THE LAYERED ULTRABASIC ROCKS OF RHUM, INNER HEBRIDES

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[Plates 1 to 5]

CONTENTS

The Tertiary volcanic centre of Rhum is best known for the ultrabasic rocks which outcrop over 9 square miles of mountain country. A. Harker (1908) and subsequent investigators attributed their formation to a series of sill-like injections of magma already partly or completely differentiated into allivalitic and peridotitic material. The object of the present investigation was to describe this interesting assemblage of rocks in more detail and to reconsider its manner of origin in the light of modern petrological research, especially recent work on layered intrusions.

The ultrabasic and associated basic rocks were re-mapped over an area of 3 square miles, including Hallival and Askival, the highest mountains of the island. Within a ring-shaped fracture which separates the igneous centre from the Torridonian sediments, there is visible a thickness of 2600 ft. of rock consisting of magnesian olivine, bytownite-felspar, diopsidic pyroxene and chrome-spinel, the minerals being arranged in layers which differ considerably in thickness and in the proportion of the constituent minerals, but yet dip regularly at about 15° towards a centre lying to the west of the area mapped. The variation in the layers is rhythmic rather than cyclic, and in this respect is comparable with the Bushveld, Skaergaard and Stillwater basic layered intrusions. The broad rhythmic pattern consists of an olivine-rich rock passing gradually upward into a plagioclase-rich rock, termed peridotite and allivalite respectively by Harker. These names are retained but their meaning is more precisely defined. A new rhythm begins abruptly with a fresh olivine-rich rock, the spinels being concentrated at the beginning and the clinopyroxenes near the end of a rhythm. Fifteen major rhythmic units have been recognized and traced over great lateral distances; each has a distinct character yet possesses a majority of characters common to the series.

The best developed rhythm, unit 10, has been studied in detail as a type, the others being considered only in so far as they diverge from the standard pattern. The range in mineralogical composition is from a rock containing 80 % of olivine to a pure felspar rock, the clinopyroxene and spinel usually constituting 5 to 15 %. Though rare concentrations of spinel occur there are no monomineralic olivine, pyroxene or spinel rocks.

The olivine, plagioclase felspar and clinopyroxene from an allivalite of the type unit were chemically analyzed. The olivine is Fa_{14}, the plagioclase An_{84} and the pyroxene $Ca_{44}Mg_{49}Fe_{7}$. There is no appreciable variation in the composition of the unzoned cores of minerals within the layered series, apart from an oscillation in plagioclase composition between An_{83} and An_{88}. Zoning is practically absent from minerals of the upper seven units, but normal zoning is developed lower in the series, the range being An_{84} to An_{44} in the lowest unit. In view of the felspar composition it is suggested that Harker's term allivalite be extended to include rocks in which the felspar, present in excess of olivine, has a composition An_{80} to An_{100}.

Most of the area originally mapped by Harker as eucrite sheets has been shown to form the three lower units of the layered series. Two broad sheets mapped earlier as allivalite are now recognized as later intrusions of a fine-grained olivine-gabbro. The lower of these sheets contains numerous inclusions, many ultrabasic, which led Bailey (1945) to support the separate injection hypothesis of Harker for the whole series, as he believed the sheet to be an allivalite of the ultrabasic series. No inclusions are found in the layered series of this area, such streaks and lenticles as are found being identified as the result of auto-brecciation, frequently associated with slumping.

The textures indicate that the layers formed from a body of magma through the bottom accumulation by sinking of crystals whose ultimate size, shape, orientation and distribution were governed by the order of crystallization and relative densities of the minerals, and perhaps also by the winnowing action of currents within the liquid and the occasional release of volatiles and influx of fresh magma associated with surface vulcanicity. The interprecipitate liquid has played an important role, adding material to the margins of the primary precipitate crystals and sometimes forming poikilitic growths where no primary crystals of the particular mineral existed. The ultimate size of minerals with a poikilitic habit is a function of the number of centres of growth developed, which is related to the ease with which diffusion could operate in the interstitial liquid. Some peridotites contain poikilitic plates of felspar and pyroxene 3 cm in diameter each enclosing about 10000 olivine crystals. Fluctuations in the rate of deposition of layers would affect the extent to which diffusion could occur between interstitial and overlying liquid, and they are believed to be responsible for variety in proportions of minerals, including the development of monomineralic felspar layers, and also for the non-systematic variation in the composition of the minerals, usually evidenced by normal zoning. The lower units are considered to have been deposited faster than the upper units, while the rate of deposition within each unit apparently decreased from bottom to top. Periods of non-deposition resulted in the upward growth from the top surface of the accumulating crystals of long, branching olivine crystals forming the 'harrisite structure'.

The composition of the magma has been estimated from the composition of interstitial liquid trapped at certain horizons, and from comparison of this with the associated undifferentiated gabbros. The composition thus obtained is that of a tholeiitic basalt, and the minerals of the layered series are such as would form during the early stages of the crystallization of many known basalt magmas.

It is suggested that the sub-crustal chamber in which this magma slowly cooled was connected with the main volcanic conduit, and that intermittent surface extrusion occasionally removed liquid from the chamber, while fresh material replaced it from below. Such replenishment would account for the great thickness of ultrabasic material crystallized within a narrow temperature range and for the absence of overlying, lower-temperature layered rocks.

Subsequent to consolidation of the layered series in depth a ring-shaped fracture developed and the layered rocks, probably representing only a small portion of an extensive complex, were driven up to their present high level with the help of the lubricating action of what is now the structureless marginal gabbro.

1. INTRODUCTION

(*a*) *Situation and topography*

The Isle of Rhum is the largest of the Small Isles of Inverness-shire with a total area of about 42 square miles (figure 1). A Tertiary igneous complex occupies 19 square miles in the south, while the northern half is mostly Torridonian sediments. The general geology of the island has been admirably described by Harker (1908), and the distribution of rock types is shown on Sheet 60 of the 1 in. to 1 mile geological survey of Scotland, published at the same time as the Memoir. For the purpose of this investigation, detailed mapping was confined to an area bounded by Cnapan Breaca in the north and Beinn nan Stac in the south, including Hallival and Askival, their western slopes down to the head of Glen Harris and the eastern contact of intrusive rocks with country rock. The area is largely made up of well-banded ultrabasic rocks, the allivalites and peridotites of Harker. These two rock types occur in gently inclined, alternating layers generally dipping westward, towards the head of Glen Harris. The layered series form Askival (2659 ft.) and are exposed on the east side down to a contact with sediments at 460 ft. To the west the ultrabasic rocks can be traced into the Harris area, but by this time the uniform layering has given way to more complicated conditions. The boundary of the ultrabasic mass with the country rock appears to have been originally roughly circular in plan view with the head of Glen Harris as a centre. Below the 1250 ft. contour in the area mapped, the structure of the ultrabasic rocks is masked to some extent by a later intrusion of slightly discordant gabbro.

The total area of ultrabasic rocks in Rhum is close to 12 square miles, the part investigated in this paper representing only a quarter of this area, but including the highest ground. Exposures are good owing to the sparsity of glacial debris and vegetation, though complete exposure along traverses is not often found because of the easy weathering of the olivine-rich rocks. The contact between marginal intrusive rocks and the country rock is a good deal obscured by vegetation. In the absence of a contoured, 6 in. topographical map the area has been mapped on vertical air photographs having a scale of approximately 6 in. to 1 mile.

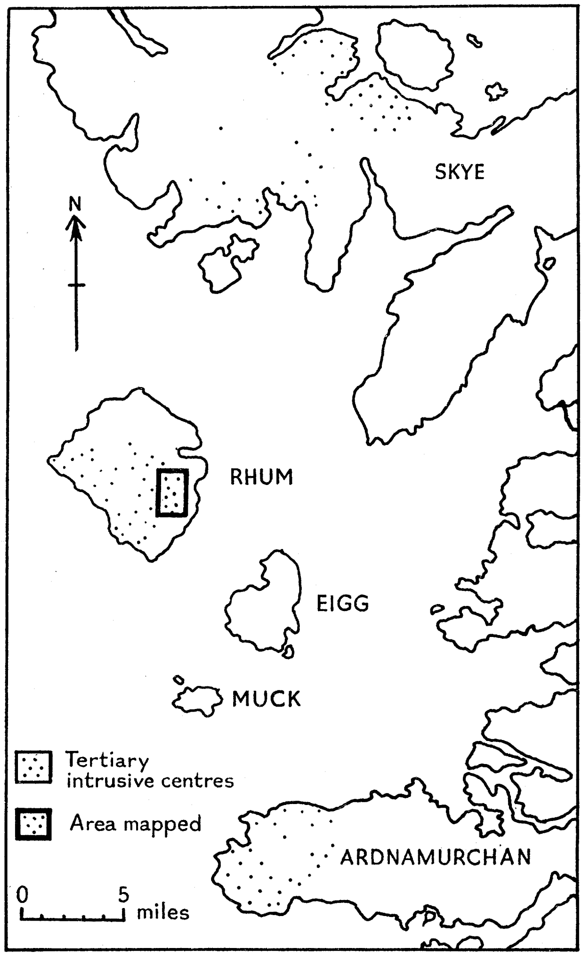

FIGURE 1. The geographical locality of the mapped Hallival-Askival area within the Inner Hebrides.

(*b*) *History of investigation*

Although the geologist Jameson visited the island, the first to record some detail of the geology of Rhum was John Macculloch (1819), who recognized that the crystalline rocks of Hallival and Askival were 'evidently posterior to some or all of the Secondary strata', and distinguished them from the more siliceous crystalline rocks of the west coast.

In 1874 J. W. Judd suggested that Rhum, together with other similar Hebridean volcanic areas, should be regarded as the site of a central volcano. In 1885 he says of the rock types that 'All these forms are found passing into one another by the most insensible gradations, and it would be possible, though, I think, most inexpedient, to propose names for other curious mineral combinations which occur here' (p. 395). He comments on the similarity between these insensible gradations and those evidenced in the Shiant Isles. He also recognizes the importance of crystal fractionation in the production of certain mineral assemblages, and the presence of a later, yet genetically related, intrusive gabbro (p. 359).

The work of Judd was followed by that of Sir A. Geikie, whose observations on Rhum are summarized in *Ancient volcanoes of Great Britain* (1897). Geikie gave several sketches showing the striking terraced features of Hallival and Askival.

In 1902 and 1903 A. Harker surveyed the major part of the Small Isles of Inverness-shire, mapping on a scale of 6 in. to 1 mile and reproducing the geology of most of the area (including the whole of Rhum) on Sheet 60 of the 1 in. to 1 mile geological survey of Scotland, in 1908. This excellent map was accompanied by the Memoir (1908) of which Geikie, then Director of the Geological Survey, said that it would not be a repetition of what had already been written of Tertiary igneous activity in Skye (1904), but would aim at bringing out points of special interest in the geology of the Small Isles.

Harker devotes the whole of chapter 8 to the ultrabasic rocks of Rhum, and it is this account which won for these rocks an important place in petrological literature. He established, amongst the ultrabasic rocks, an alternating series of almost horizontal layers of plutonic rock which differed one from another mostly in the relative proportions of calcic plagioclase and olivine. The layers rich in olivine were called peridotite and the layers rich in plagioclase were called allivalite, after the mountain Hallival in Rhum. In order to explain the rhythmic alternation Harker postulated the differentiation of a magma at depth into two distinct fractions, an olivine-rich and a plagioclase-rich, which were then alternately injected in a descending sequence, the absence of chilling being explained by the rapidity with which each injection followed its predecessor. Although he often comments on the unique regularity of the banding, the indistinct nature of some of the interstratiform contacts, and the probability, within some of the layers, of differentiation in place, the hypothesis of sill-like separate injection drew strength from the fact that the individual layers appeared to die out when traced laterally, that contacts were sometimes sharp, and that xenoliths of one band often appeared to be caught up in neighbouring bands. In addition to this series of rocks Harker recognized the existence of a later sheet of pegmatitic olivine-felspar rock which he called harrisite, intruded beneath the western exposures of ultrabasics, and of a later intrusion of eucrite, below the harrisite and conformable with the general stratiform structure of the whole area. Though he suspected an intrusion of gabbro in the lower ground to the east, he did not map it as distinct from the eucrite.

More recent work includes that of F. C. Phillips (1938), who investigated, by petrofabric analysis, the orientation of minerals in some of Harker's ultrabasic specimens, and S. I. Tomkeieff (1942) who produced an account of the Tertiary lavas of Rhum. Sir Edward Bailey (1945) investigated several problematical areas in Rhum, chiefly connected with the Tertiary igneous tectonics. Of special significance was the recognition and detailed description of a ring-shaped fault separating the Tertiary volcanic rocks from the Pre-Cambrian gneisses and sediments. C. E. Tilley (1944), subsequent to the reading of

Bailey's paper, investigated the character of the 'Tertiary' gneisses amongst Harker's specimens and concluded that they were Lewisian.

In 1945, Tomkeieff produced a brief account of the petrology of the ultrabasic and basic rocks. His conclusions, based mainly on modal analyses and field relationships, was that the peridotites, allivalites and eucrites grade insensibly one into the other. He also suggested that the evidence did not support a hypothesis of successive injection, but that xenoliths suggesting this were produced by auto-brecciation. He considered that a more tenable hypothesis would be one based on a single injection of previously differentiated heterogeneous magma, the layering being produced during the streaking out of the different components.

A preliminary note on rhythmic layering in the ultrabasic rocks, and on structures in the harrisite, was published jointly by L. R. Wager and the author (1951), on the basis of evidence obtained on the first visit to the island in the summer of 1950.

G. P. Black (1952) has considered some aspects of the geology of the west of Rhum, but this is not relevant to the ultrabasic rocks.

2. Geology of the area bordering the major intrusions

(*a*) *The country rocks*

Within the area investigated there is little variety in the rocks which border the Tertiary intrusions. The country rocks are Torridonian sediments, explosion breccias and felsites. They are separated from the intrusives by a narrow arcuate zone of dislocation. Within 50 yards of the latter the siliceous sediments usually become quartzitic, often enclosing nests of epidote, and the argillaceous become flinty and often biotitic. Over the area as a whole the most impressive metamorphic effect is the bleaching of the pink arkose to a pale green rock, the zone of bleaching being 900 yards wide to the north and north-east of the intrusive contacts.

In the field one is impressed with the similarity between the rocks which form the northern and southern margin (figure 11, plate 1). In each area the Torridonian, the

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U10 ░	The layered ultrabasic rocks divided into units (U1 ... U15), each consisting chiefly of peridotite (stippled) grading into allivalite
+ +	Fine-grained olivine-gabbro
+	Askival-plateau gabbro
˅ ˅	Barkeval eucrite
▲	Explosion breccia
•	?Metasomatized Pre-Cambrian
⬬	Non-ultrabasic inclusions
▥	Dykes and cone-sheets
?	Area not mapped in detail
\ ⁄ \	Marginal zone with structureless gabbro
▨	Zone of felsic veining of fine-grained basic igneous rock
▩	Isolated gabbro
▧	Torridonian sediments
░	Felsite
——	Boundary observed, or inferred from topograghy
- - - -	Boundary tentative
━━	Main ring-shaped fracture
··–···	Other faults
↘15	Dip of layering
↘40	Dip of cone-sheets
–·–·–·	Contours in feet
·····	Footpath
⊗	Analyzed specimens

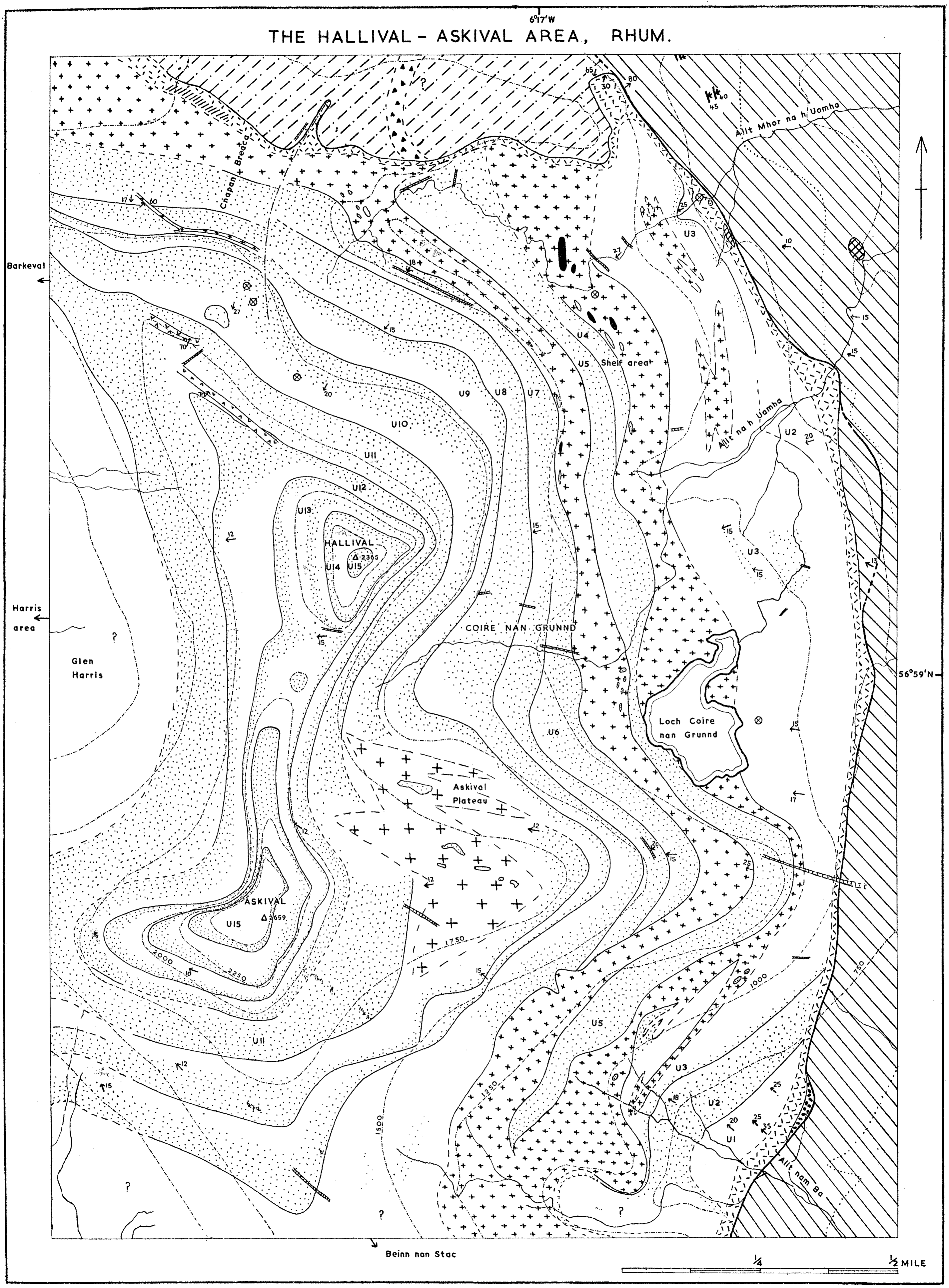

Figure 2. Geological map of the Hallival–Askival area.

explosion breccias and felsites are similar in lithology and field relationships with one another and with the intrusive gabbro. The general impression gained is that the two areas are probably collapsed wall rock of the main intrusion. The breccia represents partially exploded and partially crushed Torridonian, the fact that it passes imperceptibly into folded shales ruling out any bedded, pyroclastic origin.

(*b*) *The dislocation and associated phenomena*

Harker interpreted an arcuate fault or zone of disturbance around the major intrusions of the Hallival–Askival area as a thrust fault of Caledonian age. A brief consideration of the zone, in the field, has led the author to the view that Harker's mapping of the dislocation was as accurate as the field evidence allowed, but that Bailey's conception of a ring fault as the cause of dislocation is a more tenable hypothesis. The map (figure 2) shows the fault, as developed in this area, as a simple structure following closely the lines drawn by both Harker and Bailey. The line of the fault, once approximately established, is easily traceable along the eastern margin even from a distance; where the fault cuts through Torridonian the sediments within the fault zone are so hardened that the ground rises sharply as it is approached and the fault zone is a steep hillside. Where the fault brings Torridonian and gabbro together the actual contact is always obscured by a strip of soil-covered boggy ground, averaging 15 ft. in width, owing to the easy weathering of the gabbro.

The degree of metamorphism is frequently a guide to the position of the fault, for the bleaching and baking which characterizes sediments outside the arcuate zone contrasts strongly with the evidence of mobilization which is frequently found within the zone. There are no exposures of the actual fault, though the general lie of the ground suggests a fairly steep outward dip, best seen on the north bank of the Allt na h Uamha.

3. DESCRIPTION OF THE LAYERED SERIES OF ULTRABASIC ROCKS

(*a*) *Introduction*

From detailed mapping in the field and determinative work in the laboratory it is clear that, within the area mapped, there is a layered intrusion of ultrabasic composition which has subsequently been invaded, often in an intricate fashion, by one or more gabbros.

The ultrabasic rocks form a succession of differing layers all roughly parallel to each other. Despite minor variations in the order of the minerals in the layers a broad rhythm can be discerned, generally consisting of olivine-rich rock passing upwards gradually into one rich in felspar, such a sequence being termed a 'rhythmic unit' or briefly a 'unit'. The units vary in thickness but average 200 ft. Though minor rhythms may be developed in them, they conform to the general rule that their lower parts, containing olivine in excess of felspar, are much thicker than their upper parts in which felspar dominates over olivine. This rule does not apply to the upper 500 to 600 ft. of the intrusion where the relative thicknesses are reversed.

The units have been numbered from 1, the lowest, exposed in Allt nam Ba to 15, the highest, forming the summits of Hallival and Askival, though there is the possibility of the existence of one or two more units in the lower ground between units 2 and 4. The major units show up fairly distinctly in the topography, but the choice is somewhat arbitrary and some of the minor fluctuations could have been equally well regarded as major units. The division of the series into major units is the basis of the mapping, each unit having characteristics which can often be traced over the whole area.

The best exposed and most easily accessible major unit, number 10, is described first as a type unit and this serves as an introduction to the terminology employed throughout the series. Furthermore, the constituent minerals of the type unit and three of the rocks were chemically analysed.

(*b*) *General characters of the units, with particular reference to unit* 10 *as the type unit*

(i) *Field characters*

The layered series is fairly well exposed on Askival and Hallival (figure 10, plate 1) and a gentle dip of the layers is discernible. The dips are relatively constant in the eastern sector, ranging from 12 to 20°, in a westerly direction towards a point in Glen Harris. To the west of Glen Harris the ultrabasic rocks dip eastward. Localized small-scale collapse has produced higher dips in a few isolated localities, reaching 27° in one instance.

The topographic expression of the layering on the north and north-east slopes of Hallival is illustrated in figure 12, plate 1. The resistant bands are the leucocratic parts of each unit, the soil-covered slopes being the easily weathered melanocratic parts. The featuring appears to indicate an equally abrupt change at the top and base of each resistant band, but such is not the case, the lower contact with the underlying melanocratic band being gradational while the upper is abrupt. Thicknesses of units were found to vary laterally only within narrow limits.

The generalized sequence is given in the vertical section (figure 8). Unit 10 is the only unit which can be studied conveniently from near the bottom to the top. The true base is not exposed, but a sharp contact with the felspar rich band is believed to exist because specimen 5328*, collected less than a yard above the highest exposures of unit 9, is an olivine and chromite-rich facies. The top of the unit is marked by a very felspar-rich, platy rock 5348, above which is the olivine-rich facies of unit 11. The unit can be easily traced laterally round the eastern slopes of Hallival until the Askival plateau is reached. Here disruption due to intrusion of a later gabbro has taken place, and the unit is only found as xenoliths of varying size in the gabbro. It is found again, however, on the col between Askival and Beinn nan Stac at the level expected, and is traceable around the south-west slopes of Askival until it is lost in the scree-covered dip slopes at the head of Glen Harris. In the direction of Barkeval the unit can be traced on to the north-north-east slopes of the mountain, but its character is lost as it approaches the north-west slopes where it is invaded by gabbro. The thickness of the unit is not always ascertainable, though it normally lies between 250 and 300 ft.

The lowest exposed rocks, the peridotites, generally consist of 60 to 70 % of well-shaped olivine crystals poikilitically enclosed by plates of plagioclase felspar and, to a lesser extent, green clinopyroxene. The weathered surface is often pitted, the poikilitic felspar forming resistant knobs while the poikilitic pyroxenes weather into hollows (figure 30, plate 4).

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* Specimens 5328 to 5348 have special reference to figure 7, p. 27. All specimens referred to in the text are housed in the rock collection of the Department of Geology and Mineralogy, University of Oxford.

This feature is only observed where the poikilitic minerals are large (1 to 2 cm diameter); more commonly they are much smaller and the small-scale honeycomb surface is sometimes found.

The melanocratic facies of the unit varies in appearance, but to a much less degree than does the leucocratic. A greater grain size (specimen 5108), especially of the elongated olivines (6 to 8 mm length) is found in bands averaging 1 ft. in thickness, there being at east four in this unit. The feature is more obvious in the field than in the hand specimen. The elongation of the olivines is usually in a vertical direction, and the later growth of felspar following the same direction emphasizes the structure, owing to its greater resistance to weathering. Because it reaches its greatest development in the olivine-rich rocks to the west of the island, near Harris, and because these rocks were called harrisite by Harker, who believed them to be part of an intrusion separate from that of Hallival and Askival, the structure is called the harrisite structure. In the Harris area the thick peridotites are layered through the alternation of normal peridotite with that showing harrisite structure (figure 29, plate 4). In the units of the Hallival–Askival area, on the other hand, the harrisite structure is less commonly developed, the layering being caused by the development of a felspar-rich top to each unit of peridotite. A special feature of the harrisite structure is a tendency for the olivines to branch (figure 42, plate 5), and it has been suggested in an earlier paper (Wager & Brown 1951) that the structure was developed during periods of non-deposition and the upward growth of the branching olivines.

A type of 'lace structure' is developed in 5602 and was photographed from a large block found in the vicinity of unit 10 exposures on the Askival plateau (figure 13, plate 2). The thin section shows that small olivines (0·3 mm) are dominant, partly enclosed poikilitically by felspar, but there are also long stringers of single crystals of rather larger olivines (0·5 to 0·6 mm.) stacked end to end. Weathering produces the lace texture by hollowing out the olivine columns and thus emphasizing the felspar-olivine areas.

Other features developed in the melanocratic rocks are connected with the variation in proportions and habit of the three chief minerals present. Throughout the lower 180 ft. of the unit there appears to be little change in the proportion of felspar to olivine, but higher up the percentage of felspar increases and continues to do so throughout the next 110 ft. The division between leucocratic and melanocratic sections of the unit is not a sharp one, but the zone in which a fairly rapid change in proportions takes place is definable within a few feet. Above the zone there is a gradual increase in felspar, masked in the field by the small-scale rhythmic layering which develops at this horizon. The most felspathic part of the unit (5348), forming the top 5 ft., is immediately underlain by a narrow zone of slumped melanocratic material.

The change from melanocratic to leucocratic rocks is marked in the field because of a change in the structure of the rocks as seen on the weathered surface. The honeycomb feature disappears and the weathered rock surface becomes progressively smoother until, in the case of the rocks which Harker called allivalite, a smooth, pale-coloured weathered surface is produced. In passing through the upper part of the melanocratic section the size of the felspars gradually decreases while the number increases, until eventually a texture governed by an abundance of small primary felspar crystals is found—the allivalite texture.

Fine-scale rhythmic layering is well developed in the leucocratic horizons of most units. As shown for many other intrusions, it is the result of a rapid alternation in the proportions of minerals present in the rock. In this case the three minerals felspar, olivine and clinopyroxene vary in proportion over short vertical distances so as to produce thin layers (1 mm to several cm) ranging from pure felspar to layers consisting largely of clinopyroxene. There is rarely more than 30 % olivine or 60 % clinopyroxene, although there is every gradation between these limits. Hand specimens consisting of olivine-felspar, pyroxene-felspar, pure felspar and approximately equal proportions of all three minerals (average grain size 0·5 mm.) are common. The probable cause of the layering will be discussed later, but it may be noted that gravity stratification has not been observed except occasionally in unit 9; a fine-scale layering, confined to the upper few feet of most units (figures 14, plate 2 and 22, plate 3), usually ends with a very felspathic layer which has a platy fracture because of the igneous lamination. Linear parallelism of minerals has not been observed.

In the vicinity of the Askival plateau, despite complications due to the intrusion of the later gabbro, the various features of unit 10, particularly in the leucocratic facies, are easily recognizable (e.g. figure 14, plate 2, showing the fine-scale banding of a large exposure preserved from disruption). As unit 10 is followed into Coire Nan Grunnd the leucocratic section thins rapidly and almost disappears. This thinning is believed to be connected with plastic flow and slumping of the unit, possibly associated with an early gabbroic injection.

The melanocratic section of unit 10 is cut by occasional veins, averaging an inch in thickness, which usually dip 10 to 15° inwards, though local irregularity, with slightly higher dips, is sometimes found. These veins are never inclined at a high angle to the dip of the unit and their margins, while clearly defined, are by no means sharp. They consist of large crystals of green clinopyroxene and felspar with subsidiary olivine. Veins of this type, which will be called 'contemporaneous ultrabasic veins', are occasional found in other units, but, as in unit 10, they are never traceable beyond the limits of the melanocratic section of individual unit. Their probable origin is discussed in §3*b* (vi).

(ii) *Nomenclature*

As each unit contains rocks consisting of a varied assortment of crystals in different proportions and with different textural relationships it is unsatisfactory to establish arbitrary types, for this obscures one of the significant features of the rocks—the gradation between varieties. Nevertheless, it is apparent, both in the field and laboratory (cf. figure 7), that there are two main types: one, from the lower part of the unit, contains approximately 75 % olivine, 15 % felspar, 8 % clinopyroxene and 2 % chromite, and has a specific gravity of about 3·28; the other, from the upper part of the unit, contains approximately 70 % felspar, 20 % olivine and 10 % clinopyroxene, and has a specific gravity of about 2·90. These rocks were named by Harker peridotite and allivalite respectively and were considered to be separate sheet intrusions. As used by Harker in Rhum the name peridotite included all rocks in which 'olivine largely preponderates' and allivalite included all in which 'the two minerals are in approximately equal amount, or the felspar predominates'. Together with harrisite these rocks were considered by Harker as the 'leading types'.

A preferable terminology, in view of the insensible gradations involved, would be one which employed only one rock name and qualified it by using melanocratic and leucocratic for the two respective types. This method is, however, unwieldy, and as Harker's names are well known they are adopted here. Tomkeieff (1945) stated that a line could be drawn separating rocks with idiomorphic olivine from rocks with ophitic olivine, at a composition 35 % olivine : 65 % felspar, these proportions being related to the olivine-plagioclase eutectic. No evidence was obtained during the present investigation to support the application of such a definite dividing line, truly ophitic olivines being rarely encountered.

For the type unit it appears that a division could be drawn at the level between specimens 5339 and 5340, about 210 ft. above the base, where the modal felspar changes from 41·5 % to 54 %, and there is a loss in euhedral form of olivines and a development of it in felspars (see figure 7). This distinction proves generally of value, and the term peridotite is applied to those rocks in which the olivine:felspar ratio is greater than 50 %, while allivalite is applied to those in which the ratio is less than 50 %, there being subsidiary clinopyroxene and chromite in most cases. The dominant mineral is invariably euhedral to subhedral, while the subsidiary mineral is frequently anhedral, a point emphasized by Harker (see below). The presence of more than 20 % clinopyroxene or chromite is indicated by a prefix. In using the term peridotite for these Rhum rocks it is being regarded as a group name for olivine-dominated ultrabasic rocks; there are sufficient separate names for felspar-free subgroups of the peridotites to avoid confusion.

In connexion with the term allivalite it is necessary to anticipate the petrographic descriptions in which it is demonstrated that, in the modern sense, no anorthite exists in the layered series, the dominant felspar being a calcic bytownite. Such rocks could be described as olivine-eucrites were it not that Harker's distinction between the allivalites with ultrabasic affinities and the Ardnamurchan eucrites with basic affinities is believed to be a useful one. It would be a pity to lose this means of differentiating between sodic and calcic bytownite-bearing rocks, and it is suggested than an allivalite is defined as a dominantly olivine and felspar rock in which the felspar is more calcic than An_{80}. (If the term troctolite were extended to include also those having felspars An_{70-80}, then the rocks of olivine and basic felspar would be completely covered.)

The term eucrite is only used in this account for the rocks of a small, later intrusion of bytownite-bearing rock differing widely from the layered series. The olivine eucrites described by Tomkeieff (1945, p. 132) as basic rocks, composed primarily of anorthite, clinopyroxene and olivine, are classified as peridotites of the ultrabasic series in this account. The rock name harrisite has been dispensed with, the rocks previously grouped under this name being considered a structural modification of the normal peridotite with harrisite structure.

(iii) *Textural characters*

The textural changes in the type unit, which depend mainly on the different crystals present and their shape and size, are summarized with photomicrographs and graphically in figures 15 to 19, plate 2; figure 7. The striking features are the concentration of olivines and (to a lesser extent) chromites at the base of the unit, the increase in felspar at the expense of olivine towards the top, and the change in shape of the olivines and felspars as the relative proportions change. The clinopyroxenes show no regular change in amount, though their maximum concentration is in the upper part of the unit, but changes in their shape and size are significant (p. 17).

Because of the small number of minerals involved the variation in the habit of each may be considered in turn, prior to a discussion of the cooling history of the unit as a whole. Such variation is believed to be connected, primarily, with the accumulation of a precipitate of crystals and the subsequent crystallization of the interstitial liquid. In order to be able to employ this concept during the textural descriptions, a brief outline of the principle is included at this stage.

The concept of primary precipitate and interprecipitate material. Wager & Deer (1939, p. 127) showed that the layered series of the Skaergaard intrusion was derived from:

(*a*) A primary precipitate of discrete crystals.

(*b*) Interprecipitate material formed from the liquid occupying the interstices between these crystals.

The authors estimated that the primary precipitate formed 80 % of a layer at any one time, and that the 20 % of interstitial liquid crystallized either as a coating to the discrete crystals or as new minerals, in the interstices. This concept, also suggested by Hess (1939), is believed to be of fundamental importance in explaining the formation of many layered intrusions including the ultrabasic rocks of Rhum.

Since the publication of Harker's memoir in 1908 many aspects of the petrology of Rhum have been translated into other publications, especially his explanation of the textures of some of the rocks on the basis of the order of crystallization. Harker (1908, pp. 85 to 86) noted three important textural varieties which he related to the proportions of the minerals:

(*a*) Olivine in excess, and idiomorphic towards felspar.

(*b*) Felspar in excess, and idiomorphic towards olivine.

(*c*) Eutectic proportions, the two minerals having crystallized simultaneously with neither one idiomorphic.

Harker, believing that the rocks formed from separate sill-like intrusions of magma which crystallized entirely in position necessarily assumed that the rocks retained faithfully the composition of the magma. One of the magmas of peridotite composition crystallized to give idiomorphic olivines with some allotriomorphic plagioclase (type (*a*) above) and the other of allivalite composition gave idiomorphic plagioclases with allotriomorphic olivine (type (*b*) above). The third texture, type (*c*), was presumably derived from another magma of intermediate composition. Within the individual sills Harker recognized fine-scale banding, which was attributed to the streaking out of heterogeneous patches contained in the intruded magma. In explaining the bands of pure anorthite rock, the narrow seams of chromite, the pyroxene banding and the textures resembling 'concretionary growth' and 'the shapes of sponges and corals' (1908, p. 75) he also postulated 'differentiation and segregation subsequent to the intrusion of the sheet'.

