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On the petrology of the ultrabasic and basic plutonic rocks of the Isle of Rum.

(With Plate XII.)

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I. *Introduction.*

THE Isle of Rum contains one of the most interesting assemblages of plutonic rocks of Tertiary age in the British Isles. The pioneer work of Macculloch and the later exploratory efforts of Judd and Geikie were followed by an admirable account of the rocks by Harker (7), given with his usual lucidity and precision. In 1938 I spent a fortnight on this island, and this paper—the outcome of my visit—aims merely at supplementing Harker's petrographical description by certain quantitative data in respect of the ultrabasic and basic rocks found there and of recording certain observations relating to the igneous tectonics.

The earliest phase of igneous activity on Rum was the eruption of doleritic and mugearitic lavas (10). As shown by Bailey (2) the eruptive phase of igneous activity was followed or accompanied by the formation of a ring-fault and two subordinate vents infilled with explosive breccia and intruded by felsite. The space inside the ring-fault was then intruded by a banded peridotite-allivalite complex and later by eucrite in the form of a semicircular ring-dike and associated sheets. Finally, a granophyre boss was intruded along the western side of the ultrabasic–basic complex.

II. *Measurement of the modal composition and granularity of rocks.*

The modal composition of rocks was determined by means of the Shand stage, a method which, although more laborious than with stages of a later pattern, was preferred for the greater freedom which it gives for correction of errors in measurement. Certain minerals, such as iron-ore or olivine, can be estimated much more correctly than others, such as felspar, and by balancing the data one may obtain more accurate results. The recalculation of the volume percentages into weight percentages allowed additional corrections. The granularity (grain-size) of rocks was determined by counting the number of grains measured and then dividing the total traverse per mineral by this number. This provided the average linear intercept (l) for a given mineral in millimetres. The average linear intercept for the rock (L), which is taken to represent the granularity, was calculated by means of the following formula:

$$L = \frac{l_1 p_1 + l_2 p_2 + \ldots l_n p_n}{p_1 + p_2 + \ldots + p_n}$$

in which $l_1, l_2 \ldots l_n$ are the average linear intercepts and $p_1, p_2 \ldots p_n$ are the volume percentages of the respective minerals (mesostasis excepted).

Altogether 26 rocks were measured, but to save space only the averages for peridotite, allivalite, and eucrite are given in this paper (table I), while the individual analyses are plotted on the triangular diagram (fig. 2).

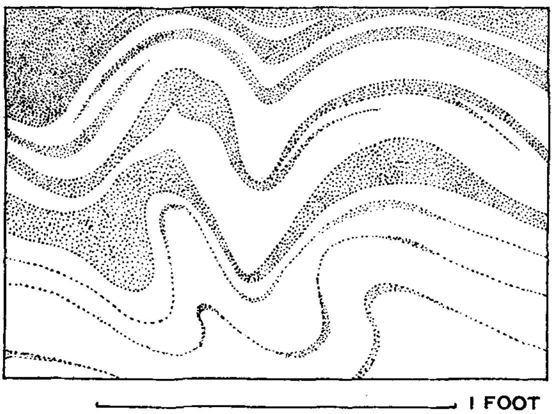

FIG. 1. Banded and contorted transition zone between peridotite (above) and allivalite (below). North-eastern shoulder of Hallival, Isle of Rum.

III. *The ultrabasic rocks.*

The ultrabasic complex of Rum consists of alternating thick sheets of peridotite and allivalite and a subsidiary sheet of harrisite. These sheets of peridotite and allivalite, which are up to 150 feet in thickness, are, as a rule, clearly separated from each other by a sharp line of junction, but in some places the junction is gradual and extending for several feet. Such banded junction zones are often highly contorted into sharp folds and overfolds, and besides distinct bands of contrasted rocks contain numerous minute streaks and lenses in a perfect fluidal arrangement (fig. 1). The line of separation between the individual melanocratic and leucocratic bands is usually very distinct and sharp. Under the microscope, however, these sharp junctions are seen to be gradational with an intimate interlocking of crystals (pl. XII, fig. 2).

