THE LAYERED ULTRABASIC ROCKS OF SOUTH-WEST RHUM, INNER HEBRIDES

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The ultrabasic rocks of the Tertiary volcanic centre of Rhum are best exposed in the mountains of Hallival and Askival, in the eastern part of the island, where they form a series of alternating peridotite and allivalite layers. Harker (1908) attributed the formation of these to a series of sill-like injections of already differentiated magma, but Brown (1956) has convincingly demonstrated that these rocks are the basal accumulates of a basic magma, and has suggested that the repetition of units comprising peridotite overlain by allivalite is the result of successive pulses of magma entering the magma chamber. The present study was initiated in the Harris area, which covers the south-western part of the ultrabasic tract, because it was believed that the rocks exposed there represented a different level in the original intrusion, and that they would provide further evidence of the mode of formation.

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A new terminology (Wager, Brown & Wadsworth 1960) has been used to describe the rocks of the layered intrusion. The general term 'cumulate' is applied to rocks formed by bottom accumulation of crystals (cumulus crystals), and a more specific designation of composition is made by using prefixes based on the nature of the mineral assemblage. For a precise description of a given rock type, the cumulus minerals are listed in order of decreasing abundance (i.e. olivine-feldspar-pyroxene cumulate) and for a general implication of composition, the terms ultrabasic or eucritic are used. More subtle distinctions are made on the basis of differences in the cooling history of the inter-cumulus liquid, trapped in the pile of accumulated crystals.

In the Harris area of south-west Rhum, a thickness of approximately 4500 ft. of layered cumulates is exposed, and has been subdivided into four petrologically distinct groups. The lowest of these is the Harris Bay series of eucritic cumulates (olivine-feldspar-pyroxene cumulates), which are at least 400 ft. thick, the base being below sea level. These are conformably overlain by a thin Transition series (150 ft.), comprising cumulates intermediate in composition between those of the underlying Harris Bay series, and the overlying Ard Mheall series. The latter consists of approximately 1200 ft. of ultrabasic cumulates (olivine, and olivine-feldspar cumulates) which exhibit prominent rhythmic layering. The Dornabac series is nowhere seen to overlie the Ard Mheall series, but is separated from it by a zone of igneous breccia. This consists of blocks of cumulates which are believed to have been derived from the Ard Mheall series by faulting within the magma chamber, and to have accumulated at the base of the fault scarp contemporaneously with settling olivine and feldspar crystals which form the matrix of the breccia. The Dornabac series overlies this breccia, and consists of approximately 400 ft. of slumped olivine-feldspar and feldspar-olivine cumulates. It is overlain by the Ruinsival series, which has been divided into a lower part (about 1500 ft. thick) and an upper part (about 1000 ft. thick), both parts consisting of a thick series of olivine-rich cumulates below a thinner series of feldspathic cumulates. The sequence in the Ruinsival series is obscured by poor exposure in the lower part, and by the complications of igneous breccia, later intrusions of eucrite, and later faulting affecting the upper part.

Thus, as in the Hallival–Askival area, there is a major pattern of layering in south-west Rhum, although the units there are not all complete, and are much thicker than in eastern Rhum. The four units are as follows:

D, the upper part of the Ruinsival series;
C, the lower part of the Ruinsival series;
B, {Dornabac series;
Ard Mheall series;
A, Harris Bay series.

A study of the variation in the composition of the cumulus minerals (in particular olivine) throughout this sequence confirms Brown's hypothesis of successive replenishment of the magma chamber to account for the major layering. There is generally an upward gradation of olivine composition from Fo_{88}, in the olivine-rich cumulates of the lower part of a unit, to Fo_{86} in the overlying feldspathic cumulates, followed by an abrupt reversal to more magnesian olivine at the base of the succeeding unit. This reversal is less abrupt between units *A* and *B*, and the intervening Transition series appears to represent an intermediate stage, probably resulting from the mixture of fresh magma and differentiated magma of the previous pulse, following incomplete removal of the latter.

Small-scale rhythmic layering is developed throughout the sequence. In part, this consists of a simple alternation of the mineral proportions, but in the Harris Bay series, Transitional series, and Ard Mheall series there are also numerous layers, varying from less than an inch to many feet in thickness, of a remarkable rock termed harrisitic cumulate. It is characterized by relatively large olivines of rather embayed or intricate shape, sometimes exhibiting well-developed parallel growth structures, and tending to have a preferred orientation with (010) vertical. These features are believed to indicate that the olivines crystallized *in situ*, growing upwards from previously settled grains at the top of the crystal pile, during periods of exceptional tranquillity when there was little or no crystal settling. It is suggested that the rhythmic layering was the result of a frequently repeated process, comprising supercooling of the magma, spontaneous nucleation, followed by crystal settling, and then a period of quiescence while the necessary degree of

supercooling was developed again. Each shower of crystals would have been sorted by the action of gravity, and if the interval between showers was long enough, upward growth from the floor would have occurred.

A comparison of the layered series in eastern and western Rhum indicates that the latter represents a distinctly lower level within the original intrusion. It is clear from structural considerations that the whole mass of ultrabasic rocks has been pushed up as a hot, but essentially solid body, into its present position, and it is suggested that there was differential uplift, bringing relatively lower units (*A*, *B*, *C*, *D*) in the west against higher units (1–15) in the east. The emplacement of the layered series is also believed to account for the development of a complex marginal zone adjacent to the Western granophyre, which seems to have been locally remelted and hybridized with a marginal gabbro. Various eucrites and gabbros which are younger than the layered series are also described, and these too may have been intruded during the emplacement of the ultrabasic mass.

1. Introduction

(*a*) *Situation and topography*

The Isle of Rhum, which is the largest of the Small Isles of Inverness-shire, consists essentially of regionally inclined Torridonian strata in which a roughly cylindrical mass of igneous rocks has been emplaced. Torridonian rocks occupy almost all the northern half of the island and continue southwards as a narrow strip flanking the eastern part of the igneous complex; they rarely approach an elevation of 1000 ft. and typically exhibit small-scale scarp and dip features. The igneous rocks, which comprise basic and ultrabasic types, granophyres, and felsites, give rise to steep mountainous country with several summits over 2000 ft., the highest being Askival (2659 ft.). There is a diversity of scenery in this area because the ultrabasic rocks tend to exhibit terrace features, best seen on Hallival and Askival, while the granophyres and felsites show characteristically smooth and rounded outlines (figure 5, plate 3).

The ultrabasic rocks occupy a roughly circular area of about 12 square miles in the southern half of the island (figure 1), although in the west this symmetrical appearance is partly obscured by the Western granophyre. In the south-east a smaller circular area of felsite, Lewisian gneiss, and explosion breccias occurs within the main ring, while in the north-east felsite and explosion breccias form a narrow strip marginal to the ultrabasic rocks.

The area described in this account (see figures 1 and 2) comprises about 4½ square miles in the south-western part of the island, and is bounded to the west by the Western granophyre and to the east by the prominent north–south line of the Long Loch fault. In the absence of contoured 6 in. topographical maps the area was mapped on vertical aerial photographs having a scale of approximately 6 in. to 1 mile.

(*b*) *History of investigation*

Judd (1874, 1885) and Geikie (1897) were the first geologists to make detailed observations on the geology of Rhum. They were followed by Harker, who mapped the island on the scale of 6 in. to 1 mile (reproduced on sheet 60 of the 1 in. to 1 mile Geological Survey of Scotland), and wrote a detailed account of the geology in the Memoir (1908) which accompanied the map. In his description of the ultrabasic rocks Harker established that the terraced features of Hallival and Askival are built of thick layers of alternating peridotite (easily weathered) and allivalite (resistant to weathering), which differ from one another only in