For a variety of reasons considered later (§6, p. 42) it is believed that differentiation of a homogeneous basic magma to give the various rocks encountered in the Rhum layered series did not take place until crystallization began, and then the primary precipitate crystals of olivine, plagioclase, clinopyroxene and chrome-spinel settled to the floor of the magma chamber to form layers varying in the proportions of the four minerals present. Whether the variation be due to the order of crystallization of the minerals from the magma, rhythmic alternation in the order being produced by temperature, pressure and compositional fluctuations, or whether it be due to a crystal sorting mechanism acting differently on the four minerals will be discussed later (p. 45). There is good evidence, however, that the layering was produced mainly by variation in the mineral proportions of a primary precipitate of crystals accumulated on the floor of a magma chamber.

In a layer consisting of olivine crystals the liquid occupying the interstices would, upon crystallizing, deposit olivine as a border to the primary crystals, the other minerals growing in the interstices from sparse centres of spontaneous crystallization, to form anhedral poikilitic patches. The size of the poikilitic growths would be dependent upon the number of centres formed which would in turn depend largely upon the composition and viscosity of the interprecipitate liquid and the ease with which diffusion could take place within it. Such a process would produce the textures of the peridotite of the layered series (type (*a*) of Harker), whilst a similar process involving layers of felspar crystals would produce the texture of the allivalite (type (*b*) of Harker). In a layer consisting of approximately equal proportions of olivine and felspar interprecipitate growth would take place about these primary crystals and the final texture (type (*c*) of Harker) would be chiefly governed by mutual interference during growth. The variety in the proportions of primary minerals is, in fact, equalled by the variety in textures and assemblages produced during the crystallization of the interprecipitate liquid.

If the interprecipitate liquid completely crystallized in the interstices between the primary crystals the rocks produced ought to contain minerals with crystallization temperatures lower than those of the primary precipitate, either as new minerals (e.g. the apatite and quartz of the Skaergaard gabbros) or as borders to normally zoned primary minerals. The absence of such rocks in the upper part of the layered series is believed to be due to a process of diffusion similar to that outlined by Hess (1939). When no great distance separated the interprecipitate liquid from the overlying magma then crystallization of a small amount of material from the liquid would produce a composition gradient in the interstitial liquid and a diffusion process, in the fashion outlined by Bowen (1921), would commence. In this case there would be homogeneous enlargement of the primary crystals. On the other hand, more rapid deposition of the primary crystals would greatly enlarge the distance between the interprecipitate liquid in the lower layers and the overlying liquid, with the result that the composition of the former would not be effectively altered by diffusion of material from the overlying liquid. Hence cooling would produce a lower temperature assemblage of minerals in the space between the primary crystals, as is found in the rocks of the lower part of the layered series. The concept of the important part played by diffusion in the interstitial liquid is considered further in §6*d* (p. 49)

The habit of the olivines. Olivine, the most abundant mineral of the unit, is present in most of the rocks as a primary precipitate mineral which has additions to its margins from the interprecipitate liquid. In the felspathic rocks near the top of the unit the shape of the olivine is largely adapted to the shape of the felspars, although a truly poikilitic texture is not seen.

The size as seen in sections varies within narrow limits, from a maximum of 2 × 1·5 mm to a minimum of about 0·3 × 0·2 mm, except for the few zones with harrisite structure where olivines may attain a length of 7 in. The average grain size and variation in shape of the olivine from base to top of the unit are indicated in figure 3. A relatively unmodified shape persists for 150 ft. above the base of unit (to 5338), after which the olivine becomes modified by irregular interprecipitate growth of olivine, controlled essentially by the neighbouring felspar crystals. Few grains, however, are so poikilitic in habit as to suggest that they formed entirely from the interprecipitate liquid; it is likely that a primary crystal existed for each olivine, the degree of modification being a reflexion of the number of such primary crystals present at that horizon. The texture of 5342 suggests that composite clusters of small felspars, enwrapped by an olivine which was subsequently modified by later olivine growth, may have been precipitated (figure 35, plate 4). Occasionally within a single thin section more than one size and shape of olivine grain is seen, in which case both types have been shown in the diagram. In the lower horizons of the unit the few small grains may represent those which have travelled only a short distance and so have

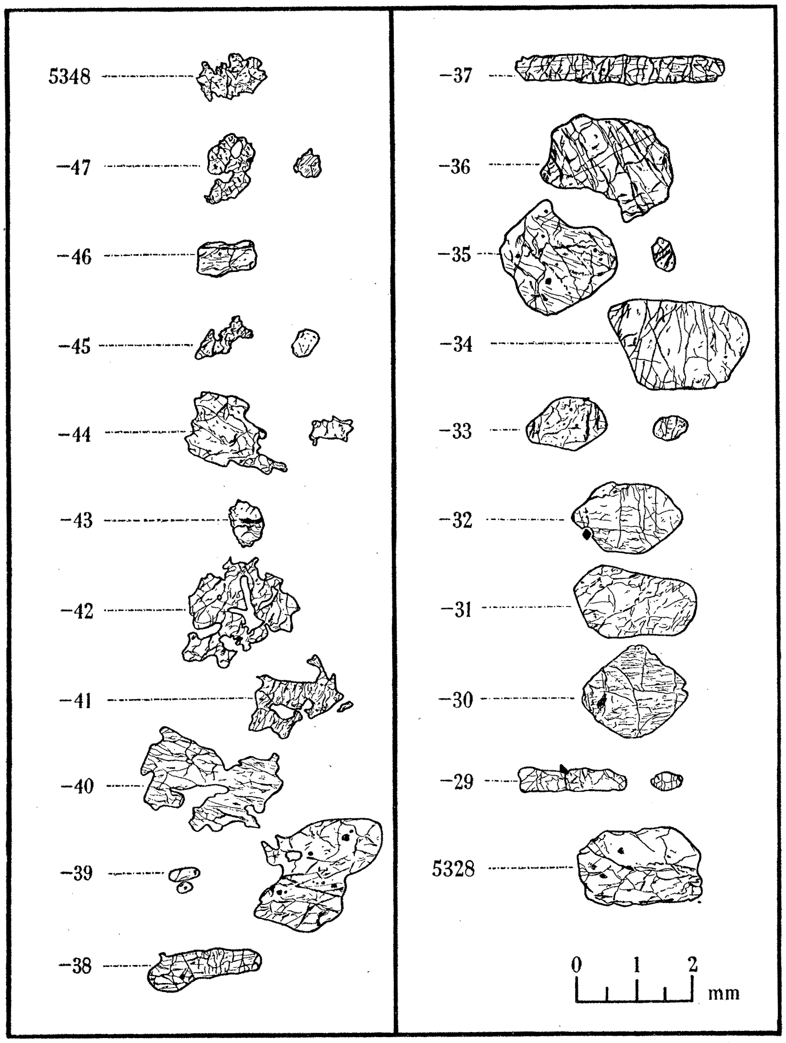


FIGURE 3. Variation in size and shape of olivines within the type unit. Illustrated by camera lucida drawings of grains which typify rocks from 5328 (base) to 5348 (top).

had little time in which to grow (Bowen 1915*a*, p. 177). In the upper horizons, however, where interprecipitate growth is important, the small grains, admittedly of rare occurrence, appear to represent primary crystals which have failed in some way to be fed with olivine-precipitating liquid. In most of the higher rocks of the unit there seem to have been olivine crystals in the primary precipitate, although it is clear that the average grain size of the crystal and, for that matter, of the whole extended grain, is less than the average for the lower rocks.

The euhedral form becomes less marked towards the top with two exceptions, 5343 and 5346; these two rocks are also exceptions in the steady upward decrease in density, and they apparently represent a minor rhythmic precipitation of a batch of crystals consisting largely of olivine in one case (5343), and largely of primary clinopyroxenes in the other (5346).

It will be noted that in two zones (5329 and 5337), a deposition of olivines occurred which are elongated parallel to c and flattened parallel to (010). The reason why such tabular crystals should suddenly appear and disappear is not understood. Phillips (1938) recognized a distinct fissility in an olivine-rich rock from the head of Glen Harris, Rhum, and indicated, by petrofabric analysis, that the olivines were flattened in a plane perpendicular to α and orientated within the rock so as to induce fissility parallel to that plane. He suggested that such fissility was induced during the intrusion of this rock in a largely crystalline state. However, Phillips has recently shown that such an apposition fabric may be produced during normal sedimentary deposition, and it is suggested that the lamination of the ultrabasic rocks of Rhum should be considered as due to this cause.

The habit of the plagioclase felspars. A calcic plagioclase is almost as abundant as olivine in the layered series. In the type unit the proportion varies from 10 to 82 %. Greater extremes are found in a few other units, a pure felspar rock being recorded from unit 14 (figure 38, plate 5). No rocks have been found, in this area, to be entirely free from felspar.

A gradual change takes place in the shape and size of the felspars from large poikilitic grains in the lower, melanocratic rocks to smaller euhedral lath-shaped prisms, flattened on (010), which constitute the bulk of the allivalites (figures 15 to 19, plate 2). There is sometimes an approach to a more equidimensional shape, and commonly the smaller grains of a section are more equidimensional than the larger ones. A comparison of felspathic rocks from the various units shows that the development of the tabular shape is not related to height in the layered series. In many of the layers igneous lamination is strikingly developed, for example, in 5042. The ratio of thickness: length of the felspar tablets averages 1:3, although in some cases it reaches 1:12. The common habit of the (010) section, throughout the layered series, is roughly equidimensional, which is in contrast to the Skaergaard intrusion where the equidimensional (010) section of the felspar tablets of the hypersthene olivine gabbros gives place upward to sections 'elongated along the X crystallographic axis until this direction is 2 or 3 times that along the Y axis' (Wager & Deer 1939, p. 70). Because of this equidimensional character the possibility of linear parallelism of felspars does not arise in Rhum. Sections parallel to the lamination show the inter-grain boundaries between felspars to be much more irregular than do sections perpendicular to this plane, where the grain boundary, subparallel to the crystallographic (010) plane, intersects the plane of section in almost a straight line. This suggests that the tablets were deposited with their (010) planes almost in contact, as now seen, and that interprecipitate growth was thereby restricted to directions perpendicular to *b*.

The habit of the clinopyroxenes. Much less common than olivine or felspar, clinopyroxene is, nevertheless, nearly always present. Thus the pure olivine-felspar rock, once thought to exist in quantity in Rhum, is, in fact, a rarity, while a rock from unit 9 contains the recorded maximum of about 70% euhedral clinopyroxene. Although a traverse from base to top of several units shows no systematic variation in pyroxene content, the concentrations are always found towards the top of each unit. In units deficient in pyroxene-felspar bands, the clinopyroxene content varies from about 1 to 15%.

In the type unit the following textural varieties are found among the pyroxenes:

(1) In the melanocratic rocks (figure 19, plate 2), large poikilitic plates, average diameter 4 to 6 mm. enclosing olivines and small felspars. The size of the large, optically continuous plates suggests few or no primary pyroxenes at the lower horizons.

(2) As the more leucocratic levels are approached (figure 17, plate 2) the pyroxene plates, though poikilitic to a great extent, have a core (up to 2 mm diameter) which contains no inclusions, and which probably represents the settled crystals. In the same rocks discrete pyroxenes, though rare, are to be found.

(3) In rocks such as 5340 and 5341 (figure 16, plate 2) the pyroxene occurs as a large plate enclosing small felspars and olivines. Because of the distance separating the felspars and olivines enclosed in this pyroxene compared with the other parts of the rock the pyroxene cannot have formed by interprecipitate growth. The texture is believed to have resulted from the accumulation of 'composite clusters', consisting of small felspars and olivines enveloped by clinopyroxene.

(4) At higher levels of the unit the pyroxenes occur as discrete crystals, their shape hardly modified by interprecipitate growth (e.g. 5343 or 5049, figure 37, plate 4). The crystals are almost equidimensional, ranging in size from 0·2 to 1 mm and averaging 0·6 mm.

(5) The highest level is a horizon of rhythmic banding on a fine scale, and includes rocks such as 5049. The bands may be of felspar, felspar-olivine, or felspar-clinopyroxene-olivine, alternating at intervals of a few millimetres, while rhythmic variation in grain size is also apparent. In the layers consisting almost entirely of olivine and felspar the clinopyroxene exists as a narrow sinuous growth, generally 0·05 mm (never greater than 0·1mm) in thickness, interstitial to both olivine and felspar. In a finely banded section of 5049 the change from discrete crystals to this kind of pyroxene takes place within a distance of 5 mm and the two types are apparently complementary.

The common poikilitic habit of the clinopyroxene and sometimes the felspar in the layered series of Rhum provides a beautiful example of growth of crystals from the interprecipitate liquid when that phase is not present among the primary precipitate crystals, as was first shown for certain rocks of the Skaergaard intrusion (Wager & Deer 1939, p. 128).

The habit of the chrome-spinels. Chrome-spinel is present at most horizons, averaging 1%. The euhedral crystals have a relatively constant size of 0·1 to 0·2 mm, and they decrease gradually toward the top of each unit. Spinel crystals are usually clustered around the larger olivines; when they are enclosed by the latter they are much smaller and more rounded than the crystals outside (figure 39, plate 5). The felspathic rocks at the very top of certain units contain a profusion of spinels, each grain lying at the contact between adjacent felspars. It is believed that they are different in composition from those which are deposited in the lower part of the unit (p. 25).

The probable manner of accumulation of the type unit. The first primary precipitate minerals to be deposited were olivine and subsidiary chromite, and there is evidence to suggest they were precipitated together from the magma (e.g. tiny chromites enclosed by some of the olivines). Felspar and clinopyroxene were not among the primary precipitate minerals or were very sporadic, for each exists as large poikilitic plates. In passing up the unit there is seen to be, initially, an increase in the size of the primary crystals which may have been due to their longer journey through the liquid and therefore the greater time available for growth. Even the chromites within the olivines of 5335 and 5339 are larger than at lower levels. Smaller grains were at times deposited with the larger, as seen at certain horizons in figure 3. Flattened orientated grains of olivine were deposited spasmodically, while at the level represented by 5339 and 5340 are found composite grains, which have probably had a more complex history than the single grains. By the time layers represented by 5341 and 5342 (figure 3) were being deposited primary olivine had become of lesser importance and felspars were exercising a greater control over the texture.

The behaviour of the clinopyroxenes was similar to that of olivines in the increase in the size of primary crystals and the formation of composite clusters during slow and perhaps complex processes of deposition at the 5339 to 5342 level. Thereafter clinopyroxene appears to have crystallized in greater abundance, furnishing primary crystals which were concentrated in narrow layers alternating with layers completely free from primary pyroxene crystals.

The felspars, absent as a primary precipitate in the lower part of the unit, become increasingly abundant towards the top. While the poikilitic felspars near the base are large they decrease in size upward, indicating further the progressive upward increase in the proportion of primary felspars. Often the distribution of chromites distinguishes between primary and interprecipitate growth in the felspars (e.g. 5334). An appreciable proportion of euhedral felspar grains was first deposited in 5338, while in rocks such as 5341 felspars were formed both inside and outside composite clusters, being smaller in the former case. At the very top of the unit changing physical conditions have allowed the deposition of small felspars.

Periods of tranquillity and non-deposition are believed to have resulted in the formation of the harrisite structure (occurring in layers up to a foot thick) and the lace texture. Occasionally the layers were disturbed, however, and slumping took place, evidence being afforded by specimen 5346 which, although included in the traverse, has a mode, density and texture which suggests that it does not belong to this particular level.

(iv) *Mineralogy of the major constituents*

The olivines. The olivine from the type unit (table 1) has a composition Fo_{86} Fa_{14}. No deviation from the optical properties of the analyzed specimen has been detected within the layered series. There is nothing unusual in the composition, and it can be compared closely with the average composition of chrysolitic olivines from peridotites (Rankama & Sahama 1949, p. 151, table 5·26). This average must include peridotites with a varied mode of formation, but generally with a higher fayalite:forsterite ratio than those occurring as inclusions in basalts (Ross, Foster & Myers 1954, p. 707.)

The olivines from the Skaergaard, Skye and Belhelvie basic layered intrusions are richer in iron than the olivines from Rhum, but the lowest recorded olivines from the Stillwater are approximately Fa_{14}, as are the olivines from the lower chromite horizons of the Bushveld Critical Zone, while in the Bay of Islands Complex (Cooper 1936) the olivines range from Fa_{11-12} in the picrites to Fa_{17-18} in the troctolites.

TABLE 1. CHEMICAL COMPOSITION (PERCENTAGE WEIGHT) OF OLIVINE FROM ALLIVALITE 5049, WITH COMPARISONS

	5049	*A*	*B*
SiO_2	39·87	40·04	40·78
Al_2O_3	0·00	0·81	0·11
Fe_2O_3	0·86	0·47	0·00
FeO	13·20	11·33	9·11
MgO	45·38	45·64	49·41
CaO	0·25	0·19	0·11
Na_2O	0·04	0·06	0·02
K_2O	0·01		0·01
H_2O^{+110}	0·33	0·42	0·13
H_2O^{-110}	0·10		
TiO_2	0·03	0·38	0·05
P_2O_5	0·01	—	n.d.
MnO	0·22	0·23	0·13
Cr_2O_3	tr.	0·08	0·03
NiO	n.d.	0·02	0·33
CoO	n.d .	—	0·01
	100·30	99·79	100·23

Analyst: G. M. Brown.

A. Average composition of olivine from peridotites (Rankama & Sahama 1949).

B. Average composition of nine analyses of olivines from inclusions in basalts, calculated from data given by Ross *et al.* (1954, table 4).

TABLE 2. OLIVINE FROM ALLIVALITE 5049: THE DISTRIBUTION OF CATIONS IN RELATION TO FOUR OXYGEN ANIONS WITHIN THE STRUCTURE AND THE PHYSICAL PROPERTIES

Si^{4+}	0·9970	0·9976	molecular proportions: $Fo_{86}Fa_{14}$	
Ti^{4+}	0·0006		atomic ratios Mg^{2+}	85·8
Fe^{3+}	0·0162	1·9961	$Fe^{2+}+Mn^{2+}$	14·2
Fe^{2+}	0·2759		$\frac{(FeO+Fe_2O_3)\times 100}{FeO+Fe_2O_3+MgO}=24$	
Mn^{2+}	0·0047			
Mg^{2+}	1·6900			
Ca^{2+}	0·0067		refractive index: α	1·6626
Na^+	0·0020		γ	1·6990
K^+	0·0004		$2V\gamma$	90°
P^{5+}	0·0002		sp.gr.	3·44

The dendritic, orientated inclusions of opaque material were separated from the olivines and analyzed colorimetrically for iron, titanium and chromium. Absence of the latter two elements and the presence of much ferric oxide suggests that the inclusions are magnetite, amounting to 0·7 % of the volume of the olivines. First illustrated by Judd (1885) these tabular inclusions have since been described from both magnesian and ferriferous olivines. In rocks such as 3186, from the harrisitic units, they are very common parallel to (100) while in addition, parallel to them run tabular inclusions of a dark brown, translucent, isotropic mineral which resembles true chromite. A further set of the latter type of inclusions run approximately parallel to the (110) plane (cf. Hatch, Wells & Wells 1949, figures 127 and 128). If the estimated character of these inclusions is correct, it would seem that the olivines, on cooling, are capable of exsolving traces of ferric and chromic oxides contained within their structure to give separate growths of magnetite and chromite (cf. Goldschmidt 1954, p. 549).

The colour of the olivines from Rhum is a variable feature. Harker (1908, p. 81) mentioned two varieties, a green (sometimes with a yellow tint) and a black, and stated that they were both colourless in thin section, contained similar proportions of 'schiller inclusions' and possessed similar chemical compositions. He did not suggest a reason for the colour variation but stated that in general the black olivine belonged to the 'harrisites' and the green to the peridotites and allivalites. The present work has led the author to agree that there is probably no direct relationship between colour and composition. In the field three types can be recognized: the dominant brownish green, the pale yellow of allivalites such as 5048 and 5049, and the 'black' (which is closer to a dark brown) of the rocks from Harris area. Examination of thin section and of crushed grains under the microscope has led to the conclusion that they are all basically colourless, that the orientated inclusions do not affect the colour, but that the cloudy opaque inclusions of a few specimens from the lower harrisitic units often have a blackening effect. The controlling factor in the colour is the type and degree of alteration, presumably serpentinization; the products of alteration range from yellow to green in colour and in amount, from a trace in the honey-coloured specimens (e.g. 5049) to relatively intense serpentinization in the deep coloured olivines from some of the western harrisitic units. The olivines having the harrisite structure have neither a characteristic composition nor a characteristic colour, and where the texture is present within higher units (e.g. 10 and 13) the constituent olivine has a brownish green coloration. It is often to be noticed that while the cracks in an olivine are yellow (?serpentine) the edges, where in contact with felspar, are pale green (?amphibole).

TABLE 3. CHEMICAL COMPOSITION (PERCENTAGE WEIGHT) OF PLAGIOCLASE FELSPAR FROM ALLIVALITE 5049, INCLUDING THE DISTRIBUTION OF CATIONS IN RELATION TO EIGHT OXYGEN ANIONS, WITHIN THE STRUCTURE, AND PHYSICAL PROPERTIES

SiO_2	47·17
Al_2O_3	33·03
Fe_2O_3 FeO	0·82
MgO	0·03
CaO	17·05
Na_2O	1·78
K_2O	0·05
H_2O^{+110}	0·39
H_2O^{-110}	0·12
TiO_2	nil
MnO	n.d.
	100·48

Si^{4+}	2·172	3·993
Al^{3+}	1·793	
Fe^{3+}	0·028	
Ca^{2+}	0·841	1·005
Mg^{2+}	0·002	
Na^{+}	0·159	
K^{+}	0·003	

molecular proportions: $Or_{0\cdot5}Ab_{15\cdot0}An_{84\cdot5}$

refractive index:	α	1·5702
	γ	1·5820
	γ' (001)	1·5780
	γ' (010)	1·5778
	α' (010)	1·5718
optical axial angle:	$2V\alpha$	80°
maximum extinction angle in zone perpendicular 010:	$X' \wedge 010$	52°
sp.gr.		2·73

analyst: G. M. Brown.

Many of the olivines from 5335 have a shape identical with an early stage in growth (Kuno 1950, figure 8 stage 4). Similar shapes have been recorded from 5010 of unit 3, though otherwise they are rare.

Zoning has rarely been detected in measurable amount. Tomkeieff (1939, tables II and III) has observed that the only unzoned olivines come from peridotites, their average composition being approximately Fa_{14}.

The plagioclase felspars. The analyzed plagioclase from the type unit is $Or_{0\cdot5}Ab_{15}An_{84\cdot5}$ (table 3). The determination of the plagioclase composition in other parts of the unit and in the layered series generally was based on optical methods which reveal more variation (chiefly in the zoned minerals) than shown by the olivines. The unzoned specimens, together with the cores of the zoned, closely approach a mean composition of An_{85}, the full range being An_{83-88} (figure 4). There is no systematic variation as in cryptic layering, but zoning extends the range to approximately An_{45}.

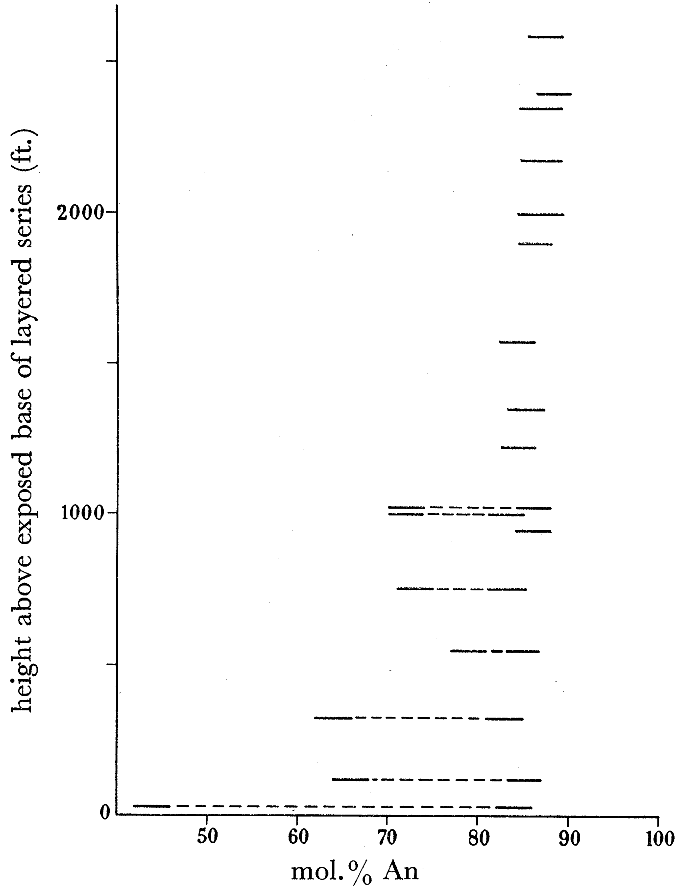


FIGURE 4. Composition of plagioclase felspars at representative horizons within the layered series. Full line represents compositional range within limits of error (± 2 % An). Broken line represents compositional range covered by normal zoning (see figure 8 for more detail).

The analysis shows 0·82 % iron oxide, a figure obtained by a colorimetric determination of all the iron present as ferric, in which state it is probably present, replacing aluminium in the oxygen tetrahedra. Although the replacement of aluminium by ferric iron in orthoclase is now accepted, work on natural occurrences having been supplemented by the synthetic work of several investigators (e.g. Faust 1936), the same cannot be said of the plagioclases. From the evidence provided by the Skaergaard plagioclases Wager & Mitchell (1951, p. 146) have suggested that limited replacement of the aluminium by ferric iron occurs under natural conditions. Faust, on the other hand, had concluded that if ferric iron is present in the plagioclases then it is there as the 'iron orthoclase molecule'. In this connexion the analysis of plagioclase given here is of interest, for it records the presence of only 0·05 % potash while there is 0·82 % total iron oxides. Thus there is not nearly enough potash compared with iron oxide to form the iron orthoclase molecule.

The prevalence of such a high iron content is confirmed to some extent by I. D. Muir (written communication August 1954), who has found 0·64 % ferric oxide in a plagioclase (An_{88}) from a pure felspar layer at the head of Glen Harris, Rhum, and by Z. Harada (1954), who records 0·88 % ferric oxide in a felspar of similar composition analyzed by K. Yagi from the Usu volcano, Hokkaido.

Twinning in the plagioclases is according to the albite, manebach, pericline and combined carlsbad-albite laws. In the more felspathic rocks albite twinning is predominant, though the lamellae are generally so broad that simple twins or even single crystals are very common. If polysynthetic twinning is developed then it usually consists of an alternation of very broad with very narrow lamellae and determination of composition by the maximum symmetrical extinction method of Michel-Levy is frequently impracticable. The existence of untwinned crystals is in accordance with Donnay's summary of the relationship between composition and 'obliquity of the twin' (1940). Simple manebach twinning may be more common than hitherto suspected. In three measurements of the analyzed felspar by the Federov method, two crystals were twinned on the albite law and one on the manebach. Results obtained from the Michel-Levy method frequently indicated confusion of (010) with (001) (cf. Barber 1936, p. 280), complementary extinction angles being thereby obtained. Pericline twinning is better developed in the large poikilitic plates of the peridotites.

Zoning is an important feature, particularly in genetical considerations. Where present it is generally of the normal continuous type, though the normal discontinuous, and rarely the oscillatory, are to be found. The lower five or six units are characterized by felspars zoned normally, to a measurable degree. If the rock is fairly rich in felspar then the zoning is discontinuous, a small core of calcic composition being enveloped by a rim zoned continuously. If, on the other hand, the felspar is scarce and poikilitic to olivine then the zoning is continuous, the inference being that in this case there was no calcic crystal as a primary precipitate. Higher in the sequence the intensity of zoning diminishes, most rocks of the upper levels being characterized by unzoned felspars. Among the allivalites of the upper layered series of Hallival, for example, that of unit 8 is the highest to show measurable zoning. The units above 8 may show zoning in the interprecipitate felspar of the peridotites of each unit (where the felspar is very scarce), but the more felspathic parts of the unit are composed of unzoned felspars. If an exception is noted then the zoning consists of a very narrow rim, often failing to encircle the grain but, rather, confined to one or two edges where interstitial liquid existed. In general, the more felspathic the rock the more homogeneous the felspar, and the almost pure layers (e.g. 5061) are clearly unzoned. Oscillatory zoning has been recognized only in the felspars of the ultrabasic veins. In addition, the felspars of these veins show a normal discontinuous zoning much more intense in character than that of the rocks which they invade.

The clinopyroxenes. The analyzed pyroxene from the allivalite of the type unit (table 4) is a 'chrome augite' according to the nomenclature of Hess (1949, p. 623), the precise composition being that of a rather uncommon member of the natural clinopyroxenes. However, the high proportion of calcium and magnesium to total Ca + Mg + Fe is a general characteristic of early clinopyroxene fractions from a slowly cooled basaltic magma, and a fairly close comparison is possible with such minerals from other intrusions (figure 5). The Rhum specimen is closely comparable with the lowest recorded clinopyroxenes from

TABLE 4. CHEMICAL COMPOSITION (PERCENTAGE WEIGHT) AND PHYSICAL PROPERTIES OF THE CLINOPYROXENE FROM ALLIVALITE 5049, WITH COMPARISONS, AND DISTRIBUTION OF CATIONS WITHIN THE STRUCTURE

	5049	*A*	*B*
SiO_2	51·90	51·98	52·73
Al_2O_3	3·40	3·67	2·05
Fe_2O_3	0·53	0·62	1·00
FeO	3·70	3·62	2·37
MgO	17·00	18·28	18·05
CaO	21·12	20·13	22·57
Na_2O	0·36	0·17	n.d.
K_2O	0·03	0·08	n.d.
H_2O^{+110}	0·13	0·11	0·48
H_2O^{-110}	0·12	0·03	0·09
TiO_2	0·46	0·15	0·25
MnO	0·12	0·14	0·12
Cr_2O_3	0·88	1·21	0·43
NiO	n.d.	0·03	0·03
	99·75	100·22	100·17
	analyst: G. M. Brown		
refractive index: α	1·6820	1·6797	—
β	1·6870	1·6844	1·6790
γ	1·7092	1·7058	—
$2V\gamma$	51°	50°	54°
sp.gr.	3·33	—	—
ex-solution lamellae	absent	(100)	absent

A. Chrome augite from felspathic peridotite, Moa district, Oriente, Cuba (Hess 1949, analysis 3).
B. Chrome augite from Dawros peridotite, Connemara, Eire (A. T. V. Rothstein, unpublished D.Phil. thesis, Oxford. Analyst: E. A. Vincent).

atomic ratios		Fe^{3+} Na	Cr Na	2Al Ti	Al Fe^{3+}	Al Al	*Z* *Y* *W*	cations to six oxygen ions
Si	864	—	—	—	—	—	*Z*	
		—	—	12	6½	24	906½	1·997
Al	66½	—	—	—	—	24	—	—
Fe^{3+}	6½	—	—	—	6½	—	—	—
Fe^{2+}	51½	—	—	—	—	—	—	—
Mg	421½	—	—	—	—	—	—	—
Ca	376½	—	—	—	—	—	—	—
Na	11½	—	11½	—	—	—	*WXY*	—
K	½	—	—	—	—	—	911	2·007
Ti	6	—	—	6	—	—	—	—
Mn	1½	—	—	—	—	—	—	—
Cr	11½	—	11½	—	—	—	—	—
O	2723	—	—	—	—	—	—	—

$Fe : Mg = 12·5$

$$\frac{(FeO + Fe_2O_3) \times 100}{FeO + Fe_2O_3 + MgO} = 20$$

unit cell dimensions: $a = 9·734$ Å
$b = 8·907$ Å
$c = 5·246$ Å
$\beta = 73° 51'$

composition (Hess 1949):
$Ca_{43·9}Mg_{49·2}Fe_{6·9}$
Al in $Z = 4·7$
calculated density: 3·341 at 23° C

the Bushveld, Skaergaard and Great Dyke layered intrusions. In addition nineteen analyzed chrome-diopsides from peridotite inclusions in basalts fall within this part of the pyroxene field, though the very high alumina content of the latter, suggesting the effect of high pressures during formation, invalidates to some extent comparisons based merely upon Ca:Mg:Fe proportions.

The specimen lies closer to the diopside field than do the early clinopyroxenes from the Stillwater complex. Only clinopyroxene crystallized as a primary precipitate mineral from the Rhum magma, whereas both clino– and orthopyroxenes were precipitated from the Stillwater magma at a similar stage in its cooling history. These differences are not incompatible with experimental results, for Bowen has shown that in the system Di-Fo-SiO_2 (1914, p. 234) enstatite and diopside form a solid solution with a minimum at $Di_{82}En_{18}$ (percentage weight) whereas in a silica-deficient melt pure diopside would form at the Fo-Di eutectic. Thus despite the complications involved in dealing with a polycomponent system one might expect the calcic augite crystallizing together with olivine to lie closer to the diopside-hedenbergite line than it would crystallizing with a pigeonite or an orthopyroxene.

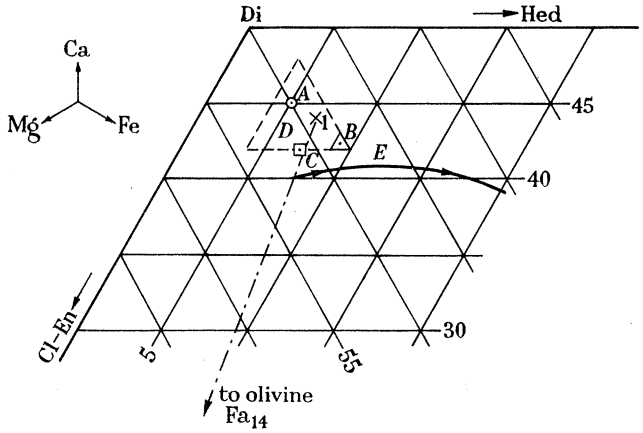


FIGURE 5. The analyzed clinopyroxene from 5049 plotted in relation to the early-formed diopsidic pyroxenes from other basic layered intrusions and to the chrome-diopsides from peridotite inclusions in basalts. 1. From allivalite (5049), ultrabasic layered series, Rhum. *A*. From bronzitite, Malips Drift Camp, Bushveld (Hess 1949, analysis 2). Interprecipitate at this horizon. *B*. From gabbro picrite, Skaergaard (new analysis by E. A. Vincent). *C*. From bronzitite, Great Dyke (Hess 1950, table 1). Composition based on optical properties. *D*. Field enclosing 19 chrome-diopsides from peridotite inclusions in basalts (computed from analyses given by Ross, Foster & Myers 1954, tables 6 and 15). *E*. Trend-line for clinopyroxenes crystallizing from a basaltic magma, followed chiefly by specimens from the Stillwater, Bushveld and Great Dyke intrusions (Hess 1941, figure 10).

The determination of the composition of pyroxenes from other rocks was difficult owing to the analyzed specimen not having the precise optics expected from Hess's curves. However, relative determinations were possible, the composition of the clinopyroxenes within the layered series being found to be almost constant. Little deviation was noted, within the type unit or throughout the upper units, from a mean $\beta = 1{\cdot}690$ and $2V\gamma = 51°$. The full range recorded is $\beta = 1{\cdot}687$ to $1{\cdot}691$ and $2V\gamma = 50$ to $52°$. Zoning extends the range to $2V\gamma = 45°$.