The major bands of peridotite and allivalite also show subsidiary minor banding and streaking, often showing parallel fluidal orientation of plagioclase crystals, especially in allivalite sheets in which the fluidal and fissile structure is often very pronounced. On the other hand, in the majority of peridotite sheets olivine crystals do not exhibit any obvious preferred orientation, but as shown by Phillips (9) in some fissile peridotites and allivalites olivine shows signs of such an orientation. Cataclastic structure has never been observed by me among these rocks, not even among rocks containing xenoliths.

A number of rocks belonging to the ultrabasic complex have been measured on the Shand stage. The samples were selected more or less at random from all parts of the complex—the only criterion being their fresh appearance. Altogether eight samples of peridotite and eight of allivalite were measured and their averages are presented in table I. As all the rocks described in this paper are composed

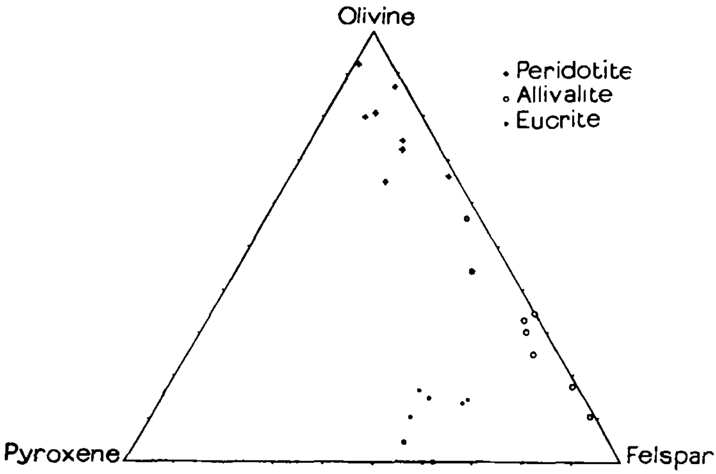

FIG. 2. Triangular diagram showing the modal composition (weight per cent.) of peridotites, allivalites, and eucrites.

mainly of olivine, pyroxene, and felspar, it is possible to represent their composition on a triangular diagram (fig. 2). This diagram shows quite clearly that the ultrabasic rocks form a continuous series ranging from an almost pure olivine rock (dunite) to an almost pure plagioclase rock (anorthitite). Rigid quantitative limits separating various groups of rocks are both impossible and unnecessary. According to Harker (7, p. 70) allivalite is composed of olivine and anorthite in approximately equal amount or with anorthite predominating.

TABLE I. Average modal composition of peridotite, allivalite, and eucrite calculated from eight modal analyses of each type of rock and expressed in weight per cent. (L = average granularity of the rock).

	Peridotite.			Allivalite.			Eucrite.		
	Average.	Min.	Max.	Average.	Min.	Max.	Average.	Min.	Max.
Olivine ...	75·55	64·30	88·20	31·60	10·80	56·70	15·45	0·00	49·25
Pyroxene ...	7·20	1·60	14·55	2·90	0·00	7·85	32·80	23·50	40·00
Plagioclase ...	14·55	0·85	31·30	65·20	40·40	88·70	49·60	9·95	61·15
Iron-ore ...	2·70	1·25	4·50	0·30	0·00	1·05	2·15	0·30	8·70
L	0·794	0·337	2·157	0·502	0·241	0·848	0·675	0·313	1·838
Sp. gr. ...	3·070	2·992	3·132	2·970	2·819	3·056	2·964	2·890	3·134

As far as I can judge the minerals in these rocks do not vary in composition, and as the iron-ore and pyroxene are present in small amounts, the successive members of this series are characterized only by the various proportions of olivine and plagioclase.