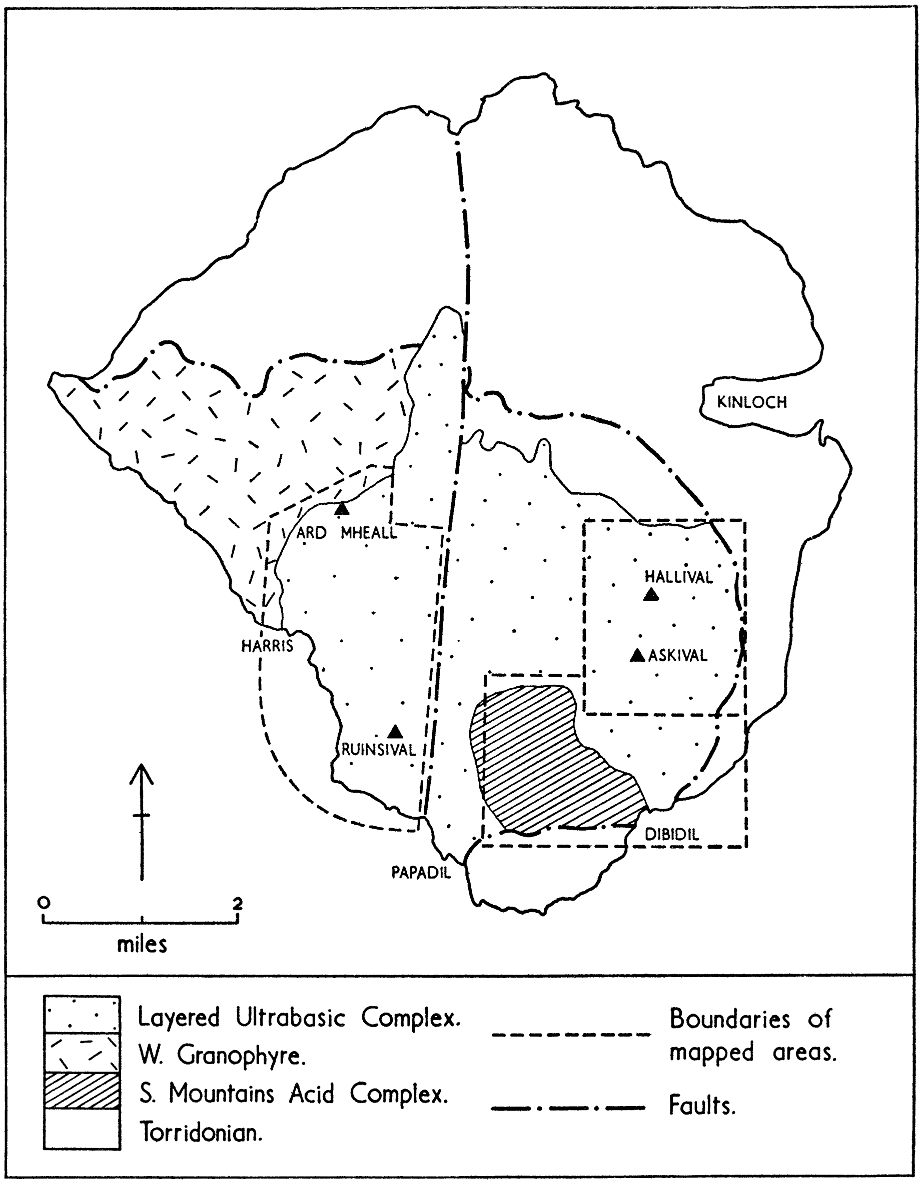

Figure 1. Sketch map of Rhum, showing the distribution of the principal rock types, and the areas mapped by G. M. Brown (Hallival–Askival), C. J. Hughes (Dibidil) and W. J. Wadsworth (Harris).

their relative proportions of olivine and feldspar. In order to explain this rhythmic pattern, Harker postulated differentiation of a magma at depth into two distinct fractions which were then alternately injected in descending sequence. He also distinguished a third variety of ultrabasic rock which occurs in the Harris area of south-west Rhum, and was therefore named 'harrisite'. It is characterized by its generally coarse grain size, and by the preponderance of olivine over feldspar, the olivine being 'of a peculiar black lustrous variety with good cleavage' (1908, p. 71). He thought that the harrisite was a distinctly later intrusion at the base of the main ultrabasic series, and that it showed pegmatitic affinities. Harker distinguished an even later intrusion of eucrite below the harrisite, and included it in his group of basic plutonic rocks, which he considered to be generally

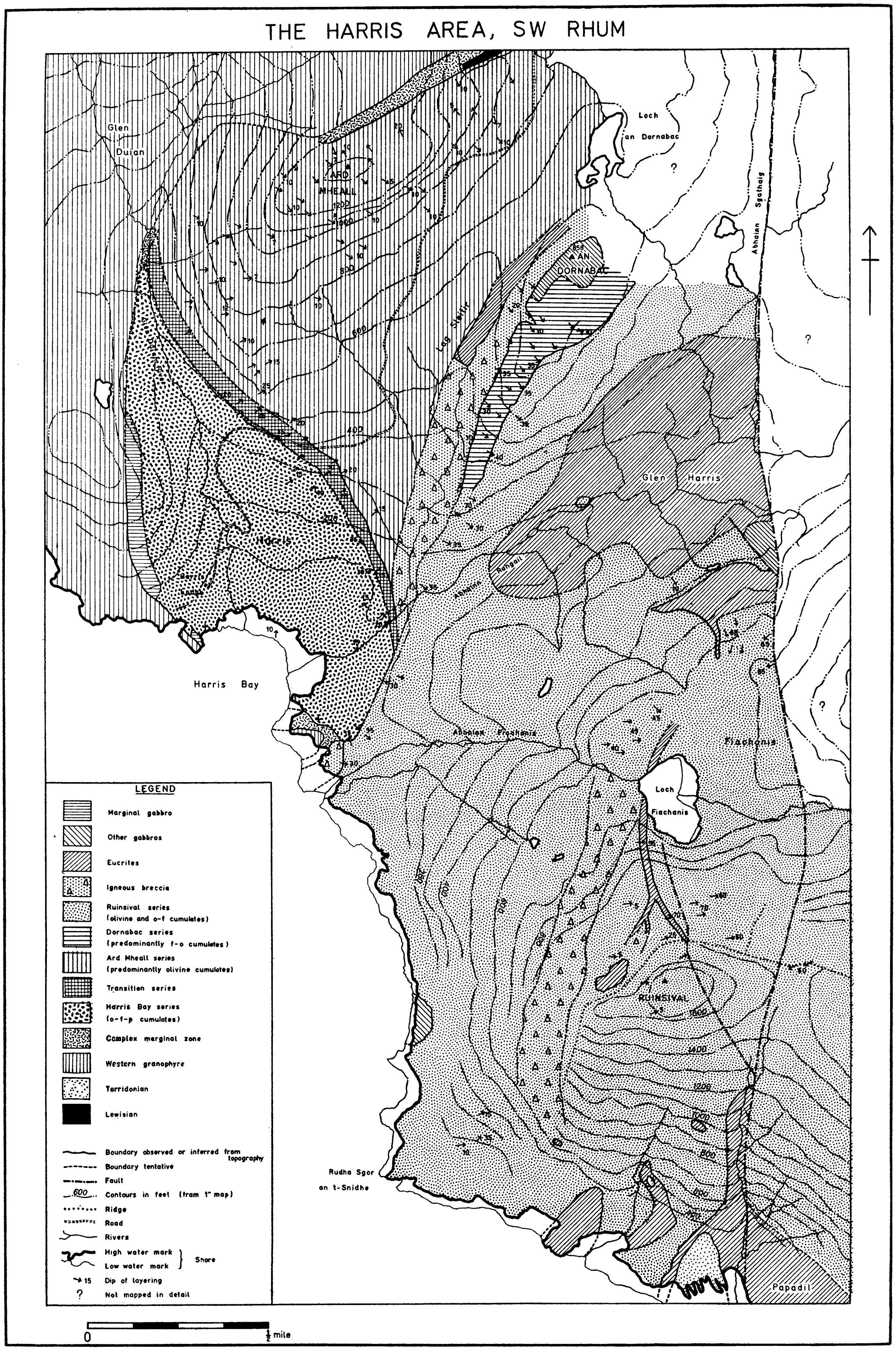

FIGURE 2. Geological map of the Harris area, south-west Rhum.

present beneath the ultrabasic mass. He also described basic rocks of transgressive habit which appear at various places in the main tract of ultrabasic rocks, and in particular he mentions the large mass of eucrite which occupies a considerable area in the lower part of Glen Harris, and shows particularly intricate relationships with the surrounding peridotite. Harker believed that the Western granophyre was younger than the basic and ultrabasic rocks, and that it followed the general pattern of emplacement at the base of the immediately preceding intrusion, thus completing an igneous complex of laccolithic habit.

More recent work includes that of Phillips (1938), who investigated the orientation of minerals in some of Harker's specimens, and Tomkeieff (1945), who concluded that the ultrabasic rocks resulted from a single injection of previously differentiated, heterogeneous magma, the layering being produced by the streaking out of the different components. Bailey (1945, 1956) recognized that the roughly circular margin of the ultrabasic and related rocks was a Tertiary ring-fault, and not a Caledonian thrust-plane as postulated by Geikie and Harker.

Wager & Brown (1951) produced a preliminary account of the rhythmic layering in the ultrabasic rocks, and of the structures in the harrisite. Brown (1956) continued this work and made a detailed study of the classic Hallival–Askival area in eastern Rhum. He mapped fifteen major layers or 'units', in each of which there is an upward gradation from peridotite to allivalite over an average thickness of 200 ft., and has convincingly demonstrated that these layers are the bottom accumulations from a crystallizing basic magma which cooled slowly in a sub-crustal chamber probably connected to a volcanic conduit. Because there is no cryptic layering in the 2600 ft succession Brown suggested that intermittent surface extrusion removed liquid from the chamber and fresh magma replaced it from below. He visualized each pulse of fresh magma as depositing olivine first of all (to give the peridotites at the base of each unit) and then, with slight cooling, olivine and feldspar (to give the allivalites above), before it was removed from the chamber.

Black (1954) has described the Western granophyre, while Hughes (1960) has described the acid rocks of south-eastern Rhum and has recognized that most of them were intruded before the emplacement of the basic and ultrabasic rocks.

The present study is a sequel to Brown's work and forms the second part of a detailed re-investigation of the ultrabasic rocks on Rhum. For this the Harris area was selected because it was believed that the succession there, although more complex than that in the Hallival–Askival area, was continuous enough for the study of a comparable thickness of the layered series, and also because certain differences between the rocks of the two areas suggested that they represented different levels within the original intrusion. The remaining areas of ultrabasic rocks lend themselves less readily to this type of investigation because of a general lack of layered features and the degree of faulting which has affected the central section of the intrusion.

(*c*) *Pre-Tertiary country rocks*

Only two small areas of Pre-Tertiary rocks occur within the area mapped. Lewisian gneiss outcrops between Ard Nev and Ard Mheall, at the complex junction of granophyre and basic rocks. Harker (1908, p. 107) recorded this occurrence, relating it to the later outcrop of gneiss on the summit of Ard Nev (referred to as Beinn a' Bharr-Shaibh), and citing it as an example of Tertiary gneiss formation resulting from the mixing of acid magma and basic rock. Tilley (1944), however, concluded that the gneisses were Lewisian, with later thermal metamorphic effects superimposed, and indeed there is evidence that these gneisses were re-mobilized when the basic rocks were emplaced, as they appear to contribute to the intricate acid veining of the latter.

