F	...	0·04	0·01	...	...	...	...
CO_2	tr.	...	...	tr.	...	...	...
Incl.	...	...	...	...	...	0·97	0·28
Totals	100·75	100·13	100·04	100·50	100·08	100·05	100·09

I. Picrite, transitional to theralite, Bellow Water, Lugar. Chemical analysis by Dr. A. Scott.
II. Augite-picrite, Glenmuir Water, Lugar. Calculated from Rosiwal analysis, Table V, No. I (p. 113).
III. Olivine-picrite, Glenmuir Water, Lugar. Calculated from Rosiwal analysis, Table V, No. II.
IV. Hornblende-peridotite, Glenmuir Water, Lugar. Chemical analysis by Dr. A. Scott.
V. Hornblende-peridotite, Glenmuir Water, Lugar. Calculated from Rosiwal analysis, Table V, No. III.
VI. Limburgite, Hahn, Habichtswald (Hesse-Nassau). Anal. Jannasch. Quoted from J. P. Iddings, 'Igneous Rocks' vol. ii (1913) p. 334.
VII. Nepheline-basalt, Uvalde County (Texas). Anal. W. F. Hillebrand. W. Cross, Bull. U.S. Geol. Surv. No. 168 (1900) p. 62.

These are typical ultrabasic rocks in their large content of magnesia, lime, and ferrous iron, combined with low silica; but they are characterized by comparatively high alkalies, as compared with other rocks of the same category. This results from the persistence of analcite into the ultrabasic end of the series, and from the alkali-content of the pyroxenes and amphiboles. In this respect it is difficult to find phaneric rocks to match with them. Some nepheline-basalts and limburgites approach closely in chemical composition (see Table VI, cols. vi and vii).

IV. PETROLOGY.[1]

The differentiation of the Lugar sill may be explained in two ways, according to whether it is considered as the product of a single act of intrusion or of more than one. Both modes of explanation involve perplexing features. Postulating the former, the

[1] [Since reading this paper I have, with the permission of the Council of the Geological Society, considerably revised the theoretical discussion of the Lugar sill. I have done this in deference to weighty opinions expressed in the

present heterogeneity of the sill suggests a very complex process of differentiation. Moreover, if it were intruded as a homogeneous body of magma the chemical composition of the contact-rocks should be similar to the bulk-composition arrived at by averaging the analyses of the different parts after weighting them according to their volumes. As will be seen later, this is by no means the case; and, consequently, if the sill is the result of a single act of intrusion, the magma must have been heterogeneous prior to intrusion. The question of its differentiation is then shifted back to an ante-intrusion stage, and its discussion becomes correspondingly difficult.

These complications are avoided, to some extent, if the mass be regarded as a composite sill resulting mainly from two acts of intrusion—the first introducing the teschenite at both contacts, the second bringing in the ultrabasic rock of the interior. All phases within the sill, however, are intimately welded together, showing that the later intrusion must have quickly followed the earlier. Moreover, the mineral and chemical composition of the rocks show that the successive intrusions have very close genetic relations, and have probably arisen by the differentiation of a single body of magma. The problem of the mode of differentiation then becomes the same as that arising from the first hypothesis.

If the sill be thus composite, it shows a surprising lack of xenocrysts and xenoliths, or of veins and dykes, along the main interior contacts. Other features, too, are difficult of explanation on this hypothesis. The subsidiary differentiation observed within the central ultrabasic stratum seems most easily explained by the hypothesis of sinking of early heavy crystals under the influence of gravity, aided perhaps by a concomitant rise of lighter constituents.

The special features of the Lugar sill will now be treated in detail, especially with regard to their bearing on the hypotheses outlined above.

(1) Mineralogical Variations.

Estimations of the modes of twelve types of rock occurring in the Lugar sill are scattered through the foregoing petrographical

discussion upon the paper, and communicated privately; and also on account of the views on differentiation in general expressed by N. L. Bowen in a recent important paper ('The Later Stages in the Evolution of the Igneous Rocks' Journ. Geol. Chicago, vol. xxiii, 1915, Suppl. pp. 1–91). Liquation theories of differentiation stand in need of drastic revision after the evidence brought forward in this paper, broad-based upon the exact experimental work carried on for many years at the Geophysical Laboratory of Washington, that liquation has never yet been observed in the melts experimented with. Neither has it been observed in lavas, which are Nature's 'quenching experiments.' Whether we can argue from experiments upon the comparatively minute laboratory scale to age-long magmatic processes under natural conditions, is at least open to doubt; and, until that doubt is resolved, it is permissible to use liquation hypotheses, but to assign to other hypotheses more weight according to their correspondence with known facts and conditions.]

descriptions (see Tables I, III, and V). Referring to these it may be seen that lime-soda felspar attains its maximum development, 34·5 per cent., in the teschenites. It dwindles steadily through the theralites, lugarites, and picrites, and is absent from

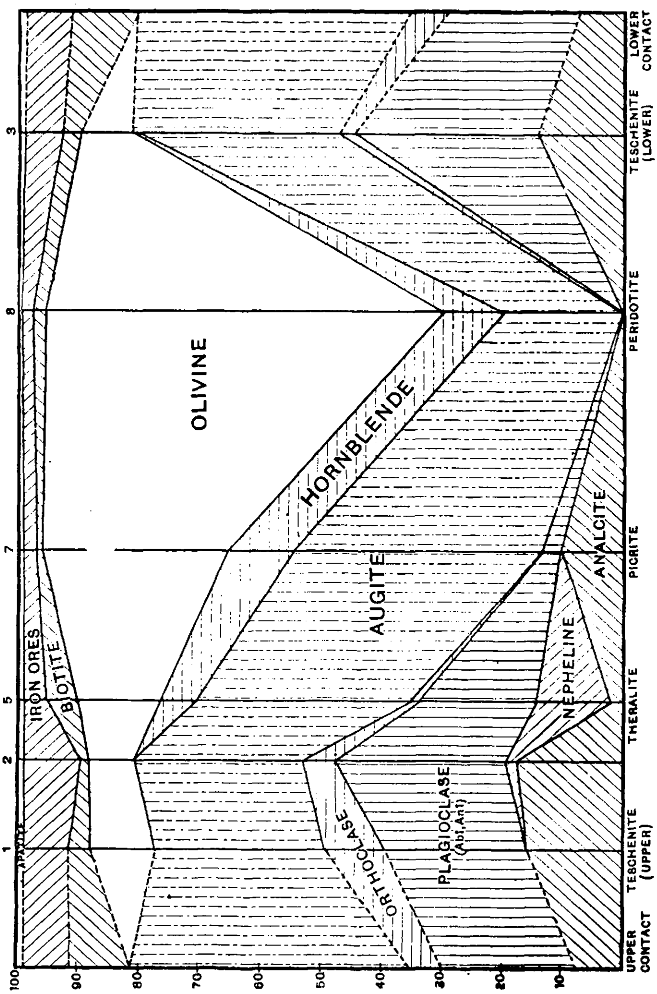


Fig. 5.—*Diagram illustrating mineralogical variation concurrent with increasing depth in the sill.*