The olivine is, on the whole, fresh with only a comparatively small proportion altered to serpentine and iron-ore. Often it shows a remarkable development of (010) cleavage planes. As shown by Harker (7, p. 82) two varieties of olivine are present in these rocks, green and black. Both of these varieties are almost colourless in thin sections. The analyses of these two varieties, as given by Harker, on recalculation show the following composition:

Green variety	21·6 fayalite	78·4 forsterite
Black variety	12·1 fayalite	87·9 forsterite

In the course of petrofabric analysis of peridotite the optic axial angles of 87 crystals of green olivine were measured. The results of these measurements are as follows:

	No. of crystals.	$2V_\alpha$	Fayalite (weight per cent.).
Berek's method	6	84	36
On one axis	66	$84\frac{1}{2}$	35
On two axes	15	88	25

The results obtained by the measurement on two axes are probably the most accurate and the results are more in agreement with those of the chemical analysis. Zoning in olivine is not conspicuous.

In the peridotites and olivine-rich allivalites olivine occurs in the form of idiomorphic and hypidiomorphic crystals with rounded edges, elongated parallel to the *c*-axis, and flattened on (010) (pl. XII, figs. 1 and 3). On the contrary, in felspar-rich allivalites olivine is invariably moulded on felspar crystals in an ophitic fashion (pl. XII, fig. 4).

The felspar is very basic and, from measurements on the Fedorov stage, the average corresponds to $Ab_{10}An_{90}$. It is very fresh and occurs in the form of large broad prismatic crystals. It is twinned according to the Carlsbad, albite, and pericline laws. Zoning is not marked.

The pyroxene is also very fresh. From measurements on the Fedorov stage ($2V$ 58°, $\gamma : c = 42°$) it appears to be a diopsidic augite. Diallage lamination and schiller structure, as described by Judd, are frequently found in this pyroxene. In the ultrabasic rocks pyroxene is always ophitic both to olivine and felspar. Orthorhombic pyroxene, probably enstatite, is found occasionally in these rocks.

The iron-ore, in the form of polyhedral grains, is probably magnetite and chromite. The ore is always enclosed in the other minerals and this suggests an early crystallization. Mesostasis and apatite are completely absent in these rocks.

Probably the most interesting feature of this series of rocks is the mutual relation between olivine and plagioclase. On the basis of modal analyses it is possible to draw a line separating rocks with idiomorphic olivine from those with ophitic olivine. It lies at olivine (25 Fa, 75 Fo) 35% and felspar ($Ab_{10}An_{90}$) 65% (fig. 3). This interesting feature was well described by Harker (7, pp. 85–87, fig. 25), who suggested that the order of crystallization of these two minerals depends on their eutectic proportions. It is interesting to note that a similar conclusion expressed in a different form was reached previously by Geikie and Teall in their study of banded gabbros. Speaking of the mutual relations between pyroxene and labradorite in the gabbro, they wrote: 'Where the felspar is most abundant, there the idiomorphism is most pronounced, and where it is least abundant it is moulded on the other constituents and shows no trace of crystalline form' (5, p. 651).

Both peridotite and allivalite contain angular xenoliths and schlieren. In peridotite the common type of xenolith is a granular labradorite-pyroxene-rock often containing large phenocrysts of labradorite. This type of rock has a certain resemblance to beerbachite and may represent thermally metamorphosed frag-