In general appearance the clinopyroxene from the layered series is extremely uniform: pale green, non-pleochroic and rarely twinned. Zoning, rare at higher levels, is sometimes detected in the lower units, but is usually patchy in character.

Of particular interest is the absence of exsolution lamellae of orthopyroxene parallel to (100), which may be due to the calcic nature of the clinopyroxene. Hess (1941, figure 13) does not indicate, in the subsolidus curves, that exsolution is capable of producing the pure end-members of the diopside-hedenbergite and enstatite-orthoferrosilite groups, so that this clinopyroxene may represent a relatively stable phase in which the small amount of iron and magnesium in excess of that contained in the diopside-hedenbergite series is not removed by exsolution, at the rates of cooling prevalent in fairly high-level basic layered intrusions.

The absence of exsolution results in the observed optic angles being lower than expected from Hess's curves, while the high alumina content may be responsible for the β refractive index being higher than expected from the curves, through substitution in the octahedral position, and for the *b*-dimension of the unit cell being much shorter (Kuno 1955).

The chrome-spinels. The composition of the spinel has not yet been determined. The analysis by Heddle (Harker 1908), though of poor quality, indicates that it is intermediate between chromite and picotite. The analysis of the peridotite of the type unit (table 9, p. 47) indicates a normative percentage of chromite much inferior to that of magnetite and suggests a chrome-magnetite composition for the spinel. For convenience, however, it is termed 'chromite'.

There is a possibility that the composition varies slightly during the deposition of certain units. For example, in 3218 (figures 26, 27, plate 3) the chromites of the narrow seam forming the base of unit 12 are mostly translucent, whereas the isolated specimens 5 to 10 mm below the seam, in the felspathic top of unit 11, are opaque. Brief examination of a polished section showed several of the grains from the top of unit 11 to contain exsolution lamellae of ilmenite, whereas those from the base of unit 12 contained no such lamellae.

An interesting reaction relationship is noted, between olivine, spinel and plagioclase, in rocks such as 5332 (figure 40, plate 5). There the olivines are embayed, where in semi-contact with chromite, the bay being moulded to the approximate shape of the latter. However, a narrow band of felspar invariably separates the two minerals, optically discontinuous with the large poikilitic felspars. It looks as though the felspar rim is a product of reaction involving chromite, or olivine, and the residual liquid. In this connexion it is interesting to note that Osborn & Tait (1952), in a study of the system diopside-forsterite-anorthite, treat spinel as a 'transient phase' and show that at temperatures between 1317 and 1270° C, spinel is unstable and will dissolve in the liquid as forsterite and anorthite crystallize. In view of diffusion and the little-zoned nature of the felspars, this reaction in the polycomponent system must have taken place over a very narrow temperature range. Sampson (1932, figure 11) described identical textures from the Bushveld rocks.

Thayer (1946) recognizes a chemical correlation between chromite compositions and the associated rocks. Thus chromite from olivine-anorthite rocks is usually fairly rich in normative spinel, and produces reactions of the type noted in Rhum. Chromites from ultrabasic rocks in Cuba show a close analogy in behaviour and association with those from

Rhum (cf. table 4 in which a clinopyroxene from these rocks is compared closely with that from 5049). Thayer figures a reaction rim (1946, figures 1*A* and 1*B*) of anorthite developed between chromite and olivine through the agency of interstitial 'diopsidic gabbro', which is closely analogous with the example shown in figure 40, plate 5.

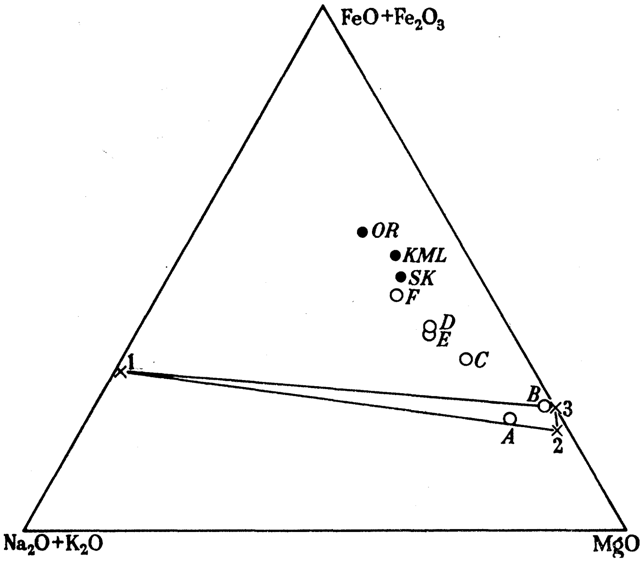


Figure 6. The relationship between the $FeO+Fe_2O_3$: MgO: Na_2O+K_2O ratios of the layered series and those of analyzed rocks from the same area which may be closely related, in chemical composition, to the magma from which the minerals of the layered series crystallized. Basalts from the other areas are included for comparison. 1. Analyzed felspar from 5049, layered series. 2. Analyzed clinopyroxene from 5049. 3. Analyzed olivine from 5049. *A*. Analyzed allivalite 5049 (unzoned minerals) from unit 10. *B*. Analyzed peridotite 5328 to 5334 from unit 10. *C*. Analyzed allivalite 5114 (zoned minerals) from unit 3. *D*. Hypothetical magma, capable of precipitating minerals of the layered series (table 8). *E*. Analyzed fine-grained olivine gabbro, 5019 (table 9). *F*. Analyzed marginal gabbro, 5186 (table 9). *SK*. Average chilled marginal gabbro, Skaergaard (Wager & Deer 1939, table XVII). *KML*. Average of 28 analyses of lavas of Kilauea and Mauna Loa, Hawaii (Tilley 1950, table 1). *OR*. Lava of olivine basalt, Orval, Rhum (Harker 1908, p. 57).

Note that the layered series, consisting generally of varying proportions of the analyzed minerals 1, 2 and 3, can only be considered as belonging to a triangular area bounded by these three points.

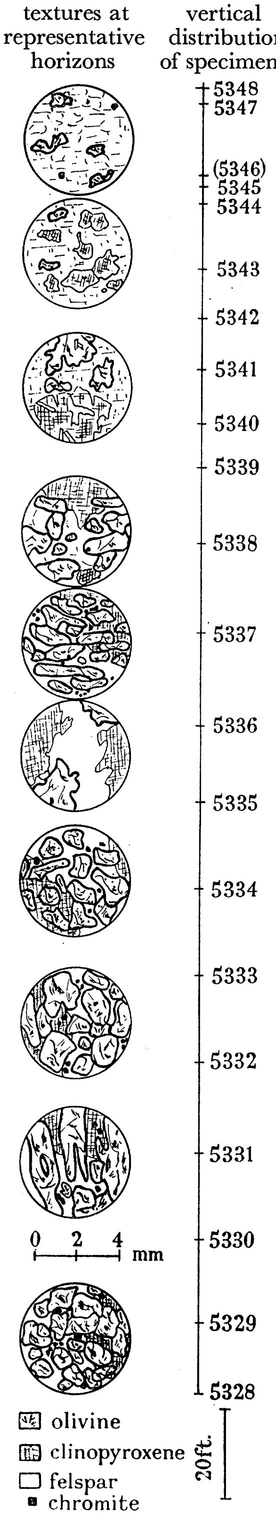
(v) *The analyses of rocks from the type unit*

Although the analyses of the constituent minerals are of chief importance in assessing the chemical character of the layered series, a peridotite and an allivalite were analyzed for comparison with rocks from other parts of the area. Comparison of the analyses (table 9, p. 47) with those of the separated minerals provides support for the statement that the felspars are more zoned in the peridotites than in the allivalites, while the ferromagnesian minerals show little evidence of zoning.

The rocks of the layered series are plotted in figure 6 on a triangular diagram showing the amounts of $FeO+Fe_2O_3$:MgO:Na_2O+K_2O; the rocks fall within the area prescribed by the composition of their constituent minerals. The possible trend of differentiation of the hypothetical magma (*D*) (see below p. 43) is roughly indicated by the link between it and the early differentiates through (*C*), representing rocks of the lower units which have zoned minerals.

(vi) *The contemporaneous ultrabasic veins*

The field characteristics of coarse veins cutting the lower rock of unit 10 at a low angle has already been discussed and illustrated (figure 7). In thin section the vein is seen to consist of large crystals of clinopyroxene and olivine (average diameter 4 to 6 mm) together



vertical distribution of specimens	explanation of textures	modal percentage				sp. gr.
		plagioclase	olivine	clinopyroxene	chromite	
5348		82·5	15·5	—	(2 spinel)	2·84
5347	Euhedral, tabular felspars orientated in plane of igneous lamination. Olivines have lost euhedral shape but are rarely poikilitic	71·5	28	—	(0·5 spinel)	2·89
(5346)	(Peridotitic subunit slumped into present position.)	(41)	(54·5)	(4·5)	—	(3·17)
5345		71	27·5	1·5	—	2·90
5344		72·5	18·5	9	—	2·89
5343	Discrete clinopyroxenes concentrated by fine-scale rhythmic layering	61	7·5	31·5	—	2·99
5342		76	23	1	—	2·87
5341	Olivines losing euhedral shape. Chiefly composite grains of olivine-felspar and clinopyroxene-felspar.	69	19	12	—	2·93
5340		64	16·5	19	0·5	2·95
5339		41·5	47	11·5	—	3·21
5338	Felspars developing into smaller, euhedral grains. Clinopyroxenes no longer completely poikilitic, having olivine-free cores	44	52	4	—	3·17
5337	Tabular olivines orientated in plane of weak igneous lamination.	21·5	66·5	12	—	3·26
5336	Contemporaneous vein of coarse ultrabasic material. There are several at this horizon, semi-horizontal and averaging 1 in. in thickness.	(46·5)	(21·5)	(32)	—	(3·08)
5335		18·5	71·5	8·5	1·5	3·30
5334	Abundant tiny chromites enclosed by olivines. Larger, and probably later, chromites outside the olivines.	24	68	5	3	3·27
5333		16	76·5	6·5	1	3·29
5332	Little change in general peridotitic textures over a great vertical thickness, apart from an increase in olivine grain size at this horizon	18·5	74	6·5	1	3·26
5331	Harrisite structure developed, in layers averaging a foot in thickness, through the upward growth of long, branching olivine crystals. (Suitable specimen not obtainable from this unit, the diagram being drawn from another unit.)	10	76·5	13·5	—	3·28
5330		18	74·5	6	1·5	3·31
5329	Euhedral crystals of olivine and subsidiary chromite poikilitically enclosed by large, anhedral plates of felspar and clinopyroxene.	13·5	77	8·5	0·5	3·27
5328		11	68	19	2	3·28

FIGURE 7. Vertical section of the type unit, showing textural (diagrammatic), modal and density variation.

with at least 60 % plagioclase in a tightly locked mosaic of grains, average diameter 1 mm. The pyroxenes are slightly zoned, the olivines are traversed by a complex system of translation lamellae, while the felspars are zoned in both normal continuous and rhythmic reversed fashion. Furthermore, the felspars have the tapering and bent lamellae associated with cataclastic deformation. The analysis (table 9, p. 47) indicates that the rock is ultrabasic in affinity and far removed from the later gabbroic veins which also cut the layered series. The normative composition of the olivine, the Fe: Mg ratio of the rock and the more sodic composition of the felspar are significant differences from the layered series rocks.

The texture of the ultrabasic vein does not resemble any layered rocks of the unit even if the deformed character is ignored. The most marked difference is in the large clinopyroxenes which are either discrete or contain a few small felspars and olivines. The expulsion of interstitial liquid from the peridotites cut by the veins would produce, on cooling, a more gabbroic assemblage. Perhaps the minerals of the veins, each with an appreciable core of ultrabasic composition, were derived from a leucocratic accumulation of crystals, similar to that found in the central to upper parts of the type unit, together with a rather high proportion of the associated interstitial liquid.

(c) *The characters of individual units of the layered series with particular reference to their divergence from the type unit*

Certain textural and structural features, not well displayed by unit 10 but found in other units, will now be discussed. In addition, certain peculiarities of composition and texture of the lower units and the increase in the ratio of leucocratic to melanocratic rocks towards the top of the series, will also be considered.

Units 1 to 3 form the more complex part of the area considered here. Harker (1908) mapped the intrusive rocks below 1100 ft. as a thick sheet of 'eucrite' enclosing a large block of ultrabasic material in Allt nam Ba (unit 2 of the present investigation). Bailey (1945, plate VIII) proposes a division of Harker's eucrite into an inner, semi-horizontal series of injections, and an outer, semi-vertical ring-dyke. During the present investigation the detailed mapping of easily recognizable marker horizons and the subdivision of the more complex zones with the aid of felspar composition has resulted in the broad characteristics of the upper units being detected in the rocks from the lower ground. Although a ring-dyke form is apparently characteristic of the gabbro occupying the few yards nearest the margin, the extensive ring-dyke suggested by Bailey was not confirmed by the present investigation.

(i) *Unit* 1

This layer, about 60ft. thick, is relatively leucocratic with good igneous lamination, but without small-scale banding. The thin section of 5197, a typical specimen, contains approximately 60 % plagioclase, 35 % clinopyroxene and 5 % olivine and iron ore. The plagioclases occur as subparallel laths, their outlines modified by zoned growth. The composition varies from An_{84} in cores which range from one-third to one-fifth of the whole grain down, through continuous zoning of the outer rim, to An_{44}. The clinopyroxenes are frequently zoned with $2V\gamma$ varying from 52 to 47° in a normal continuous fashion. The few large olivines are badly altered to deep yellow serpentine, iron ore and (less commonly) orthopyroxene, while the few grains of iron ore are interstitial to the other minerals.

At the top of the unit is a 4 to 5 ft. band of fresher, more resistant material (5475) which has a closer resemblance to some parts of the higher units. The rock is still pyroxenic but has developed a weak fine-scale layering, involving variation both in mineral proportions and grain size. Of special interest is the fact that 3 to 5% orthopyroxene occurs, interstitial to both olivine and felspar; the larger grains of the orthopyroxene associated with olivine could perhaps represent primary precipitate crystals. It will be noted later that orthopyroxene is entirely absent from units above 6, while in units 1 to 6 it is mainly present as an interstitial rim to olivine. Only in this unit is the mineral present as grains which might have formed as a primary precipitate mineral.

(ii) *Unit* 2

The limits of the unit were established in Allt nam Ba where the rocks are fresher and better exposed. The allivalite of unit 1 is divided by a few feet of unexposed ground from the overlying peridotite which represents the base of unit 2, and which shows all the characters typical of the peridotites of the higher units. An upward-growing pyroxene structure is found at a single horizon in the leucocratic part. This is a phenomenon well developed in the leucocratic sections of units 8 and 14 and is discussed in detail with unit 8. The olivine from the peridotite (5433) is approximately Fa_{15} and shows no zoning, though small patches of associated orthopyroxene, noted also in the more leucocratic rock, suggest that at lower temperatures the olivine, rather than becoming more iron rich, inverted to orthopyroxene. The latter mineral is too small to obtain its composition by optical measurement, but similar material has been examined more fully in unit 3.

Elsewhere difficulty is experienced in correlating the various exposures belonging to this unit, the chief criterion being that they lie conformably beneath the melanocratic base to unit 3, about 780 ft. above sea-level.

The rocks of this unit show the marked effect of the interstitial liquid. Thus one (5220) contains subhedral felspars zoned from An_{78} to An_{53} in addition to a good deal of interprecipitate orthopyroxene and iron ore, while another (5221), though differing from the former in that there is less ore and the clinopyroxene occurs as subhedral grains instead of poikilitic plates, contains a good deal of orthopyroxene rimming both olivine and clinopyroxene, and felspars zoned from An_{84} to An_{60}. The clinopyroxene is zoned, $2V\gamma$ ranging from 51 (core) to 44° (narrow, discontinuous rim). The latter rock shows, in addition, the warping of the felspar lamination by deposition of composite clusters—a feature noted in higher units as indicative of formation by crystal accumulation. Unusual, however, is the fact that sections of two allivalites (5110 and 5221) contain at least six small stubby crystals of apatite which, in view of their absence from the upper layers, are probably to be regarded as formed from the interprecipitate liquid.

(iii) *Unit* 3

This unit is the most complex of all, for it has been invaded by a later gabbro; furthermore, exposures are poor. Because unit 2 can be easily recognized in Allt nam Ba and another well-defined unit easily traced in the gabbro area between the Uamha streams, the well-banded material between, with an easily recognizable melanocratic layer at the base, has all been grouped as unit 3. Although it is impracticable to subdivide the 250 ft. which constitute this zone into smaller units, minor rhythms are frequently recognized, and less interrupted exposures would have led to further subdivision.

In Allt nam Ba the unit begins with a 40 ft. melanocratic section which is only markedly olivine-rich in the lower 6 ft. At the top there is a finely banded zone (5434) which passes into a 20 ft. allivalite (5435), the succession suggesting a rhythmic hesitation prior to the formation of the latter. This hesitancy, reflected in minor rhythms, is characteristic of most of unit 3. An invading gabbro cuts through the unit directly above the allivalite, so that except for isolated patches of easily recognizable dark and light ultrabasic material within the gabbro the rest of unit 3 is absent from this valley.

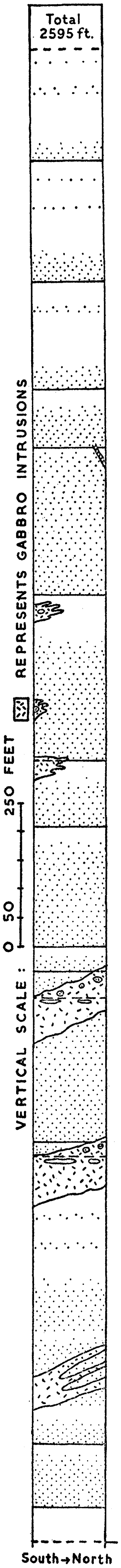
The specimens in thin section are typical of the lower units, the felspar of the finely banded rock ranging from An_{85} to An_{70} and of the allivalite from An_{84} to An_{66}. The interstitial orthopyroxene, frequently rimming the olivines, has a composition of Of_{24}.

Unit 3 can easily be traced to the area of its greatest development, on the scarp directly east of Loch Coire nan Grunnd. There a vertical face, approximately 100 ft. high, provides a complete traverse of the upper part of the unit, while the stream running down from the loch bares an incomplete section in the lower ground of the scarp. The face shows small-scale banding with 1 to 2 ft. melanocratic bands, felspathic layers with 90 % plagioclase, and pyroxenic concentrations which have, as their base, an undulating surface. In sections perpendicular to a line from exposure to probable centre of intrusion, this surface assumes the form shown in figures 24, 25, plate 3. The feature is best seen in unit 9 and is discussed later. Slumping is observed, but will be discussed later with unit 14.

The poor exposures at the foot of the scarp are chiefly of peridotites fairly rich in biotite, with approximately 50 % olivine and 20 % poikilitic felspar zoned from An_{81} to An_{64} (5010). A good exposure in the stream bed, 40 ft. above the peridotites and 6 ft. in thickness, shows passage from a rock containing 15 % olivine and 60 % plagioclase (5013) to one containing 2 to 3 % olivine and 80 % plagioclase (5014). The latter appears to mark the top of a subunit and is an unusual rock. The laths of plagioclase approach parallelism of their longer axes more closely than in any other from the series, while the large poikilitic plates of clinopyroxene attain a diameter of 2 cm. The individual patches of the latter are often quite small (0·1 mm) and are least developed in the rare spaces between the flat faces of adjacent felspars, where packing is closest. The olivines are modified by interprecipitate growth, but this is shown even more strikingly by the iron oxides, which consist of well-formed grains modified by narrow angular projections extending from the primary crystal.

In an attempt to determine the full range of zoning in the felspars of this unit, measurements were made on several felspars from three rocks, the results being 5113: An_{83} to An_{64}, 5114: An_{85} to An_{66}, and 5115: An_{85} to $An_{78\cdot5}$. Although it is never certain that the full range is being determined there is no doubt that 5115, near the top of the unit, is much less zoned than the lower members.

As a sample of the lower units, and in order to estimate the extent of modification by zoning, 5114 (collected 30 ft. from base of vertical face) was analyzed (table 9, p. 47). The norm shows clear evidence of the effect of interstitial liquids on the ultrabasic mineral assemblage. The normative felspar, An_{74}, is more sodic than that from the allivalite of the



unit	comment on macroscopic features	felspars	other minerals
15	Thin olivine-rich layers persist at the highest level, alternating with the thicker pyroxene-rich allivalites which form the summit of Askival.	u.z. An_{87} (z. = zoned, u.z. = unzoned)	cP: $\beta = 1{\cdot}691$, $2V\gamma = 50°$
	Harristic structure. Contemporaneous ultrabasic veins.		Olivine = Fa_{14}
14	Pure felspar layers, less than 3 in. thick.		
	Upward-growing pyroxene structure.	u.z. An_{87-88}	
	Slumping, restricted to 4 to 5 ft. thick zones.		
	Well-developed rhythmic layering on a fine scale, individual layers averaging 2 to 3 cm in thickness.		
	Good honeycomb texture.		
13	Uppermost 5 ft. very felspathic and well laminated.	u.z. An_{86-87}	
	Several thin peridotitic layers occur within the upper part of the unit.		
	Fine-scale rhythmic layering.		
12	Good harrisitic layer 4 ft. thick, due east of Hallival–Askival col.	u.z. An_{86-87}	A few pyrites in upper part of chromite seam
	Well-developed chromite seam, 2·5 mm thick.		
11	Almost pure felspar layer, 2 in. thick. The thin allivalite, 5 ft. thick, developed from peridotite within a foot.	u.z. An_{86}	
	Good harrisite structures developed in 2 to 3 ft. layers.		
	Thin olivine-rich layers, almost dunitic, best seen at the head of Glen Harris.		
10	Well-laminated felspathic layer, fairly rich in chromites (unit 10).		
	Minor slumped layers of peridotitic material.		01 = Fa_{14}
	Fine-scale rhythmic layering, including thin layers rich in primary clinopyroxene.	u.z. An_{84} (analyzed)	cP = $Ca_{44}Mg_{49}Fe_7$ (both anal.)
	Harrisite structure developed in 2 to 3 ft. layers.	z. An_{77} (norm)	
	Coarse, contemporaneous ultrabasic veins, semi-horizontal and approximately 1 in. thick.		
9	Invasion of coarse-grained gabbro in the Plateau region.		
	Wispy banding in Plateau region, concerning felspar and clinopyroxene; layer, with an undulating base, of primary clinopyroxenes, 4 ft. thick and 20 ft. from unit top.	u.z. An_{85}	cP (zoned): $\beta = 1{\cdot}690$ (core), $2V\gamma = 51°$ (core) to 47° (rim)
	Gravity stratification between felspar and pyroxene, on Cnapan Breaca.		
8	Top of the unit shows fine-scale rhythmic layering, though none of the layers are markedly leucocratic (maximum 56 % felspar).	u.z. An_{84}	
	Upward-growing pyroxene structure.	z. An_{83} to An_{70} Thin zones of An_{87-88} round a few chromites	
7	Felspathic layer (81 % felspar) well laminated, 9 in. thick, with 1 to 2 mm chromite seams at base, middle and top.	z. An_{86} to An_{72}	
6	Allivalite layers traceable farther than any others.	z. An_{83} to An_{72}	
	Slump structures preserved in finely layered upper part.	u.z. An_{86} (block of allivalite)	
	Upper fine-grained gabbro invades the whole of this unit, 6, north of the Allt na h Uamha.		
5	Xenoliths easily recognizable as part of the layered series.	Gabbro An_{62-64} (oscillatory zoning in a few grains)	01 = Fa_{30} (gabbro norm)
	In the Barkeval and Plateau regions, over 100 ft. of ultrabasic material is found free from invasion by the gabbro.		
4		z. An_{86} to An_{56}	
	Layers with composite grains of olivine enclosing felspar and pyroxene alternate with layers of pyroxene enclosing felspar and olivine, textures being identical in each case.	z. An_{83} to An_{73} z. An_{83} to An_{64}	01 (zoned?) = Fa_{16-20}
	Lower fine-grained gabbro richest in xenoliths at the top, particularly in the Shelf area.	Gabbro An_{62} (u.z.)	oP = Fs_{26-28} (peridotite)
3	Slump structures of clinopyroxene-felspar concentrations.	z. An_{85} to An_{79}	
	Layers, rich in primary clinopyroxenes, with an undulating base.		
	The thin (1 to 2 ft.) olivine-rich layers rarely contain more than 50 % olivine.	z. An_{85} to An_{66}	Apatite as a few small grains (interstitial),
	The top of a subunit contains 80 % felspar and is strongly laminated.	z. An_{83} to An_{64}	oP = Fs_{24} cP: $2V\gamma = 51°$
	A 6 ft. resistant peridotite layer is traceable for over a mile in the low ground near the eastern margin. Often used as a marker horizon for the base of unit 3.	z. An_{84} to An_{70} (a few narrow rims of An_{44})	01 (zoned?) = Fa_{16-20} Biotite
	Upward-growing pyroxene structure.		Apatite
2	Composite grains of pyroxene-felspar.	z. An_{85} to An_{66}	01 = Fa_{16}
	Olivine-rich layers only seen in Allt nam Ba.	u.z. An_{75-77}	cP (zoned) $2V\gamma = 51°$ to 44°
1	Layer, 4 to 5 ft. thick, of felspathic allivalite showing fine-scale rhythmic layering; pyroxenic, laminated to base.	z. An_{84-44}	A few grains of primary oP

FIGURE 8. Generalized vertical section of the layered series, with petrographic data for the fifteen units. Dots represent major olivine concentrations in each unit.

higher type unit (with normative felspar An_{81}), while the Fe:Mg ratio is 37 compared with 23 in the allivalite from the type unit. The low amount of chromic oxide in the 2·38 % of iron ore is also significant.

(iv) *Unit* 4

The gabbro intrusion which obscures the upper part of unit 3 may also contain part of unit 4, or even a separate minor unit. The top of the lower gabbro, between the Uamha streams, is full of inclusions, many of which can be recognized as part of the layered series. Immediately overlying this inclusion-rich zone, however, is a thin unit which has been termed unit 4, even though it is of little significance, cannot be detected elsewhere (because of the gabbro), and is of the dimensions of the minor rhythms within unit 3.

The lowest specimen of the well-defined part of the unit 4 is a peridotite (5483) so close to the gabbro that the weathered surface has the appearance frequently associated with baking. A point of interest is the schiller structure developed markedly in the clinopyroxenes, parallel both to (010) and (001) (salite subordinate), which may be attributed to thermal metamorphism by the gabbro.

From the 10 ft. layer of allivalite, a rock was collected (5244) in which occur composite clinopyroxene clusters, enclosing felspars smaller and less orientated than the surrounding felspar crystals. In this rock there is only 10 % of olivine, sometimes enclosed by the large pyroxenes. Complementary to this specimen is another (5253) which is chiefly composed of primary plagioclase and clinopyroxene together with *olivine* as the host mineral of the composite clusters. This complementary relationship is most strikingly seen in the hand specimens where the yellow of the olivine and green of the pyroxene bring out the texture.

Harker (1908, pp. 97 to 99) described as representative of the abundant invading 'eucrites' a specimen from '...near bend of Allt Mor na h Uamha, 1200 yards north-east of summit of Allival...', coinciding with the position of an isolated exposure on the south bank of the stream at this horizon. It is unusually rich in orthopyroxene and may have resulted from contamination with the orthopyroxene-labradorite inclusions which are abundant in this small area.

(v) *Unit* 5

The continuity of this unit has been largely destroyed by the upper invading gabbro, relics and inclusions being often the only means of recognizing its former presence. The base is recognized in the shelf-like area between the Uamha streams where a melanocratic layer directly overlies unit 4, but here, after 50 ft. of unexposed ground, the upper invading gabbro, containing blocks of ultrabasic material, is found. An ultrabasic inclusion (5518) from near the top of the gabbro consists of at least 90 % unzoned plagioclase laths with olivine playing the interprecipitate role even better than in 3218 (figure 41, plate 5), the plates averaging 6 mm in diameter.

(vi) *Unit* 6

From this level the units have closer affinities with the type unit. This particular one has little to distinguish it from those at higher levels. A complete traverse reveals minor oscillations within the major trend from peridotite to allivalite. Evidence of slumping was observed in the level ground at the north-west corner of the loch.

(vii) *Unit* 7

This unit is easily traceable on account of its well-defined leucocratic section, which hardly varies in thickness. It is the most clearly defined unit along the foot of the northern slopes of Barkeval, where it is cut by several stringers of gabbro. On the hillside to the south-west of the loch a detailed traverse was made of the full unit, the mode of which is reproduced (table 5).

Table 5. Approximate modes* of rocks from units 8 and 7

specimen	height above base (ft.)	olivine	plagioclase	clinopyroxene	chromite	secondary products
			unit 8			
5103	140	32·80	55·60	10·70	—	0·90
5102	120	53·10	40·10	4·70	0·90	1·20
5101	100	69·10	18·60	7·70	1·60	3·20
5100	30	67·40	21·50	7·20	1·20	2·70
5099	6	69·80	24·70	2·30	2·90	0·30
			unit 7			
5583	105	14·06	80·92	4·96	—	0·06
5582	95	22·03	66·22	11·57	0·09	0·06
5581	85	41·89	53·02	5·10	—	—
5580	70	74·80	18·45	6·03	0·71	—
5579	55	53·71	44·40	1·30	0·58	—
5578	40	72·13	23·47	4·02	0·38	—
5577	25	68·90	17·40	12·11	1·37	0·23
5576	10	64·01	21·13	13·63	1·22	—
5575	0	70·41	23·01	5·26	1·34	—

* In the relatively coarse-grained rocks greater distances of traverse would be necessary to obtain the true modes than was usually possible in the sections available.

These specimens, collected at approximately 10 ft. intervals, show the same general features as the type unit. Thus one can detect a general increase in felspar towards the top, but there is no regular progression. The advent of a minor olivine-rich phase high in the unit (70 ft. from the base), above which the increase in felspar content continues, is common to many of the units.

In thin section felspar zoning, though present, is seen to have diminished in extent; in 5030 zoning is from An_{83} to An_{72}, while in the more felspathic 5031 the range is from An_{86} to An_{72}. In the latter case the outer, discontinuous rim to the ultrabasic core is much narrower than in 5030.

(viii) *Unit* 8

The large pyroxenes give to the upper part of this unit a coarse-grained appearance, making it easily recognizable in the field. The horizon marks the stage at which many plagioclases of the allivalites have grown without changing their composition.

As with unit 7 the increase in felspar content, towards the top, is by no means gradual (table 5), and the establishment of a fairly olivine-rich layer 100 ft. from the base is analogous with that developed 70 ft. above the base of unit 7.

The 'upward-growing pyroxene structure', also recognized in units 2 and 14, is well seen (figure 20, plate 2). Developed directly above a thin melanocratic phase within the leucocratic section of the major unit the structure is seen, on the weathered surface, to consist of patches of clinopyroxene which have grown in such a manner as to taper upward to a point, reaching 5 to 10 cm into the overlying felspathic layers like the fingers of an outstretched hand. The pinnacle shape emphasized by the photograph is slightly exaggerated by weathering processses, for the removal of a hand specimen (3198) showed the three dimensional structure to be more in the nature of a series of fairly rounded humps than pinnacles.

The thin section of 3198 shows that pyroxene poikilitically encloses only olivines, while in the same horizontal plane is an abundance of euhedral felspars. This is indicative neither of upward, uninhibited growth of pyroxene nor of the normal poikilitic growth hitherto encountered. A consideration of the section (figure 21, plate 2) shows that the pile of olivines has, in all probability, been pushed or drawn into position, for the elongated grains are orientated parallel to the periphery of the hump, while in the core they are random. In the immediate vicinity of the hump, several of the otherwise horizontal felspar crystals are turned subparallel to the outline of the structure.

It is likely that an olivine-rich layer, containing a few pyroxenes, was warped before or during the early stages of the deposition of a layer of felspars with subsidiary olivine. When the interprecipitate liquid crystallized there would be, at this disturbed horizon, abundant primary crystals of both olivine and felspar. The only poikilitic mineral would be the pyroxene, which would grow from the few primary grains lying within the olivine-rich humps, producing the uniquely distributed, upward tapering pyroxene growths.

The top of the unit is marked by an impressive fine-scale rhythmic layering (figure 22, plate 3), the primary precipitate minerals being felspars and clinopyroxenes. This layering is cut off abruptly by the sharp base of the next unit.

(ix) *Unit* 9

This has as its most distinctive feature in the field a pyroxenic layer with an undulatory base, at least 4 ft. thick, developed approximately 20 ft. from the top (figures 24, 25, plate 3). This important diagnostic structure can be used in tracing the unit and has been recognized both on the northern foot-slopes of Hallival and, a mile to the south, on a steep vertical face overlooking the loch from the south-west.

The cause of this 'undulatory pyroxene base' is as problematical as that of the 'upward-growing pyroxene layer' in the underlying unit. The two structures are similar in that each consists of a series of round-topped humps. The analogy ends there, for the structures in unit 9 are mounds of felspar crystals adjacent to which are basins filled with discrete, elongated crystals of clinopyroxene. Although figure 24 strongly suggests a channel structure (cf. the trough-banding of the Skaergaard intrusion, Wager & Deer 1939, p. 45), the face perpendicular to this (figure 25) seems to exclude a simple system of channels. In both units 3 and 8 euhedral pyroxenes in abundance fill the hollows of the structure. In common with the upward-growing pyroxene structure, therefore, it is not only a feature which is repeated at various stages in the layered series, but the mineralogical association is similar. The undulatory structures of units 3 and 9 are fairly regular, their smooth outline suggesting either deformation of competent material or the agency of a stable system of channelling currents. They are somewhat analogous with the dome structures ('hillocks') and circular depressions ('potholes') described by Schmidt (1952) from the Merensky Reef horizon of the Bushveld complex.

To the west of the locality considered above, on Cnapan Breaca, large blocks dislodged from this unit show good examples of gravity stratification, the participating minerals being felspar and clinopyroxene. This is the only occurrence so far found in Rhum, and it is unfortunate that the disposition of the blocks did not permit it to be photographed.

(x) *Unit* 11

This unit is well exposed only at the head of Glen Harris. There rocks are found which are the closest approach to a dunite of any in the Hallival–Askival area, occurring as 4 to 6 in. layers in the otherwise rather uniform peridotite. Harrisite structures (figure 23, plate 3) averaging 2 to 3 ft. in thickness occur, similar in appearance to the thinner layers within the type unit. Far from being a later injection as postulated by Harker, the harrisite layer is here seen to grow from a well-defined base at the top of a minor felspathic accumulation, $1\frac{1}{2}$ ft. thick, within the main olivine-rich layer (partly seen at the base of the photograph, with dark pitted surface).

(xi) *Unit* 12

The base of unit 12 is marked by a thin accumulation of chromite resting on the almost pure felspar layer at the top of unit 11. Above the chromite is an olivine accumulation, and thus three rocks which are almost monomineralic may be collected in a single hand specimen (figure 26, plate 3). As best seen at the 1800 ft. level, about 800 yards north-west of the summit of Hallival, the resistance of the chromite seam (2·5 mm thick) results in its preservation as a table-like exposure formed by the chromite together with a thin irregular capping (usually 2 to 3 in. thick) of knobbly olivine rich rock of unit 12. The top of unit 11 consists largely of euhedral felspar crystals together with interprecipitate olivine which is visible on the polished surface of 3218 as large, isolated dark patches. Figure 41, plate 5 illustrates, in thin section, one of these patches. All the olivine in the area covered by the photomicrograph extinguishes simultaneously and illustrates well the rare poikilitic habit of olivine.