A small area of sedimentary rocks, assigned by Harker to the Diabaig shale group of the Torridonian, occurs three-quarters of a mile to the west of the main Torridonian tract at Papadil. It is surrounded by the Papadil eucrite (except where it is truncated by the coast), and comprises siltstones and flaggy sandstones with shaly partings. The bedding is generally horizontal, but small-scale contortions of the ribbon-banding are also typical. The junction with the Papadil eucrite appears to be steep, and the eucrite is seen to chill against bleached sandstone, and to penetrate it as small veins and stringers. The marginal eucrite, which is sometimes quartz-bearing, and the basic veins are themselves cut by acid stringers which have probably been generated by the local melting of the sediment.

2. The layered series—introduction

(a) *Terminology*

From the results of Brown's investigations in the Hallival–Askival area, and by analogy with other layered intrusions, there can be little doubt that the ultrabasic rocks of Rhum were formed by crystal accumulation at the bottom of a magma chamber. Therefore it is intended that the nomenclature proposed by Wager *et al.* (1960) to describe such rocks should be applied in this account. For convenience, a brief summary of this nomenclature is given below.

The term 'cumulus' is applied to the pile of crystals as precipitated from the magma, before any modification by later crystallization, and replaces the term 'primary precipitate' introduced by Wager & Deer (1939) in describing the Skaergaard intrusion, and used by Brown (1956) in his account of the Hallival–Askival area. The term may also be used as an adjective to describe the units of the crystal pile. The liquid held in the interstices of the cumulus is called the intercumulus liquid (instead of interprecipitate liquid), and the crystalline material which occupies the same position is called the intercumulus material (instead of interprecipitate material). The resultant rock, which comprises cumulus crystals and intercumulus material, is termed a 'cumulate'. The type of cumulate concerned can be indicated in a general way by using qualifying terms such as ultrabasic or basic, and a more precise description of the rock is achieved by naming the cumulus minerals in order of decreasing abundance as a prefix to the term cumulate. It has also been found necessary to introduce other prefixes to describe more subtle differences among the cumulates, and these differences appear to be the result of the various ways in which the intercumulus crystallization has been effected.

The simplest case is that in which the intercumulus liquid was effectively sealed off from contact with the overlying magma almost as soon as the crystals settled, and subsequently crystallized partly as successive lower temperature zones around the latter and partly as new, lower temperature, mineral phases. The resultant intercumulus material, formed from trapped intercumulus liquid, would therefore have a bulk composition identical to that of the magma at the time of accumulation, and is termed pore material.

A rock formed in this way is called an orthocumulate. Under certain conditions, however, it seems that the intercumulus liquid was not immediately trapped, but, instead, acted as a medium for the diffusion of substances from the overlying magma to the cumulus crystals, which were thus enlarged at much the same temperature as their original formation. By this mechanism, the intercumulus liquid, still retaining the composition of the contemporaneous magma, would gradually be expelled from the crystal pile. This is called the adcumulus process, and the high temperature material added to the cumulus crystals is termed adcumulus material. If this process was prolonged sufficiently to eliminate all the intercumulus liquid it would produce a rock consisting of cumulus crystals and adcumulus material only. Such a rock is termed an adcumulate, and its formation would probably depend on conditions of relatively slow crystal accumulation, since the adcumulus process can only have affected the topmost layers of crystals. Between these two extremes are cases in which some of the intercumulus liquid was eliminated by the adcumulus process before it was effectively trapped, and the intercumulus material of the resultant rock would consist partly of adcumulus material and partly of pore material. Such a rock is termed a mesocumulate. Another special variety of cumulate is the heteradcumulate, in which some of the intercumulus material, although formed in a manner similar to the adcumulus process, has not been added to the original cumulus crystals, but is consequent upon the nucleation of a new high temperature mineral phase in the intercumulus liquid. Such material is termed heterad material and typically forms large, evenly distributed, poikilitic crystals.

Certain of the cumulates on Rhum are believed to have been formed by upward growth of olivine crystals which formed the temporary top of the crystal pile. This type of growth can be viewed as an extension of the adcumulus process when the rate of crystal settling was reduced almost to zero. The term harrisitic cumulate is applied to these rocks in order to perpetuate a well-established local name (harrisite) for an apparently unique textural variety of peridotite. Where necessary, the associated fine-grained cumulates are termed normal cumulates to distinguish them from the harrisitic variety.

The qualifying terms used to give a general indication of the cumulate composition are based on the composition of the cumulus material only, and not on that of the whole rock or the probable parent magma. This method of description is chosen because the bulk composition of the rock is partly determined by the course of intercumulus crystallization, which may vary significantly among cumulates of identical parentage, and because the composition of the magma cannot always be accurately assessed merely by studying the earliest crystal fractions produced from it. However, an indirect reference to the magma composition is given, since it is clear that in general a gabbroic magma would produce a eucritic cumulate, and similarly a eucritic magma would produce an ultrabasic cumulate. It is suggested, following Brown (1956, p. 12) that the definitions of the terms gabbroic, eucritic, and ultrabasic, should be based primarily on the composition of the plagioclase, the ranges being An_{50-70}, An_{70-80}, and $An_{>80}$, respectively. For the cumulates these figures are taken to refer to the composition of the cumulus plagioclase, and not to the normative or average modal values for the rock as a whole. Within the ultrabasic cumulate group the adjectives peridotitic and allivalitic may be used to describe a general preponderance of cumulus olivine or plagioclase, respectively, thus linking the well-established terms used by Harker, and subsequently by Brown, with the new nomenclature. For the description of individual minor layers the general compositional terms are replaced by a more precise designation of the mineral proportions of the rock, for instance, feldspar-olivine-pyroxene cumulate (abbreviated to f-o-p cumulate in the tables).

The terms rhythmic layering, cryptic layering, and igneous lamination, as defined by Wager & Deer (1939), are used in describing the layered rocks of the Harris area. The large-scale pattern of rhythmic layering, as described by Brown in the Hallival–Askival area, is termed major layering, each complete rhythmic sequence being termed a rhythmic unit, or more briefly, a unit (Brown 1956, p. 8).

(*b*) *Summary of the layered sequence in south-west Rhum*

In the layered series of south-west Rhum five major lithological groups have been distinguished on the basis of field mapping (figure 3), but these subdivisions do not correspond exactly to rhythmic units because the pattern of major layering is incomplete and on too broad a scale in this area for such a subdivision to be useful in the field. However, an indication of the probable large-scale rhythmic pattern is given in table 1, where the units are designated *A*, *B*, *C*, *D*, to avoid confusion with units 1–15 of the Hallival–Askival area.

TABLE 1. A SUMMARY OF THE LAYERED SEQUENCE IN SOUTH-WEST RHUM, SHOWING PRINCIPAL PETROLOGICAL AND MINERALOGICAL FEATURES

units	approximate thickness (ft.)	lithological divisions		principal rock types	cumulus olivine composition (Fo %)	cumulus plagioclase composition (An %)
D	1000	5. Ruinsival series	(*b*) Upper	o-f-(p) adcumulates	$85\frac{1}{2}$	$84\frac{1}{2}$
				o-(f) adcumulates	88	—
C	1500		(*a*) Lower	o-f-(p) adcumulates	86	84
				o-(f) adcumulates	86	—
B	400	4. Dornabac series		o-f-(p) adcumulates	$85\frac{1}{2}$	84
		(Lag Sleitir zone of igneous breccia)				
	1200	3. Ard Mheall series		o-(f) adcumulates	$88\frac{1}{2}$	85
	150	2. Transition series		o-f-(p) adcumulates	86 82	84 78
A	400	1. Harris Bay series		o-f-p mesocumulates	82	78

The lowest member of the layered sequence in south-west Rhum is the Harris Bay series of eucritic cumulates which is exposed in the low ground around Harris Lodge. Above this there is an upward gradation through a thin transition series, which forms a small scarp on the lower slopes of Ard Mheall, into the Ard Mheall series of ultrabasic cumulates. These three groups form the most westerly outcrops of the intrusion, and are bounded to the west by granophyre, the junction being steep and of roughly arcuate outcrop. To the east they are separated from the remainder of the layered series by a north–south line of disturbance, along which movement probably took place during the deposition of the cumulates (see §3(*f*)). Thus the Dornabac series of ultrabasic cumulates is never seen to rest directly on the Ard Mheall series, because the two form separate hills and are divided by a zone of igneous breccia. However, from mineralogical and structural evidence the Dornabac series is believed to have been deposited on top of the Ard Mheall series. The Ruinsival series of ultrabasic cumulates overlies the Dornabac series on the eastern flanks