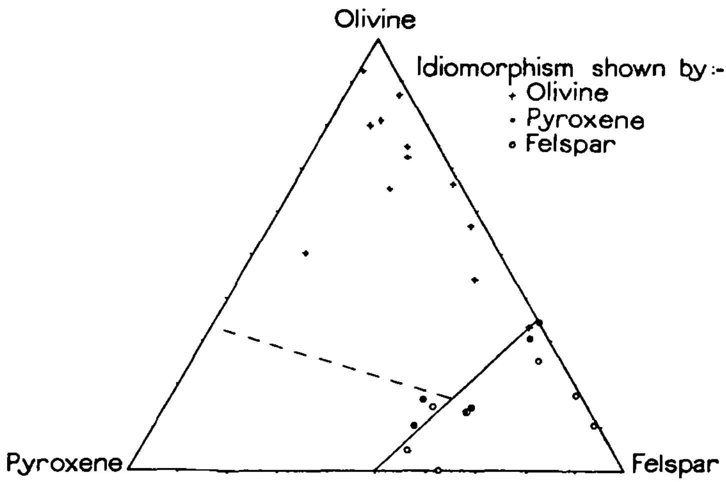

FIG. 3. Triangular diagram showing the individualization fields of olivine, felspar, and pyroxene in the ultrabasic and basic rocks shown in fig. 2.

ments of porphyritic basalt or dolerite perhaps belonging to the plateau lavas. Peridotite also encloses in places angular xenoliths of more or less identical peridotite and schlieren of dunite. On the south slope of Barkeval I have also found peridotite enclosing angular xenoliths of allivalite. Xenoliths of peridotite are also found in allivalite, and on the eastern slope of Hallival I have seen several drawn-out fragments of a pure plagioclase-rock (anorthitite) enclosed in allivalite.

Harrisite, the third member of the ultrabasic complex, represents the latest intrusion of the ultrabasic magma. It was apparently intruded as a banded sheet into the peridotite in the western part of the complex and its junction with peridotite is marked by an igneous breccia (7, p. 77). Harrisite is a very coarse rock composed mainly of olivine and basic plagioclase. According to Harker, in a typical harrisite olivine preponderates over anorthite, and the more felspathic varieties of this rock are called by him anorthite-peridotite. In my opinion this last name is unnecessary, as harrisite can be made to include all the varieties of coarse olivine-anorthite-rock. My impression is that harrisite differs only in the coarseness of its texture from rocks of the peridotite-allivalite series and that it is in fact a pegmatitic equivalent of these rocks.

The olivine in harrisite usually occurs in the form of platy crystals or platy crystal-groups, often in a parallel or slightly radiating arrangement. It is usually quite fresh and has a good (010) cleavage. Its colour is dark green or black. Very often olivine plates enclose a central plate of anorthite or even a number of such plates in a sort of pegmatitic intergrowth (pl. XII, fig. 5). Anorthite in this rock varies in its degree of freshness. Besides olivine and anorthite small amounts of pyroxene and iron-ore are also present. Harrisite is an extremely variable rock—in composition, texture, and degree of alteration. Probably it represents a final intrusion of a more fluid, volatile-rich residual fraction of the ultrabasic magma.

IV. *The basic rocks.*

The basic plutonic rocks of Rum are mainly represented by eucrite. The eucrite found in the northern and eastern part of the intrusive complex is a massive medium-grained gabbroidal rock without marked banding. In the south-western part of the complex, especially near Harris, eucrite is most strongly banded.

The name eucrite (from the Greek *ευκριτος*, meaning easily discerned) was originally given by G. Rose in 1864 to a stony meteorite composed of anorthite and augite. In 1872 P. Öberg applied the name eucrite to a terrestrial rock of a similar composition found in Sweden. According to Öberg and other Swedish petrologists the type eucrite does not contain olivine, and the olivine-bearing variety is distinguished under the name of olivine-eucrite.

Olivine-eucrite is the basic rock predominant in Rum. It is a fairly coarse gabbroidal rock composed of anorthite, clinopyroxene, and olivine, with accessory iron-ore and occasional orthopyroxene (pl. XII, fig. 6). Eight samples of eucrite from various localities were measured on the Shand stage and averaged (table I). The dominant type of eucrite has a moderate amount of olivine, but in the region of Harris olivine-rich bands and schlieren approaching pyroxene-peridotite are very abundant (table II). Olivine-rich eucrite is rather variable both in texture and in the degree of alteration. Some olivine-rich varieties contain platy olivines intergrown with anorthite after the manner of harrisite.