The chromite grains forming the basal layer of unit 12 are not so well sorted, according to size, as in the specimen from the Bushveld illustrated by Hatch *et al.* (1949, figure 116). There is a suggestion of chromite synneusis similar to the 'chain structure' described by Sampson (1932) from the Bushveld. The character of the mineral interstitial to the chromites is of interest; in both the Rhum and the Bushveld rocks it is felspar, which in each case is in large poikilitic units, whereas in the underlying felspathic layers the felspar is in small discrete crystals. Hence an intermingling of the two primary mineral precipitates has not, in itself, produced the texture of the chromite-rich layer. In 3218 several of the large units of felspar in the chromite layer are optically continuous with a primary precipitate felspar crystal below. In the same way several small irregular growths of olivine in the upper part of the chromite layer are optically continuous with primary precipitate olivine crystals above.

Subsequent to the primary precipitation of felspar, chromite and olivine in that order, the interprecipitate liquid would tend to crystallize in the manner described in an earlier section. It appears, however, that diffusion was not such as to allow a monomineralic chromite rock to be produced (perhaps due to the low chrome content of the liquid) and thus the texture of the almost monomineralic felspar layer below is not reproduced. Instead, the interstitial liquid partly crystallized in continuity with certain of the underlying felspar crystals, producing the poikilitic felspars, and near the overlying olivine crystals the same thing happened, growth of poikilitic olivine crystals taking place downwards. This is further evidence to substantiate the view that interprecipitate growth was subsequent to the deposition of overlying crystals. The rim of felspar separating chromite from olivine indicates that the reaction producing the texture shown in figure 40, plate 5 took place at this horizon, between chromite and residual liquid.

It is of interest to note the type of base formed by two different accumulations of crystals (figure 27, plate 3). Large crystals of felspar give a hummocky surface; the one near the centre of the picture, for example, sticking up from the floor so that chromites have fallen not only on top but on either side of it. The small chromites, on the other hand, would pack to give the more even surface which forms the base on which the olivines rest.

(xii) *Unit* 13

This unit closely resembles, in general features, the more accessible unit 14. On the eastern face of Hallival unit 13 forms steep cliffs (figure 28, plate 3), while on the western slopes it forms a broad, scree-covered dip slope contrasting with the steep but accessible exposures of unit 14, which continue to within 25 ft. of the summit. The leucocratic part of unit 13 is riddled with thin melanocratic layers ranging from a few inches to a foot in thickness.

(xiii) *Unit* 14

The summit of Hallival is rounded and largely grass-covered; this is the lower 25 ft. of unit 15. Below is 160 ft. of well-banded rock which is dominantly leucocratic, followed downwards by 65 ft. of melanocratic rock. The whole of this 225 ft. is classed as unit 14, for it would be impracticable to consider the minor phases, well seen in figure 28, as separate units.

The peridotites, usually the type which ring when struck, show the development of harrisitic, lace and honeycomb structures. The cause of surface pitting is well shown by 3223 (figure 30, plate 4). This rock is composed of small discrete olivine crystals which, during the crystallization of the interprecipitate liquid, have become enwrapped by the minerals unrepresented amongst the primary crystals, that is, plagioclase and clinopyroxene. The poikilitic plagioclase and pyroxene crystals have grown in the way already described, from a limited number of spontaneously developed centres of crystallization. This number of centres must have been small, for the individual patches of felspar and pyroxene average 1·5 cm and may reach 3 cm in diameter, and enclose between 1000 and 10000 small olivine crystals. The honeycomb appearance is due to the pyroxenes weathering into hollows while the felspars stand out as irregular knobs. The ultimate size attained by the poikilitic patches would be limited by the number of centres of growth developed which, in turn, would depend on the ease with which diffusion took place, for should the distance apart of any two centres be too great then a fresh one would spontaneously develop to bridge the gap.

A photomicrograph of a part of this rock with poikilitic felspar (figure 31, plate 4) and of a part with poikilitic clinopyroxene (figure 32, plate 4), both from the same section (within 1 in. of one another), present a problem in nomenclature. Assemblages similar to the two portrayed have been, in the past, designated by entirely different names; Johannsen (1937–8), indeed, classifies the two types in separate volumes of his work on petrography.

From modal measurements of extensive sections of 3223 the amount of olivine in the rock is shown to be 79 %, of plagioclase 13 % and of clinopyroxene 8 %. The amount of interprecipitate liquid must therefore be rather more than 21 %, since besides forming the plagioclase and clinopyroxene it would also have formed some olivine, extending the primary precipitate grains. A maximum for the interprecipitate liquid is imposed if we assume that the grains, in contact, formed a loose pile which could have about 48 % interstitial space (Wager & Deer 1939, p. 120). Shaking and pressure exerted by the overlying crystals would reduce this, and for Rhum, as for the Skaergaard intrusion, the amount of interstitial liquid may be accepted as lying mostly between 10 and 30 %. In Rhum the figure of 30 % for the interstitial liquid would be applicable to the peridotite horizons and 10 % to the closely packed, well-laminated allivalite horizons. Carr (1954) has described evidence from slumped structures in the Cuillin gabbros of Skye which indicates a greater proportion of interstitial liquid and therefore a greater mobility in the massive rocks than in the well-laminated varieties.

Fine-scale pyroxene-felspar bands are particularly well developed in unit 14 and are identical with those seen in fallen blocks in Coire nan Grunnd (figure 33, plate 4), which have come from either unit 13 or 14. Other features noted in the leucocratic section include the upward-growing pyroxene structure and the development of highly felspathic layers. The most felspar-rich rock so far collected in this area, 5061, came from a layer 2 in. thick within 6 ft. of the top of the unit, on the western face of Hallival. The rock, shown in figure 38, plate 5, contains almost 100 % plagioclase of composition An_{88}.

Nowhere is the important role played by diffusion recognized more clearly than in the formation of this monomineralic rock. Professor H. H. Hess (verbal communication March 1953) pointed out the significance of diffusion in the formation of the monomineralic bands within the Stillwater Complex, and it was at once clear that the concept applied in Rhum. During the presumed tranquil period necessary for the deposition of the last remaining and often small felspars at the top of the unit, there was apparently time in many cases for diffusion to produce an almost pure felspar rock.

The best development of slump structures occurs high on the eastern face of Askival, within 10 ft. of the top of unit 14. There is a striking resemblance between these structures, such as shown in figure 34, plate 4, and those shown by Jones (1937, 1939) in his study of slumping in the submarine sediments of the Lower Palaeozoic system in north Wales and Kuenen's drawings of the type of structure developed during slumping of Carboniferous sediments in Pembrokeshire (1948). The usual postulate is that unconsolidated sediment under the influence of gravity slides down a gentle slope. The 'Miniature nappes, wildly distorted and crumpled beds...and complete brecciation...', as reported by Kuenen (1948, p. 241), are found in Rhum, made conspicuous by differential weathering.

A requisite for slumping is that the sediment should be laid down on a gentle slope. In Rhum such a slope may be indicated by the radial dips, which average 10 to 15°, but these might also be due to later movement. Kuenen (1948, p. 246) draws attention to evidence, offered by Archanguelski, of slumping near the shore of the Black Sea which has occurred wherever the inclination of the bottom attains 2 to 3°, occasionally even only 1°. In the layered series it is of interest to note that the slumped zones never exceed 4 to 5 ft. in thickness, the layers above and below the zone being undisturbed, and this is interpreted as indicating that the maximum thickness of unconsolidated material at any one time was of this order.

(xiv) *Unit* 15

The peridotites which form the uppermost 25 ft. of the summit of Hallival are classed as the lower part of unit 15. On Askival this unit consists of 30 ft. of peridotite succeeded by 165 ft. of leucocratic rock. Harker (1908, p. 75) believed that the leucocratic part of the unit capping Askival dipped *beneath* the melanocratic top of Hallival, whereas mapping has now shown that it overlies the summit rock of Hallival and that the upper 165 ft. of Askival represent the highest rocks of the layered series so far identified in Rhum.

The top rocks of Askival in general show banding on a fine scale, the actual summit being composed of a fairly melanocratic layer, a few inches in thickness. The plagioclase in the rocks from the top of Askival, which are topographically and structurally the highest in Rhum, is still An_{87} and the olivine still Fa_{14}.

(xv) *Interesting rocks from the layered series, unidentified with specific units*

A fallen block (3237*b*), collected from the level of unit 4 on the north-east slopes of Hallival, contains discrete, composite clusters of olivine-felspar and clinopyroxene-felspar. In thin section (figure 35, plate 4) the plagioclases show well-developed igneous lamination except in the centre of the photomicrograph where a large grain of olivine encloses felspars, smaller than those outside and showing no parallelism. Furthermore, the orientation of the crystals immediately surrounding the cluster is such that their length is almost tangential to the periphery of the latter. The texture suggests deposition of bulky composite clusters among platy felspars, which became orientated parallel to the surface of the cluster.

From the south-east slopes of Trallval (mountain west of Askival), which were not mapped during the course of this investigation, come melanocratic rocks showing signs of having grown under tranquil conditions (such as lace and harrisite structure), and among them is one rock (3293) which is dominated by large broad plates of olivine (some 20 mm long) arranged in curving, often radiating, sheaves, like bent packs of playing cards placed at odd angles to one another. The broad faces can exist in all vertical planes, whereas the horizontal section (figure 36, plate 4) shows no broad face approaching the horizontal plane. Apparently this rock is another case of upward growth, the plates having grown roughly perpendicular to the surface of the precipitate in a manner similar to the growth of long felspars perpendicular to the cooling surface at certain places in the Skaergaard intrusion (Wager & Deer 1939, p. 144). The rock appears to possess most of the features of the specimen from this part of Rhum investigated by Turner (1942) and described by him as a texture produced by the plastic flow of an olivine-rich magma. Thus any vertical section shows a good 'lineation' which lies in a plane marked by moderate fissility. The pole of the broad face (X) would, on account of the changes in direction of growth within a horizontal plane, form a girdle in that plane, with the axis of lineation acting as pole. The incomplete nature of the girdle, recorded by Turner, would suggest slight preference in the direction of maximum horizontal growth.

4. The associated later basic intrusions

Harker's map (Sheet 60, 1917) shows a broad expanse of basic rock which, in the Hallival–Askival area, forms an outcrop roughly circumferential to the ultrabasic mass. He divided the basic rocks (1908, p. 93) into eucrites and later gabbros, believing that the former were intruded into the lower part of the ultrabasics as conformable sheets. Nevertheless, it was 'not found practicable to separate the two on the map', except that several small masses which cut the Torridonian on the south side of Kinloch Glen (off figure 9) are described as gabbro (1908, p. 96). Bailey (1944, plate VIII) divided the 'gabbro' (Harker's 'eucrite') into an inner portion intruded as sheets, conformable with the ultrabasic series, and an outer transgressive dyke portion. Tomkeieff (1945) believed that the basic rocks of Rhum are mainly represented by eucrite, finding gabbro only on the shore at Papadil (off figure 9). In part of his description of eucrite in the Harris area (1945, p. 132) he states, '...varieties contain platy olivines intergrown with anorthite after the manner of harrisite'. In this account such varieties are classed with the ultrabasic layered series.

The present investigation has led to a division of the rocks mapped by Harker as eucrite into part of the main layered series (see earlier sections) and later basic intrusions (chiefly gabbros). Comparison of the map (figure 9) with the 1 in. sheet shows that while most of Harker's eucrite has been grouped with the layered series, two late gabbro sheets have been traced outside his eucrite zone. No direct evidence was obtained, in the area mapped, of the presence of basic rock with a dyke-like structure, although the outermost narrow zone of structureless, quick-weathering gabbro (average 50 yards wide) could well be dyke-like in form. By careful mapping, the gabbros can be successfully separated from the lower units of the layered series. They are found to be fairly simple rocks showing little variation and differing from the allivalites both in textures and in composition. It is believed that there was more than one gabbro intrusion, even though each one may have followed closely on its predecessor; at least three types are recognizable in the field.

(a) *The fine-grained olivine gabbro*

The main basic intrusion consists of two sheets cutting the ultrabasic units 3 to 6. Because of the close similarity between allivalite and gabbro on the weathered surface and the often complex nature of the veining the contact cannot be traced with precision. The upper portion of each sheet is full of ultrabasic inclusions in the shelf-like area between the Uamha streams, and the contact can be roughly mapped. In Allt nam Ba, some way from the margin, the sheets join. Furthermore, thickening takes place towards the centre; in Allt nam Ba the total thickness of gabbro reaches about 350 ft. as opposed to a thickness of about 70 ft. for each sheet in the shelf-like area.

The gabbro is relatively homogeneous, being compact, resistant and free from any form of banding or igneous lamination. A typical example (5019), has been analyzed (table 9, p. 47) and a thin section is shown in (figure 44, plate 5). The felspars (An_{62-64}) are euhedral as are the clinopyroxenes ($\beta = 1{\cdot}692$, $2V\gamma = 47°$). On the average the clinopyroxenes from the ultrabasics have a $2V\gamma$ of 50°, while for those from the gabbros the figure is 47°. The olivines occur in larger grains often poikilitically enclosing felspar crystals; the iron oxide is interstitial. Some textural and mineralogical variation has been detected in connexion with grain size, the olivine content, and the presence of a few larger zoned felspars with cores of An_{67}.

The presence of inclusions of ultrabasic material within the gabbros has been mentioned. Apart from the slabs of allivalite near the top of the upper sheet, particularly on the south bank of the Allt Mhor na h Uamha, the rounded blocks of peridotite on the north bank of the loch and the profusion of the latter in Allt nam Ba (together with a pure felspar inclusion), the majority of inclusions in Rhum are found near the top of the lower sheet, especially on the south bank of the Allt Mhor na h Uamha. Harker mapped this sheet as his lowest allivalite, and this misinterpretation is one of the factors which has led Bailey (1944, p. 182) to state his belief that Harker may well have been right in his theory of successive sheet injection, because the '...top layer of the lowest allivalite band...' (actually the late gabbro intrusion) contained numerous xenoliths of peridotite and pale beerbachite. Such xenoliths are common in the intrusive gabbros, and these are the only rocks containing true xenoliths in the Hallival–Askival area. The blocks of peridotite in allivalite and vice versa in Glen Harris are attributed to auto-brecciation of some sort and the lenses of felspathic material in some of the leucocratic layers are believed to be due to slumping. Thus there is no evidence from xenoliths to lend support in Rhum to a separate-injection hypothesis as the origin of the layered series.

(b) *The gabbro of the Askival plateau*

The upper parts of unit 9, together with most of unit 10, have been invaded by a gabbro at the 1750 to 1850 ft. level south-west of the loch. This gabbro was injected in a horizontal plane and its emplacement was accompanied by disruption of the layers, a pinching out of part of the unit 10 peridotites and collapse and faulting of part of the unit near the line of weakness which passes from Coire nan Grunnd to Glen Harris, via the Hallival–Askival col. The gabbro, which is rich in anhedral iron oxide, mainly occurs as thin sheets and veins (average thickness 3 in.) in the ultrabasic rocks. Granular and bent felspars suggest intrusion in a partly solid condition or slight movement during consolidation. The area shown on the map as gabbro includes much ultrabasic rock and is in the position of the thick band of eucrite and gabbro recorded on the earlier maps.

(c) *The Barkeval 'eucrite'*

On the col separating Hallival from Barkeval two highly inclined sheets of coarse basic material dip 70° north-north-east. Averaging 20 to 30 ft. in thickness each consists of a streaky rock, the irregular bands lying roughly parallel to the intrusion margin. Specimen 5317 shows felspars with a cataclastic structure similar to those in the gabbros of the Askival plateau. In addition, the rock contains several felspars with a striking zonal structure. The inner zone in each case forms a distinct grain (An_{86-89}), while the outer zone (An_{66}) has a more ragged boundary (figure 43, plate 5). Despite the small volume of calcic felspar, the rock shows more marked affinities with the ultrabasic rocks than do the other gabbros. For this reason it has been termed a 'eucrite' on the basis of its composition, though the name obscures, to some extent, its true genetic relationship. These high-angle sheets, related to those on Barkeval and the western slopes of Cnapan Breaca, may be formed from interstitial liquid, together with a few early formed crystals, squeezed out from the layered rocks in the highly disturbed Barkeval region.

5. The marginal gabbro

The actual contact between ultrabasic and marginal rocks has not been detected. The reason for this is the presence of the marginal gabbro which weathers easily to produce a grass-covered zone varying in width from 20 yards in the higher ground south-west of Loch Coire nan Grunnd to about 50 yards in the stream valleys.

The easterly flowing streams cut through the zone in two areas, in each of which it is possible to collect specimens from the small resistant cores in the crumbling, quick-weathering gabbro. Specimens 3146 and 5186 from the Allt Mhor na h Uamha and 3195 from the Allt na h Uamha are each characterized by intensely zoned felspars, large orthopyroxenes and patches of quartz and apatite. Olivine is present in the two specimens from the Allt Mhor, while 3195 is richer in orthopyroxene and quartz. The quartz in each case appears to be present as a contamination from the marginal sediments, occurring either as isolated patches (with apatite and felspar) or as irregular stringers cutting across large felspars.

The zoning of the felspars is of the normal continuous variety, those from 5186 having a compositional range An_{77} to An_{51}. Bytownite cores sometimes occur but usually the zoning is continuous from the centre. Specimen 5186 was analyzed (table 9, p. 47), the normative composition of the felspar being An_{63} and indicative of an overall gabbroic composition.

It is suggested that this gabbro was intruded during the upheaval and emplacement of the layered series. The manner in which the layered series approaches the margin without showing structural change, such as those which are a marked feature of the Skaergaard intrusion, suggests that the layering was not formed at the present horizon.

Bailey (1944) has considered in detail the Tertiary igneous tectonics of Rhum and has produced evidence for a great upheaval, followed by collapse. As evidence he cites (1944, p. 184) the fact that the layered complex continues down to sea-level, while 'pre-peridotite' Lewisian and Torridonian occur 'alongside it above the 2000-feet level'. The validity of this argument, however, is based on the supposition that the Lewisian–Torridonian rocks referred to formed a base to the layered series, whereas it is suggested here that they formed the upper part of the sides of the intrusion. No evidence has been found to support an outward dip to the ring fracture and collapse is not envisaged; on the contrary, appreciable upheaval is proposed. The absence of any impressive zone of rupture is attributed to the marginal gabbro, acting as a lubricant during the upward movement of the layered series.

6. Discussion on the formation and emplacement of the layered series

(a) *Origin of the constituent minerals*

The minerals of the ultrabasic rocks of the layered series have a composition similar to those of the earlier crystals formed during the slow cooling of basaltic magma. Phenocrysts within the Hawaiian basalt lavas include olivines close to Fa_{15} (Daly 1911), diopsidic pyroxenes and plagioclase felspars zoned from An_{80}. Tomkeieff (1934) analyzed the olivine basalt from the middle part of an Antrim lava flow, and the large olivines which, he believed, had separated from the flow and collected in the lower part. Not only does the basalt (1934, table I analysis 2*a*) closely resemble the estimated composition of the hypothetical Rhum basalt reproduced in table 7, but the olivine accumulate has a composition close to Fa_{15}. Tsuboi (1926, p. 171) studied the tholeiitic basalt lavas with labradorite in their ground-mass which make up most of the volcano of Oshima, and was impressed by the constant composition of the phenocrysts, the felspars being An_{85} and the olivines Fa_{14}. Yet another example comes from Rhum, where the rock from a 2 ft. basic dyke contains plagioclase phenocrysts (An_{87}) set in a doleritic ground-mass (plagioclase An_{66}).

In basic intrusions which are believed to have formed through crystal settling the earlier crystal fractions are detected with more certainty, and the compositions of the early phase in some of the better-known cases are listed in table 6.

Table 6. Early crystal phases of layered basic intrusions

		composition of earliest crystal phases recorded		
intrusion	magma likely to have precipitated early crystal phases	olivine	plagioclase	clinopyroxene
(1) Stillwater	chilled floor (norite) has normative felspar An_{68}	Fa_{14}	An_{86}	$Ca_{37}Mg_{56}Fe_7$
(2) Bushveld	chilled floor (norite) has normative felspar An_{68-69}	Fa_{14}	An_{85}	$Ca_{45}Mg_{50}Fe_5$
(3) Great Dyke	same as Bushveld? (Hess 1950)	Fa_{12}	An_{76}	$Ca_{42}Mg_{51}Fe_7$
		(amongst the lower crystal accumulates)		
(4) Skaergaard	chilled margin (gabbroic) has normative felspar An_{65-68}	Fa_{19}	—	$Ca_{43}Mg_{48}Fe_9$

Experimental work on the artificial systems from which these silicates can crystallize has shown that in the system anorthite-albite a solid phase of composition An_{86-88} is in equilibrium with a liquid of composition An_{62-68} (Bowen 1913), while in the system forsterite-fayalite (Bowen & Schairer 1935) a solid phase of composition Fa_{14} is in equilibrium with a liquid of composition Fa_{40}. The introduction of diopside into the plagioclase melt has been considered by Bowen (1915*b*), but apart from a lowering in the crystallization temperature of mixtures there does not appear to be any significant modification in the shape of the plagioclase curves.

In view of the above evidence it seems justifiable to assume that a basaltic magma (normative felspar An_{62-68}) is capable of precipitating the minerals found in the ultrabasic layered series of Rhum. Speculation as to the character of that magma is, unfortunately, necessary in view of the absence of a chilled margin to the intrusion which might have provided direct evidence of the composition of the original liquid.

The analyzed specimen 5114 from unit 3 (table 9, p. 47) differs from the rocks of the upper units in the degree of zoning of constituent minerals. This is believed to be due to cystallization of the interstitial gabbroic liquid without its modification by diffusion. In view of the constant composition of the primary crystals within the layered series it may be assumed that the primary assemblage of unit 3 differed little from that of unit 10. Subtraction, therefore, of an appropriate proportion of these analyzed crystals from the analysis of 5114 ought to yield, approximately, the composition of the interstitial liquid. (The clinopyroxene is interstitial and therefore the olivine : felspar ratio indicated by the norm of 5114 was employed.) Assuming close packing, the estimate of composition is some way from that of normal magmas, but assuming 50 % interstitial liquid, i.e. a less closely packed system, the composition shown in table 7 is obtained, which is regarded as the best available estimate for the composition of the magma. It may be noted that the fine-grained olivine gabbro, locally available immediately after the formation of the layered series, bears a close resemblance to the estimated composition of the magma.

TABLE 7. ESTIMATED COMPOSITION OF INTERSTITIAL MATERIAL OF 5114 FROM UNIT 3

	5114*a*			
SiO_2	46·8	Or	1·7	58·3
Al_2O_3	18·7	Ab	18·9	
Fe_2O_3	1·4	An	37·7	
FeO	7·7	Ne	2·3	
MgO	11·0	Wo	6·1	11·8
CaO	10·6	Cl-En	4·0	
Na_2O	2·7	Fs	1·7	
K_2O	0·3	Fo	16·2	24·0
TiO_2	0·8	Fa	7·8	
P_2O_5	0·0 (4)	Mt	2·1	
MnO	0·1	Ilm	1·5	
Cr_2O_3	0·0 (4)	Chr	0·0 (6)	
		Ap	0·1	

plagioclase: $Or_3Ab_{32}An_{65}$
olivine: $Fo_{67}Fa_{33}$

$$\frac{(FeO+Fe_2O_3)\times 100}{FeO+Fe_2O_3+MgO}=45$$

Comparison with basalt from other areas (table 8) shows that the estimated composition of the magma from which the layered series is considered to have crystallized is similar to the non-porphyritic basalts, rich in normative calcic plagioclase and olivine, described by Tilley (1950, p. 55). Within the Hebridean Province the Mull Porphyritic Central basalt represents this type except for a lower normative olivine.

Among experimental systems that most capable of precipitating a mineral assemblage closely related to that found in the layered series is the one investigated by Osborn & Tait (1952).

From the thermal diagram it is seen that at least 47° C. separates the temperature of crystallization of the chrome-spinel and the diopsidic augite of the layered series. For the Stillwater mass Hess (1941, p. 582) has suggested that 60 % of the whole complex solidified during a fall in temperature of about 40° C. Furthermore, because of the lack or relatively small amount of zoning the crystallization of the interstitial liquid is believed to have taken place over a slight range in temperature with the necessary diffusion between the site of crystallization and the overlying liquid. It is believed, therefore, that the four minerals found together as a primary precipitate crystallized at the same temperature.

Despite the fact that the ultrabasic rocks could be derived from a basaltic magma, the problem as to the relative volumes of rock produced by such a process of crystal differentiation remains. By analogy with the Stillwater and Bushveld complexes, in which the thickness and mineralogy of the lower part of the ultrabasic and critical zones respectively are to some extent comparable with the layered series in Rhum, one might have expected 10000 to 12000 ft. of overlying material representing the later differentiates. The present diameter of the intrusion, in the neighbourhood of 5 miles, suggests that on the basis of the above analogy the crystallization chamber would have had a depth at least half its diameter. The fine-scale banding and other structures indicative of a high degree of crystal sorting have, in other intrusions, been closely identified with deposition in wide funnel-shaped intrusions or shallow lopoliths, and it is believed that similar conditions operated in Rhum. It may be, therefore, that the part of the layered series at present exposed is merely a portion of a larger complex, and that an uplift has brought it to the present level. A preferable alternative hypothesis, however, is that the layered rocks were deposited in a sub-crustal chamber connected with a conduit leading to a surface volcano and that intermittent flow of magma to the surface removed the upper portions of the liquid overlying the precipitate with concomitant accession of fresh supplies from below. Such a theory, accounting for the deposition of a great thickness of homogeneous material through a constant replacement of the crystallizing liquid, is similar to that postulated by Ochsenius (the Bar Theory) to explain the accumulation of a great thickness of salts from the evaporation of sea water. In this case the evaporation and deposition took place in a shallow lagoon which was so connected with the sea that a constant supply of sea water was available to replace that lost by evaporation, the result being the deposition of minerals of a particular composition for a great length of time, the composition of the crystallizing liquid being stabilized by the incoming liquid. A thick deposit of anhydrite does not

TABLE 8. HYPOTHETICAL RHUM MAGMA COMPARED WITH OTHER BASALT MAGMAS

	1	2	*A*	*B*
SiO_2	46·8	49·12	47·92	48·19
Al_2O_3	18·6	17·76	18·87	18·55
Fe_2O_3	1·4	1·38	1·18	0·83
FeO	7·7	6·10	8·65	7·91
MgO	10·9	9·67	7·82	9·09
CaO	10·6	12·56	10·46	11·20
Na_2O	2·7	2·70	2·44	2·54
K_2O	0·3	0·17	0·19	0·18
TiO_2	0·8	0·29	1·40	0·96
P_2O_5	0·0 (4)	0·01	0·07	0·08
MnO	0·1	0·29	0·11	0·08
Cr_2O_3	0·0 (4)	0·05	tr	n.d.
H_2O and others	—	0·53	0·51	0·16
	100·00	100·66	99·62	99·77
normative plagioclase	An_{65}	An_{62}	An_{66}	An_{65}

1. Hypothetical Rhum magma as calculated in table 7.
2. Fine-grained olivine gabbro, 5019, from table 9.
A. Average of chilled marginal olivine gabbro. Skaergaard intrusion (Wager & Deer 1939, p. 141).
B. Average of three sub-ophitic basalts, Medicine Lake Highland, California (Anderson 1941, table 1).

indicate that the parent liquid was extremely rich in that mineral, nor does it follow that because the sea water contains only small amounts of calcium sulphate then the crystallizing body at any one time must have been of enormous thickness, and finally the complete series of minerals capable of crystallizing from the body of liquid will not necessarily be found in crystal precipitate. The rare occurrence of bitterns in evaporite deposits is ascribed to the flowage away of the bittern solutions from the precipitating area as fresh material flowed in. The absence of layers of lower temperature minerals in Rhum may similarly be due to the loss of the low-temperature crystallizing magma from the volcanic vent.

It is thus suggested that the layered series now preserved in Rhum is formed of early crystal fractions from a constantly replenished body of basalt magma which cooled slowly. The liquid overlying the crystal pile, which would contain the lower temperature crystallizing material, is believed to have been periodically removed by extrusion at the surface, the magma chamber being filled by fresh magma from below.

(*b*) *Deposition of primary precipitate crystals to form the layers*

The bottom accumulation of crystals by sinking through magma is now accepted as the explanation of certain layered intrusions. There is good evidence that this process also operated in Rhum. The details of the processes responsible for the sorting of the crystals to give the peculiarities of the Rhum layered series is, however, a matter of conjecture.

The simple sinking of crystals in a thin sill or basalt layer has often produced a bottom accumulation of the more dense minerals, but in thick intrusions such as the Skaergaard or Stillwater such a process has also produced bands of average rock. The small-scale 'gravity stratification' first described by Buddington from the Adirondacks (1936) and later demonstrated in the Stillwater, Skaergaard, Belhelvie and Skye gabbros, and the fine-scale rhythmic layering usually associated with it, have been attributed generally to the winnowing effects of currents within the magma chamber. In the Skaergaard there is good evidence that convection currents have swept across the floor of the chamber; in the Stillwater localized turbulence is suggested by Hess (1938).

In Rhum the small-scale gravity stratification has scarcely been detected (see p. 35). The major rhythmic layering might be classed as large-scale gravity stratification, for olivine-rich layers 120 ft. in thickness are overlain by felspar-rich layers 30 to 50 ft. in thickness, were it not for several difficulties involved in such a marked change in scale of the phenomena. First, normal crystal settling of different minerals might be expected to produce bands of average rock as in other cases. Secondly, although evidence of the winnowing effect of currents is to be seen at certain horizons, in the development of fine-scale rhythmic layering and igneous lamination, no evidence comparable with that of the Skaergaard is found to suggest the large overturns of magma (Wager 1953) necessary to keep felspars and pyroxenes in suspension during the deposition of such thick layers of olivine crystals. Thirdly, if gravity had been the chief factor responsible for the rhythm of the layering it is difficult to see why the clinopyroxenes, of density almost the same as that of the olivines, should be concentrated with the felspars near the top of each unit.

It is suggested that had the olivines, felspars, pyroxenes and spinels been generally present at the same time in the magma chamber, then the absence and presence of winnowing currents would have produced bands of average rock and fine-scale gravity stratified rock respectively. On the rare occasions at the beginning of a unit when olivine and spinel were present together, the latter has been concentrated by gravity in a layer below the olivines, while the upper part of each unit is occasionally gravity-stratified on a small scale where heavy and light minerals were available together at the time of deposition. In view of this evidence it is suggested that olivine and spinel crystallized first from the magma, followed by felspar and clinopyroxene, and that although winnowing currents were present and may have occasionally produced minor reversals in the order of deposition as well as several important features of the banding, the major layering was dependent upon the order of crystallization of minerals from the magma. Whether the majority of these minerals sank to the floor of the chamber under gravity or were carried down by currents cannot be answered from available evidence. The composite nature of certain grains suggests that many have had a complex journey through the magma chamber, while the growth of crystals upwards from the temporary floor indicates that crystallization was taking place at the lower levels and many crystals may have sunk only a short distance.

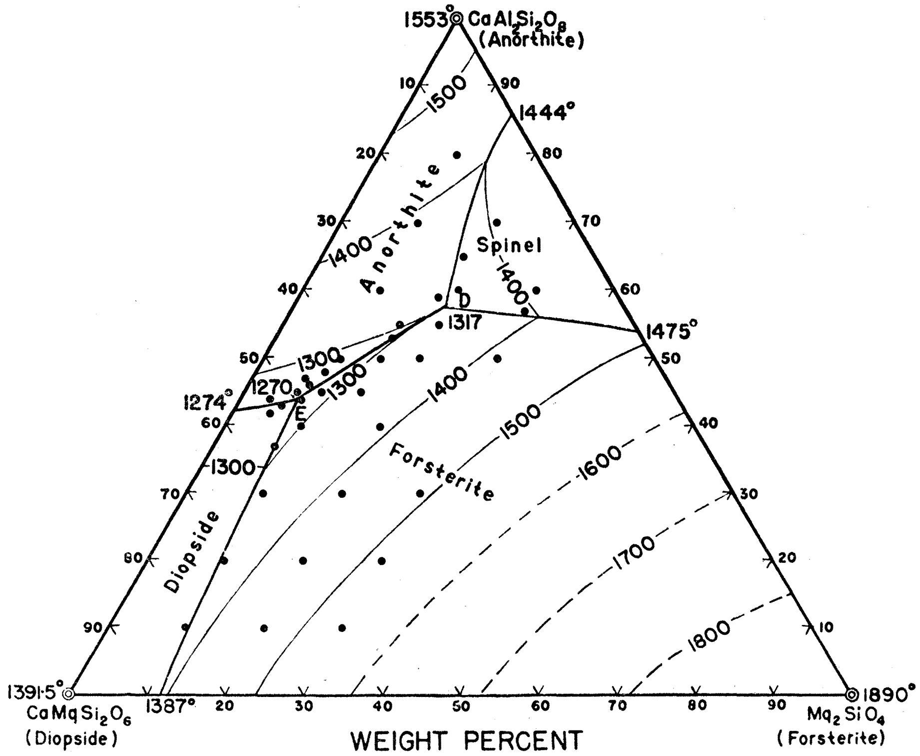


FIGURE 9. Equilibrium diagram of the system diopside-forsterite-anorthite, reproduced (from Osborn & Tait 1952, figure 5) to illustrate the wide extent of the forsterite crystallization field.

By analogy with the anhydrous synthetic system forsterite-anorthite-diopside (Osborn & Tait 1952) it is evident that a wide range of melts would, on cooling, precipitate forsterite before diopside or anorthite (figure 9). From the estimated composition of the Rhum magma it would be reasonable, bearing in mind the limits involved in applying the data for a three-component system to natural magmas, to suppose that it fell within the extensive field from which olivine and spinel would crystallize before felspar and pyroxene. During crystallization there would be an increase in vapour pressure within the magma chamber, and H. S. Yoder (verbal communication May 1955) has found that within the system forsterite-anorthite the effect of an increase in water vapour pressure is to lower the eutectic and shift it towards the anorthite end of the system, thus extending the field from which forsterite would crystallize before anorthite.

TABLE 9. CHEMICAL ANALYSES OF ROCKS FROM THE LAYERED SERIES, AN ULTRABASIC VEIN, AND LATER BASIC INTRUSIONS

	1	2	3	4	5	6
SiO_2	41·06	47·33	45·56	47·67	49·12	48·89
Al_2O_3	4·82	20·08	21·17	20·76	17·76	19·26
Fe_2O_3	2·07	0·55	1·10	1·26	1·38	1·68
FeO	9·46	3·24	5·59	3·22	6·10	6·75
MgO	36·15	12·53	11·48	8·91	9·67	7·46
CaO	4·27	14·47	11·42	15·19	12·56	11·45
Na_2O	0·65	1·34	1·99	1·91	2·70	2·52
K_2O	0·02	0·07	0·16	0·07	0·17	0·41
H_2O^{+110}	0·97	0·21	1·21	1·02	0·40	0·58
H_2O^{-110}	0·06	0·14	0·07	0·17	0·13	0·13
TiO_2	0·15	0·15	0·40	0·15	0·29	0·72
P_2O_5	nil	tr.	0·02	nil	0·01	0·05
MnO	0·17	0·08	0·10	0·07	0·29	0·12
Cr_2O_3	0·51	0·18	0·02	0·23	0·05	0·02
Total	100·36	100·37	100·29	100·63	100·66	100·04

1. Peridotite from unit 10. Average of seven specimens (5328 to 5334).
2. Allivalite from unit 10 (5049).
3. Allivalite from unit 3 (5114).
4. Contemporaneous ultrabasic vein cutting unit 10 (3236).
5. Fine-grained olivine gabbro (5019).
6. Marginal gabbro (5186).