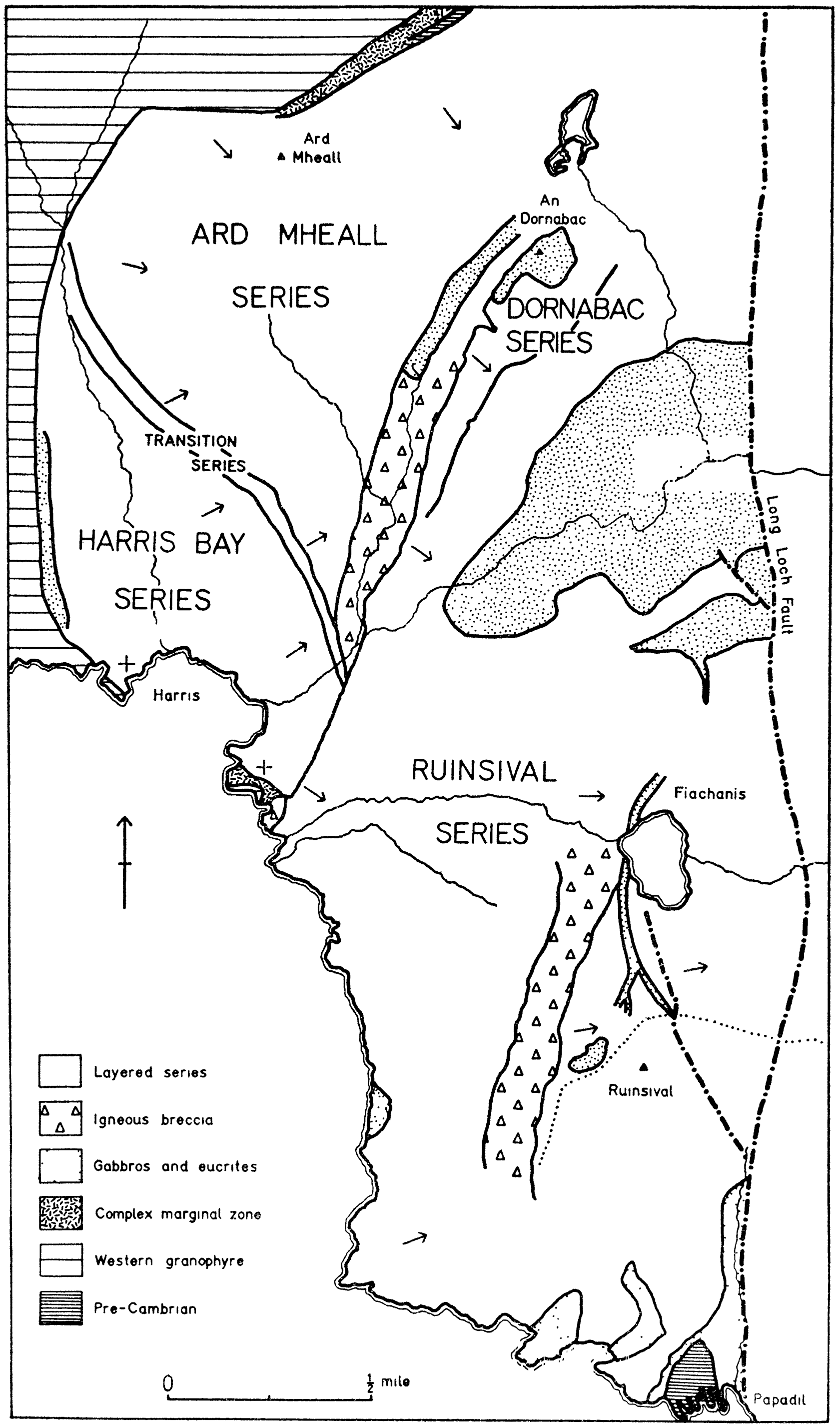

FIGURE 3. Sketch map of the Harris area, showing the distribution of the various members of the layered series.

of An Dornabac ridge, making a considerable spread in Glen Harris and reaching the highest point of the area (approximately 1700 ft.) on top of Ruinsival. The Ruinsival series is adjacent to the Harris Bay series at the mouth of the Abhainn Rangail, but the junction is the southward continuation of the line of disturbance separating the Dornabac series from the Ard Mheall series.

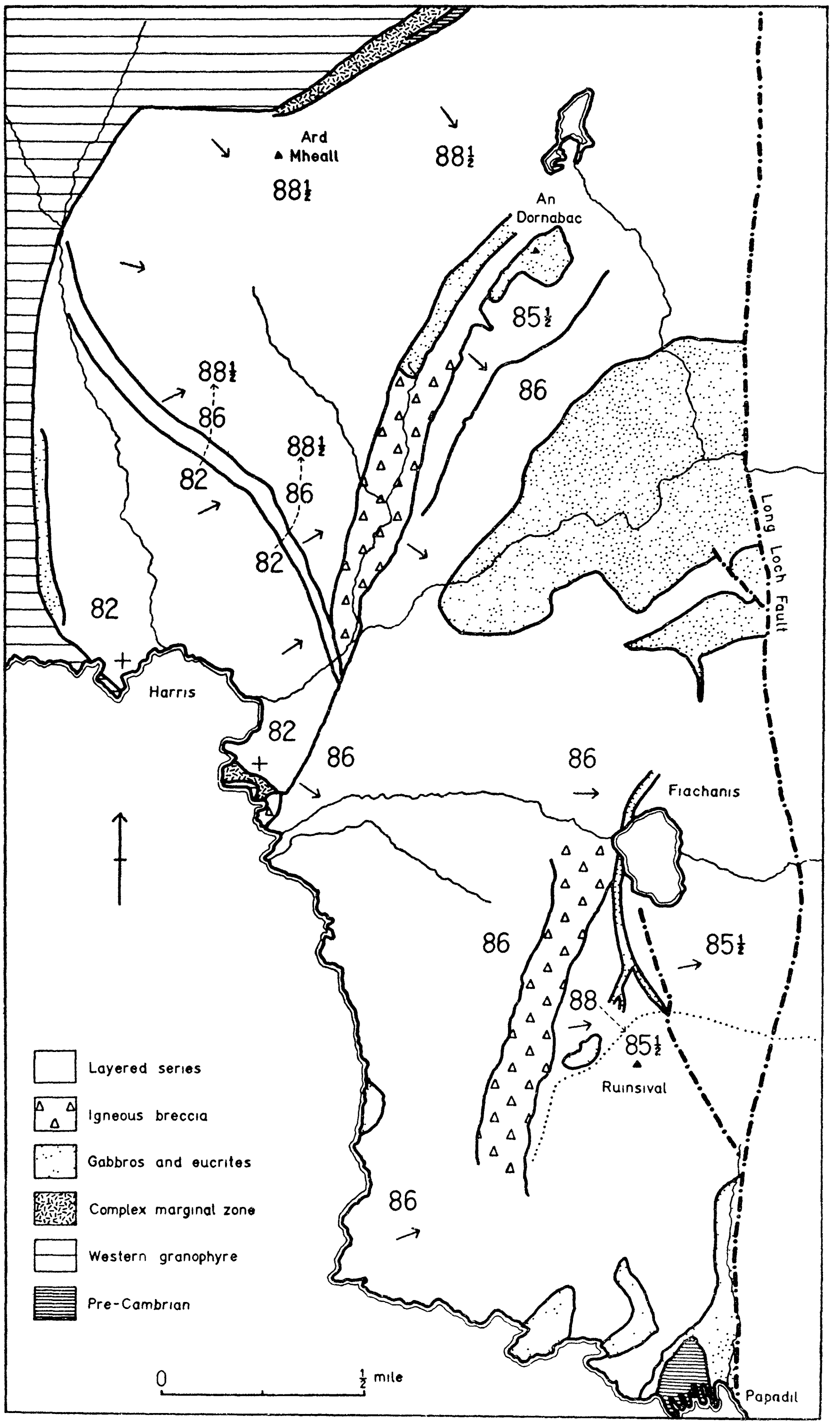

FIGURE 4. Sketch map of the Harris area, showing the variation in olivine composition (the figures indicate forsterite percentage) in the layered series. The small arrows show the direction of dip, and the dotted arrows indicate an upward gradation of composition.

Most of the layered structures dip generally eastwards, although the strike varies gradually from N.E.–S.W. in the northern part of the area, to N.N.W.–S.S.E. in the south-western part. Around Harris Lodge and on Ard Mheall the dips are mostly between 5 and 15°, but on An Dornabac they average 35 to 40°. Layering is rarely seen in south-eastern

Glen Harris and on the western slopes of Ruinsival, but where present it generally shows low dips. Near the Long Loch fault line rhythmic layering is again well developed, and shows peculiar variations of strike, and much steeper dips (40 to 65°).

(c) *Composition of the cumulus minerals*

There is slight cryptic variation throughout the layered series (table 1 and figure 4), and although this variation is not simple and progressive from bottom to top, it is of considerable significance when related to the pattern of major layering. It is most sensitively shown by the olivines, which are relatively abundant throughout the succession, while the feldspars and pyroxenes exhibit sympathetic variation to a small extent.

(i) *Olivine*

The composition of the olivines was determined from optical measurements, using Poldervaart's curves (1950, p. 1073) to relate the physical and chemical properties, and some confirmatory chemical evidence (table 2). Of the optical methods applied, direct measurement of $2V$ was by far the most useful, since it is fairly precise and is very easily performed. All the results quoted are based on direct measurements about the α bisectrix (Wyllie 1959). Measurement of β refractive index was used as a check on selected olivines, and was found to provide results in close agreement with those obtained from measurements of $2V$. Much of the cryptic variation in the Rhum intrusion falls within the limits of error normally quoted for optical determination of olivine composition ($\pm 1\,\%$ Fo). However, it is believed that, in this case, the experimental error is smaller and that the variation observed is truly significant, because statistical methods have been employed, and the results are based on the $2V$ determination of many olivines in individual rocks and on many rocks from each part of the layered series.*

TABLE 2. PARTIAL ANALYSES OF OLIVINES FROM THE LAYERED SERIES

	9789	5049*
SiO_2	39·26	39·87
Fe_2O_3	0·52	0·86
FeO	16·43	13·20
MgO	41·85	45·38
MnO	0·27	0·22
molecular proportions	$Fo_{82}Fa_{18}$	$Fo_{86}Fa_{14}$
atomic proportions: Mg^{2+}	81·7	85·8
$Fe^{2+}+Mn^{2+}$	18·3	14·2
refractive index: α	—	1·6626
β	1·689	—
γ	—	1·6990
$2V_\alpha$ (measured about α)	$87\frac{1}{2}$°	90°

localities: 5049—allivalite of unit 10
9789—col between Ruinsival and Ainshval

analyst: 5049 G. M. Brown
9789 W. J. Wadsworth

* These figures are taken from a complete analysis of the olivine in 5049 (Brown 1956, p. 19).