TABLE II. Modal composition of olivine-rich eucrite (Harris) and quartz-biotite-gabbro (Papadil) expressed in weight per cent.

	Olivine-rich eucrite.	Quartz-biotite-gabbro.		Olivine-rich eucrite.	Quartz-biotite-gabbro.
Olivine ...	57·70	—	Iron-ore ...	3·10	6·95
Pyroxene ...	8·60	25·55	Apatite ...	—	0·30
Hornblende	3·15	17·80	Serpentine mesostasis	14·15	—
Biotite ...	—	4·70	*L*	0·377	0·322
Felspar ...	13·30	41·45	Sp. gr. ...	3·162	2·833
Quartz ...	—	3·25			

From a distance the strongly banded eucrite of Harris looks like a well-banded sedimentary rock. It is composed of alternating bands 2–5 feet in thickness of a normal eucrite and a very coarse eucrite with long curving blades of pyroxene projecting from the margins inwards like tufts of grass. This coarse eucrite is usually much more altered than the normal eucrite—the felspar is saussuritized and the pyroxene partly altered to hornblende. The junction between the bands is sharp but gradational, and the crystals at the junction are intimately interlocked. Veinlets of the coarse eucrite often penetrate into the bands of normal eucrite and some even pass from one coarse band to another, cutting the normal eucrite bands in a zigzag fashion. Some junctions, however, are gradational over an inch or two and also indefinitely outlined nests of coarse rock are found in the normal eucrite.

The coarse rock may be called eucrite-pegmatite. In type and in its mode of occurrence it resembles dolerite-pegmatite found in the Whin Sill and in other basic sills.

The banded eucrite was probably formed from a flow-banded heterogeneous magma, the two fractions of which differed both in composition and in the degree of fluidity. The most fluid fraction, which gave rise to eucrite-pegmatite, was probably solidified last, and this would explain the intrusive veinlets. The intense deuteric alterations of the eucrite-pegmatite were probably due to the hydrous nature of the magma.

Harker mentions the occurrence of subordinate masses of gabbro in Rum (7, p. 96), but whether these are separate intrusions or differentiated portions of eucrite is not definitely established. I have found quartz-biotite-gabbro only in one locality, namely on the shore at Papadil (table II). The relation of this rock to the eucrite found farther to the north could not be determined, it may, after all, be a separate intrusion. The quartz-biotite-gabbro consists of hypidiomorphic labradorite, hypidiomorphic pyroxene partly altered to hornblende, iron-ore in part ringed by biotite, allotriomorphic quartz, and apatite. It is rather difficult to imagine such a type of rock being genetically connected with eucrite.

V. *The junction of granophyre with eucrite.*

The shore near Harris offers a number of excellent exposures of granophyre-eucrite junction. This junction is apparently vertical, but the granophyre sends large horizontal tongues among the bands of eucrite. In places the eucrite along the junction is shattered and penetrated by numerous ramifying veinlets of granophyre. The granophyre situated at a good distance from the junction consists almost entirely of a micrographic intergrowth of quartz and alkali-felspar. The junction between granophyre and eucrite is distinct, but not marked by a very sharp line. The granularity of both rocks remains unchanged at the junction. A few feet from the junction the granophyre assumes a spotted aspect. This is due to the incoming of hornblende in small clusters. Nearer the junction pyroxene makes its appearance, quartz is gradually reduced in amount, and alkali-felspar makes way to plagioclase. The contact eucrite is not much modified beyond a certain uralitization of the pyroxene and increased serpentinization of olivine. In some olivine-rich bands of eucrite olivine occurs in the form of large plates and encloses anorthite, but this may be an original feature of the rock and not a feature due to contact metamorphism.