the peridotite. Orthoclase occurs most abundantly in the teschenites, but is present in small amount (although unrecorded) in all the other rocks, save picrite and peridotite. It is a mineral hard to detect and measure when associated with abundant lime-soda felspar, but its presence is demonstrated by the potash of the chemical analyses. Analcite is the characteristic mineral of the suite, and is present in all the rocks except the peridotite. It occurs in small amount in the theralites, although unrecorded in the Tables. Where present in notable quantity its amount varies from 30 to 40 per cent. (allowing for the presence of nepheline) in the lugarites, to an average of 15 per cent. in the teschenites. Nepheline occurs in measurable amount only in the theralites (up to 16·6 per cent.), but is almost certainly present in small quantity in the teschenites and lugarites. Titanaugite is the most abundant and constant mafic mineral of the suite. It averages about 30 per cent. in the teschenites, increases to 36 per cent. in the theralites, and attains its maximum development, 55·6 per cent., in an augitic variety of picrite. Red soda-hornblende (barkevikite) is absent from the teschenites, save in a domafic schlieren (Table I, No. 5, p. 103), but is present in amounts ranging from 8·6 to 29·5 per cent. in all the other rocks, the latter amount occurring in veins of lugarite devoid of titanaugite. Olivine averages about 10 per cent. in the teschenites and theralites, is absent from the lugarites, and attains its maximum development in the peridotite, where it may form 70 per cent. of the rock. Biotite averages about 3 per cent. in most of the types, and is most abundant (6·7 per cent.) in the hornblendic variety of the theralite. Iron-ore is most abundant in the teschenites, averaging about 7 per cent., but dwindles steadily downwards through the sill, although it is never entirely absent. Apatite is a comparatively abundant and constant constituent. It averages about 1 per cent. throughout the sill, is absent from the peridotite, and is most abundant in the lugarites, thus illustrating its association with analcite.

The mineralogical variation with depth in the sill may be shown by means of a diagram (fig. 5, p. 116). For this purpose it has been found advisable to average the types (see Table VII, below), thus smoothing over minor mineralogical irregularities.

Table VII.

Modes of Rocks in the Lugar Sill.

	1.	2.	3.	4.	5.	6.	7.	8.
Plagioclase (Ab_1An_1 to Ab_2An_3).	23·2	27·9	31·7	28·6	19·9	12·6	2·9	...
Orthoclase	10·2	5·6	1·4	4·7	...	...	...	...
Analcite	16·1	19·9	14·7	16·3	...	} 45·7	11·1	...
Nepheline	...	...	...	...	14·6			
Titanaugite	28·1	27·2	33·6	30·6	36·0	10·8	41·4	20·5
Barkevikite	...	...	...	...	6·1	23·4	10·6	10·0
Olivine (serpentine)	10·6	7·5	8·7	8·9	13·6	...	30·1	65·2
Biotite	3·4	1·5	2·5	2·5	5·2	...	0·2	2·0
Iron-ores	7·1	9·3	6·8	7·5	3·3	3·8	3·0	2·3
Apatite	1·3	1·1	0·6	0·9	1·3	3·7	0·7	...
Felsic constituents	49·5	53·4	47·8	49·6	34·5	58·3	14·0	0
Mafic constituents	50·5	46·6	52·2	50·4	65·5	41·7	86·0	100

1. Upper teschenite (Table I, 1); 2. Analcitic teschenite (Table I, 2); 3. Lower teschenite (Table I, 3, 4); 4. All teschenite, except melanocratic variety of Table I, 5 (Table I, 1, 2, 3, 4); 5. All theralite (Table III, 1, 2); 6. All lugarite (Table III, 3, 4); 7. All picrite (Table V, 1, 2); 8. Peridotite (Table V, 3).

The diagram (fig. 5, p. 116) shows the relation of the mineral constituents to depth within the sill. The depths are plotted as the abscissæ and the proportions of the various mineral constituents as the ordinates, utilizing the averages Nos. 1, 2, 5, 7, 8, 3, in Table VII, in the order given. The break between the theralite layer and the teschenite, where different types occur on opposite sides of a sharp boundary (between 2 and 5), and the similar break between the peridotite and the lower teschenite (between 8 and 3), are clearly shown by the marked changes in the directions of the lines at the points indicated. The sill can thus be divided into three sharply-bounded portions, in each of which a more or less continuous variation may be traced. By far the largest part is that which constitutes the central body consisting of theralite at the top, passing downwards into picrite, and ultimately into peridotite. In this portion plagioclase, analcite, and nepheline show a more or less continuous decrease in a downward direction within the stratum; while olivine rapidly increases in amount, forming about 65 per cent. of the peridotite, and augite and barkevikite find maxima in the picrite and theralite respectively.

(2) Chemical Variations.

The chemical variations within the Lugar sill naturally reflect and follow the lines of the mineralogical variations. Again, as in the preceding section, the variation in 'basicity,' or rather 'maficity' (if one may coin such a term), is the significant variation. In this case, however, it cannot be shown by using the silica percentages as is customary in chemical diagrams, since the silica percentage varies but slightly throughout the series. The percentages of the ferromagnesian oxides show a much more sympathetic

TABLE VIII.