Analyses 1 and 4 by Dr E. A. Vincent and Miss R. Hall.
Analyses 2, 3, 5 and 6 by G. M. Brown.

THE CIPW NORMS OF ROCKS IN TABLE 9

	1	2	3	4	5	6
orthoclase	0·11	0·56	1·11	0·39	1·11	2·22
albite	2·99	11·32	15·20	14·04	20·96	21·48
anorthite	10·17	48·93	48·37	47·86	35·50	40·03
nepheline	1·36	—	0·85	1·14	1·14	—
diopside: Wo	4·58	9·55	3·48	11·44	11·20	6·96
Cl-En	3·50	7·26	2·40	8·50	7·30	4·30
Fs	0·59	1·28	0·79	1·80	3·10	2·25
hypersthene: En	—	—	—	—	—	5·10
Of	—	—	—	—	—	2·77
olivine: Fo	60·32	16·70	18·20	9·52	12·04	6·45
Fa	11·34	3·26	6·22	2·22	5·10	3·90
magnetite	3·02	0·79	1·62	1·85	2·10	2·55
ilmenite	0·29	—	0·76	0·29	0·61	1·37
chromite	0·76	—	—	0·33	—	—
apatite	—	—	—	—	—	0·10
plagioclase	$Or_1Ab_{22}An_{77}$	$Or_1Ab_{18}An_{81}$	$Or_2Ab_{24}An_{74}$	$Or_1Ab_{22}An_{77}$	$Or_2Ab_{36}An_{62}$	$Or_3Ab_{34}An_{63}$
olivine	$Fo_{84}Fa_{16}$	$Fo_{84}Fa_{16}$	$Fo_{75}Fa_{25}$	$Fo_{81}Fa_{19}$	$Fo_{70}Fa_{30}$	$Fo_{62}Fa_{38}$
$\frac{(FeO+Fe_2O_3)\times 100}{FeO+Fe_2O_3+MgO}$	24	23	37	33	44	53
						$En_{65}Of_{35}$

There are at least fifteen major rhythmic units, and the reason for the rhythmic repetition of the order of crystallization remains to be considered. It has been suggested that the magma chamber in Rhum was connected both with a volcanic conduit leading to the surface and with a reservoir of basic magma at greater depth. Periodic volcanic activity—

and volcanic activity is normally markedly periodic—would result in the escape of dissolved water vapour and of lava drawn from the liquid above the accumulating layered series. It is believed that the activity would be followed by a fresh influx of magma from below. The effect of the release of vapour pressure would be to promote rapid crystallization, particularly of felspar, but the fresh magma would soon restore the system to the conditions of temperature and composition at which olivine or spinel would once again crystallize before felspar and clinopyroxene. It is believed that such a mechanism might account for the major layering, evidence for the introduction of fresh magma being afforded by the layer rich in chromite, in the case of unit 12, and by sulphides (pyrrhotite and chalco pyrite) at the base of certain units.

It has been suggested by Yoder, on the basis of experimental work on the system diopside-anorthite-water (Abelson 1954, p. 107), that the rhythmic layering of basic layered intrusions such as the Stillwater or Bushveld might be explained solely on the basis of variation in water vapour pressure within the cooling magma over a critical range, allowing alternatively a pyroxene or a plagioclase to crystallize and settle out. Such alternation would require very critical conditions in order to avoid the necessity for temperature as well as pressure fluctuations, and until more evidence is available it is suggested that the numerous fine-scale rhythms in Rhum formed by the action of winnowing currents within the magma, a mechanism which could have also produced the igneous lamination.

(*c*) *The absence of cryptic layering*

No cryptic layering, which is so marked a feature of the Skaergaard intrusion, is demonstrable in the 2600 ft. of layered rocks so far examined in Rhum, and this implies little decrease in temperature during the lengthy period of deposition of this thickness of layered rocks. In the ultrabasic part of the Stillwater (Hess 1939) and in the Belhelvie complex (Stewart 1946) there is no cryptic layering; Hess attributes slight fluctuations in the composition of the Stillwater minerals to the rate of crystal accumulation, and therefore the degree to which diffusion could operate to produce interstitial material of the same composition as the settled crystals. He believes that the interstitial liquid, if trapped, would react with, and make over the primary crystals, but Wager & Deer have shown that this has certainly not taken place to any extent in the Skaergaard case. The slight fluctuations recorded in the Rhum felspars (figure 4, p. 21) refer to the primary crystals, and changes in the composition of interstitial material, as evidenced by zoning, have been neglected. It has been suggested that these gentle fluctuations of composition represent either slight changes in the temperature of the fresh supplies of magma or slight pressure changes attendant upon the introduction of these supplies or the extrusion of magma at the surface. The changes are not considered to imply a difference in composition of the fresh magma, as is suggested by Hall and subsequent investigators, to account for the sharp reversals found at certain horizons in the Bushveld. If the lack of appreciable cryptic layering is characteristic of the ultrabasic part of layered intrusions in general, then it may be that, as suggested for Rhum, a fresh supply of magma was available to replenish the magma chamber at this early stage in the cooling history, and that in doing so it kept the temperature relatively constant over a great period of time. Tsuboi (1926, p. 171) was impressed by the constancy in composition of the phenocrysts precipitating from basalts of

Oshima at the early stage when the felspars were An_{85} and the olivines Fa_{14}, and he remarked that the temperature of magma in the volcanic pile could not have changed much over a long period of time; this again suggests evidence of magma replenishment. At these temperatures slight fluctuations of temperature would hardly be detected in the changing composition of the felspars or olivines owing to the steeper gradient of the solidus at high temperatures. Thus Larsen & Irving (1938, figure 26) note that, assuming the conditions of the two component systems hold, 50 % of a plagioclase melt, An_{60}, would crystallize in the range An_{85} to An_{75}, under extreme fractionation. Indeed, the fluctuation in temperature indicated for the Rhum layered series by the total recorded range in felspar composition (An_{83-88}) amounts to 20° C, and this would produce no detectable change in the optical properties of the olivines.

(*d*) *The crystallization of the interstitial liquid*

The liquid which crystallized in the interstices of the settled crystals may account for 30 to 50 % of the total rock, depending on the quality of the packing. Although the main features of each rock type are dependent on the primary crystals and the manner in which they accumulated, there are others due to the interstitial material. The interstitial liquid was probably originally basaltic in composition but, except in the lower 4 to 5 units, it became modified during crystallization, as suggested by Hess (1939) for the Stillwater Complex, by diffusion of material from the overlying magma 'into and out of the interstitial liquid'. The diffusion is postulated to have been such that the further deposition of material had the same composition as the settled crystals. Thus once the interstitial liquid had deposited a film of solid material around each primary crystal a composition gradient would exist between it and the overlying magma, and diffusion would commence. The extremely slow cooling of the main body of magma, the low rate of deposition (as evidenced by the thickness of unconsolidated material), and the probability of stirring of the overlying liquid are the factors which would favour an efficient diffusion system. No other mechanism has been suggested which could adequately explain the complete infilling of the interstices by high-temperature minerals of the same composition as the primary precipitate. The degree to which diffusion has operated is thus believed to be reflected in the extent of zoning of the primary crystals. In the upper units zoning is only detected with certainty in the felspars; it is always stronger in the olivine-rich layers than in the felspathic, and it is absent from the almost pure felspar layers at the top of each unit. This is believed due to the rate of deposition being greater for the olivines than the felspars, the latter being deposited slowly perhaps during a waning or almost tranquil phase of current activity. On the other hand, when the different units are compared, the rate of deposition during formation of the lower units is considered to have been greater than for the upper as zoning of the felspars and clinopyroxenes is conspicuous and interstitial orthopyroxene, iron ore and apatite were formed. The composition of the original liquid has been estimated (see above p. 43) on the basis of this hypothesis and seems reasonable.

(*e*) *The emplacement of the layered series*

The ordered disposition of the layered series appears to have been upset to the west of Hallival–Askival by disturbances which have produced autobrecciation and may also have been responsible for the contemporaneous ultrabasic veins and for the slumping and irregularities of the crystal-mush floor which have been described from certain horizons. Moreover, the transgressive gabbros show that later disturbances accompanied by injection of basic magma into the layered series also occurred.

Evidence has been given to suggest that the ultrabasic rocks could have formed not far below the level at which they are now found; however, marginal relationships suggest that the ultrabasic complex probably represents part of a much bigger layered complex faulted up into its present position subsequent to consolidation.

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APPENDIX

Methods and accuracy of physical determinations

The composition of the felspars was based chiefly on the determination of refractive index of cleavage flakes and the application of the results to Tsuboi's curves (1923, figure 2). In the case of the analyzed specimen α and γ were determined, in addition, and the composition checked against the curves of Chayes (1952).

The Rittmann zone method was found unsuitable for felspars more calcic than An_{84} owing to the emergence of an optical axis close to the zone parallel to (010), the maximum value of X' on to (010) almost coinciding with the parallelism of this optical axis with the axis of the microscope.

The Federov method was used as a check on twin laws but was found inaccurate in composition determination (using migration curves of Duparc & Reinhard 1924), giving a consistently higher value for the anorthite content (+5 to 7 %) than that obtained by analysis or any other optical method.

The results for the analyzed felspar were applied to Reynolds's extension of Kohler's $\beta\beta'$ curve (1952, figure 3), but it was found that although the average and all but one reading indicated An_{88-91} on the low-temperature curve, one reading indicated An_{91} on the high-

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* Figures 12, 20, 22, 28 and 29.

temperature curve. Not only does this support Reynolds's contention that it is difficult to discriminate between the two types of lime-rich plagioclase by optical methods, but indicates the same high anorthite content obtained by using Kohler's curves, which are based on Reinhard's data.

The clinopyroxenes were investigated by determining $2V\gamma$ and β on (100) parting tablets (with a simple temperature variation technique). Exact correlation with Hess's curves (1949) was found impracticable owing to the complete lack of exsolution and the high alumina content in the Rhum pyroxenes. The analyzed specimen fits the curves modified for chrome-rich pyroxenes only after the addition of 3° to the optical axial angle and the subtraction of 0·004 from the observed value for β.

Refractive indices are accurate to ± 0·002 except for felspars where the use of Ng and Np curves is believed to reduce the limits of error to ± 0·001.

Optical axial angle accurate to ± 1°.

Specific gravity accurate to 2nd decimal for minerals and rocks.

Unit cell measurements accurate to ± 0·003 Å and β to ± 2′ (method described by Hess (1952) and Kuno (1955)). Radiation CuKα, using the North American Phillips X-ray spectrometer at Princeton University, and the sample preparation method described by Kuno.

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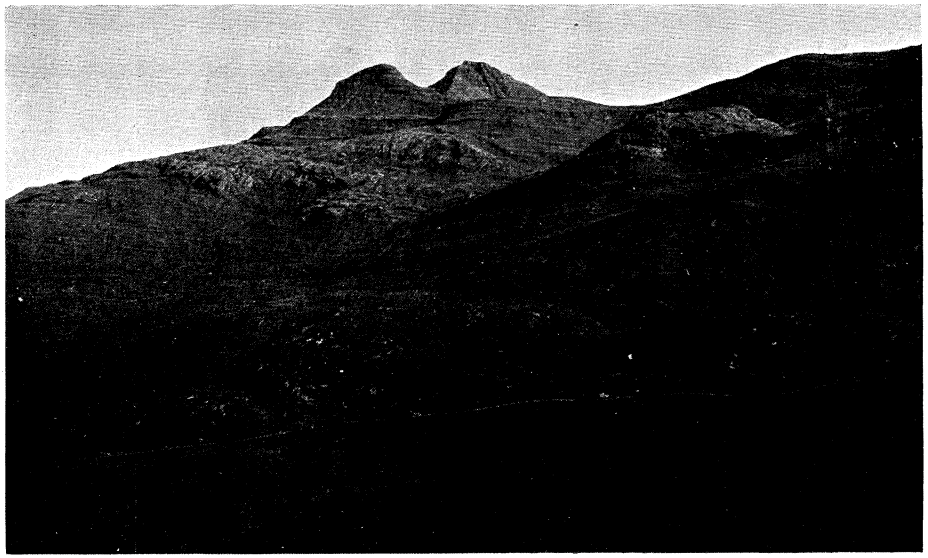

FIGURE 10. View of Hallival and Askival from the north. The topography of the layered series contrasts with that of the light-coloured marginal felsites in the middle distance. Torridonian forms the lower ground to the north and south of the Kinloch-Harris road, separated from the felsites by the ring-fault.

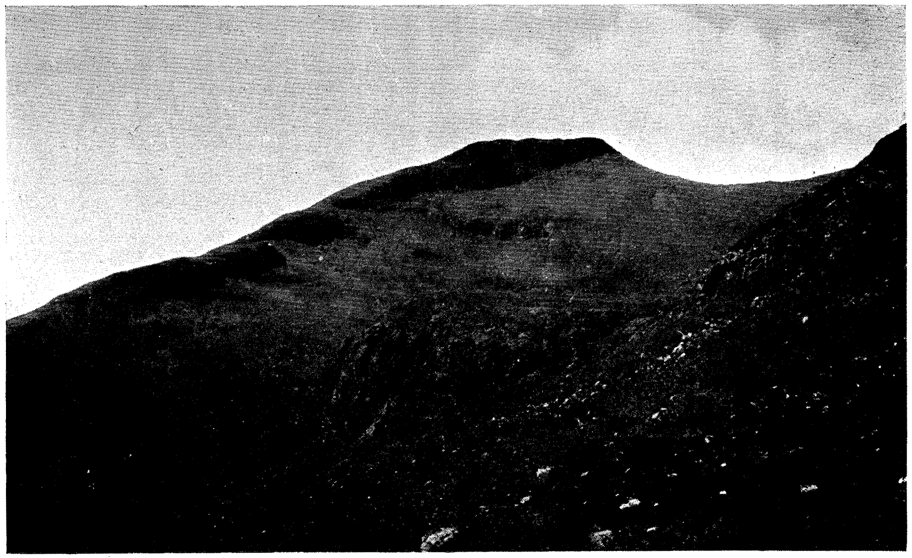

FIGURE 11. The south-eastern margin, looking south. Skyline formed by the Torridonian, explosion breccia and felsites of Beinn nan Stac. Layered series in foreground. The col and grassy slopes of Beinn nan Stac consist of quick-weathering gabbro.

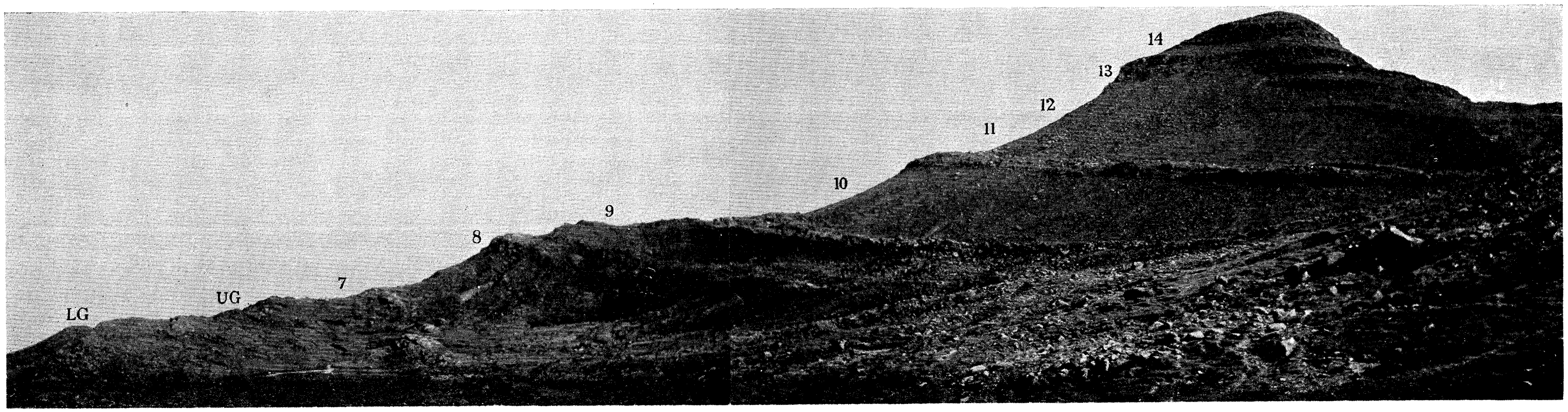

FIGURE 12. Hallival from the north-east. The resistant layers of allivalite alternate with weathered layers of peridotite. 7...14. Units 7 to 14 of the layered series. U.G. Upper fine-grained olivine gabbro. L.G. Lower fine-grained olivine gabbro.

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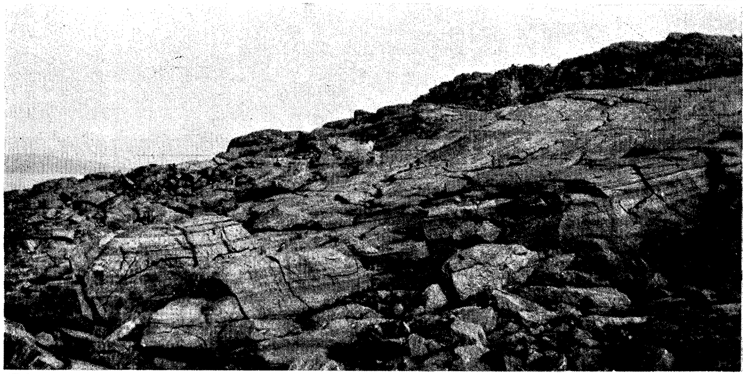

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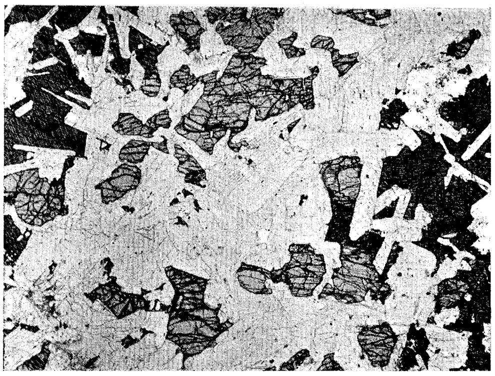

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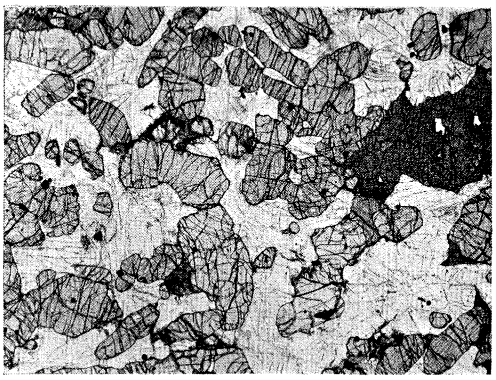

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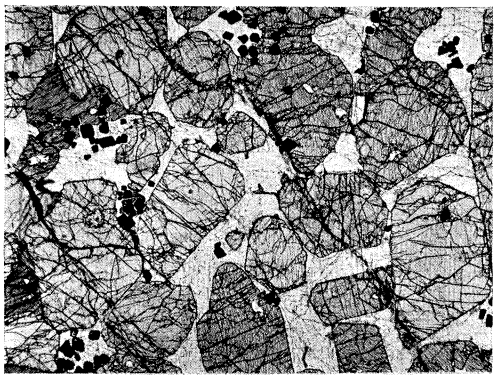

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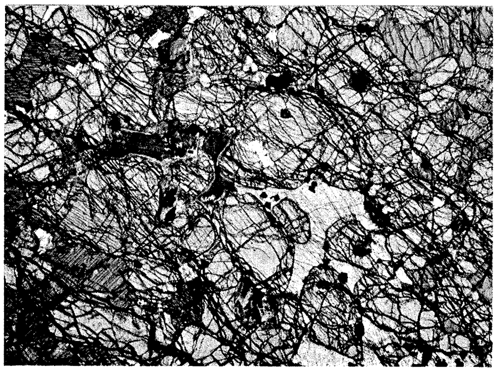

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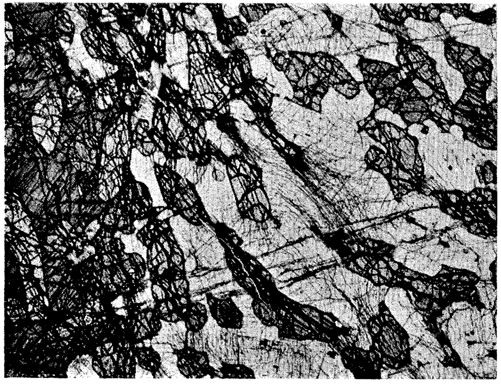

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PLATE 2

FIGURE 13. Lace texture in peridotite of type unit, Askival-plateau.

FIGURE 14. Fine-scale rhythmic layering near top of type unit, Askival plateau.

FIGURES 15 to 19. Photomicrographs of specimens from the type unit, to illustrate the change in mineral content and textures from base to top (see figure 7 for relative positions of specimens) (Magn. × 8). 15, specimen 5348; 16, 5341; 17, 5338; 18, 5334, 19, 5328.

FIGURE 20. Upward-growing pyroxene structure developed at the top of a minor peridotitic phase within the main allivalite of unit 8. Northern escarpment to Askival plateau.

FIGURE 21. Thin section of upward-growing pyroxene structure (3198), showing change in orientation of elongated olivines in and near to the poikilitic pyroxene (Magn. × 8).

Plate 3

Figure 22. Fine-scale rhythmic layering at the top of unit 8. Note sharp base to overlying unit. Northern escarpment to Askival-plateau.

Figure 23. Harrisite structure (upper half of photograph) developed with the lower part of unit 11. North-eastern slopes of Askival.

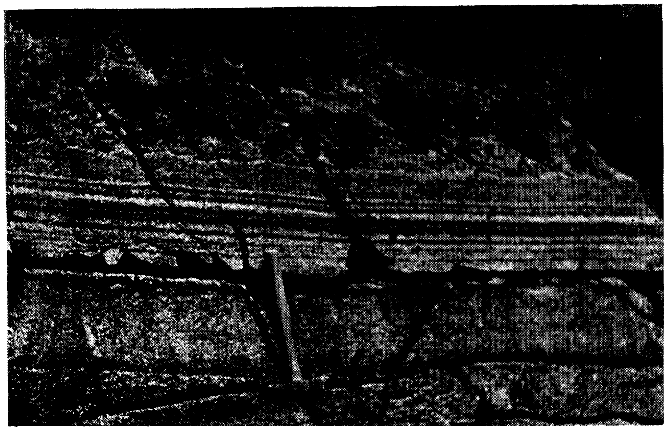
Figure 24. Undulatory base to pyroxene-rich layer in upper, felspathic part of unit 9, north-east shoulder of Hallival. Dip section.

Figure 25. As in figure 24, strike section.

Figure 26. Specimen 3218, showing a thin layer of chromites between the felspar concentrations at the top of unit 11 and the olivine concentrations near the base of unit 12. Natural size.

Figure 27. Photomicrograph of thin section of 3218. Magnification × 8.

Figure 28. Hallival and the Col, from Askival. The major allivalites illustrated belong to units 12 (below the col level), 13 (partly forming the col) and 14 (to within 25ft. of the summit). Coastline of Skye in the distance.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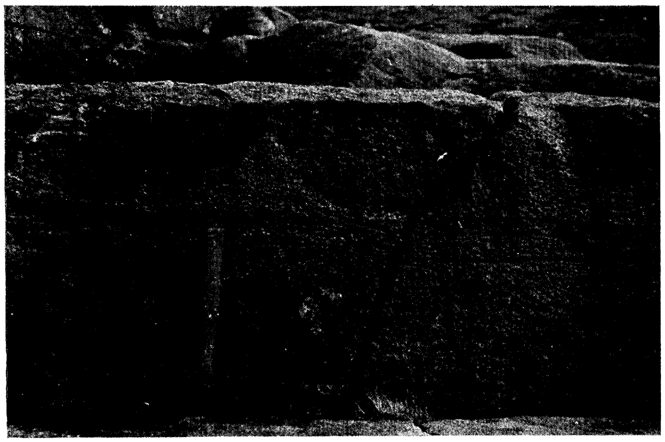
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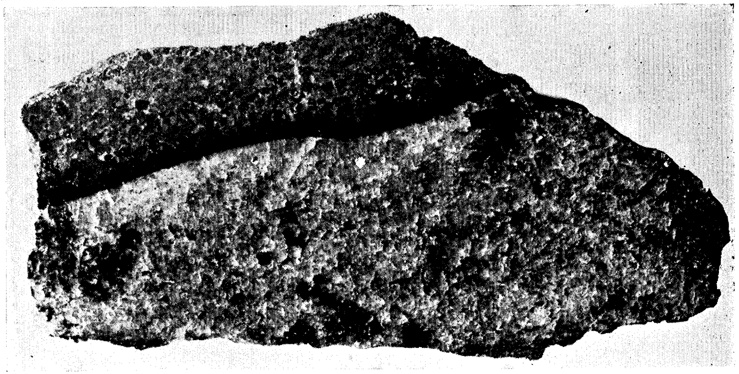
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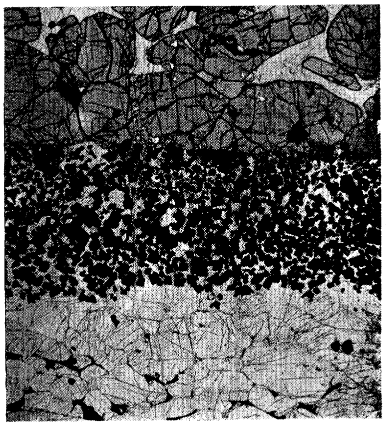
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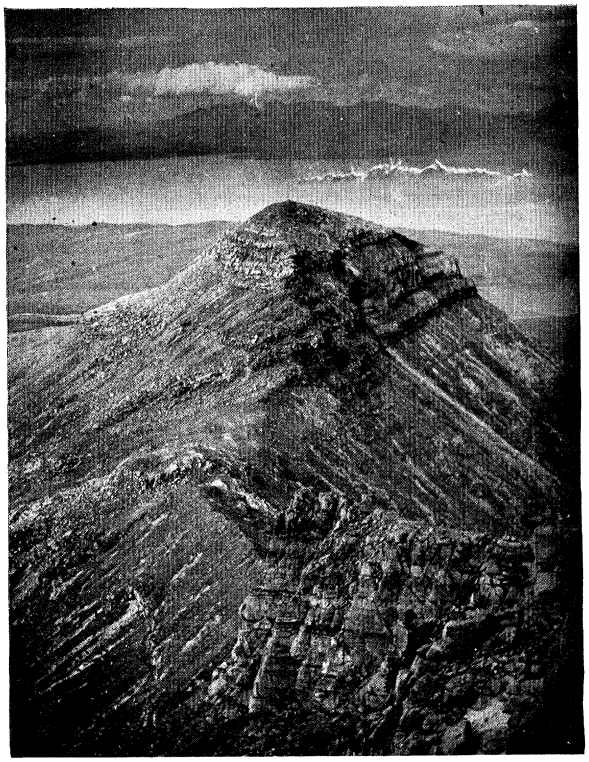
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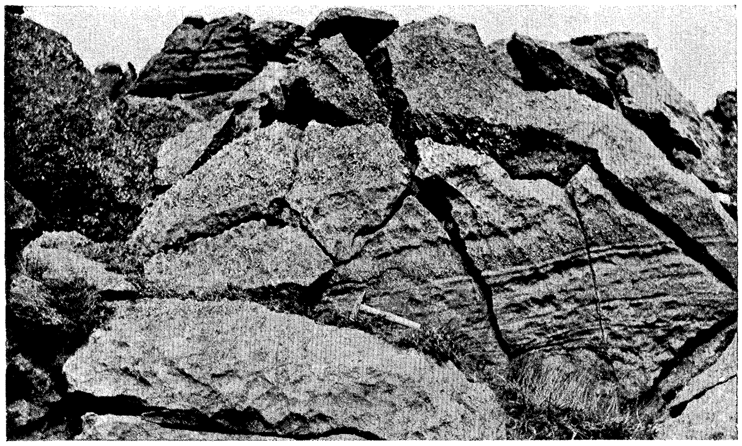

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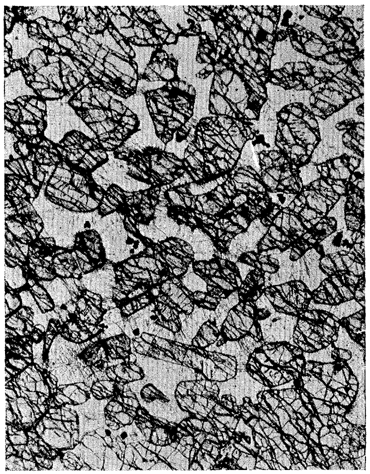

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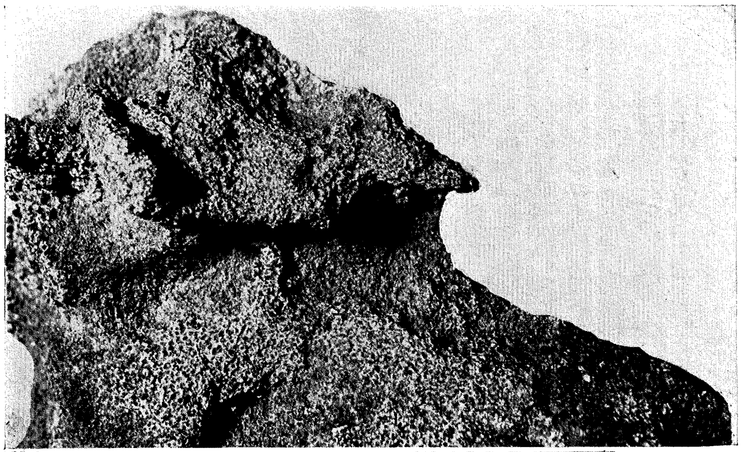

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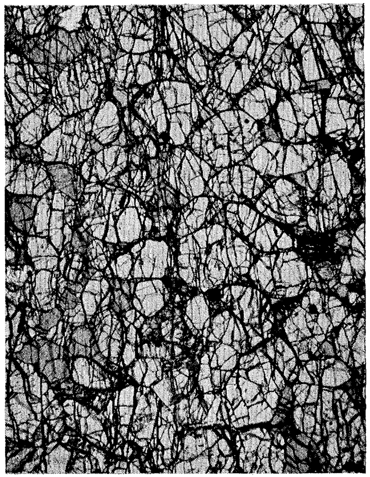

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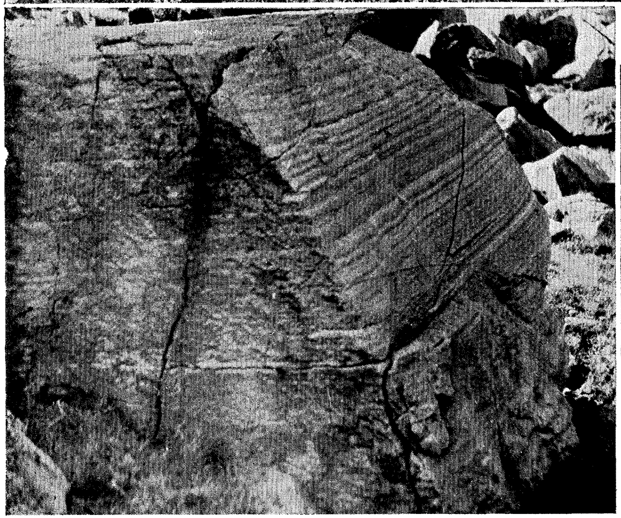

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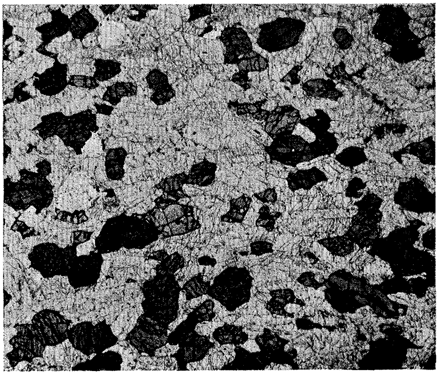

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PLATE 4

FIGURE 29. Harrisite structure developed as layers within the peridotites of the Harris area, 1½ miles north-north-east of Harris Lodge.

FIGURE 30. Peridotite (3223) with the pitted surface produced by the relative resistance to weathering of poikilitic felspars (protuberances) and poikilitic clinopyroxenes (hollows). Two-thirds size.

FIGURE 31. Photomicrograph of part of one of the poikilitic felspars shown in figure 30 (Magn. × 8).

FIGURE 32. Photomicrograph of part of one of the poikilitic clinopyroxenes shown in figure 30. Both olivines and chromites are enclosed, as in figure 31 (Magn. × 8).

FIGURE 33. Fine-scale rhythmic layering in fallen block of allivalite, Coire nan Grunnd.

FIGURE 34. Slump-structures developed from olivine-felspar layers near top of unit 14, eastern face of Askival. The hammer lies radially with respect to the shape of the intrusion, the head lying nearest the centre.

FIGURE 35. Photomicrograph of allivalite found as a fallen block, 3237*b*. The olivine in the centre, enclosing tiny unorientated felspars, is believed to have settled as a composite grain. Note the banking of the discrete felspar crystals round this grain (Magn. × 6·6: crossed polars).

FIGURE 36. Peridotite from the south-east slopes of Trallval (3293). The plane of the section is almost horizontal, the long radially orientated olivines being plates in the semi-vertical plane. Large poikilitic grains of felspar and clinopyroxene fill the interstices (magn. × 6·6).

FIGURE 37. An allivalite from unit 10, north-east shoulder of Hallival (5049). Note the discrete character of the plagioclase, clinopyroxene and olivine grains each of which, together with the rock, have been chemically analyzed (magn. × 8).