A number of basalt dikes cut through the granophyre and eucrite across the junction. They dip in various directions, intersect each other and thin out, some in the upward and some in the downward direction.

VI. *Conclusions.*

The Tertiary plutonic rocks of the Isle of Rum consist of (1) an ultrabasic peridotite-allivalite banded complex, intruded by (2) olivine-eucrite, and (3) an adjoining granophyre of a later period. The results outlined in this paper are based on twenty-six modal analyses of peridotite, allivalite, and eucrite. These analyses give an adequate picture of the composition range of the rocks in question. The ultrabasic rocks comprise a continuous peridotite-allivalite series and an analogous parallel series is provided by olivine-eucrite (fig. 3). In their composition as well as in the field relations these two series are quite distinct.

The order of crystallization of minerals in the ultrabasic rocks was apparently conditioned by the composition of the initial magma-fractions. In the melanocratic fraction olivine began and finished to crystallize first, in the leucocratic—plagioclase. The early crystallization products of these magma-fractions are represented by dunite and anorthitite schlieren and inclusions. The order of crystallization of these two minerals is admirably exhibited by their textural relations. In olivine-rich members of the ultrabasic series olivine is idiomorphic, while in the plagioclase-rich members olivine is ophitic to plagioclase. It was suggested by Harker that the degree of idiomorphism of these two minerals may have been determined by their eutectic proportions. From the modal analyses the line separating the field of idiomorphic olivine from idiomorphic plagioclase can be fixed at olivine 35%, plagioclase 65%. Applying a similar method, the individualization fields for all the three principal minerals—olivine, plagioclase, and pyroxene—can also be tentatively attempted, but with a lesser degree of certainty. According to Vogt (11) and Bowen (3) the eutectic proportion between pyroxene and bytownite is 50 : 50 and this proportion fits well into the triangular diagram (fig. 3) in which the boundary line of the felspar field can be drawn from olivine 35 : felspar 65 to pyroxene 50 : felspar 50. The boundary between pyroxene and olivine is more difficult to establish, because of the absence of corresponding rocks. According to Bowen (3) the eutectic between diopside and forsterite is at 87 : 13, while according to Vogt this proportion is nearer to 67 : 33. In view of this uncertainty, which is obviously due to the variability in composition of the two components, the boundary line of the pyroxene field is drawn conjecturally on the diagram (fig. 3). The modal analyses of the Swedish eucrites and allivalites, as given by Du Rietz (4) and Lundegårdh (8), seem to fall well into this diagram.

The suggested eutectic between olivine and plagioclase is based entirely on the study of the textural relations of these two minerals in the rocks of the peridotite-allivalite series. In his study of the ternary system anorthite-forsterite-silica, Andersen (1) found that in the binary system anorthite-forsterite the eutectic is not present and the field of magnesium-spinel intervenes between the fields of olivine and plagioclase. A small increase in silica in the ternary system, however, brings into existence a cotectic line between forsterite and anorthite. A direct application of Andersen's results cannot be made to the ultrabasic series of Rum, for the simple reason that the two minerals in question are not the pure forsterite and anorthite, but olivine (25 Fa, 75 Fo) and plagioclase ($Ab_{10}An_{90}$), and therefore the possibikty of a eutectic is not excluded.