	1.	2.	3.	4.	5.	6.
SiO_2	45·09	42·61	46·40	42·77	40·14	43·16
TiO_2	2·95	2·63	2·12	2·73	1·98	2·06
Al_2O_3	15·49	14·70	17·14	7·48	3·25	10·95
Fe_2O_3	3·72	3·37	3·12	4·51	3·01	3·77
FeO	7·78	8·59	6·49	10·79	11·83	8·97
MgO	6·68	11·20	1·98	16·49	29·29	13·84
CaO	8·63	8·54	7·25	8·62	4·40	7·62
Na_2O	5·16	5·91	9·09	4·41	2·48	4·61
K_2O	1·45	1·14	0·52	0·51	0·43	1·07
H_2O	2·17	0·15	4·48	1·04	3·10	2·69
P_2O_5	0·72	1·05	1·36	0·76	0·26	0·65
Rest	...	0·07	0·28	0·21	0·15	...
Totals	99·84	99·96	100·23	100·32	100·22	99·99

1. Average of teschenites. 2. Average of theralites. 3. Average of lugarites. 4. Average of picrites. 5. Average of peridotites. 6. Average rock of the Lugar sill.

relation to the 'maficity,' and may accordingly be used as abscissæ in a diagram, against which the other oxides may be plotted as ordinates (see fig. 6). Just as in dealing with the mineralogical variations, it has been found necessary and desirable to average

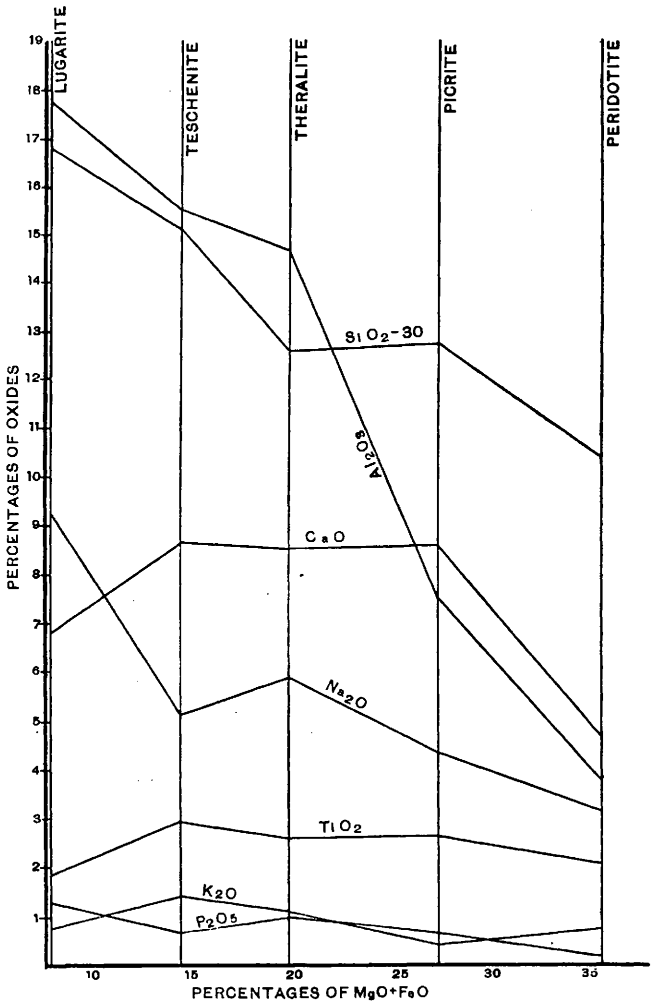


Fig. 6.—*Diagram illustrating variations in chemical composition in the Lugar sill.*

the chemical composition of the various rock-types for use in the diagram. The averages thus arrived at are given in Table VIII. In the calculation of these averages most of the chemical compositions calculated from the graphic analyses have been used, omitting those which duplicate the actual chemical analyses made by Dr. Scott. Thus No. 3 in Table II (p. 104), No. 5, Table IV (p. 110), and No. 5, Table VI (p. 114), have not been used on this score. Furthermore, No. 7, Table II, has been omitted, because it represents merely a small and unimportant schlieren, which would have an effect on the average of the teschenites incommensurate with its size and importance.

The sum of the ferromagnesian oxides being utilized as abscissæ, the diagram shows that the order of increasing richness in these oxides is lugarite, teschenite, theralite, picrite, and peridotite. The most striking feature of the curves (fig. 6) is the rapid and regular fall in alumina from lugarite to peridotite, and the slight fall in silica. Soda also falls; but potash, along with phosphorus pentoxide and titanium dioxide (ignoring small irregularities), remains approximately at a constant level. Lime rises to a maximum in the middle of the series, and drops in the lugarite and peridotite at the extremes. The variation of the curves in this diagram may obviously be correlated with the mineralogical variations which have already been described.

(3) Average Magma of the Lugar Sill.

In the question of the differentiation of the Lugar sill it is of importance to know the chemical composition of the magma before it split up into its present heterogeneous parts. Assuming that the variation has resulted from the differentiation of an originally homogeneous magma, the composition may be calculated by weighting the analyses of the various components according to their bulk, adding, and then dividing by the number of units taken. The average composition of the principal types is given in Table VIII. The proportions have been taken as follows:—

Peridotite (Table VIII, 5)	$\frac{4}{16}$.
Picrite (Table VIII, 4)	$\frac{3}{16}$.
Theralite (Table VIII, 2)	$\frac{2}{16}$.
Teschenite (Table VIII, 1)	$\frac{5}{16}$.
Contact-teschenites (Table VIII, 1) ...	$\frac{2}{16}$.

Since the analyses of teschenite and of the contact-rocks are for all practical purposes identical, seven parts of Anal. 1, Table VIII, have been taken for the last two items. Lugarite is omitted, as it forms an insignificant proportion of the mass of the sill. The result of the calculation is given in Table VIII, 6.

These figures possess significance only if the hypothesis of an intrusion of homogeneous magma, followed by differentiation in place, be accepted. On the hypothesis of successive intrusion it is impossible to assume that the relative volumes of the facies have any necessary connexion with the relative volumes developed within the differentiation chamber. If the former hypothesis be assumed correct the figures show that the original magma must have had a composition intermediate between that of theralite and that of picrite. It had a certain correspondence with that of theralite, but was richer in magnesia, and poorer in lime, soda, and alumina, indicating a greater richness in olivine-molecules and poverty in those of felspars, as compared with theralite; in short, the magma must have been transitional towards the picrite. Consequently, we arrive at the important conclusion that the original magma had a composition different from that of the present contact-rock, and hence, that the sill was heterogeneous when emplaced, and has been shifted since differentiation.