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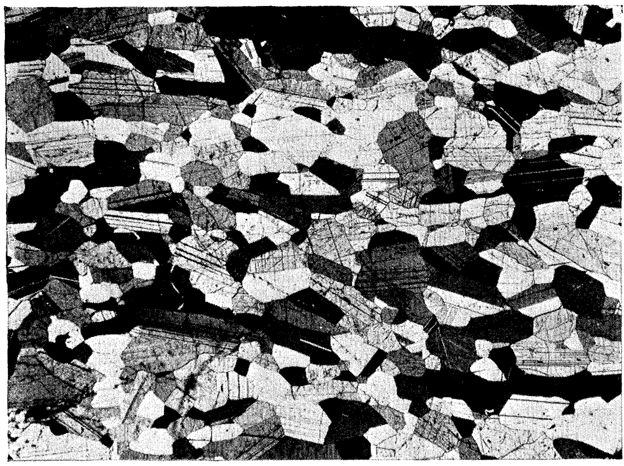

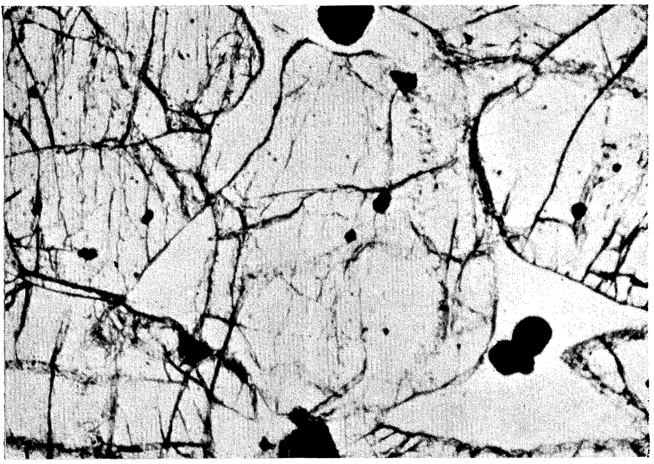

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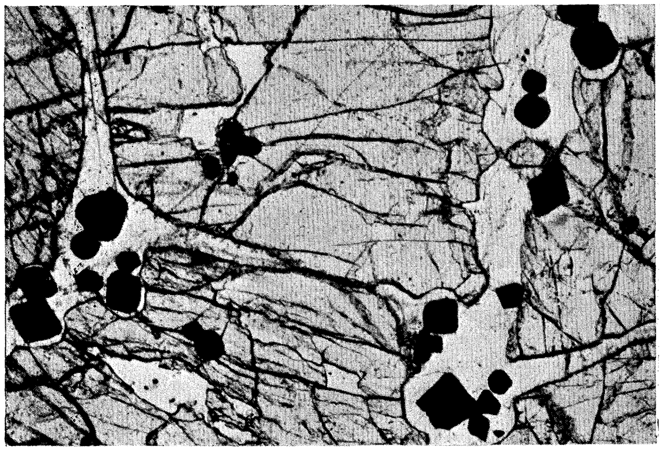

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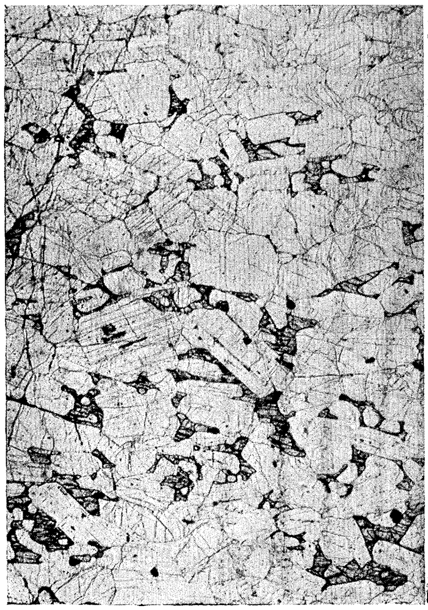

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PLATE 5

FIGURE 38. A pure felspar rock from unit 14 (5061), showing igneous lamination (magn. × 10: crossed polars).

FIGURE 39. A peridotite from unit 10 (5333), in which there is a great difference in size between chromites outside and inside the olivines (magn. × 61).

FIGURE 40. A peridotite from unit 10 (5332) in which rims of felspar (each in optical discontinuity with the poikilitic grains) separate chromite from olivine in small embayments (magn. × 38).

FIGURE 41. The felspathic part of 3218, a banded allivalite from unit 12 (see figures 26 and 27), in which a single grain of olivine (each part in optical continuity with the whole) poikilitically encloses felspar crystals (magn. × 10).

FIGURE 42. A type of harrisite structure within a peridotite (fallen block, 3192). Note the long, single olivine crystals which show a tendency to 'bud' (magn. × 8·3).

FIGURE 43. The Barkeval 'eucrite', 5317. Note the marked discontinuous zoning of the felspars (cores An_{86-89} and rims An_{66}) (magn. × 10: crossed polars).

FIGURE 44. The analyzed fine-grained olivine gabbro, 5019 (magn. × 10).

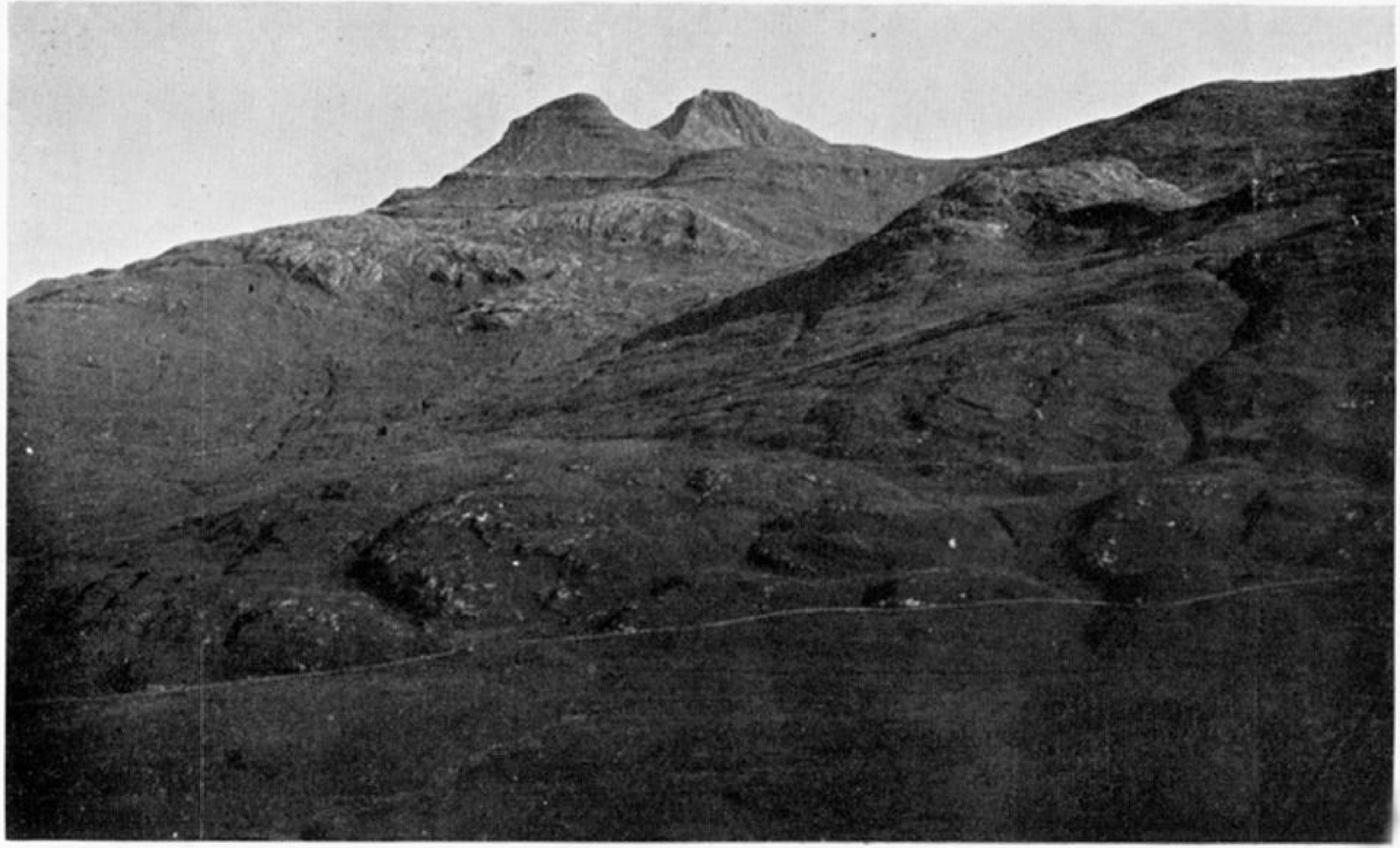

FIGURE 10. View of Hallival and Askival from the north. The topography of the layered series contrasts with that of the light-coloured marginal felsites in the middle distance. Torridonian forms the lower ground to the north and south of the Kinloch-Harris road, separated from the felsites by the ring-fault.

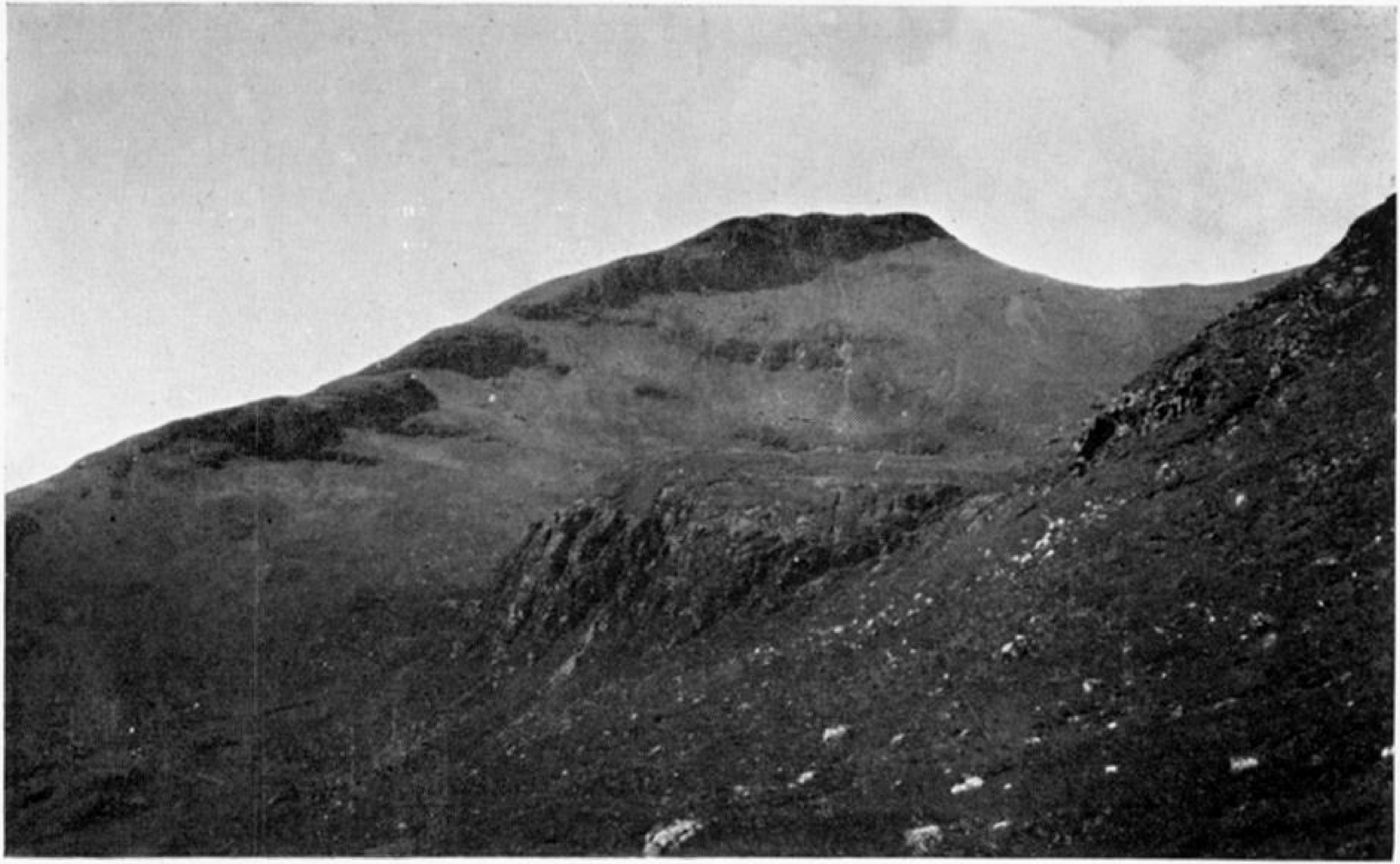

FIGURE 11. The south-eastern margin, looking south. Skyline formed by the Torridonian, explosion breccia and felsites of Beinn nan Stac. Layered series in foreground. The col and grassy slopes of Beinn nan Stac consist of quick-weathering gabbro.

FIGURE 12. Hallival from the north-east. The resistant layers of allivalite alternate with weathered layers of peridotite. 7…14. Units 7 to 14 of the layered series. U.G. Upper fine-grained olivine gabbro. L.G. Lower fine-grained olivine gabbro.

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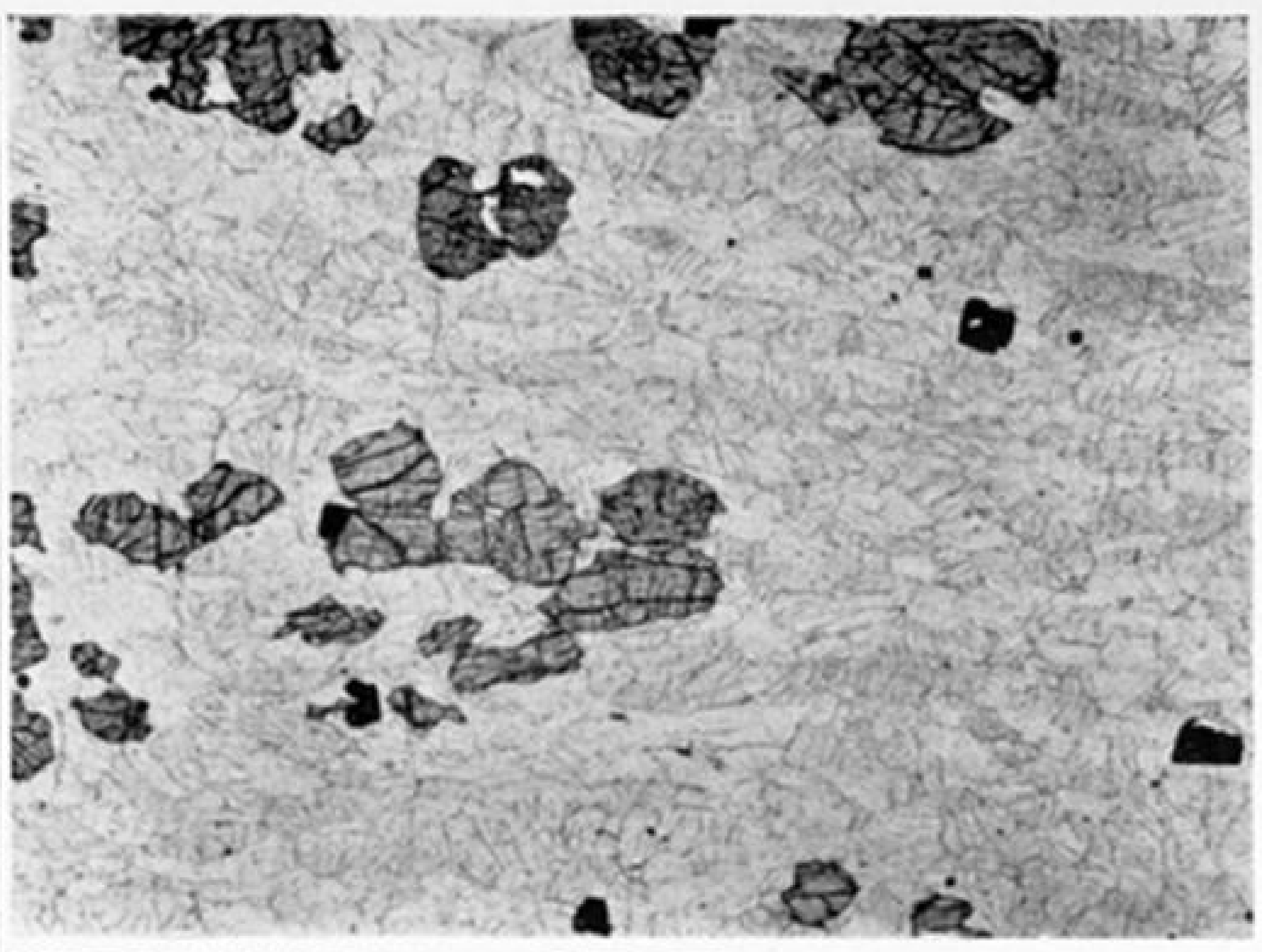

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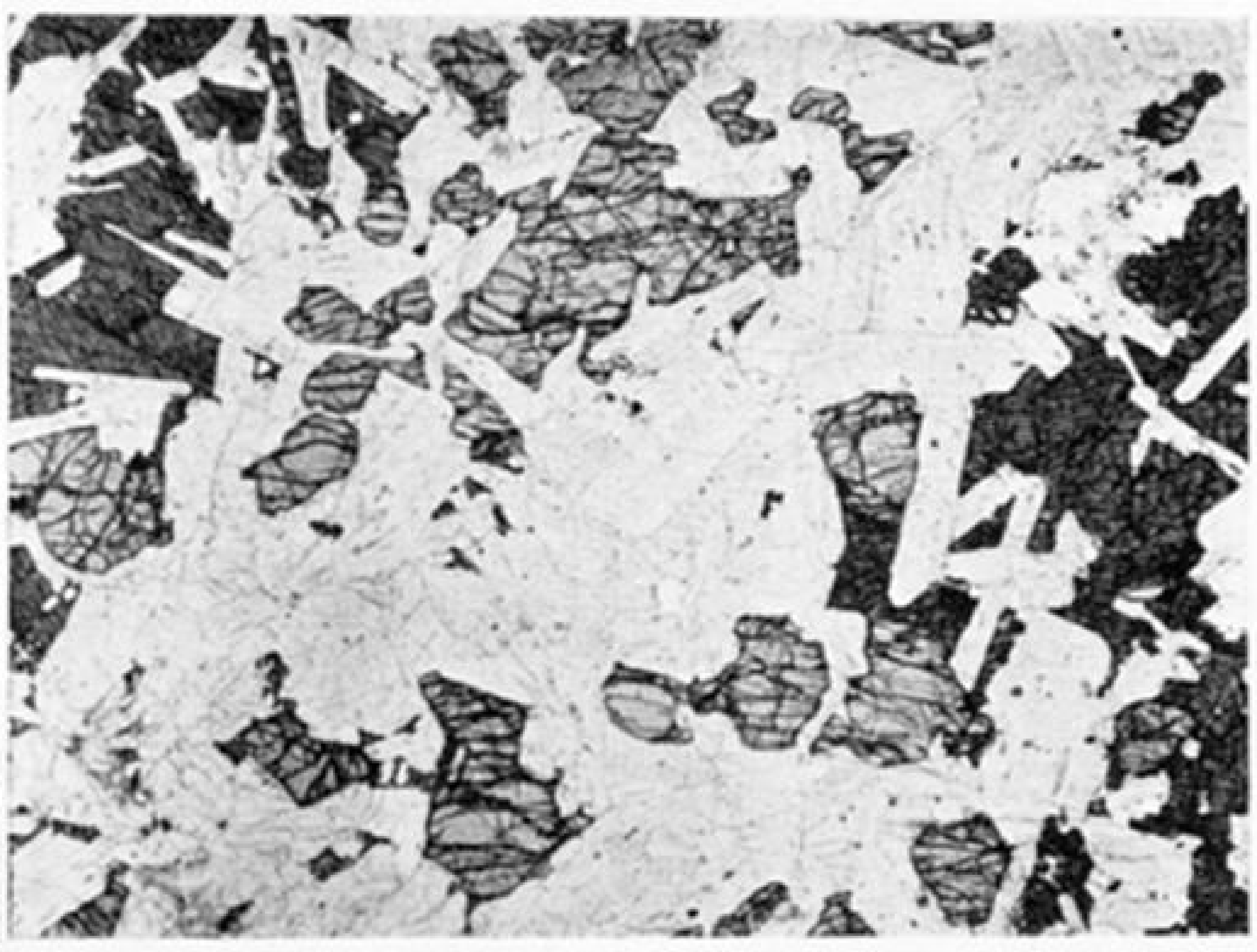

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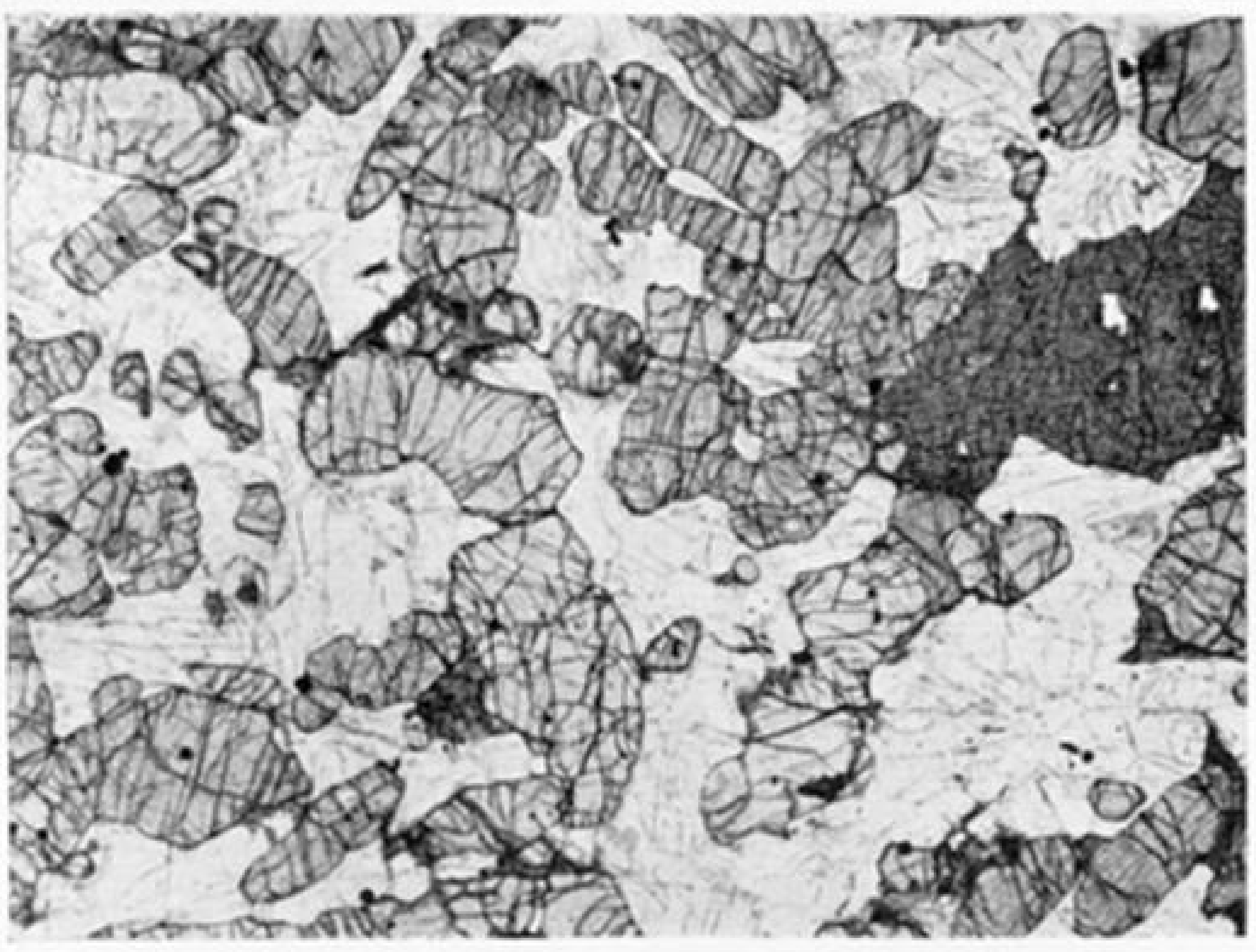

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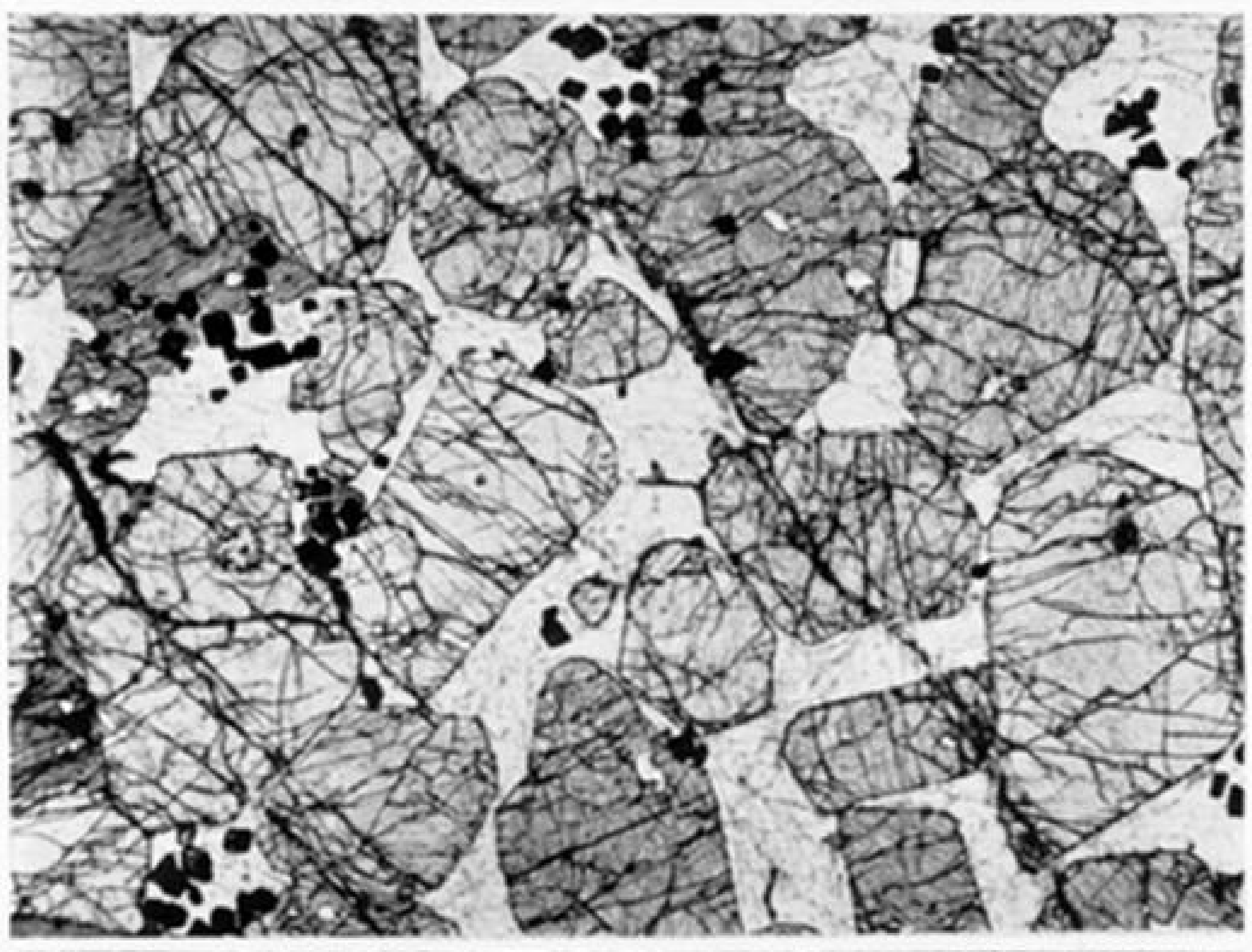

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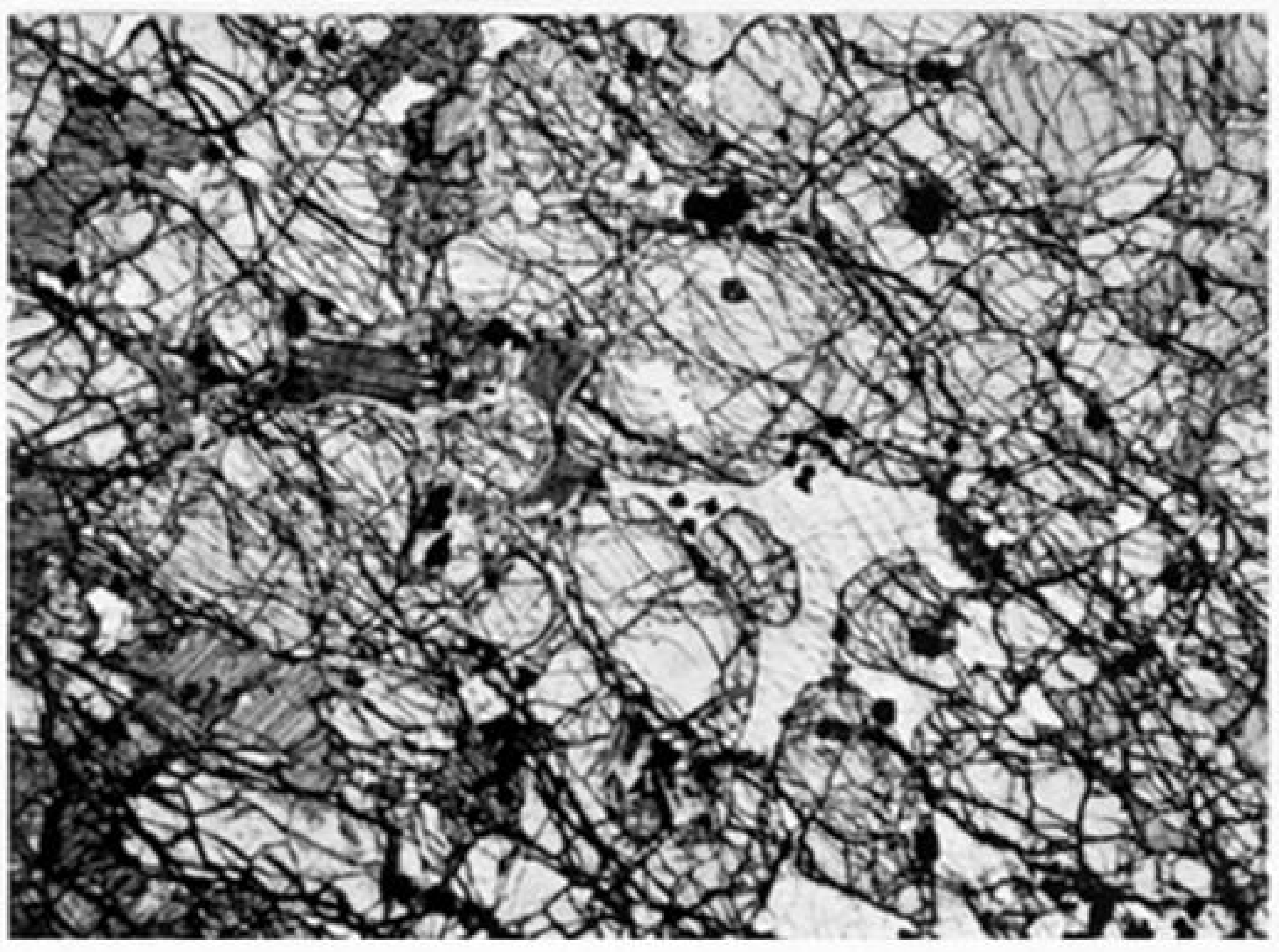

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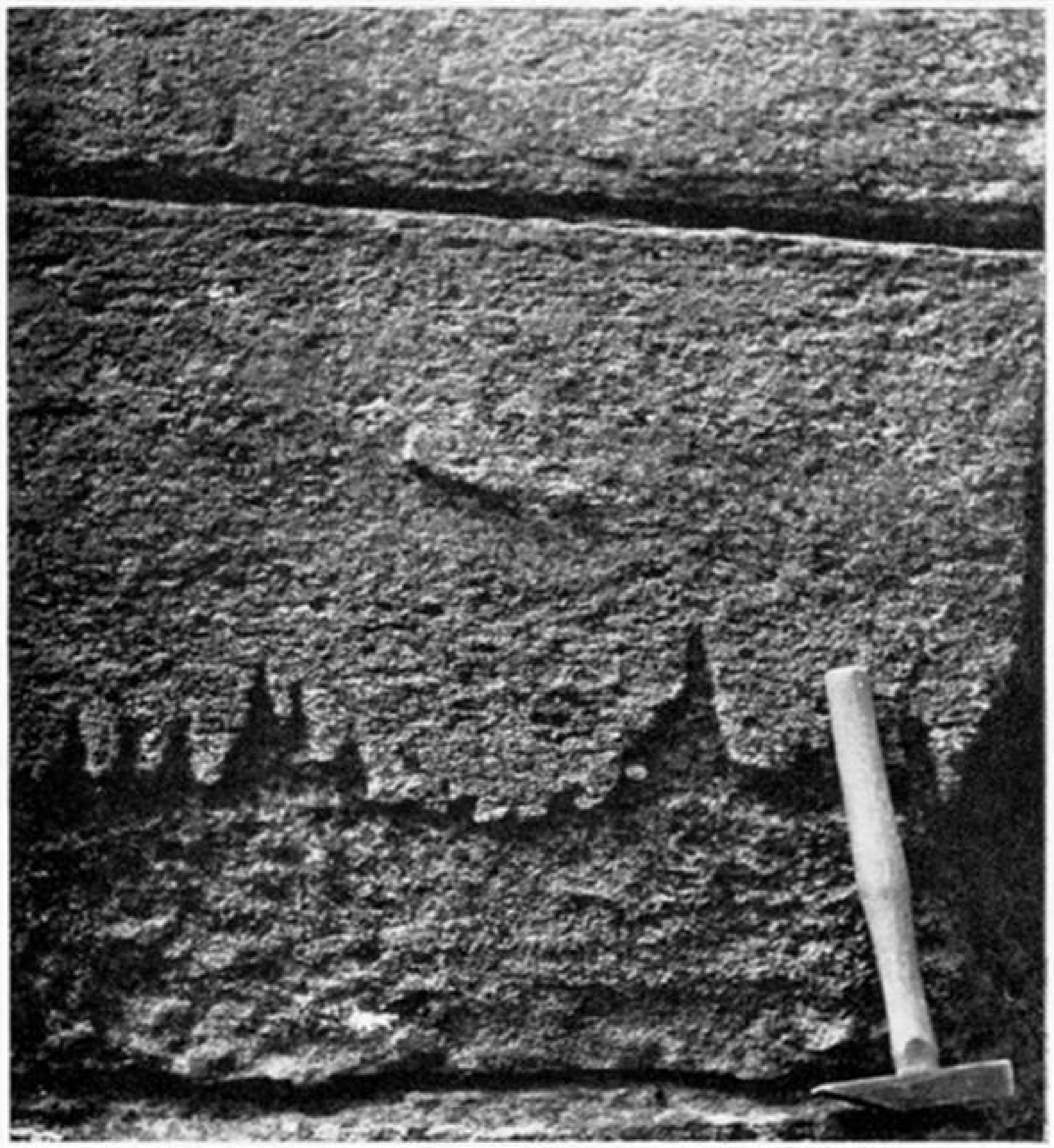

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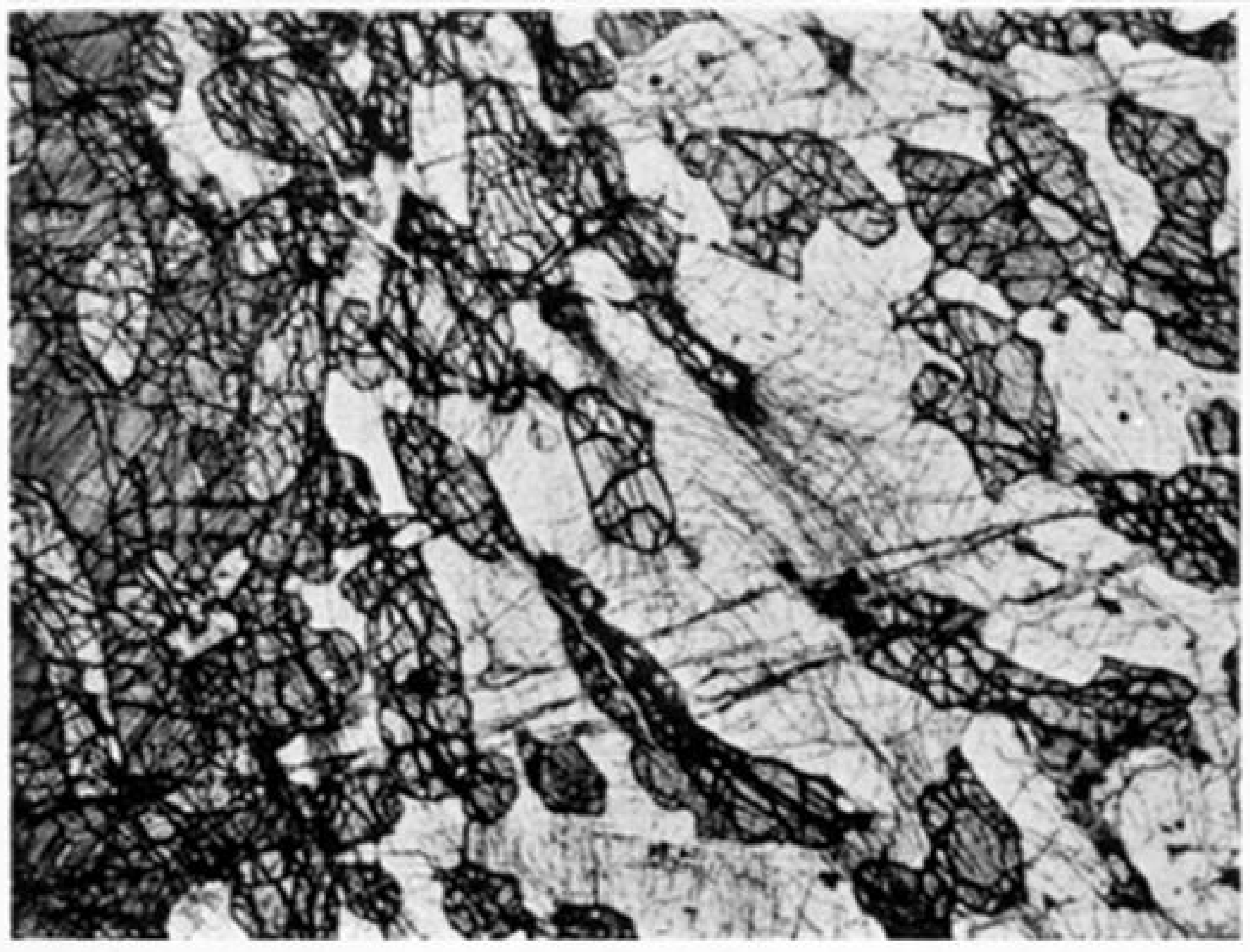

PLATE 2

FIGURE 13. Lace texture in peridotite of type unit, Askival-plateau.