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* Details of the optical determinations are given in an appendix to the writer's unpublished D.Phil. thesis on 'An investigation of ultrabasic igneous rocks in south-west Rhum' (1958), available for reference in the Bodleian Library, Oxford.

It is an anomalous feature of the cumulates in south-west Rhum that the structurally lowest rocks, namely, the eucritic cumulates of the Harris Bay series, contain olivines which are the least magnesian of the whole series, having a composition of Fo_{81-82}. This is in strong contrast to the composition of the olivines in the overlying Ard Mheall series (Fo_{88-89}). Further, the upward change is gradational, but is in a direction which is the reverse of normal cryptic variation. The gradation is not uniform, since the greater part of the change (Fo_{82-86}) takes place over a thickness of a few feet of cumulates at the base of the Transition series, but the most magnesian olivines are reached in the lower part of the Ard Mheall series, about 100 ft. above the top of the Transition series.

The olivines of the major part of the Ard Mheall series are the most magnesian variety found in the layered series of Rhum (Fo_{88-89}), but the more feldspathic cumulates of marginal distribution (to the north-east and south-west of Ard Mheall summit) contain slightly less magnesian olivines (Fo_{86-87}). The olivines of the Dornabac series are distinctly less magnesian (Fo_{85-86}) than those of the bulk of the Ard Mheall series, and this fact confirms the impression, based on the upward increase in the proportions of cumulus feldspar to olivine, that the Dornabac series was deposited after the Ard Mheall series. The olivines at the base of the Ruinsival series seem to be very slightly more magnesian (Fo_{86-87}) than those of the underlying Dornabac series, but there is no obvious variation throughout the lower half of the series, despite the upward change in the mineral proportions of the cumulates from peridotitic to allivalitic. However, in the olivine-rich cumulates at the base of the upper part of the Ruinsival series the olivines are distinctly more magnesian (Fo_{88}) again, but higher in the series, above the horizon where cumulus feldspar becomes abundant once more, there is a return to the less magnesian variety (Fo_{85-86}). To the east of the Long Loch fault, where it crosses the Ruinsival–Ainshval col, alternating olivine-feldspar and feldspar-olivine cumulates dip steeply towards the west and contain olivines which vary in composition from Fo_{86} to Fo_{82} with increasing height in the series.

(ii) *Plagioclase*

The composition of the plagioclase feldspars was determined by the optical methods of maximum extinction angle of $X' \wedge (010)$ in the zone normal to (010) and the refractive index of cleavage flakes, but these did not provide supporting evidence of the slight cryptic variation indicated by the olivines, except in the Transition series where the composition of the cumulus plagioclase grades upwards from An_{78} ($X' \wedge 010 = 46°$), typical of the Harris Bay series, to An_{84-85} ($X' \wedge 010 = 51–52°$). The latter composition is apparently maintained throughout the sequence of ultrabasic cumulates, although the scarcity of plagioclase in the Ard Mheall series and in parts of the Ruinsival series may have prevented the detection of a slight variation corresponding to the upward change in olivine composition from Fo_{88} to Fo_{85-86} in units *B* and *D*.

(iii) *Clinopyroxene*

Cumulus pyroxene occurs throughout the Harris Bay series of eucritic cumulates and the Transition series, but only in the upper parts of the ultrabasic units where it is apparently of constant composition $Ca_{44}Mg_{49}Fe_7$($\beta = 1{\cdot}687$, $2V\gamma = 51°$). However, there is an upward gradation through the Transition series from a composition of $Ca_{45}Mg_{45}Fe_{10}$ ($\beta = 1{\cdot}691$, $2V\gamma = 51\frac{1}{2}°$) in the Harris Bay series, to $Ca_{44}Mg_{49}Fe_7$, the composition of the heterad pyroxene in the Ard Mheall series, but typical of the ultrabasic cumulates as a whole. These compositions have been determined using the corrections for the optical data suggested by Brown (1956, p. 51).

(iv) *Chrome-spinel*

The composition of the chrome-spinels has not yet been accurately determined, although an analysis by Heddle (Harker 1908) and the generally opaque nature of the crystals suggest that the spinel is strictly a chrome-magnetite, and this has been confirmed qualitatively by reflectivity measurements. In view of the change in composition of the other cumulus minerals from the Harris Bay series upwards into the Ard Mheall series, it seems likely that the chrome-magnetite in the eucritic cumulates is slightly richer in iron than that in the ultrabasic cumulates, although such a difference has not yet been detected.

3. The layered series—field and petrological description

The detailed account of the layered series will follow the general upward sequence, except that the Harris Bay series and the Transition series will be described last because they present some anomalous features and these are best discussed after an account of the more typical cumulates. In this way the harrisitic cumulates receive a more logical treatment since they are best developed in the Ard Mheall series, but also occur in the Harris Bay series and the Transition series.

(*a*) *Ard Mheall series*

(i) *Field characters*

The Ard Mheall series of ultrabasic cumulates forms the main bulk of the hill Ard Mheall, and is generally well exposed except in the south-eastern sector where there is a wide expanse of dip slope inclined gently eastwards towards Lag Sleitir. The exposed thickness of the Ard Mheall series is approximately 1200 ft., but the top of the series is nowhere observed and the original thickness may have been considerably greater. The series comprises olivine and olivine-feldspar cumulates (a small amount of cumulus chrome-magnetite is usually present but will not be listed when naming a cumulate). It is the alteration of the olivine that gives rise to the characteristic pale brown colour of the weathered surfaces. The feldspar is relatively resistant to weathering, and stands out as a network of interstitial patches and stringers, frequently defining the shape of the discrete olivines. Intercumulus pyroxene is distinguished on weathered surfaces by its dark green colour and its typically poikilitic habit. Ultrabasic veins, of the type described by Brown (1956, p. 27) are quite common throughout the Ard Mheall series.

Rhythmic layering is developed throughout the Ard Mheall series and is responsible for the general terraced appearance which is especially characteristic of the south-western scarp. The dip of the layering is mostly in a general easterly direction, but local reversals occur just to the north of the summit. The strike changes gradually from N.E.–S.W. on the northern part of Ard Mheall to N.N.W.–S.S.E. nearer Harris. Because of its regularity this change is thought to represent an original depositional feature of the layered series, and is presumably related to the form of the original margin. The dip of the layering is usually between 5 and 10°, rarely exceeding 15°, and this too is probably the original dip. The layering is particularly regular except for small-scale features of a few layers or groups of layers. Most of these irregularities are developed immediately above the harrisitic layers, which typically have undulating top surfaces, and such irregularities are progressively reduced upwards (figure 9, plate 4). However, other layers may show local variations in thickness, producing small-scale trough-like features, but not related to the irregularities of harrisitic layers (figure 7, plate 3). Very occasionally the layering exhibits minor unconformities but most individual layers seem to be extensive, although they can rarely be traced for more than 50 yards because of the discontinuity of outcrops and the lack of distinctive horizons in the layered sequence of adjacent outcrops.

The rhythmic layering of the Ard Mheall series not only comprises the normal small-scale variations in modal proportions, but also harrisitic layers, and there is some degree of systematic variation with height in the layered series, both in the relative proportions of harrisitic and normal cumulates and in the average thickness of the harrisitic layers.

The junction of the Ard Mheall series with the underlying Transition series is drawn at the level where there is a fairly sharp upward reduction in the amount of feldspar present. When viewed from a distance there is an obvious upward colour change from grey-brown to the distinct pale brown of the olivine cumulates, but at close quarters it is more difficult to define the junction within a few feet. For 150 to 200 ft. above the base, the Ard Mheall series consists of a high proportion (a half to two-thirds) of harrisitic cumulates which often form quite massive layers. The range in thickness of the harrisitic layers is from 1 or 2 in. to many feet, although the majority are between 1 and 6 ft. thick. Between each harrisitic layer the rhythmic layering rarely comprises more than two or three layers of normal cumulates in succession, and these are often slightly irregular. In the succeeding 200 to 300 ft. the harrisitic cumulates are less important quantitatively, comprising about one-third of the total thickness, and individual layers are generally thinner, still ranging from about an inch to 6 or 8 ft., but averaging 6 in. to 2 ft. (figure 8, plate 4). The intervening normal cumulates may range from an inch or two to many feet in thickness, but in general they are considerably thicker than the majority of harrisitic layers associated with them, and show a very regular and prominent development of rhythmic layering (figure 6, plate 3). In the uppermost 700 ft. of the Ard Mheall series the harrisitic cumulates are slightly more important quantitatively, probably comprising about half of the total thickness, and they generally occur as thicker layers, averaging 2 to 3 ft. The normal cumulates, although reduced in total bulk, often exhibit well-developed rhythmic layering. To the north-east of the summit, and again in the poorly exposed part of the hillside to the west of the summit, the cumulates are more feldspathic, and all the layers clearly contain cumulus plagioclase. This group of feldspathic cumulates does not appear to form a particular horizon within the layered series as Harker (1908, p. 78) suggested, and more probably it represents an impersistent lateral variation, perhaps related to a marginal position in the intrusion.

Although the harrisitic cumulates and the normal cumulates are intimately associated throughout the Ard Mheall series, the detailed characteristics of each are described separately, because they show such distinct textural features, and because it is believed that the harrisitic cumulates were probably formed under special conditions which interrupted the more normal sequence of gravity accumulation.

(ii) *Normal cumulates*

The normal cumulates of the Ard Mheall series are essentially adcumulates, in that there are no zoned additions to the margins of the cumulus mineral phases and no new lower temperature intercumulus phases. Strictly they are heteradcumulates as the pyroxene, although of high temperature crystallization, is always of intercumulus habit.