(4) Composition, Identity, and Banding of the Contact-Rocks.

Petrographical examination shows that the upper and lower contacts of the Lugar sill are identical, even down to the smaller microscopical features. Both consist of black, basalt-like rocks, curiously streaked and drawn out in slightly-varying layers, and injected by veins of coarse pink teschenite. They both pass gradually into coarser and more normal teschenites towards the interior of the sill. The upper teschenite becomes more analcitic as it is traced downwards; the lower teschenite remains comparatively uniform as it is followed upwards. These facts show that the teschenite must have been injected into cold rocks, which exercised the chilling effect proper to such contact.

The banding is evidence of considerable movement of the viscous magma during or after emplacement. That the movement and banding took place prior to crystallization is shown by the fact that the textures of the various types are perfectly granular. There is no sign whatever of the parallel arrangement of columnar or tabular minerals such as felspar or augite.

As has been shown in the previous section, the chemical composition of the contact-rock is dissimilar to the average rock of the sill, and consequently the facies cannot be considered as due to the differentiation of an original homogeneous teschenite magma. The fact has no significance if the hypothesis of successive intrusion be accepted. If, however, the sill be considered as due to a single act of intrusion, its heterogeneity must have arisen prior to emplacement. It would have originally had the composition of an ultrabasic theralite or picrite, and contact-rocks of like composition would have been formed. To account for the present disposition of the facies it would be necessary to assume that the intrusion has been moved on from its first position, where it was differentiated, into the position that it now occupies, leaving its picritic contact-rocks behind adhering to the old contacts. This view has some support in the marked flow-banding of the contact-rocks; but it is difficult to understand why this movement did not more seriously disturb the stratified arrangement of the various layers within the sill. This assumption of movement of the sill as a whole, subsequent to differentiation, is not necessary if the alternative hypothesis of successive intrusion be accepted.

(5) Asymmetry of the Sill.

When the arrangement and petrographic nature of the various layers composing the sill is examined in detail, a decided asymmetry becomes apparent. The bands, while generally strictly parallel to the contacts, are not repeated in the same order at the top and at the bottom of the sill. The upper layer of teschenite, becoming richer in analcite downwards, comes to an abrupt end at a sharp junction with fine-grained theralite. The lower layer of teschenite likewise passes very rapidly into the base of the peridotite stratum, although the actual junction is everywhere obscured. The theralite band consequently does not appear in the lower half of the sill (fig. 4, p. 96).

The asymmetry is much accentuated if the densities and sizes of the various bands are taken into consideration. The heaviest and largest layer, the peridotite, is not arranged centrally, but is so situated that its centre-line is well below the geometrical centre-line of the sill. On its upper margin it is flanked by a big mass of the somewhat less heavy picrite and theralite, and on its lower margin by a considerably lighter and smaller band of teschenite. Thus the centre of mass of the whole sill must be considerably below its geometrical centre-line. This, of itself, suggests that gravity must have been the controlling factor in the arrangement, at least in the central ultrabasic stratum. The densities of the layers, bearing out the above facts, are shown in the vertical section (fig. 4, p. 96). When plotted, they form a curve which bulges in an asymmetric manner below the centre-plane of the sill.

(6) Density-Stratification in the Sill.

Apart from the outer sheath of teschenite and its contact-facies, the remainder of the sill, constituting the central ultrabasic stratum, has itself suffered a subsidiary gravity-stratification. This is indicated by the distribution of olivine, which has collected in the lower layers of the mass. The upper portion of the stratum consists of theralite with 14 per cent. of olivine. This passes gradually downwards into picrite with 30 per cent., and finally into peridotite with 65 per cent. of olivine. The inference is that olivine, the earliest constituent to crystallize, has sunk under the influence of gravity to the lower levels of the stratum. This is in accordance with the experiments of Dr. N. L. Bowen,[1] who found that olivine-crystals, forming in an artificial melt approximating in chemical composition to a basic igneous rock, segregated in a dense layer at the base of the crucible in which the melt was contained.

[1] 'Crystallization-Differentiation in Silicate Liquids' Amer. Journ. Sci. ser. 4, vol. xxxix (1915) pp. 175–91.

(7) Variations in Texture.

Rapid variation in texture is common in alkali-rich rocks, and is highly characteristic of the Lugar sill. These variations are doubtless connected with local variations in the physical and chemical characters of the magma, especially in regard to the gas-content. A textural feature is the comparatively fine grain of the theralite stratum, which is poor in analcite. At the other extreme are coarse-grained teschenites, especially those rich in analcite. The controlling factor is probably the comparative abundance of fluxes, especially water; but the fine grain of the theralite may also be partly due to chilling against the teschenite, as well as to comparative poverty of aqueous residuum. The peridotite is medium- to coarse-grained, but this is assignable to the slow rate of cooling in the centre of the sill. The dense teschenitic contact-facies are clearly due to rapid chilling consequent upon intrusion into cold rocks. The general granularity and lack of parallel orientation among the crystals has already been commented upon.

(8) Segregation-Veins.

Many veins of a coarse pink teschenite cut the dense contact-rocks, and show that a richly-analcitic magmatic residuum remained in a liquid condition long after the consolidation of the contact-rocks. Thin veins consisting largely of analcite and felspar also cut the peridotite. Both types of vein doubtless represent a slight pegmatitic phase in the development of the intrusion. These veins are coarse-grained, and show no signs of chilling at their margins. They were doubtless injected while the rocks were still hot. There are also a few veins of a black fine-grained rock resembling the teschenite-basalts of the contacts. These are probably to be interpreted as injections of teschenitic material at a later stage, when the contact-rocks were colder and able to exercise a chilling effect.

(9) Mode of Intrusion and Differentiation.

Whatever hypothesis of intrusion be adopted, the main differentiation of the Lugar sill must be referred to the stage of its history prior to its emplacement. It is not possible, therefore, to discuss it as fully as might have been done if it had occurred *in situ* at a post-intrusion stage, with all the details clearly displayed. The discussion of the petrography makes it clear that all the different facies are genetically related, and it is highly probable that they have arisen by the differentiation of a single body of magma.