FIGURE 14. Fine-scale rhythmic layering near top of type unit, Askival plateau.

FIGURES 15 to 19. Photomicrographs of specimens from the type unit, to illustrate the change in mineral content and textures from base to top (see figure 7 for relative positions of specimens) (Magn. × 8). 15, specimen 5348; 16, 5341; 17, 5338; 18, 5334, 19, 5328.

FIGURE 20. Upward-growing pyroxene structure developed at the top of a minor peridotitic phase within the main allivalite of unit 8. Northern escarpment to Askival plateau.

FIGURE 21. Thin section of upward-growing pyroxene structure (3198), showing change in orientation of elongated olivines in and near to the poikilitic pyroxene (Magn. × 8).

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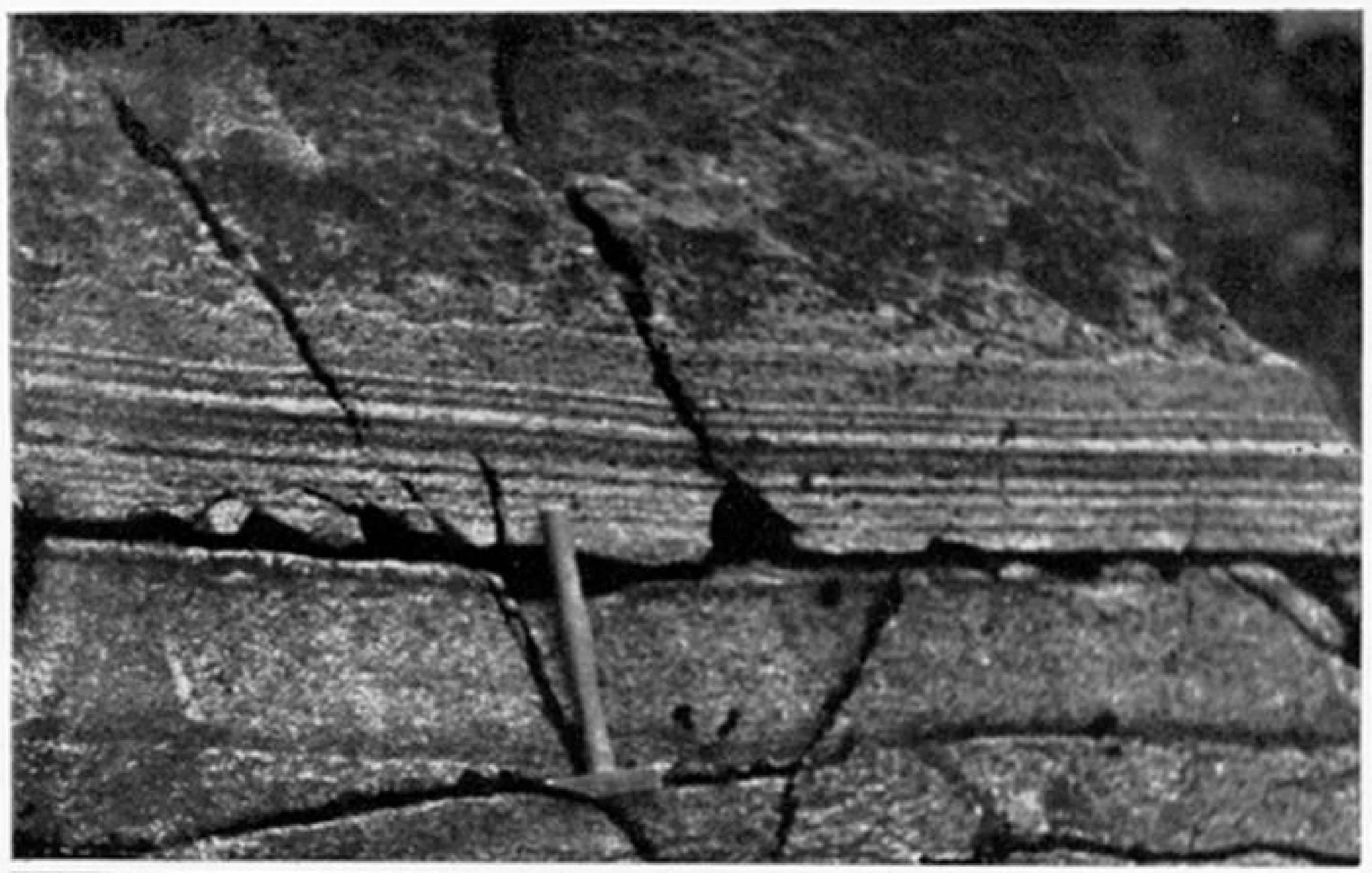

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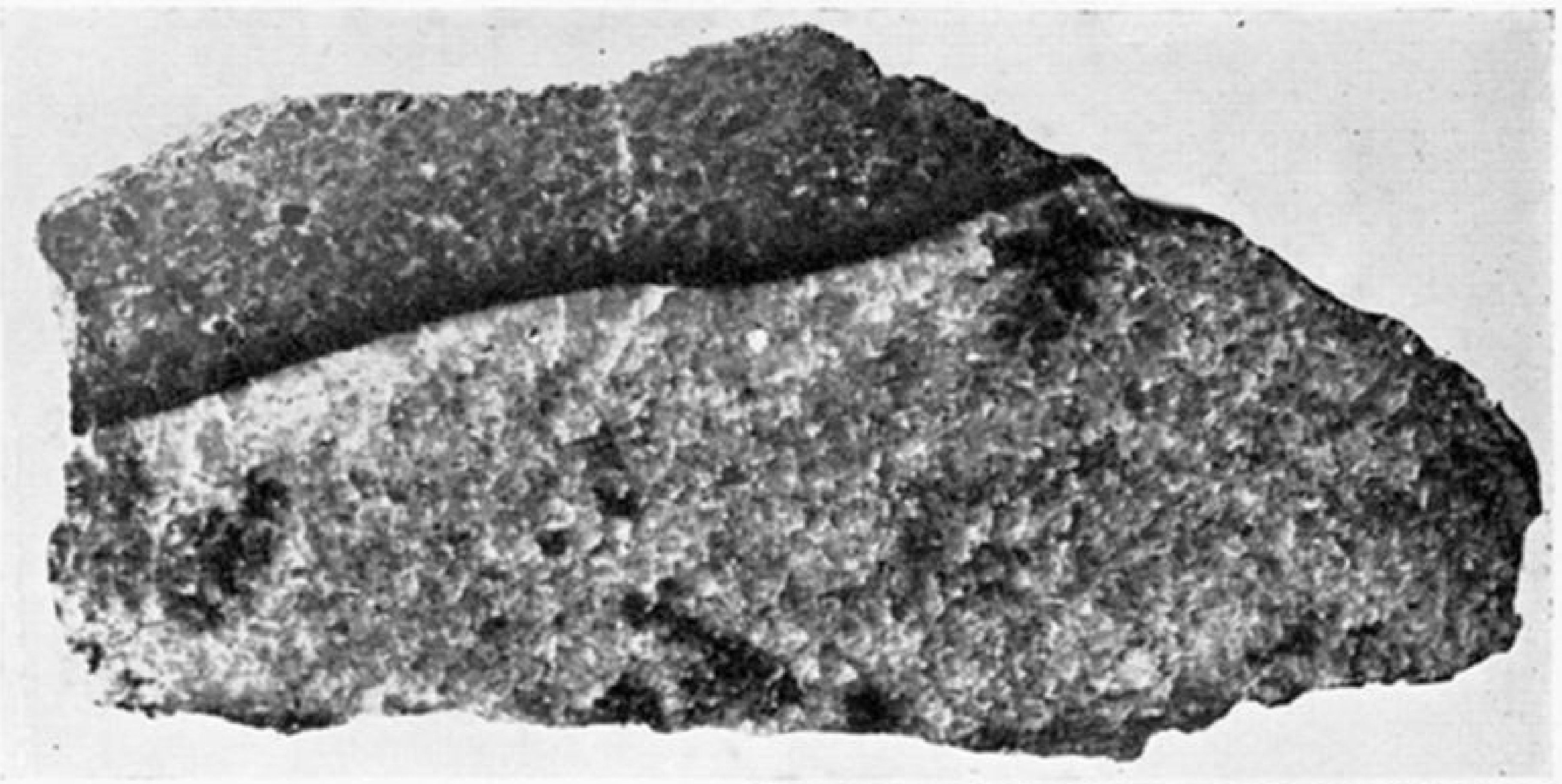

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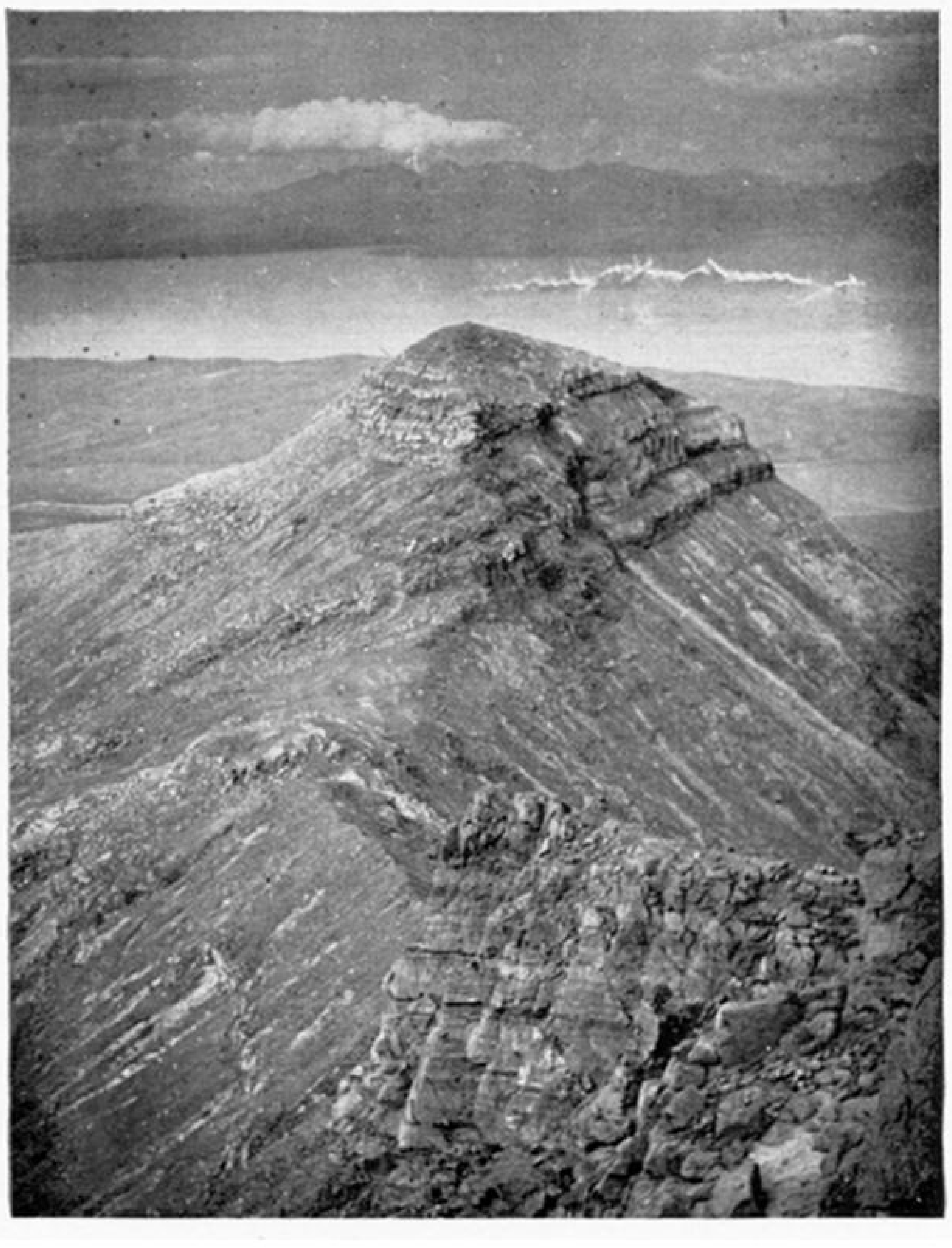

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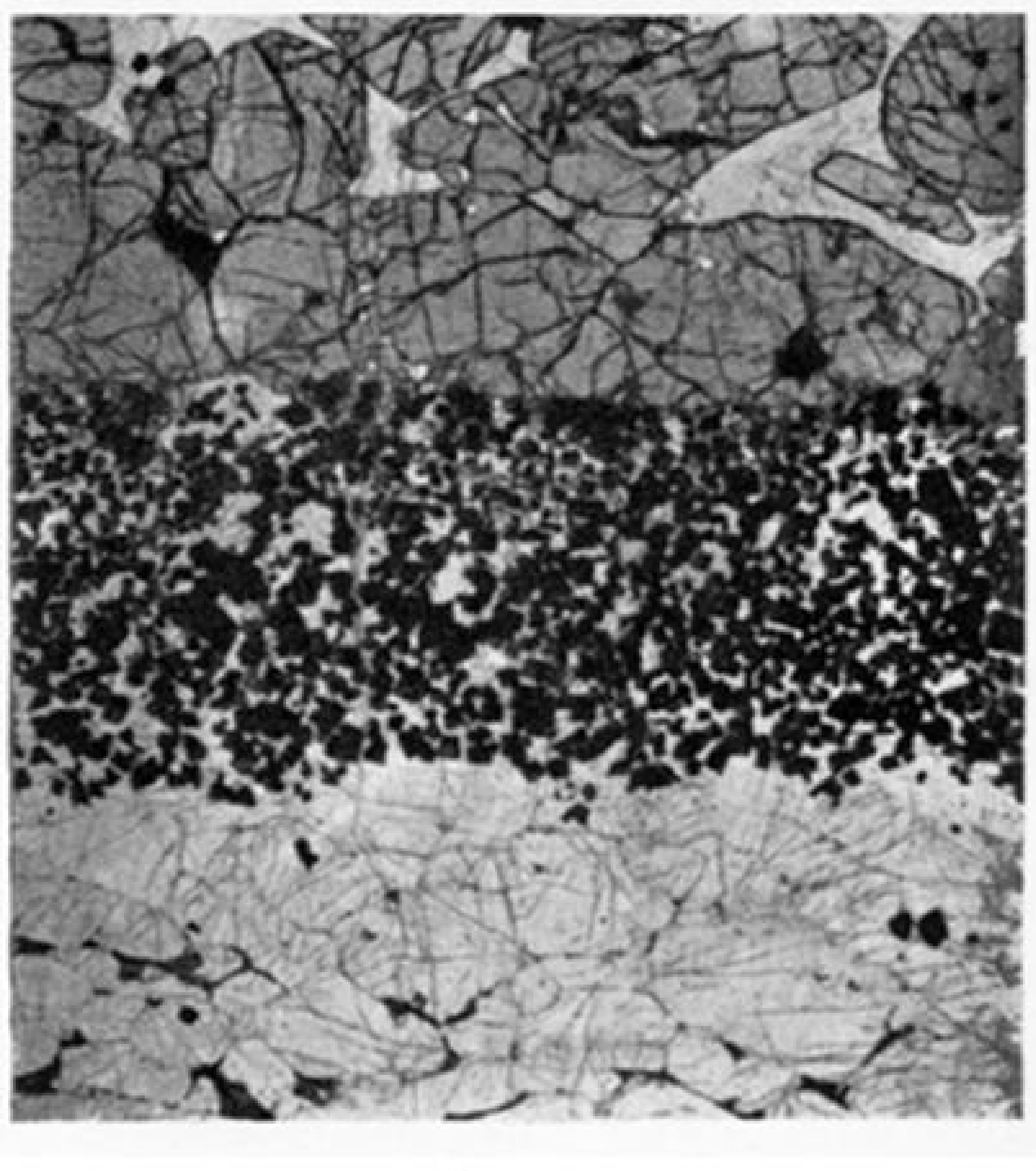


PLATE 3

FIGURE 22. Fine-scale rhythmic layering at the top of unit 8. Note sharp base to overlying unit. Northern escarpment to Askival-plateau.

FIGURE 23. Harrisite structure (upper half of photograph) developed with the lower part of unit 11. North-eastern slopes of Askival.

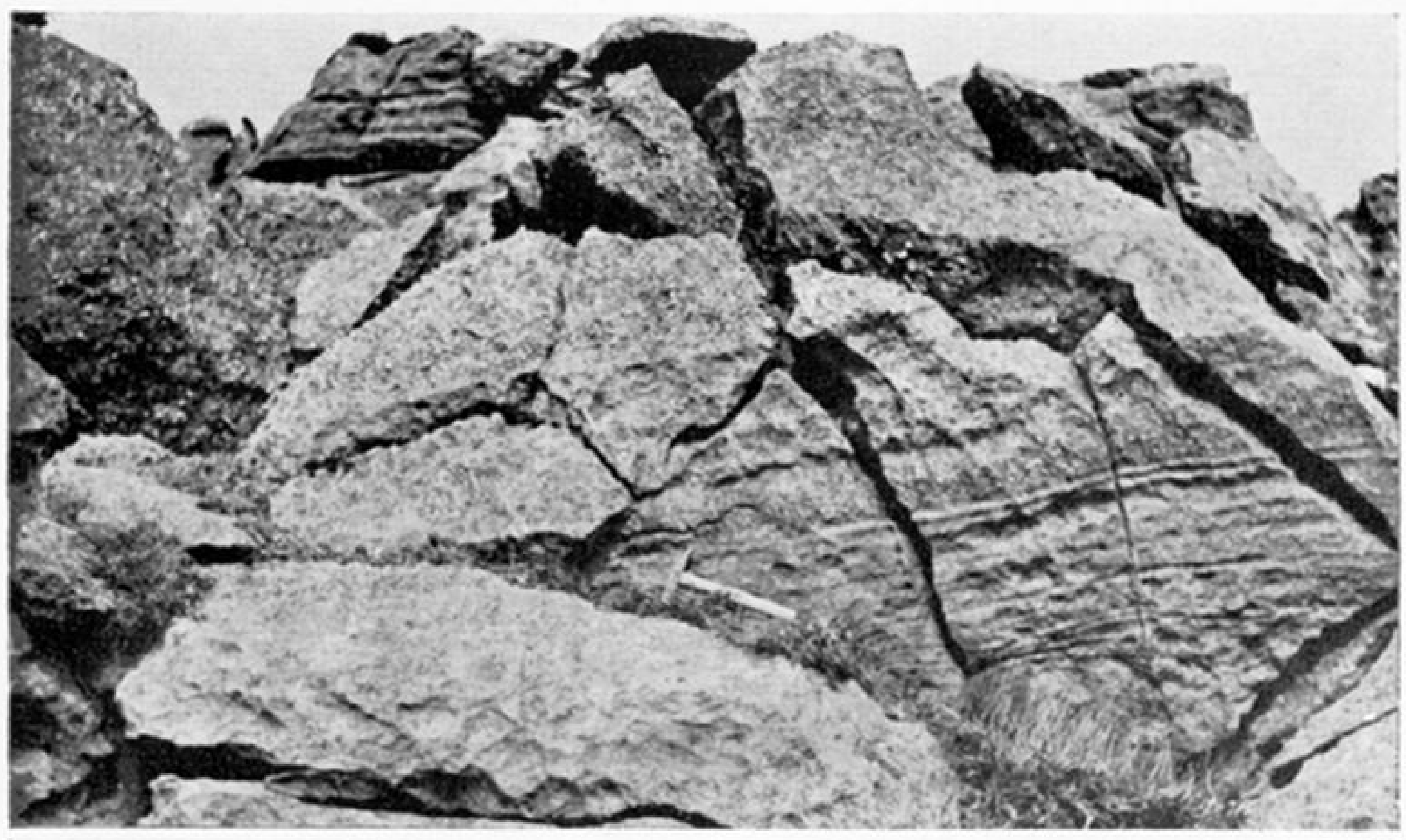
FIGURE 24. Undulatory base to pyroxene-rich layer in upper, felspathic part of unit 9, north-east shoulder of Hallival. Dip section.

FIGURE 25. As in figure 24, strike section.

FIGURE 26. Specimen 3218, showing a thin layer of chromites between the felspar concentrations at the top of unit 11 and the olivine concentrations near the base of unit 12. Natural size.

FIGURE 27. Photomicrograph of thin section of 3218. Magnification × 8.

FIGURE 28. Hallival and the Col, from Askival. The major allivalites illustrated belong to units 12 (below the col level), 13 (partly forming the col) and 14 (to within 25ft. of the summit). Coastline of Skye in the distance.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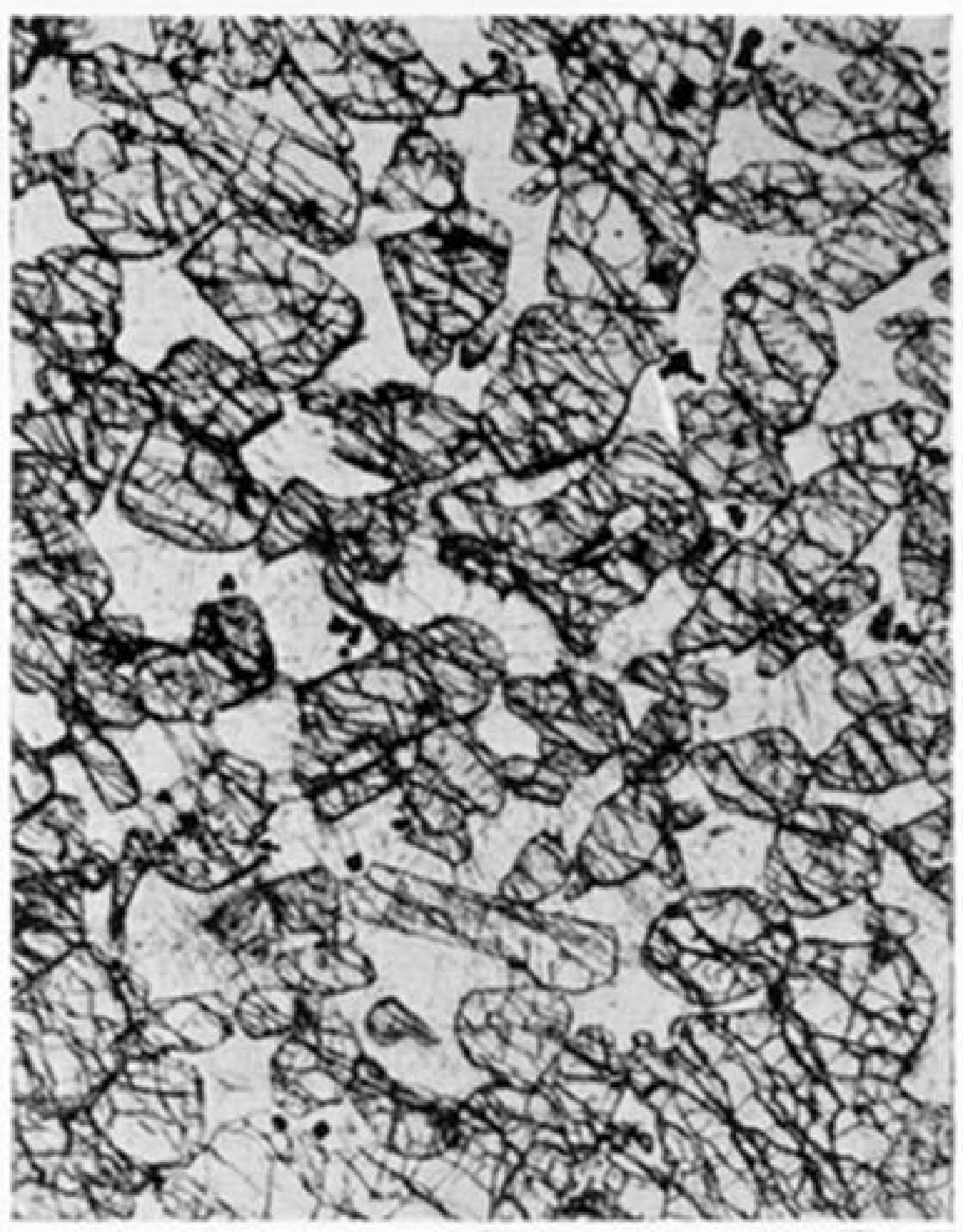
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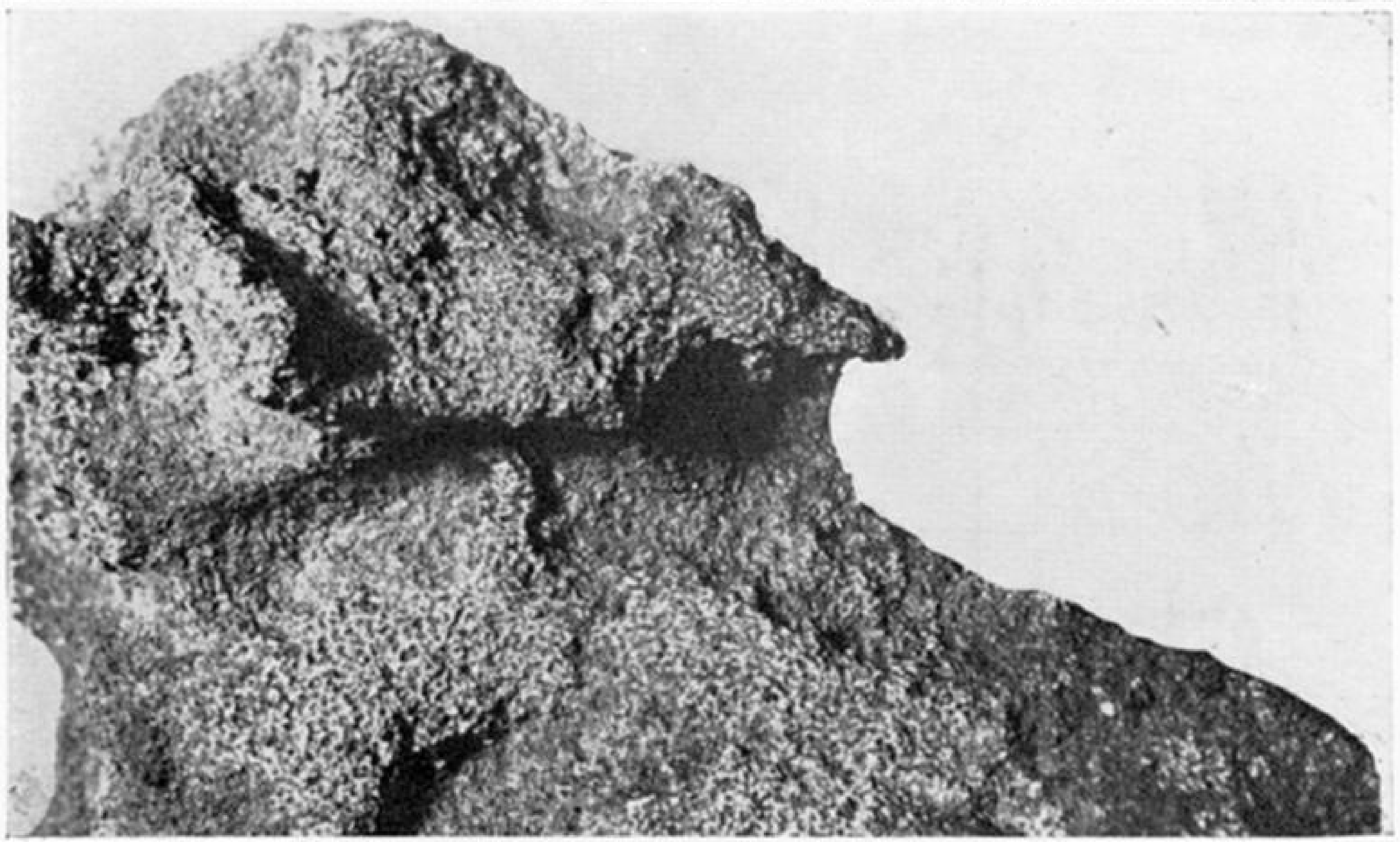
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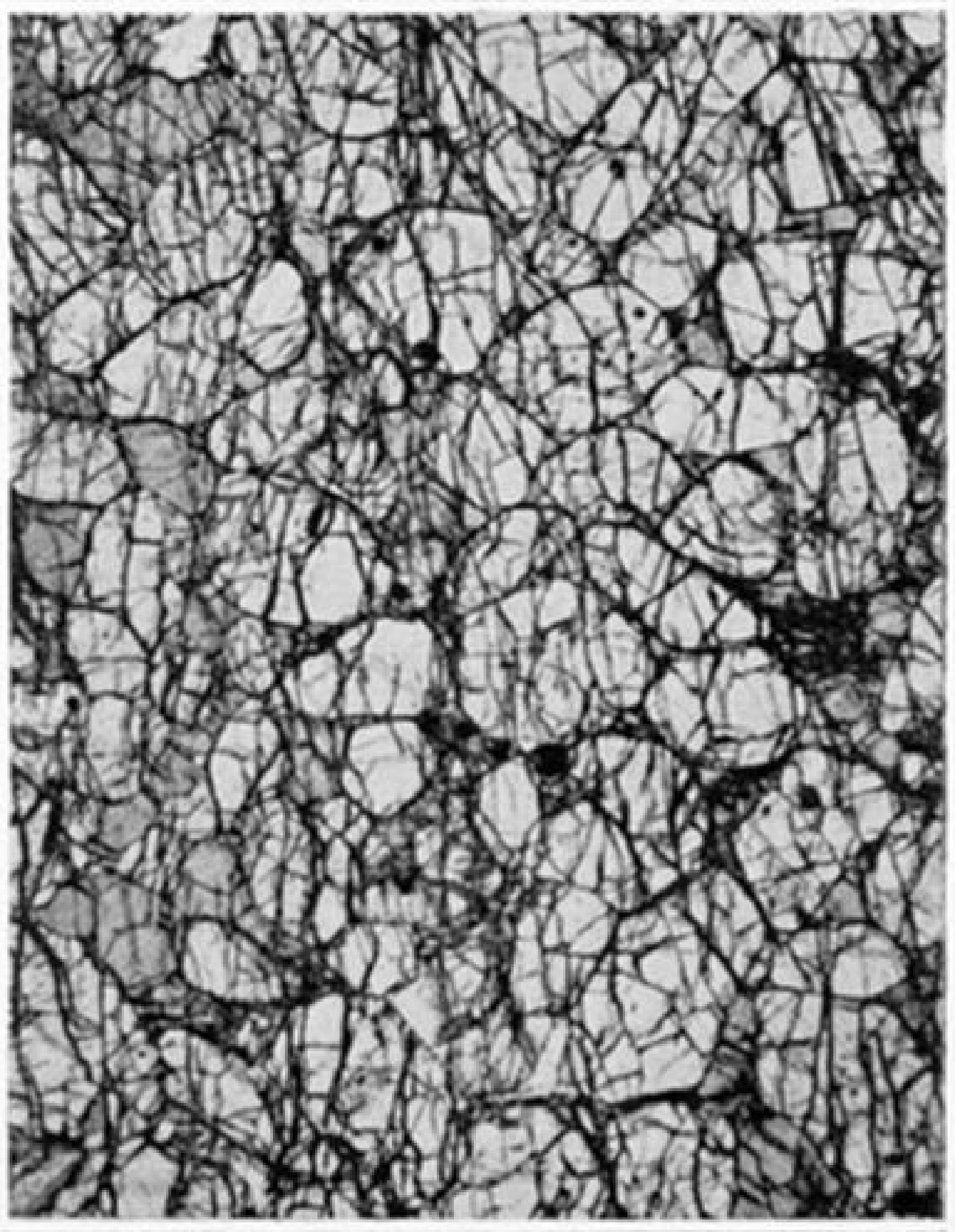
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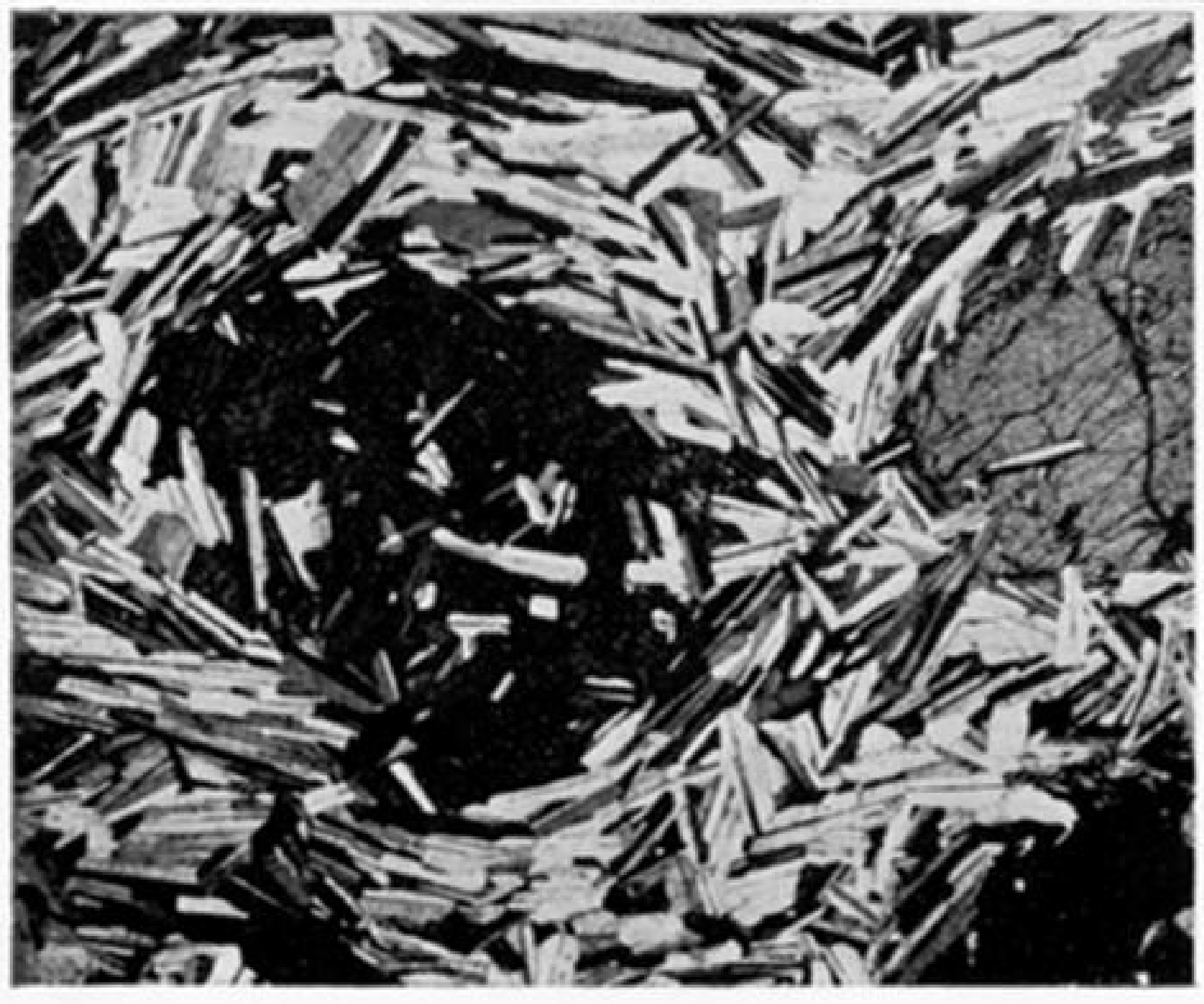
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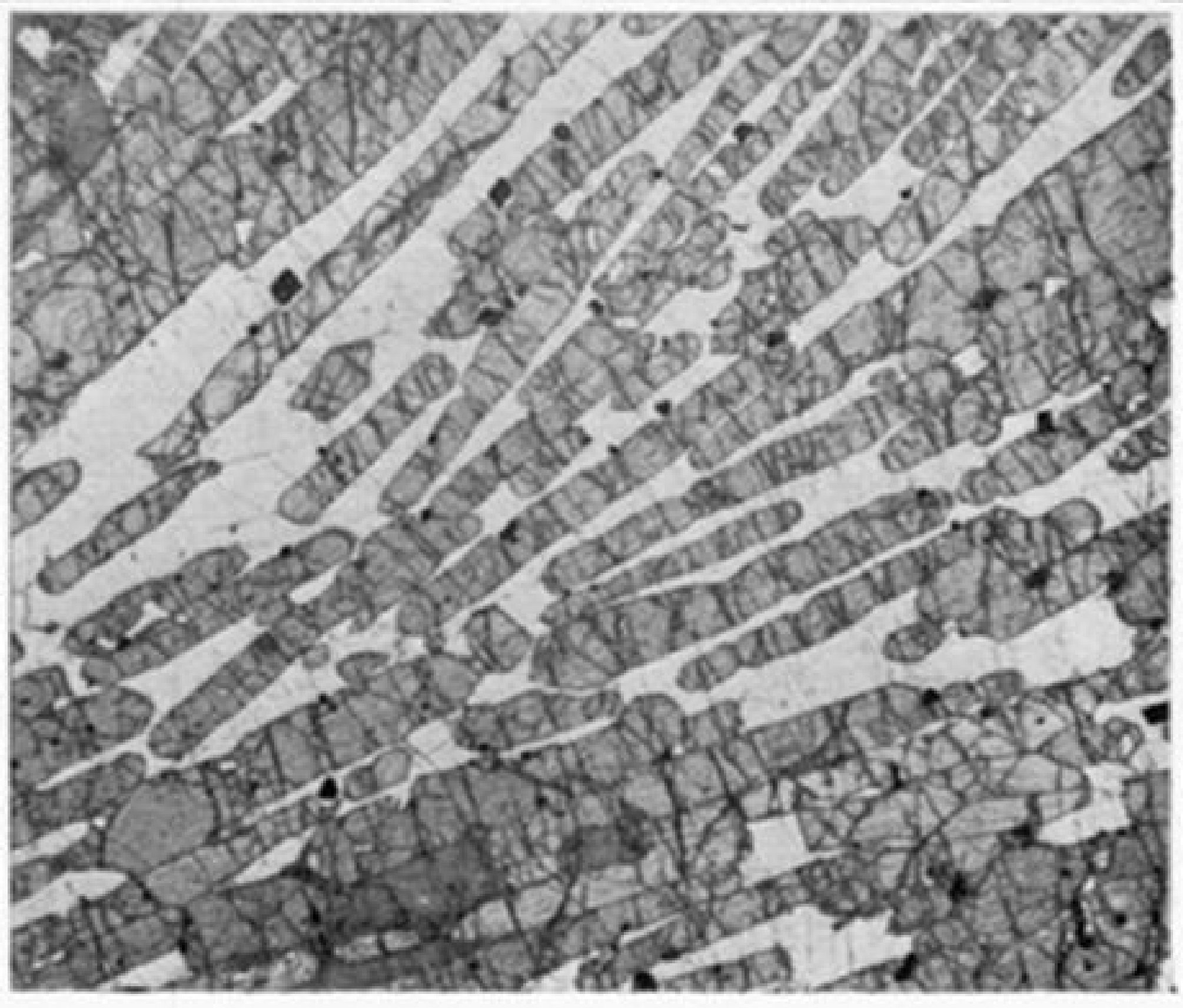
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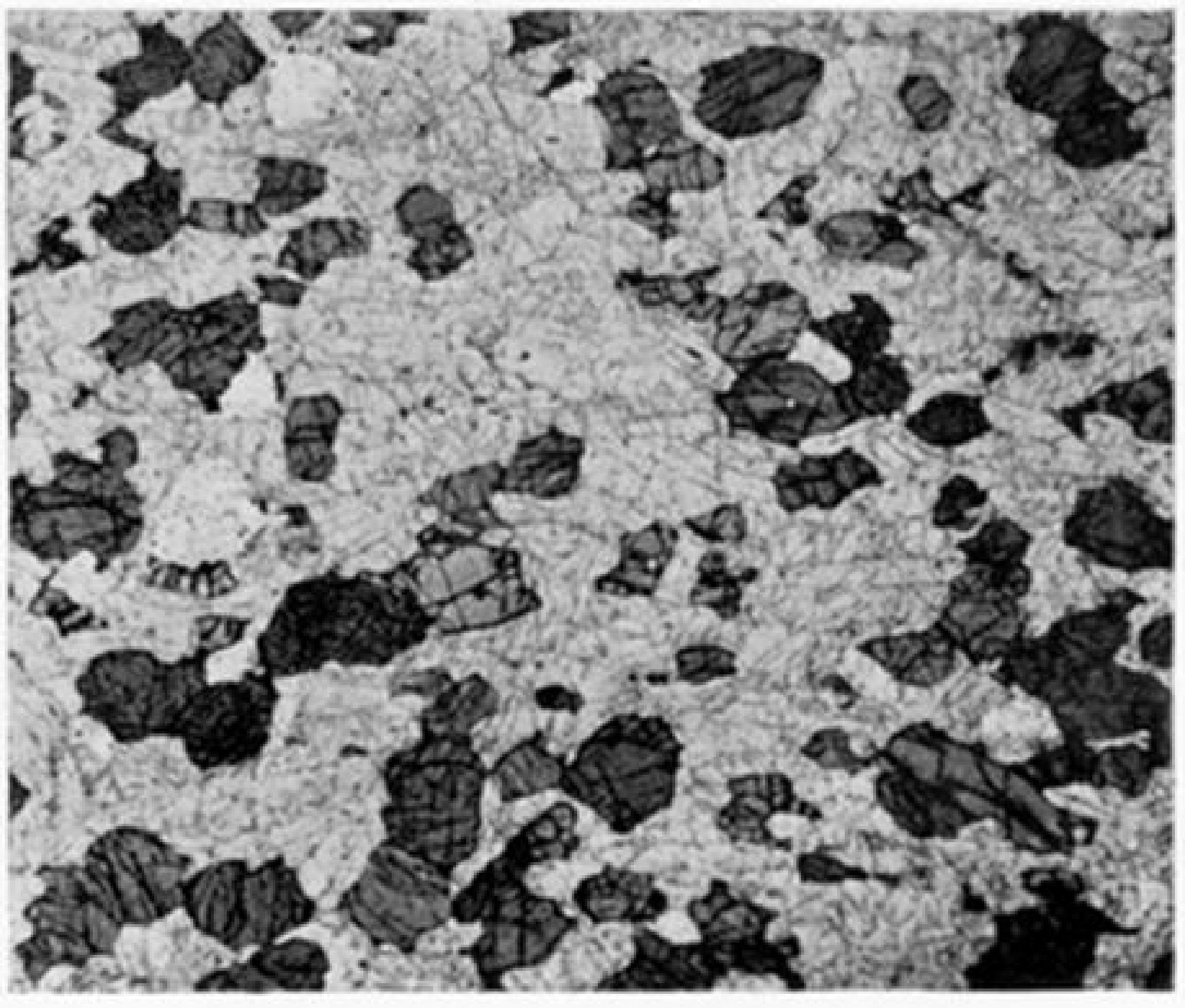
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PLATE 4