Olivine forms a high proportion of the normal cumulates and occurs mainly as small idiomorphic grains. Many of them are equidimensional, ranging in diameter from 0·25 to 1·5 mm, and averaging a little less than 1 mm, or are slightly elongated along the '*c*' or '*a*' axes and reach 1 to 1·5 mm in length (figure 19, plate 6), while others are prominently tabular and reach 3 or 4 mm in length and breadth (figure 18, plate 6). Closely packed olivines show adjacent faces that are straight or very slightly curved, while olivines poikilitically enclosed in pyroxene or feldspar often show a distinctly rounded form. There is no preferred orientation of the equidimensional grains, but the large tabular crystals tend to be orientated with their plane of flattening, (010), subparallel to the layering. They also frequently exhibit a lamellar structure subparallel to (100), but this is only noticeable close to an extinction position because adjacent lamellae have a very slightly different relative orientation, but no other distinctive features (see also Hamilton 1957). It is suggested that these are a deformation fabric, formed after the intrusion of the magma, during the accumulation of the crystals. It would naturally be best developed in the tabular crystals resting on an irregular surface of more equidimensional grains, and the pressure exerted by the overlying material seems to have caused translation to occur along planes of weakness approximately perpendicular to the (010) faces. No idea can be given of the thickness of overlying layers needed to effect this, and it is possible that the upward emplacement of the layered series, after consolidation, may also have contributed to the deformation. Dendritic iron ore inclusions are rare in the small equidimensional crystals but are nearly always present in the large tabular crystals (figure 21, plate 6), orientated parallel to (100). There is no optically measurable compositional difference between crystals of different sizes, or those containing different amounts of orientated ore inclusions, and no zoning has been detected.

Plagioclase is never abundant, but rarely forms the large poikilitic crystals which are characteristic of similar olivine cumulates in the Hallival–Askival area (Brown 1956, p. 16), and were there taken to indicate that the plagioclase was entirely of intercumulus crystallization. Instead they form rather small irregular crystals in the interstices of the olivine cumulus. In certain layers there are textural features which are believed to indicate that plagioclase was a cumulus phase, despite the fact that it comprises less than 10% by volume of the rock. In these layers many of the small optically distinct units of plagioclase are seen to be in direct contact with each other (figure 18, plate 6), and more rarely, the pyroxene crystals enclose small idiomorphic plagioclase grains. However, in other layers the plagioclase is very scarce (often less than 5%), and must be entirely of intercumulus crystallization. The scarcity of plagioclase and its failure to form large poikilitic crystals in these layers is probably the result of diffusion of potential feldspar material from the intercumulus liquid towards cumulus plagioclase crystals in adjacent layers, until a late stage in the crystallization process. This view is supported by the fact that these intercumulus plagioclase crystals typically exhibit normal continuous zoning, although the rocks are essentially adcumulates. Most of the cumulus feldspars are unzoned, but a few show local marginal zoning which extends the composition range from An_{85} to about An_{80}. There is often marginal sericitization of the feldspars and in many layers there are numerous interstitial patches of green chlorite which may have developed at the expense of feldspar.

The clinopyroxene always forms large, evenly distributed, poikilitic crystals, and there is no evidence that it ever occurred as a cumulus phase. Because of its high temperature composition, equivalent to that of the cumulus olivines, it must have formed as heterad material. It varies in amount from less than 1 % by volume in some layers to nearly 10 % in others, but it is usually between 3 and 5 %. No zoning has been detected and alteration is rare, although occasional small patches of colourless, green, or brown amphibole are found in association with the pyroxene.

Chrome-magnetite is invariably present as small idiomorphic or rounded crystals and is regarded as a cumulus phase. The chrome-magnetite grains typically lie between the discrete olivines or within embayments in the olivines, and very often they are concentrated in small clusters. Sometimes they form persistent seams, up to $\frac{1}{2}$ in. in thickness.

The rhythmic layering of the normal cumulates consists essentially of slight variations in mineral proportions and texture, and is generally apparent as an alternation of more and less feldspathic cumulates. Slight differential weathering of these has caused the more feldspathic layers to stand out slightly, so that the structures are very prominent despite the small variation in the composition of the layers. The less feldspathic cumulates consist of a very high proportion of small, typically equidimensional olivine grains, a few cumulus chrome-magnetite grains, and small amounts of intercumulus plagioclase and pyroxene (figure 19, plate 6). The more feldspathic cumulates also contain a fairly high proportion of olivine grains, but the average grain size is always greater than that of the less feldspathic cumulates, while many of the olivines are tabular and exhibit well-developed igneous lamination (figures 18 and 20, plate 6). Sharply defined layers of exceptionally large tabular olivines occur at many horizons in both the less feldspathic and the more feldspathic layers, and these crystals exhibit almost perfect igneous lamination. Chrome-magnetite grains are usually relatively abundant in the more feldspathic layers, but they are not different in size or shape. The variation in the amount of plagioclase seems to be dependent upon its periodic appearance as a cumulus phase, when it is slightly more abundant than in its intercumulus occurrence. Clinopyroxene does not appear to show any systematic variation from layer to layer, presumably because it was always of intercumulus crystallization. The degree of modal variation in the rhythmic layering is shown in table 3. A chemical and spectrographic analysis of a typical olivine cumulate is given in table 4.

(iii) *Harrisitic cumulates*

The harrisitic cumulates are distinguished from the normal cumulates by their coarse grain and unique texture, both of which are mainly determined by the dominant mineral, olivine. The base of a harrisitic layer is usually quite even and parallel to the underlying rhythmic layers, and the upward increase of grain size usually occurs as a fairly sharp gradation (figure 9, plate 4). The top of a harrisitic layer is typically rather uneven, and almost always shows an abrupt change back to fine-grained normal cumulate (figure 12, plate 4). The irregularity of the top surface may be on a fairly large scale, as the building of the crystal pile took place at slightly different rates in different places, sometimes with the local development of reef-like clusters of olivines. On a smaller scale, individual olivines often protrude into the overlying layer of normal cumulate, sometimes, in the case of the largest crystals, to the extent of some inches (figure 10, plate 4). Within individual layers of harrisitic cumulate there may be some upward variation of grain size and texture, but this does not give rise to distinct subsidiary layering comparable to the rhythmic layering of the normal cumulates. However, chrome-magnetite grains are sometimes relatively concentrated to form rather diffuse seams within the harrisitic layers.

Table 3. Modal analyses of rocks from the Ard Mheall series

specimen	description of predominant textural feature	olivine	plagioclase	pyroxene	chrome-magnetite	secondary products
		typical groups of normal minor layers				
9655*	small rounded olivines	91·6	4·5	3·3	0·5	—
	large tabular olivines	86·5	6·9	0·6	2·7	3·2
9656	large tabular olivines	77·2	17·5	3·0	2·4	—
	small rounded olivines	93·8	0·5	0·6	0·7	4·3
	some tabular olivines	81·6	11·1	2·7	0·6	4·0
9665	small rounded olivines	89·6	5·8	3·8	0·7	—
	some tabular olivines	84·4	9·0	3·3	3·3	—
		other typical minor layers				
9668	small rounded olivines	99·6	—	tr.	0·4	—
9669	small rounded olivines	94·1	1·5	0·9	0·3	3·1
9670	some tabular olivines	86·7	11·7	0·4	1·1	—
		more feldspathic cumulates from N.E. and W. of summit				
9677	small rounded olivines	78·4	12·9	7·9	0·8	--
	large tabular olivines	69·5	26·7	0·9	2·9	—
		harrisitic cumulates				
9670	medium grain size	88·6	6·6	1·3	0·6	3·0
9659	coarse grain size	75·2	11·2	1·9	1·4	10·4

The olivines of the harrisitic cumulates are generally distinguished from those of the normal cumulates on account of their large size, their intricate shape, and their tendency towards a preferred orientation with (010) perpendicular to the layering. However, there are all gradations in size, shape, and orientation from normal cumulates to the best-developed harrisitic cumulates. The smaller harrisitic olivines may be roughly equidimensional or tabular, with few embayments and haphazard orientation with relation to each other (figure 16, plate 5). With increasing grain size the embayments become more pronounced and regular, and there is generally some indication of a preferred orientation. The bulk of the harrisitic cumulates are of this moderately advanced type. The largest harrisitic olivines have a most intricate but ordered shape, and a strongly preferred orientation (figures 14 and 15, plate 3). These crystals frequently extend some inches in all three dimensions, and

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* All specimens referred to in the text are housed in the rock collection of the Department of Geology and Mineralogy, University of Oxford.

occasionally exceed 1 ft. in length (figure 11, plate 4). The overall shape is difficult to determine because of the well-developed parallel growth structures, which in hand-specimens are emphasized by the interstitial feldspar or pyroxene and give the olivine a distinctly platy appearance. However, the individual olivines are not platy in habit, but consist of a number of 'branches', of which the most prominent have a tabular habit parallel to (010) and exhibit regular crystal faces.

It is the largest olivines which best exhibit a preferred orientation. There is a tendency for the (010) plane to be inclined at a steep angle to the layering, and hence the branches tend to be approximately vertical too. Adjacent crystals rarely show precisely the same orientation with respect to the layering, and there is no alinement of the '*b*' axes within the plane of layering. These features of large size, parallel growth structures, and preferred orientation are believed to indicate that the olivines of the harrisitic cumulates grew upwards from the crystal pile forming the temporary floor of the magma chamber (see § 6 (*c*)).

The dendritic iron ore inclusions, orientated parallel to (100), attain their best development in the harrisitic olivines, thus following the pattern observed in the normal cumulates, where in general they occur only in the larger olivines. The lamellar structures subparallel to (100) are rare in the harrisitic olivines, presumably because the (100) plane was usually orientated roughly parallel to the layering, so that the stresses induced by the weight of the overlying material could not easily be relieved by translation gliding. The olivines of the harrisitic cumulates have precisely the same composition as those of the associated normal cumulates, and no zoning has been detected.