The differentiation appears first to have produced bodies of teschenite and an ultrabasic rock, which may be designated as picrite.[1] The mineralogical and chemical relations of these rocks

[1] The term picrite was first employed by Tschermak in the sense of a melanocratic derivative of teschenite.

support the view that the gravitational sinking, either of immiscible fractions, or of crystals, was the chief factor concerned in their differentiation. In any case the details of the process are not open to direct inspection, as the magma has been moved since differentiation, and we are, therefore, limited to indirect inference as to its nature. But the gravitational factor receives further support from the phenomena directly observable in the central ultrabasic stratum of the sill, where a gravitational differentiation occurred subsequent to intrusion. This may be regarded as an indication of the process which took place, one stage previously, in the larger chamber whence the Lugar sill was immediately derived.

During the progress of this work I favoured the view that the units of differentiation were immiscible fractions of water-rich teschenite, and comparatively anhydrous picrite, respectively. The sharp interior contact between the upper teschenite and the underlying theralite was regarded as analogous to the sharp contact-plane that is developed between immiscible fractions, such as aniline and water, or various mixtures of metals, which have arranged themselves in order of density. It also became necessary to assume that the sill was the product of a single act of intrusion, and that it was heterogeneous at the time of intrusion. In order to account for the dissimilarity between the teschenitic contact-facies and the bulk-composition of the sill as a whole, the differentiated sill was believed to have received an onward impulse, which pushed it forward into cold rocks, leaving behind its original picritic or theralitic contacts, and establishing new contacts with the succeeding layers of teschenite.

The recent work of Dr. Bowen has discredited liquation theories of differentiation, and has emphasized the importance of crystallization-differentiation, where the crystals are continually removed, either by sinking or zoning, from contact with the liquid in which they were formed.[1] This process receives convincing support from the results of experimental work upon silicate magmas, which has now been carried on for many years in the Geophysical Laboratory at Washington. I am now inclined to ascribe the main differentiation at Lugar to the sinking of heavy crystals in a teschenitic magma. This process is dealt with in greater detail in the next section.

The hypothesis of successive intrusion removes many of the difficulties, and makes unnecessary many of the assumptions, mentioned above. On this hypothesis the teschenite was intruded first into cold rocks, forming fine-grained basaltic facies at both margins. While it was still cooling, but probably solid, a thick mass of picrite magma was intruded along its centre-plane. During its crystallization the ultrabasic layer became stratified according to density mainly by the sinking of olivine-crystals, as

[1] 'The Later Stages in the Evolution of the Igneous Rocks' Journ. Geol. Chicago (1915) Suppl. pp. 1–91.

described in the next section. This, in its turn, was intruded at a later stage, probably while still partly liquid, by a small mass of lugarite, which spread out as a thin sheet at a horizon about a third of the depth of the ultrabasic stratum from its upper surface.

If the emplacement of the Lugar sill took place in this way, it is difficult to understand why there are no xenocrysts or xenoliths, intrusive veins, or signs of disturbance, along the main interior contacts. The interposition of the ultrabasic magma must have taken place very quietly and gradually, welding itself intimately to the teschenite without wedging off fragments from the contacts. That the teschenite was fractured and comparatively cool before the intrusion of the picrite is shown by the presence of the black veins of basaltic teschenite, which represent teschenitic magma chilled by intrusion into cold, or comparatively cold, rocks.

(10) Sinking of Crystals in the Central Ultrabasic Stratum.

Dr. R. A. Daly and others have shown that the earlier and generally heavier minerals must tend to sink in the ordinary silicate magma. Actual cases of phenocrysts that have sunk (or risen) in lavas have been described by authorities of no less weight than Scrope, Darwin, King, E. S. Dana, and Iddings.[1] In the great quartz-dolerite sill of the Palisades (New Jersey) J. V. Lewis has shown that a concentration of olivine has taken place near the lower contact, giving rise to a stratum of olivine-dolerite.[2] This is interpreted as being due to the sinking of early-formed olivine crystals. Dr. Bowen has shown that olivine- and pyroxene-crystals collect towards the bases of crucibles containing a suitable silica melt, but that olivine sinks more readily.[3] That the process cannot be more often demonstrated in natural occurrences is probably due to the fact that in most small magmas the onset of an inhibitive viscosity, or of crystallization, is too rapid for the gravitational action to take place; and in large magmas the final products of the process are not often exposed by erosion. The sinking of olivine-crystals is believed to have taken place in the central ultrabasic stratum of the Lugar sill, where a downward succession from theralite, through picrite, to peridotite, may be demonstrated, a succession characterized by a gradually increasing proportion of olivine.

Dr. Daly has calculated that a holocrystalline 'basalt' of sp. gr. 3·10 at ordinary temperatures would have a specific gravity of only 2·83 when molten at 1200° C. The figure 3·10 may be taken as a fair average for the specific gravity of picrite, and we may therefore conclude that picrite molten at 1200° C. would have a

[1] See R. A. Daly, 'Origin of Augite-Andesite' Journ. Geol. Chicago, vol. xvi (1908) p. 411.

[2] Ann. Rep. Geol. Surv. New Jersey 1907, pp. 125, 129–33.

[3] Amer. Journ. Sci. ser. 4, vol. xxxix (1915) pp. 175–91.

specific gravity somewhere near 2·83. Similarly, Dr. Daly has calculated that olivine, which has a specific gravity of 3·40 at ordinary temperatures, would only have a specific gravity of approximately 3·30 when crystallized at 1100° C.[1] The contrast between the specific gravity of crystallized olivine at 1100° C., and that of molten picrite at 1200° C., is sufficiently great to warrant the conclusion that the olivine-crystals, when formed, would sink to lower levels within the magma, and would continue to do so at decreasing speed until the increase of viscosity consequent upon cooling inhibited further movement.

It is conceivable that, under favourable conditions, an almost monomineralic layer might be formed in a magma by the sinking of crystals. The favouring conditions would be early crystallization of a comparatively heavy mineral in a highly fluid magma, unimpeded by the presence of other minerals. The rate of crystallization should be rapid, the sizes of the crystals should be large (as the rate of sinking is proportional to their bulk), and the mineral should appear suddenly in large quantity. Olivine and augite frequently satisfy these conditions, and on sinking they would form, respectively, layers of dunite and pyroxenite. Iron-ores less frequently satisfy the conditions requisite for the formation of monomineralic layers. In most magmas their crystals are small, and the development of the minerals is feeble, though they may be the first to crystallize. Nevertheless, in a few cases, the formation of an iron-ore rock as a result of gravity-settling has been recorded.