FIGURE 29. Harrisite structure developed as layers within the peridotites of the Harris area, 1½ miles north-north-east of Harris Lodge.

FIGURE 30. Peridotite (3223) with the pitted surface produced by the relative resistance to weathering of poikilitic felspars (protuberances) and poikilitic clinopyroxenes (hollows). Two-thirds size.

FIGURE 31. Photomicrograph of part of one of the poikilitic felspars shown in figure 30 (Magn. × 8).

FIGURE 32. Photomicrograph of part of one of the poikilitic clinopyroxenes shown in figure 30. Both olivines and chromites are enclosed, as in figure 31 (Magn. × 8).

FIGURE 33. Fine-scale rhythmic layering in fallen block of allivalite, Coire nan Grunnd.

FIGURE 34. Slump-structures developed from olivine-felspar layers near top of unit 14, eastern face of Askival. The hammer lies radially with respect to the shape of the intrusion, the head lying nearest the centre.

FIGURE 35. Photomicrograph of allivalite found as a fallen block, 3237*b*. The olivine in the centre, enclosing tiny unorientated felspars, is believed to have settled as a composite grain. Note the banking of the discrete felspar crystals round this grain (Magn. × 6·6: crossed polars).

FIGURE 36. Peridotite from the south-east slopes of Trallval (3293). The plane of the section is almost horizontal, the long radially orientated olivines being plates in the semi-vertical plane. Large poikilitic grains of felspar and clinopyroxene fill the interstices (magn. × 6·6).

FIGURE 37. An allivalite from unit 10, north-east shoulder of Hallival (5049). Note the discrete character of the plagioclase, clinopyroxene and olivine grains each of which, together with the rock, have been chemically analyzed (magn. × 8).

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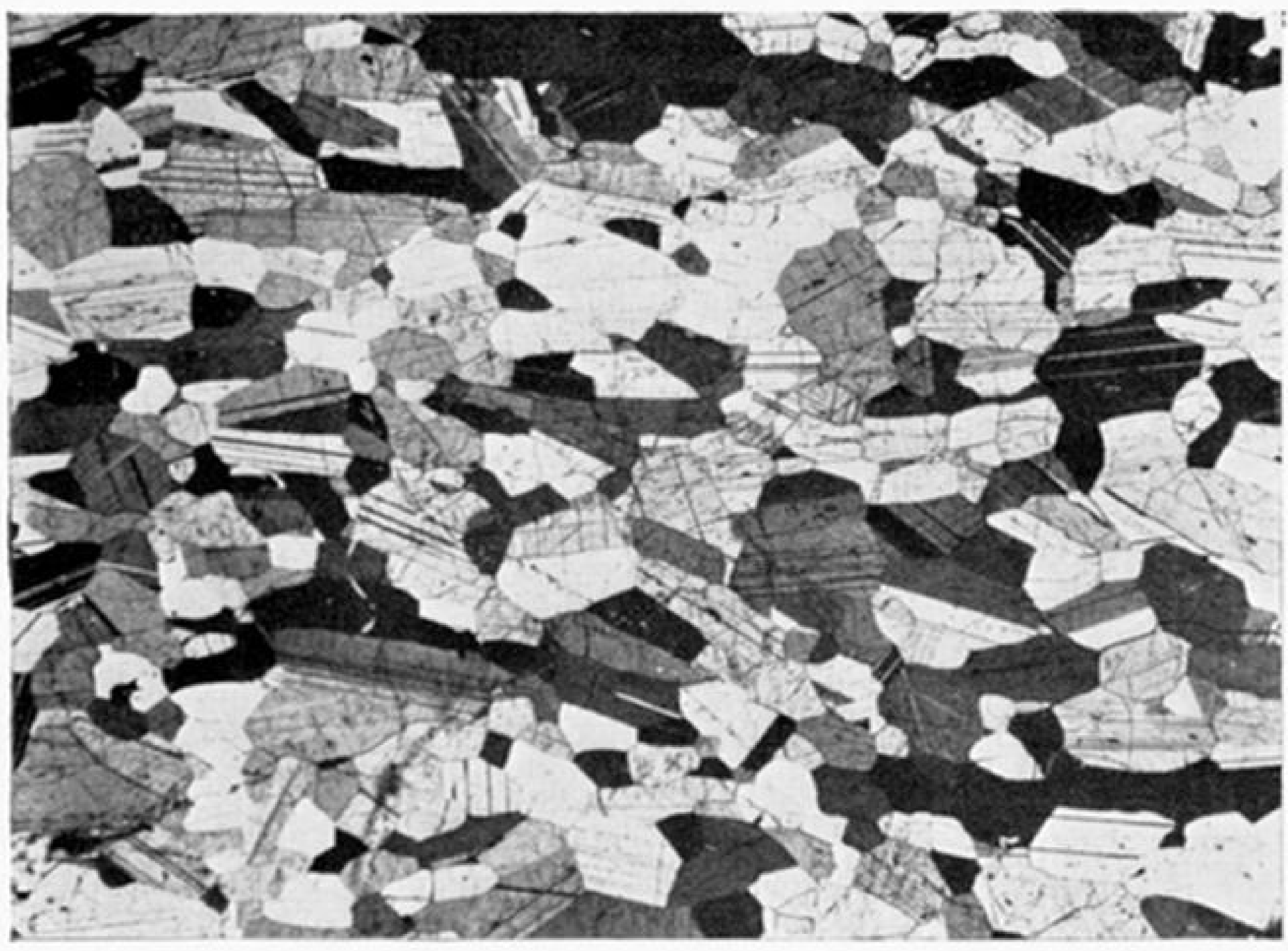

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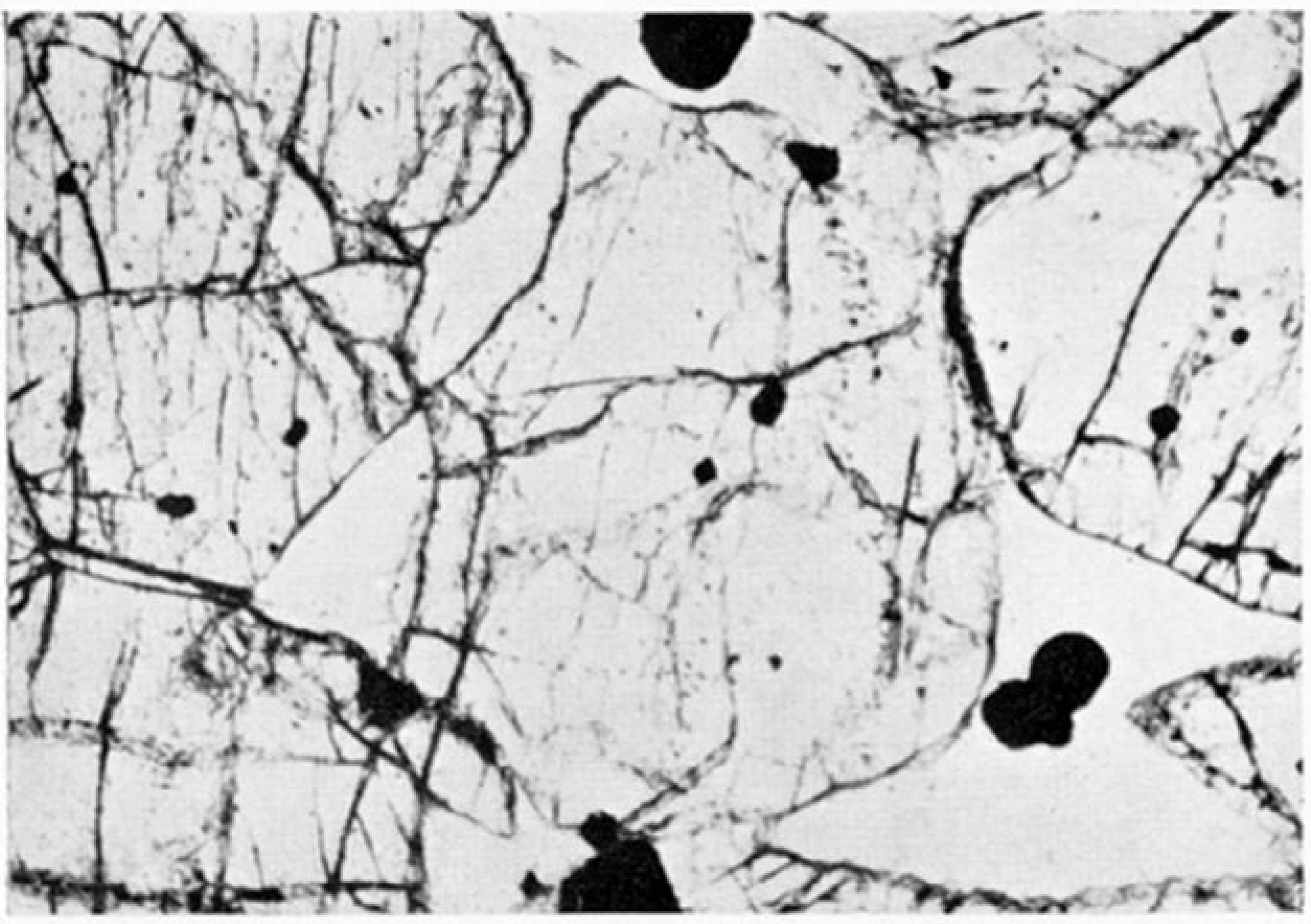

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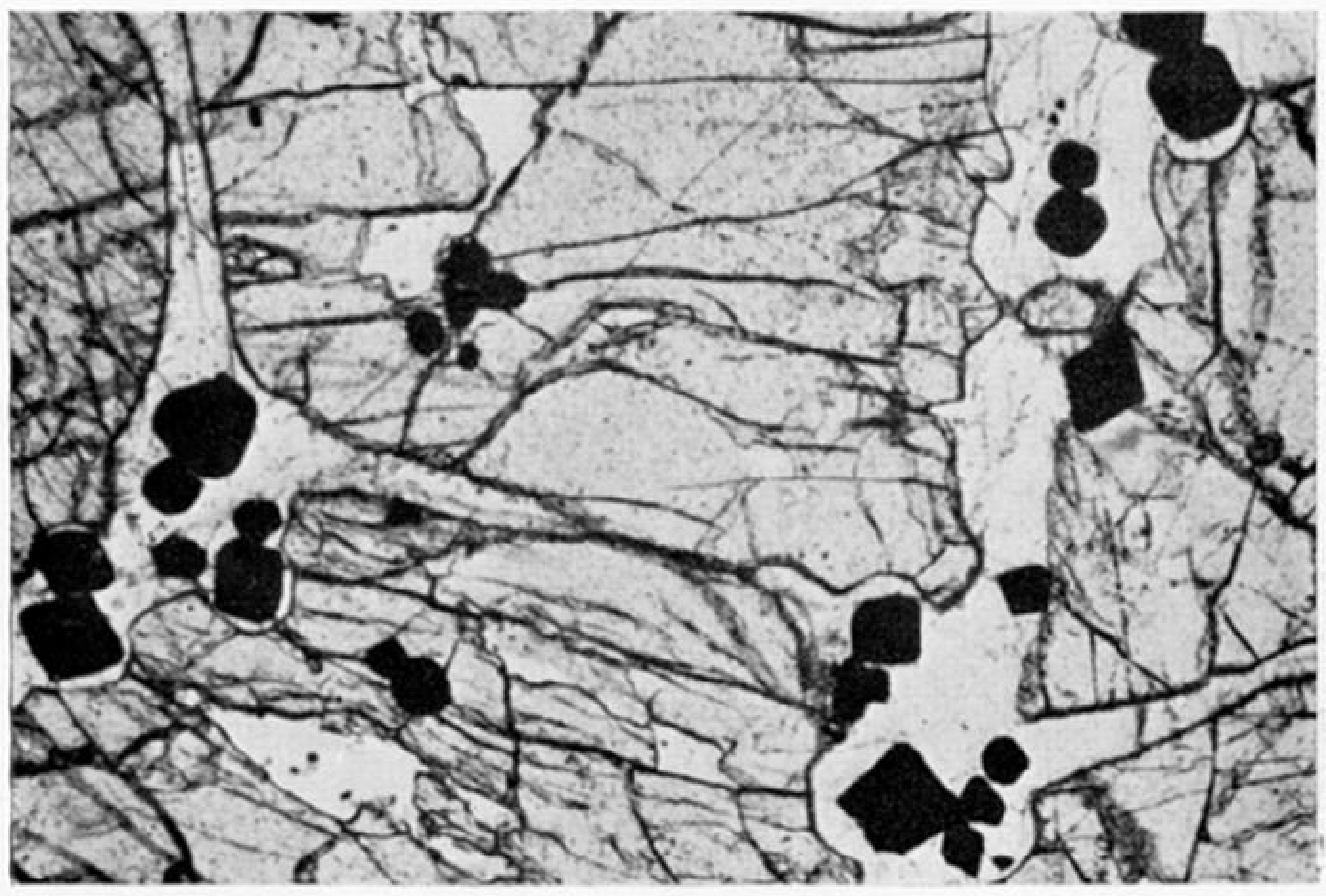

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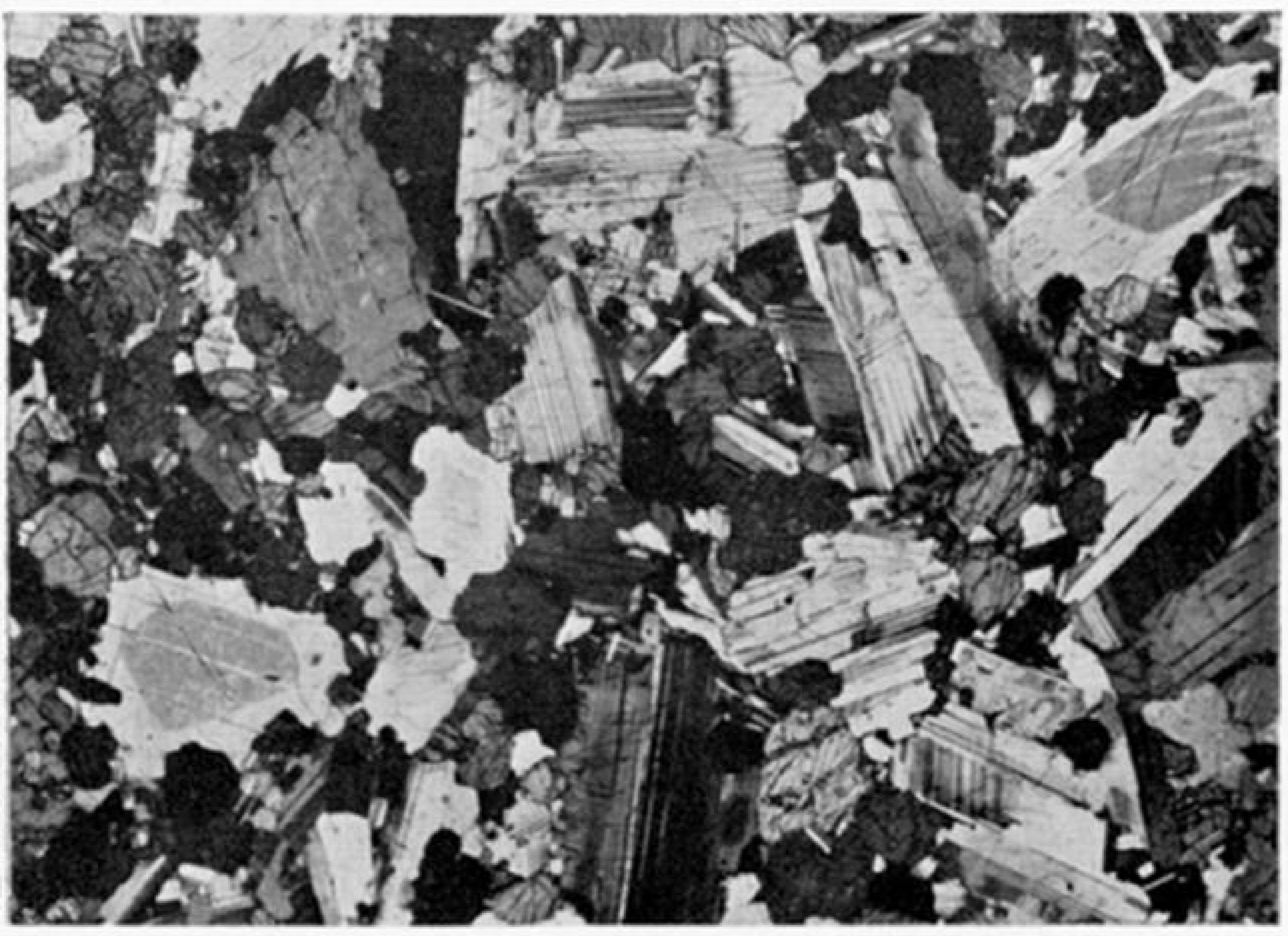

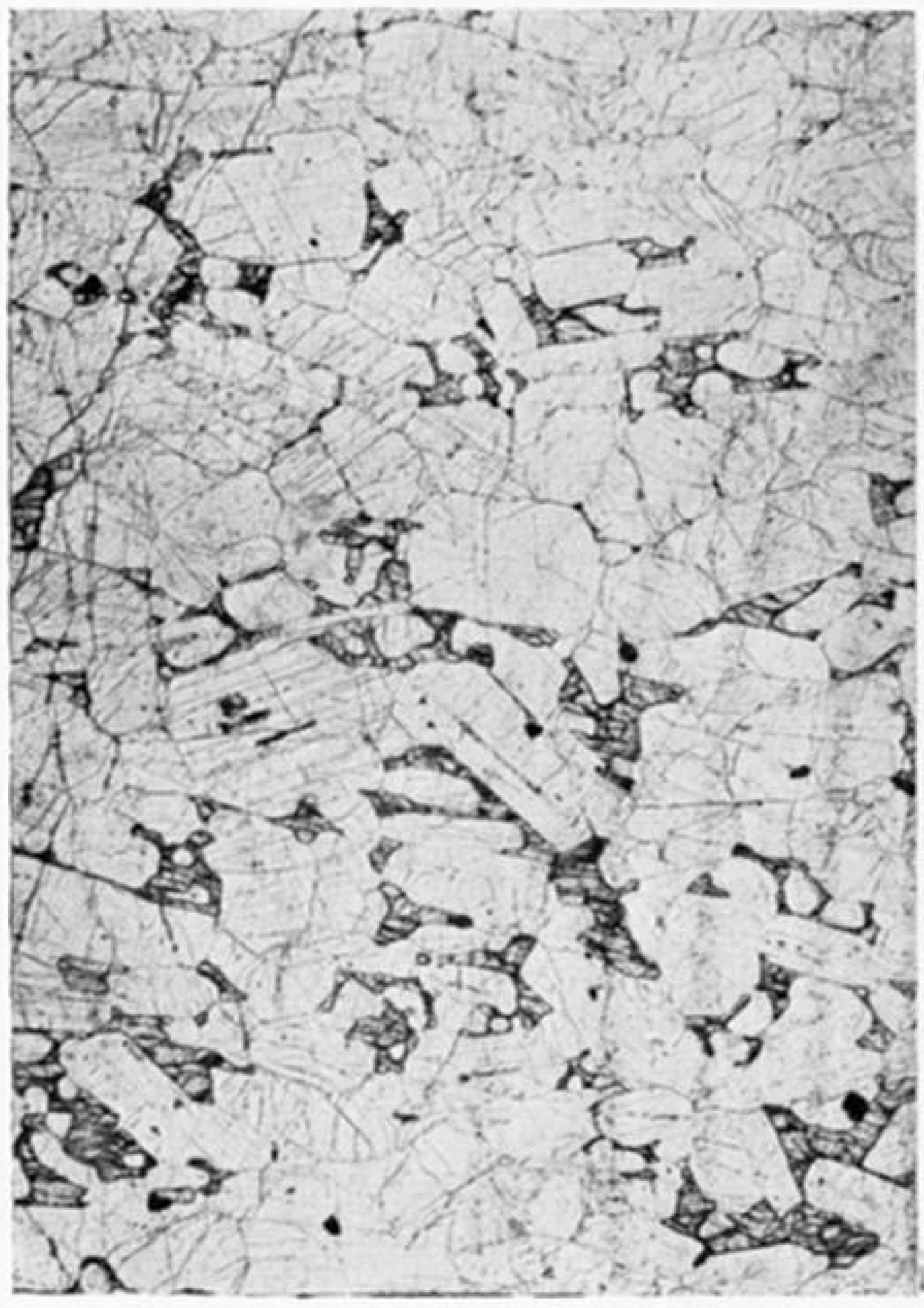

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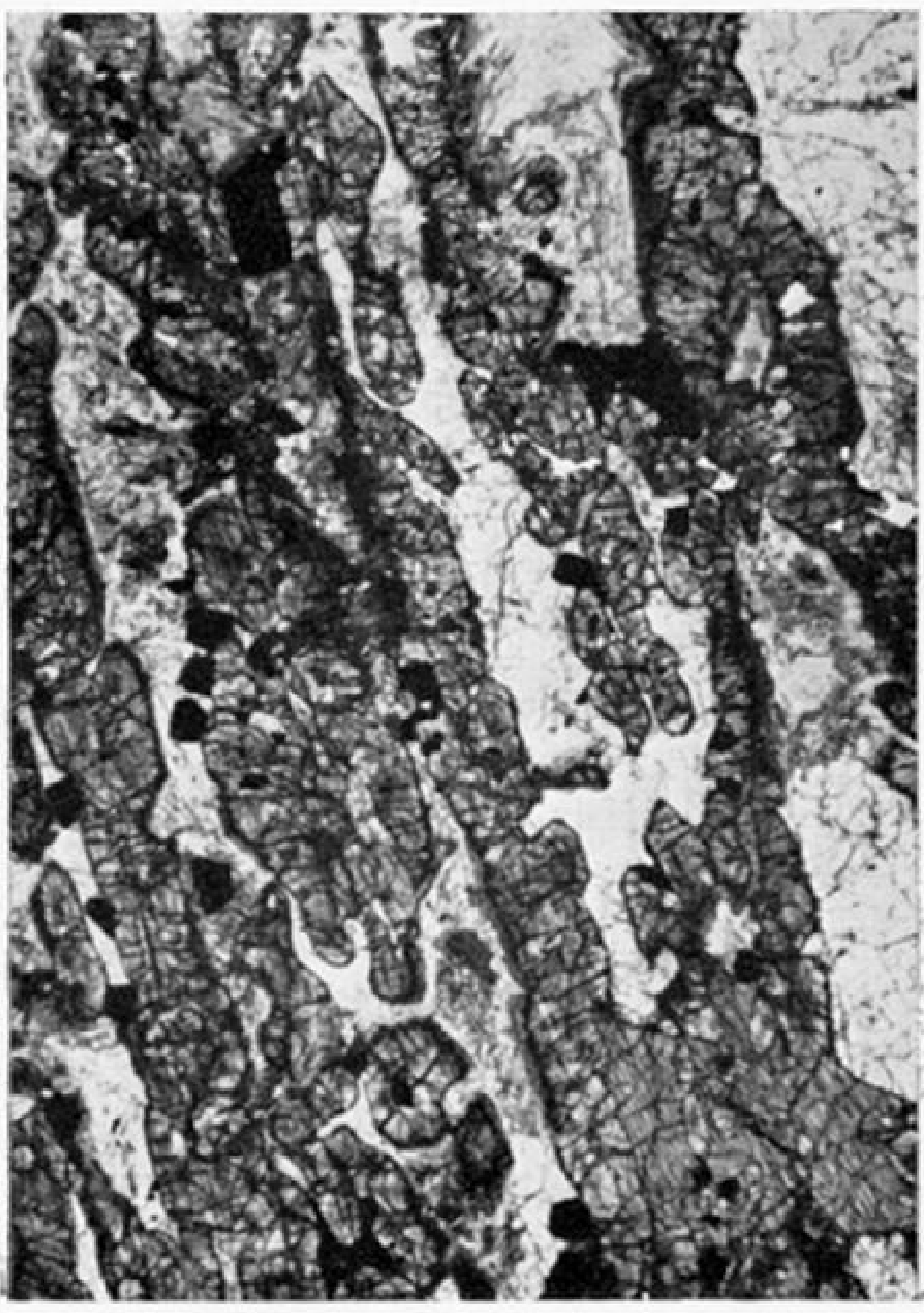

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PLATE 5

FIGURE 38. A pure felspar rock from unit 14 (5061), showing igneous lamination (magn. × 10: crossed polars).

FIGURE 39. A peridotite from unit 10 (5333), in which there is a great difference in size between chromites outside and inside the olivines (magn. × 61).

FIGURE 40. A peridotite from unit 10 (5332) in which rims of felspar (each in optical discontinuity with the poikilitic grains) separate chromite from olivine in small embayments (magn. × 38).

FIGURE 41. The felspathic part of 3218, a banded allivalite from unit 12 (see figures 26 and 27), in which a single grain of olivine (each part in optical continuity with the whole) poikilitically encloses felspar crystals (magn. × 10).

FIGURE 42. A type of harrisite structure within a peridotite (fallen block, 3192). Note the long, single olivine crystals which show a tendency to 'bud' (magn. × 8·3).

FIGURE 43. The Barkeval 'eucrite', 5317. Note the marked discontinuous zoning of the felspars (cores An_{86-89} and rims An_{66}) (magn. × 10: crossed polars).

FIGURE 44. The analyzed fine-grained olivine gabbro, 5019 (magn. × 10).