Fresh plagioclase usually comprises between 5 and 12% by volume of the harrisitic cumulates, and when allowance has been made for the amount which has been completely altered it seems probable that there was an original plagioclase content of 10 to 20% in these cumulates. The crystals are very variable in size, and although they are almost always smaller than the associated olivines, the size relationship of the two minerals seems to remain roughly constant. The habit of the plagioclase in the harrisitic cumulates is also variable, even over the area covered by a single thin section. Most of it is obviously interstitial to the olivine and typically occurs as quite extensive subpoikilitic crystals, but it sometimes occurs as small discrete units of hypidiomorphic habit, probably indicating that a few cumulus crystals were available. Most of the plagioclase is completely unzoned, but very occasional marginal zoning extends the composition range from An_{85} to An_{80}.

Clinopyroxene is rather scarce in the harrisitic cumulates and is probably only present to the extent of 1 to 2% by volume of any layer, although sampling difficulties make an accurate assessment impossible. The pyroxene is always interstitial, not only to the olivine, but also to the plagioclase, and it often occurs with extensive optical continuity in narrow stringers between olivine and plagioclase crystals, thus indicating the relatively late stage at which it crystallized. However, it is always of high temperature composition and unzoned, and must therefore be heterad material.

Chrome-magnetite grains are invariably present in the harrisitic cumulates to the extent of 1 to 2% by volume, although their distribution is somewhat variable, as they are sometimes well dispersed and sometimes concentrated into rather diffuse and irregular layers. Occasionally they form small clusters in the lower parts of upward-opening olivine embayments.

The harrisitic cumulates contain a much higher proportion and a wider variety of secondary minerals, or minerals of late-stage crystallization, than do the other types of cumulate in the Rhum intrusion, and this fact suggests that a greater amount of interstitial liquid was trapped in them. Even excluding the serpentinization of olivine the alteration products comprise up to 10% of the rock in many cases. These secondary minerals are mainly restricted to the interstices or embayments of the olivines, although they have also developed at the expense of olivine in part, but their distribution within this interstitial environment seems to be quite haphazard. Within the area of one thin section the olivine interstices may be filled with fresh plagioclase and pyroxene, while in the adjacent area the plagioclase and pyroxene may be entirely replaced by secondary material. In many cases the most pronounced alteration has occurred within the intricate embayments of the largest harrisitic olivines, which effectively trapped some of the magma as they grew upwards. Thus it is probable that the harrisitic cumulates are strictly mesocumulates, but that the late-stage alteration effected by the residual fluids destroyed any zoning developed at a slightly earlier stage. The principal products of the alteration are chlorite and serpentine, with small amounts of amphibole, biotite, muscovite, zoisite, and grossular or hydrogrossular.

Modal analyses of two examples of harrisitic cumulate are given in table 3. One (9670) comes from a thin layer of relatively fine-grained harrisitic cumulate with a rather even texture (figure 16, plate 5), and the other (9659) from a thick and coarse-grained layer, which has also been analysed chemically and spectrographically (table 4). For the former example an area of 8 cm^2 was traversed, but since the latter showed a rather patchy distribution of plagioclase and the pockets of secondary material, an area of 50 cm^2 was covered.

(*b*) *Dornabac series*

Between the Ard Mheall series and the Dornabac series is a zone of igneous breccia which is transgressive to the layered structures of the former, but appears in general to be overlain with only slight discordance by the latter. However, both the field relationships and the mineralogy suggest that the Dornabac series was formed soon after the deposition of the Ard Mheall series, following a period of structural disturbance and brecciation, and that both series comprise a single rhythmic unit (*B*). The thickness of cumulates missing between the present base of the Dornabac series and the highest members of the Ard Mheall series (exposed on Ard Mheall summit) is not known.

The Dornabac series comprises about 400 ft. of ultrabasic cumulates and forms part of the low ridge which extends S.S.W. from An Dornabac (858 ft.), descending gradually towards Abhainn Rangail. The western side of the ridge is a relatively steep and rugged escarpment, but the eastern slopes are gentler and slightly less steep than the dip of the layering. The exposures of the Dornabac series are mainly restricted to the scarp face because the top of the ridge, and hence the dip slope, are composed of the overlying Ruinsival series. However, because the strike of these layered cumulates is slightly oblique to the trend of the ridge, the rocks of the Dornabac series spread on to the dip slope at the northern end, and the width of outcrop is thus considerably increased. To the south the outcrop tapers out completely as the conformably overlying Ruinsival series comes up against the zone of igneous breccia.

The cumulates of the Dornabac series are considerably more feldspathic than those of the Ard Mheall series and exhibit many features similar to the allivalites of the Hallival–Askival area. Rhythmic layering, comprising an alternation of feldspar-olivine cumulates and olivine-feldspar (-pyroxene) cumulates, is emphasized by pronounced differential weathering. The layering is locally regular, with an eastward dip of 35 to 40°, but more typically it is streaky and uneven (the average dip is still 35 to 40°), as the individual layers are markedly impersistent, especially the less feldspathic ones (figure 24, plate 7). The feldspar-olivine cumulates are generally the more important quantitatively, and at certain horizons they form fairly homogeneous layers 10 to 15 ft. thick. Obvious slump structures are seen at many horizons (figures 25 and 26, plate 7), and the general streakiness or impersistence of the layering is probably the result of sliding and slumping of unconsolidated

TABLE 4. CHEMICAL ANALYSES OF ROCKS FROM THE LAYERED SERIES

	1	2	3
SiO_2	38·66	39·20	43·36
Al_2O_3	1·95	5·11	9·97
Fe_2O_3	3·33	3·28	1·99
FeO	9·52	8·24	10·15
MgO	41·99	36·38	23·58
CaO	0·64	2·94	7·55
Na_2O	0·12	0·38	1·32
K_2O	0·05	0·05	0·13
H_2O^{+110}	2·91	3·39	1·49
H_2O^{-110}	nil	nil	nil
TiO_2	0·15	0·26	0·54
P_2O_5	0·03	0·03	0·04
MnO	0·20	0·18	0·19
Cr_2O_3	0·37	0·45	0·30
totals	99·92	99·89	100·61

Analyst: W. J. Wadsworth

TRACE ELEMENT ANALYSIS (given in p.p.m.)

	1	2	3
Cr^{3+}	3100	2500	2050
Ti^{4+}	2700	2200	4800
Ni^{2+}	1800	2100	1100
Co^{2+}	110	150	79
Cu^{2+}	120	40	110
V^{3+}	56	51	135
Zr^{4+}	25	44	53
Mn^{2+}	1250	1400	1500
Sc^{3+}	46	36	53
Sr^{2+}	31	8·4	130
Ba^{2+}	24	33	44
Li^{+}	1·0	—	2·6
Rb^{+}	10	10	10
Ni/Co	16·4	14	13·9
Ni/Mg	0·008	0·008	0·008
Ni/Fe^{2+}	0·028	0·028	0·014

Analyst: S. R. Taylor

1. Olivine adcumulate (9656) from Ard Mheall series.
2. Harrisitic cumulate (9659) from Ard Mheall series.
3. Eucritic olivine-feldspar-pyroxene mesocumulate (9605) from Harris Bay series.

material on a sloping floor. The evidence given by Brown (1956, p. 38) from eastern Rhum, suggests that the minimum angle of slope required for slumping was about 10 to 15°. It is believed that the steeper dips of the Dornabac series are those of the original cumulus deposit and that the high proportion of slumped material in the series is due to this. Brown has pointed out that the slump zones in the Hallival–Askival area never exceed 4 or 5 ft. in thickness, the layers above and below them being undisturbed, and this is taken as an indication of the maximum thickness of unconsolidated material at any one time. Where individual slump zones can be identified in the Dornabac series the thickness of unconsolidated material seems to have been of the same order, but there are also thicker and more complex zones of disturbance, and it seems likely that these were the result of successive periods of slumping, between which there was not long enough for the accumulation and consolidation of more regular layers. A few blocks of olivine cumulate occur within the Dornabac series, but since such a rock type never forms more persistent layers it is believed that these blocks must have been derived by brecciation of an earlier series of cumulates (see §3 (*f*)). Occasional layers exhibit gravity stratification, with upward gradation over a few inches from olivine-feldspar to feldspar-olivine cumulates (figure 27, plate 7).

TABLE 5. MODAL ANALYSES OF TYPICAL ROCKS FROM THE DORNABAC SERIES

specimen	type of cumulate	olivine	plagioclase	pyroxene	chrome-magnetite
9701	f-o-p	12·0	54·5	33·4	0·1
9698	f-o-p	17·5	65·7	16·5	0·3
9697	f-o	19·5	76·6	3·3	0·6
9693A	f-o	15·5	83·1	1·3	0·1
9693B	o-f	67·0	30·5	1·9	0·6
9690	o-f	71·0	26·9	0·4	1·6
9689	o-f	70·8	27·1	1·7	0·4

The mineral proportions in the two principal types of layer are rather constant throughout the Dornabac series, apart from some variation in the amount of pyroxene (table 5). The olivines are generally larger than the feldspars and therefore the olivine-feldspar cumulates appear coarser grained than the feldspar-olivine cumulates. The olivine and feldspar crystals are all of cumulus origin, although their original idiomorphic habit has been somewhat modified by adcumulus extension. The olivines are usually equidimensional, but many of the feldspars, especially those in the feldspar-olivine cumulates, are tabular prisms flattened on (010). These commonly show a marked tendency towards igneous lamination, but with no preferred orientation in the plane of lamination. The pyroxenes are somewhat variable in occurrence and habit; they are only of obvious cumulus origin in the upper part of the series (figure 23, plate 6), and elsewhere they are of heterad crystallization, as they form large, evenly distributed, poikilitic crystals enclosing closely packed olivine and feldspar grains. In a few layers the pyroxenes are generally poikilitic in habit, but each one has an approximately central portion which is free of enclosed grains, and presumably represents an original cumulus crystal. Brown has noted a similar threefold variation in the habit of the pyroxenes from the cumulates of the Hallival–Askival area, as well as a fourth variety, the 'composite cluster', not recognized in southwest Rhum (1956, p. 17). Chrome-magnetite grains are scarce throughout the Dornabac series, rarely exceeding 1 % by volume of any layer, and they are never concentrated into seams. All the rocks of the series are adcumulates, although those without cumulus pyroxene are strictly heteradcumulates.