The sinking of crystals heavier than the surrounding liquid would probably continue to a diminishing extent, through practically the whole period of crystallization. In this case Dr. Bowen believes that the crystals would tend to sink as a swarm, rather than as individuals, with little tendency to relative movement between the different kinds.[2] The swarm, however, would be dominated by the mineral crystallizing earliest, by the heaviest or largest mineral, or by the mineral crystallizing in the greatest bulk with the greatest speed, according to circumstances. The development of any one mineral within the swarm would be controlled, in general, by a combination of these conditions.

Before the density-stratification of the central part of the Lugar sill can be accepted as due to the sinking of early-formed olivine-crystals, it is necessary to explain why augite and iron-ores are not segregated to the same extent. In the first place, the olivine had a start of the other minerals in crystallization. It is a rapidly crystallizing mineral, and it was forming in large quantity from a richly-magnesian magma. Hence it would form the major constituent of the sinking swarm. Augite, iron-ores, and labradorite began to crystallize somewhat later, and the two first-named would probably participate in the sinking movement. They would find the magma appreciably more viscous, and the field already largely

[1] Journ. Geol. Chicago, vol. xvi (1908) pp. 404–406.

[2] 'The Later Stages in the Evolution of the Igneous Rocks' *Ibid.* (1915) Suppl. p. 15.

occupied by olivine-crystals. Moreover, the iron-ores are sparsely developed, and would be prevented from sinking to any great extent because of the small size of the crystals. The augite, on the other hand, forms large platy or columnar crystals, shapes, however, which would not facilitate sinking as readily as that of the more compact equidimensional olivine-crystals. Furthermore, the augite tends to form subophitic aggregates with labradorite-laths, a circumstance which would still further hinder sinking. In view of these considerations it is easy to see why olivine should dominate the sinking swarm, and hence why the gravity-stratification in the Lugar sill should be defined mainly by the relative abundance of olivine-crystals. That augite has sunk to some extent is shown by the existence of richly-pyroxenic layers in the picrite part of the stratum, and by the general greater abundance of augite in the picrite than in the overlying theralite (see Table VII, p. 117). This is exactly where one would expect the augite to concentrate, in view of the fact that it is the second heavy mineral to crystallize in bulk. The lowermost layers, on the view adopted here, would be dominated by olivine, a deduction matched by the presence of peridotite in this position.

The hypothesis of sinking of heavy crystals, which is believed to be well attested in the central stratum of the Lugar sill, may be applied to the differentiation of the Lugar magma as a whole. Teschenite and picrite may be regarded as the opposite poles of a gravitative differentiation effected by the sinking of heavy crystals in the magma-chamber whence the Lugar sill proceeded. The teschenite, as the lighter differentiate, would occupy the upper part of the reservoir, and thus, on the application of stress, would probably be injected first, the picrite following as the result of renewed stress. The sunken olivine-crystals might be partly dissolved in depth, and the rounded condition of the crystals in the Lugar peridotite may be cited in favour of this conclusion.

The slight concentration of analcite in the upper teschenite at the junction with theralite (fig. 4, p. 96), may be accounted for by a little settling of heavy crystals in the teschenite, prior to the intrusion of the picrite, aided, perhaps, by a concomitant upward movement of the light aqueo-alkaline material which solidified as analcite. The later history of the sill is mainly that of continued crystallization. After the crystallization and sinking of olivine-crystals had well progressed, the augite, hornblende, iron-ores, and felspars crystallized almost simultaneously, leaving a hot, chemically-active, aqueo-alkaline residuum which finally crystallized as analcite and alkali-felspar. The formation of analcite in this way opens up some interesting magmatic and mineralogical problems, which I do not propose to discuss in this paper.[1] The presence of this residuum is attested by the numerous veins of

[1] See A. Scott, 'Primary Analcite & Analcitization' Trans. Geol. Soc. Glasgow, vol. xvi (1916) pp. 32–43.

teschenite which pierce the contact-rocks, presumably after the solidification of the latter; and by the corrosion and replacement suffered by the earlier minerals. The origin of the veins, irregular dykes, and sheet of lugarite, is also probably to be referred to this late stage in the history of the sill. This rock, in all probability, represents the extreme analcitic term of differentiation effected in the magma-chamber, injected later along the same channel as the teschenite and picrite.

(11) Comparison of the Lugar Sill with the other Picrite-Teschenite Sills of Scotland.

Including the Lugar sill six picrite-teschenite sills have been described from the Midland Valley of Scotland. The other localities are Ardrossan and Saltcoats in the west; and Blackburn, Barnton, and Inchcolm in the east.[1] Those that have been described in any detail show marked correspondences with the Lugar sill. There is always a central ultrabasic stratum, flanked towards both contacts by teschenite, or by dolerite of teschenitic affinities (save in the Blackburn sill where the base is not seen). The upper band of teschenite is usually the thicker (Lugar, Ardrossan, Barnton). In only two cases, Lugar and Blackburn, is there a sharp contact between the upper teschenite and the ultrabasic stratum; and for these sills some degree of liquation has been postulated. In the others the two types of rocks, where the relation is observable, are said to pass gradually one into the other. The differentiation in this case may be ascribed simply to the gravitational settling of olivine. In the Blackburn, Barnton, and Inchcolm sills, the ultrabasic rock is a picrite in the original sense of Tschermak, an olivinic differentiate from teschenite, and still contains a little felspar and analcite. At Lugar and Ardrossan the gravitational action must have been effective for a longer period, as a felspar-free hornblende-peridotite has been formed, very rich in olivine; and at Lugar, increasing richness in olivine from the upper to the lower part of the stratum has been observed. Flow-banding at both contacts has been observed at Lugar, but at Ardrossan and Inchcolm it apparently occurs only near the upper contact. At Barnton the central picrite shows a rude banding parallel to the contacts.

In two cases, Ardrossan and Inchcolm, the respective observers have postulated heterogeneity in the magma prior to intrusion. At Lugar also, both teschenite and picrite were slightly heterogeneous before intrusion, as shown by schlieren differing in mineral composition or texture. The process of liquation has been invoked to explain a sharp plane of separation between teschenite and an underlying ultrabasic stratum in the Blackburn sill.[2] The influence

[1] For references, see pp. 84–85.