Although the highly controversial problem of banding in igneous rocks cannot be discussed here, as it would involve the consideration of many banded complexes such as the Bushveld complex, the Skaergaard complex (12), and many others, some conclusions may be outlined regarding the banded rocks of Rum. Of the three principal hypotheses, among many others, applied to the origin of banded igneous rocks, namely (1) intrusion of a previously differentiated heterogeneous magma, (2) post-emplacement differentiation in situ, and (3) intrusion of separate magmas, the facts alluded to in this paper favour the application of the first of these hypotheses. The origin of the banded olivine-eucrite cannot, in my opinion, be explained by any other hypothesis, but the banded ultrabasic complex presents a much more difficult problem. On the one hand, we have here, especially in the transition zones between peridotite and allivalite, well-marked fluidal structure, with contorted bands and streaks, so strikingly illustrating a simultaneous intrusion of a heterogeneous magma (fig. 1). On the other hand, we have the evidence of xenoliths, which suggests that at least some of the rocks were solidified before the final emplacement of the magma as a whole. In their study of the Tertiary banded gabbros of Skye, Geikie and Teall have suggested that the banding was produced by the intrusion of a heterogeneous magma (5). Harker, on the other hand, applied this hypothesis only in the case of minor banding within the larger sheets (6, p. 75; 7, p. 74), suggesting that the larger sheets themselves represented distinct intrusions of different magmas which 'followed one another very closely, with intervals scarcely sufficient for the consolidation of one sheet before the next one succeeded it' (7, p. 74). Such a double hypothesis is, in my opinion, unnecessary, as a single hypothesis—the intrusion of a heterogeneous magma—is quite sufficient to explain all the observed facts. An attempt to explain such intratelluric differentiation is quite outside the present field of inquiry. One can only assume that during the process of intrusion the magma-fractions were drawn out together into flow-layers which did not mix because of the highly viscous nature of the magma which was near or at the point of crystallization. Such a crystallization began probably before the final emplacement of the magma, and the products of this early crystallization—dunite and anorthitite, and even later products, peridotite and allivalite—were torn away by a still mobile magma and incorporated in it in the form of schlieren and xenoliths. Such a phenomenon is well known among many igneous rocks under the name of autobrecciation.

There is, however, a certain parallelism between the mechanism of differentiation in the ultrabasic and basic magmas—both of them show a tendency to separate into two fractions. As to the relation between the ultrabasic and the basic magmas, the rock assemblage found on Rum does not provide an answer. In the Swedish localities described by Du Rietz (4) and Lundegårdh (8), peridotite, allivalite, and eucrite apparently form a closely intermixed complex and are either derived from a common magma or are products of intermixing of magmas derived from different crustal layers. The present study of the ultrabasic and basic plutonic rocks of Rum suggests no more than that these were probably formed by the consolidation of fluidally arranged heterogeneous magmas, the two ultrabasic magmatic fractions appearing as olivine-rich and plagioclase-rich bands, while in the basic magma the differentiation gave rise to volatile-rich and volatile-poor bands.

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EXPLANATION OF PLATE XII.

Ordinary light. $\times 4$. L = average granularity of the rock in mm.

FIG. 1. Peridotite, Abhuinn Rangail, NE. of Harris. A very coarse rock with rounded idiomorphic crystals of olivine, set in ophitic plagioclase. ($L = 0{\cdot}957$.)

FIG. 2. Junction of allivalite (upper part) with peridotite (lower part). NE. shoulder of Hallival. The transition between the two rocks is sharp but gradational. The olivine is ophitic to plagioclase in the allivalite and idiomorphic in the peridotite.

FIG. 3. Allivalite, east slope of Hallival. An olivine-rich variety of allivalite with idiomorphic and hypidiomorphic olivine. ($L = 0{\cdot}589$.)