[2] 'The Geology of the Neighbourhood of Edinburgh' Mem. Geol. Surv. Scotland, 1910, p. 281.

of gravity in the settling of olivine-crystals has only been appealed to in the case of Lugar, although its effects are clearly demonstrable in the other sills.

EXPLANATION OF PLATES X & XI.

(The slide numbers are those of the collection in the Geological Department, University of Glasgow.)

PLATE X.

Fig. 1. Slide R 1045. × 24. Ordinary light. Upper contact of teschenite, Bellow Water, above Bellow Bridge, Lugar. A felt of minute felspar-laths and grains of augite, with magnetite, and a little interstitial analcite. Note numerous variations of granularity and banding within a small compass. (See p. 95.)

2. Slide R 1044. × 12. Ordinary light. Analcite-rich teschenite, upper band, Bellow Water, above Bellow Bridge, Lugar. Labradorite, augite, and analcite, with numerous flakes of biotite and skeletal ilmenite. Note the central area of analcite with alteration proceeding from the margins. (See p. 98.)

3. Slide PV 249. × 12. Ordinary light. Theralite, augite-rich variety, light-grey patch below the contact of theralite with teschenite, Bellow Water, Lugar. This rock is rich in a beautiful lilac-coloured augite with darker margins. Fresh olivine occurs in small grains about the centre of the field. The turbid interstitial material consists of labradorite and nepheline. (See p. 105.)

4. Slide PV 161. × 24. Ordinary light. Hornblende-theralite, Bellow Water, Lugar. Swarms of minute augite-grains are poikilitically enclosed in a comparatively-coarse ground-mass of labradorite (clear) and nepheline (turbid). Abundant pseudo-porphyritic olivine and barkevikite. The grain of this rock appears deceptively fine, owing to the granular augite. (See p. 105.)

PLATE XI.

Fig. 1. Slide PV 164. × 12. Ordinary light. Lugarite, vein in picrite, Glenmuir Water, Lugar. Large prisms of barkevikite, labradorite (white), ilmenite, and interstitial turbid analcite. This field contains much more felspar than the normal type of lugarite. (See p. 107.)

2. Author's slide. × 12. Ordinary light. Picrite, south of the railway viaduct, Glenmuir Water, Lugar. Consists mainly of augite and olivine, with interstitial turbid analcite, labradorite, and a little barkevikite.

3. Slide R 155. × 12. Ordinary light. Hornblende-peridotite, Glenmuir Water, Lugar. Consists mainly of olivine partly serpentinized, with granular augite, and large poikilitic plates of barkevikite. Note that the augite has the same habit as in the theralite. (See p. 111.)

4. Slide R 1085. × 12. Ordinary light. Lower contact of teschenite, Glenmuir Water, Lugar. Note the varying granularity and the number of different bands within a very small distance. The coarse white band is a later vein of teschenite. (See p. 95.)

DISCUSSION.

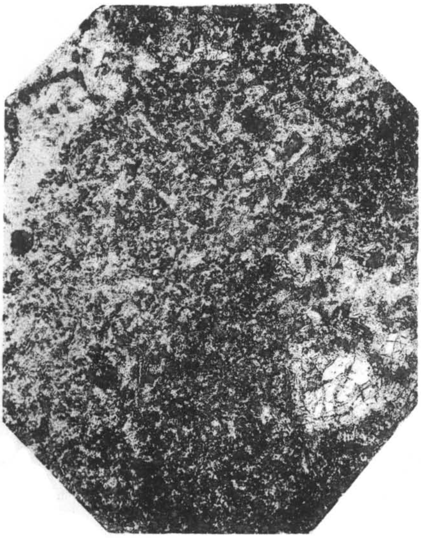
The PRESIDENT (Dr. A. HARKER) congratulated the Author on having found so interesting a subject of investigation. His full and careful account of this remarkable composite sill would make a valuable addition to our knowledge. The theoretical discussion based on the facts opened up several interesting questions. The Author had proved that there was a discontinuous variation, with a continuous variation superposed upon it. It had been clearly demonstrated that the latter effect was due to the settling-down of the earlier-formed crystals. With regard to the discontinuity, however, the experiments of the Washington chemists made it difficult to accept any explanation postulating immiscible partial magmas. The speaker would like to see the relations of the various rocks re-examined upon the alternative hypothesis of successive intrusions: the suggestion being that the picrite had been intruded in the midst of an earlier intrusion of teschenite, just as the lugarite was admittedly intruded later in the midst of the picrite.

Prof. W. J. SOLLAS complimented the Author on a remarkably thorough piece of work, which gained in presentation by the conscientious manner in which fact and hypothesis had been kept distinct. He was inclined to think, however, that the sill had been formed by two separate infillings: that the upper and the lower teschenite were parts of the same intrusion, which followed a widening and reopening of the fissure.

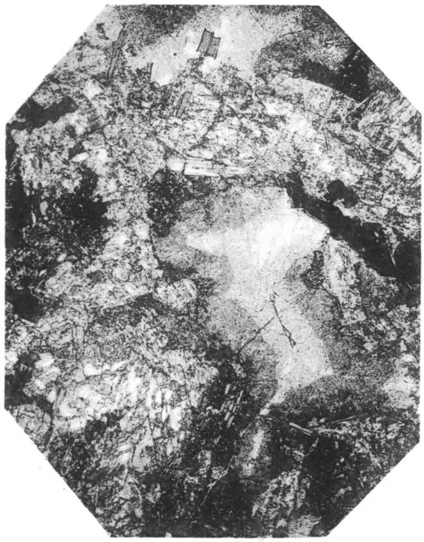
Dr. J. W. EVANS welcomed the paper as a valuable contribution to the study of the difficult problem of the differentiation of igneous magmas. He saw no reason for rejecting the supposition that, if it contained sufficient water, a rock-magma might separate on cooling to a certain point into two non-miscible portions, the lighter and uppermost of which contained the greater part of the water, silica, alumina, and alkalies. It was true that no experimental evidence of differentiation had been obtained, when mixtures of silicates had been fused together; but, in the experiments, no considerable amount of water under pressure was present. Continuous gravitational differentiation might be expected to take place in a reservoir of sufficient depth, but the amount of such differentiation that would occur with any particular magmatic composition, temperature, pressure, and depth of reservoir, remained for determination. The succession of the igneous rocks at the Lizard appeared to point to a more or less continuous differentiation from an ultrabasic magma to one with the composition of a dolerite, and then a discontinuous differentiation to a granitic type. The intrusion of the two latter together gave rise to the Kennack gneisses, in which they remained distinct, except where the loss of water before complete consolidation permitted local diffusion. Differentiation as the result of crystallization, in the manner described by Dr. Harker in his 'Natural History of Igneous Rocks,' was now universally accepted.

In the case of the sill described by the Author the possibility of successive injections could not be ignored. If this had happened, the teschenite must have been first intruded and then, before it had completely consolidated, it was followed by still more basic

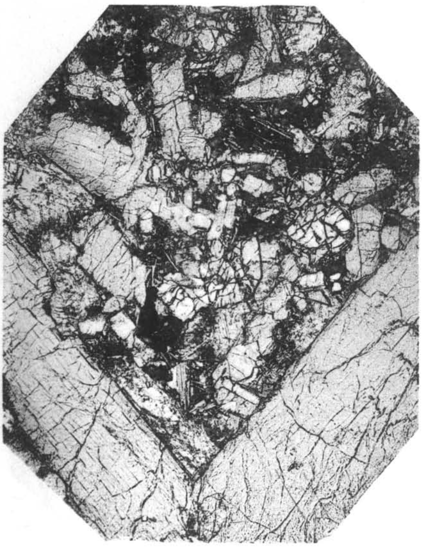
1. × 24



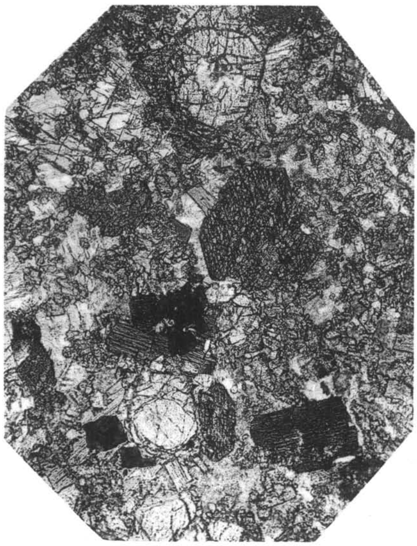
2. × 12



3. × 12



4. × 24



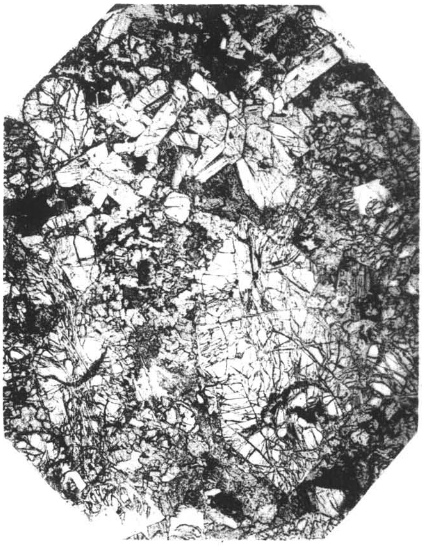
G.W.T., Photomicro.

Bemrose, Collo., Derby

TESCHENITES AND THERALITES.

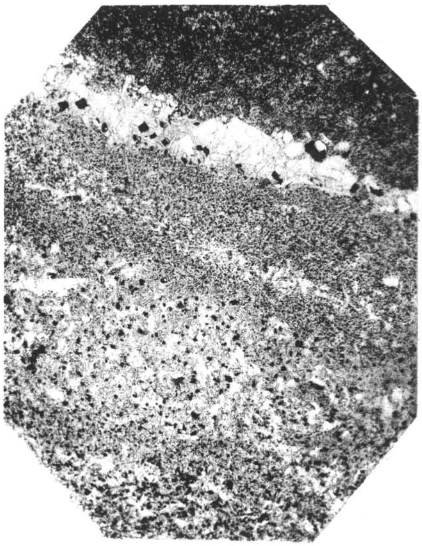
1. × 12

2. × 12



3. × 12

4. × 12



G.W.T., Photomicro.

Bemrose, Collo., Derby

LUGARITE, PICRITE, PERIDOTITE, AND TESCHENITE.

material. This would indicate that the magma had differentiated in a separate reservoir which was tapped near the top. That was contrary to the usual course of events giving rise to deep-seated intrusions: as a result of folding or faulting of the earth's crust, a fluid magma may come to be at a higher level than the adjoining solid rocks, and the reservoir thus formed is then gradually emptied from a point near its base, where there was the maximum hydrostatic pressure; consequently the succession of the intrusions was from basic to acid, as at the Lizard.

Mr. T. CROOK joined previous speakers in congratulating the Author on his clear description of this extremely interesting sill. He asked whether the conditions described held true for only a small portion of the sill, or whether they obtained over a considerable area. He raised the question, because of its important bearing on the mode of intrusion. It seemed to him that this sill, so far as the particular portion described was concerned, was best explained by successive intrusions after differentiation had taken place. First, the teschenite was injected; then, before the middle layer of teschenite had completely crystallized, the sill was substantially widened and the peridotite was injected. Finally, and in the same manner, a further slight widening permitted the injection of the 'lugarite' along the median portion of the sill. He considered it impossible to give a satisfactory explanation of the petrology of the sill, except by assuming that the widening of the sill took place in three distinct stages corresponding to the intrusion of the three different rock-types described. The assumption that liquation had taken place after intrusion raised serious difficulties, and seemed to be an unnecessary complication.

The AUTHOR, in reply, said that he was much obliged for the kind reception accorded to his paper. He thought that the conditions under which magmatic experiments were conducted scarcely approximated to those obtaining in natural magmas, especially in relation to the content of water and other fluxes. He hoped that liquation might yet be experimentally demonstrated in silicate-magmas. With regard to his interpretation of the differentiation of the Lugar sill, he admitted that successive intrusion offered a plausible alternative to liquation, but thought that observations in the field favoured the latter theory. An almost constant feature of composite sills and dykes was the occurrence of xenoliths and xenocrysts along the interior contacts. No such phenomena were to be observed in the Lugar sill, and there were no veins or dykes springing from the interior contacts. Whether liquation was the true explanation of certain features presented by this sill, or not, he thought that the evidence for subsidence of crystals under the influence of gravity remained overwhelming.