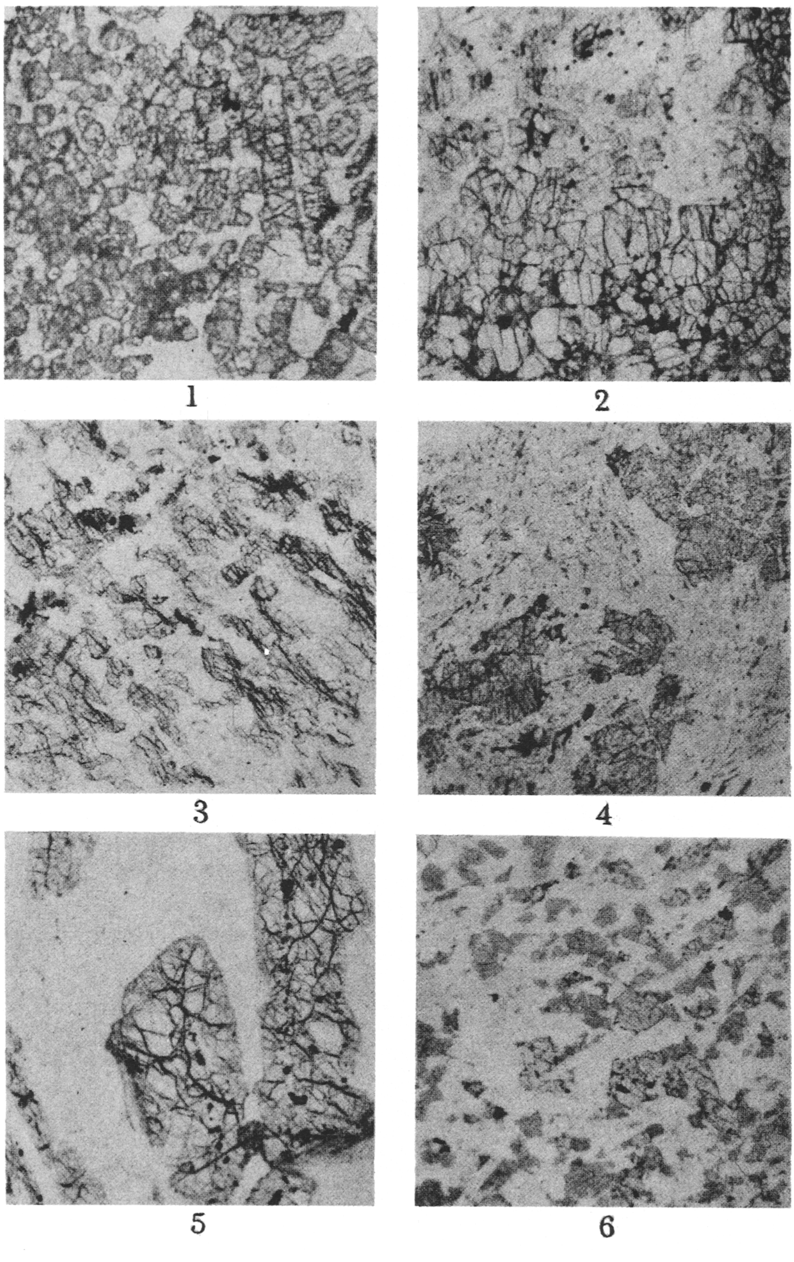
FIG. 4. Allivalite, north of Hallival. A plagioclase-rich variety of allivalite with ophitic olivine. ($L = 0{\cdot}422$.)

FIG. 5. Harrisite, one mile north of Harris. The photograph shows only a small portion of large crystals of olivine set in plexus of plagioclase laths. In the left bottom corner is seen a composite crystal of olivine enclosing plagioclase.

FIG. 6. Eucrite, Allt na h'Uamha, north of Hallival. This rock is composed of plagioclase laths, ophitic pyroxene, ophitic olivine, and a small amount of ore. ($L = 0{\cdot}322$.)

Note on the method of photomicrography.

All the photomicrographs reproduced in this plate have been taken without the help of microscope and camera. This method consists in printing contact negatives directly from the rock sections on a 'positive' cine-film. The negatives thus obtained are then placed in an ordinary enlarger and enlarged prints are obtained. The whole process, apart from the time taken in drying the negatives and the positives, takes only a few minutes per section. Only coarse-grained and medium-grained rocks can be photographed in this way. The enlargement, as a rule, cannot exceed $\times 15$ linear without losing in definition. The advantage of this method, besides economy both in time and money, is the large field which can be obtained by using low magnification.



S. I. TOMKEIEFF: ROCKS FROM ISLE OF RUM.