(*c*) *Ruinsival series*

The Ruinsival series of ultrabasic cumulates forms much of the eastern part of the area, extending from An Dornabac ridge in the west to the Long Loch fault in the east. The rocks are poorly exposed on the lower slopes of Ruinsival and in Glen Harris, where a large mass of younger eucrite also obscures the sequence, but the cliffs from Harris Bay to Papadil, and the upper 1000 ft. of the steep north-west face of Ruinsival, provide almost continuous exposures. Layered features are rarely seen except on the upper slopes of Ruinsival, and hence it is difficult to give an accurate estimate of the thickness, although it is probably between 2000 and 3000 ft.

The strike of the layered structures varies slightly from N.E.–S.W. on An Dornabac and in Glen Harris to N.–S. on Ruinsival. There is considerable complication within a quarter of a mile of the Long Loch fault, not only in the area mapped but also further north and on both sides of the fault. In this disturbed region the dips are steep, often reaching 60°, while there are also local variations in the strike. In one particular area, on the lower slopes of Trallval, the strike changes progressively through about 90° within 300 yards, and the dips in this area are 60 to 70°. Because of the general regularity of the minor layering in this narrow belt of disturbance, the steep dips are not believed to be original depositional features, but the result of tectonic movements following the consolidation of the cumulates.

Along the principal traverses from An Dornabac ridge and Harris Bay to the summit of Ruinsival the series can be divided into lower and upper parts, each of which is a rhythmic unit (units *C* and *D*, respectively) showing an upward gradation from olivine (-feldspar) cumulates to feldspar-olivine (-pyroxene) cumulates. The boundary between these units cannot be mapped satisfactorily because of poor exposures and such complicating factors as the transgressive eucrites, the zones of igneous breccia, and the structural disturbances in the region of the Long Loch fault. Therefore, they are generally grouped together, despite their importance in the elucidation of the sequence of major layering.

The lowest rocks of the Ruinsival series are fine-grained olivine cumulates, which are generally separated from the underlying feldspathic cumulates of the Dornabac series by a transition layer of olivine-feldspar cumulate (see table 6) 1 to 2 ft. in thickness. Some tens of feet from the base there is a considerable thickness of coarse-grained olivine cumulates, containing very dark and lustrous olivines full of orientated iron ore inclusions. Cumulus feldspars gradually make their appearance at higher levels within this distinctive rock type, and become more abundant upwards. Just below Loch Fiachanis streakily layered olivine-feldspar and feldspar-olivine cumulates (figure 29, plate 7), similar to those of the Dornabac series, dip eastwards at about 40°, exhibiting slump structures and occasional gravity stratification. To the south these cumulates are replaced by a zone of igneous breccia which spreads high on to the face of Ruinsival and appears to be transgressive to the layered series (see §3 (*f*)).

In the lower part of the main north-west face of Ruinsival there is a return to olivine or olivine-feldspar cumulates, which are approximately 400 ft. thick and exhibit very occasional rhythmic layering, generally in the form of chromite seams, the dip being gentle ($< 5^\circ$) to the east. These cumulates are taken as the base of unit *D* on account of their high olivine content, and the slightly more magnesian nature of the olivines (Fo_{88}) compared those of the underlying cumulates (Fo_{86}). Above these olivine-rich cumulates, cumulus feldspar becomes more abundant again and cumulus pyroxene re-appears sporadically, while the olivine is slightly enriched in iron. Prominent rhythmic layering is developed in these more feldspathic cumulates, which extend to the summit of Ruinsival. Sometimes the layering is quite regular, with a gentle eastward dip, but slump structures occur at certain horizons. Near the summit the upward sequence is complicated by transgressive eucrites, faults, and zones of igneous breccia. When a lateral correlation on to the steep northern face is attempted these complications are even more apparent, and further difficulties arise because the layered sequence has been disturbed in the vicinity of the Long Loch fault. Immediately below the summit on this northern face the layering has a gentle eastward dip, but further east, across a fault zone, olivine-feldspar cumulates exhibit streaky layering with dips of 60°, still towards the east. From mineralogical and petrological evidence it is believed that these cumulates are approximately equivalent to the higher members of the main sequence of Ruinsival. The Long Loch fault crosses the col between Ruinsival and Ainshval. On its eastern side layered olivine-feldspar and feldspar-olivine cumulates dip steeply (60 to 65°) westwards, but the relationship of these rocks to the Ruinsival series exposed on the western side of the fault is not known. The south-west slopes of Ruinsival give much poorer exposures, and it is impossible to trace the various members of the layered sequence in that area.

Table 6. Modal analyses of rocks from the Ruinsival series

specimen	description	olivine	plagioclase	pyroxene	chrome-magnetite
	unit *D*				
9769	strongly layered cumulates from the upper part of the unit	67·1	25·0	5·9	2·0
9763		76·0	10·6	10·6	2·8
9761		31·4	55·5	12·9	0·2
9760		41·3	54·1	4·3	0·3
9759		28·2	71·6	0·1	0·1
9758	o-f cumulate typical of lower part of unit	83·6	9·2	2·9	4·4
	unit *C*				
9749	layered cumulates from upper part of unit	52·1	39·2	8·0	0·7
9748		24·2	73·8	1·7	0·2
9727	olivine-rich cumulates typical of lower part of unit	70·4	19·2	8·3	2·0
9720		95·8	1·9	1·3	1·0
9704	cumulates from narrow transition zone (1 to 2 ft.) above Dornabac series	53·5	37·0	8·2	1·3
9703		57·7	35·6	5·3	1·4

All the rocks of the Ruinsival series are adcumulates, and their variations in modal proportions are summarized in table 6.

(*d*) *Harris Bay series*

The Harris Bay series is believed to be structurally the lowest exposed member of the layered sequence in south-west Rhum, despite the fact that it is composed of less basic cumulates than the other series. It was first mapped by Harker who described it as a eucrite intruded beneath the ultrabasic complex, and Tomkeieff (1945) also followed this interpretation despite the fact that, as he observed, 'some olivine-rich varieties contain platy olivines intergrown with anorthite after the manner of harrisite'. The rocks are in fact olivine-feldspar-pyroxene cumulates, and only differ notably from the remainder of the layered series in that the cumulus minerals are lower temperature members of their respective solid solution series. This is emphasized by the use of the prefix eucritic. They are also distinguished by the relative abundance of cumulus pyroxene, and by the fact that they are mesocumulates rather than adcumulates.

The series is exposed in low ground around Harris, and is best observed along the shores of Harris Bay, and in the two stream sections, Glen Duian River and Abhainn Rangail. Elsewhere in this area exposures are scarce, partly because the rocks are locally covered by raised beach deposits, and partly because they have been slightly altered and seem to weather more easily than the ultrabasic cumulates. In the field they are distinguished by their dark weathered surfaces which are due to numerous small inclusions in the pyroxenes and feldspars. The base of the Harris Bay series is not seen, and the exposed thickness is approximately 400 ft.

TABLE 7. MODAL ANALYSES OF ROCKS FROM THE HARRIS BAY SERIES

specimen	description	olivine	plagioclase	pyroxene	chrome-magnetite	biotite
9633	normal o-f-p cumulates	45·4	36·8	15·4	1·8	0·6
9628		48·5	31·2	18·3	1·0	1·0
9618		45·2	38·2	15·4	1·2	—
9617		*39·6	41·7	17·9	0·6	0·2
9605		*42·1	34·9	20·8	1·4	0·8
9602	harrisitic cumulate	*39·0	34·8	24·7	1·5	—

* This figure includes a small amount of orthopyroxene (< 1 % of the rock), believed to have been olivine originally.

As Harker and Tomkeieff both observed, the rhythmic layering in the Harris Bay series is quite prominent, and has a low angle of inclination. It is generally very regular, with a dip of 5 to 10° towards the north or north-east, although in the Abhainn Rangail sections dips of 15 to 20° are common, while near the granophyre the layers are horizontal. Unlike the other olivine-feldspar-pyroxene cumulates of the Rhum layered series the mineral proportions in the Harris Bay series are rather constant (see table 7) and the layering comprises an alternation of rather uniform normal cumulates with layers of harrisitic cumulate. The normal cumulates frequently exhibit igneous lamination of tabular olivines and lineation of prismatic feldspars. This texture is most strongly developed in the fine-grained normal cumulates, and becomes less apparent with increase in grain size as larger, roughly equidimensional feldspars and pyroxenes tend to dominate the fabric. Where tabular olivines and elongated prismatic feldspar crystals have accumulated on the irregular top surface of a harrisitic layer they are sometimes seen to be banked up against the protruding harrisitic olivines. The harrisitic cumulates of the Harris Bay series are similar in most features to those of the Ard Mheall series, but they are distinct in that they contain considerably more feldspar and pyroxene, and have olivines of markedly acicular appearance. They comprise much less than half of the Harris Bay series, and they typically occur as rather thin layers. However, one or two more massive layers, some feet in thickness, occur on the shore near Harris Lodge.

A peculiar type of layering is seen in the Glen Duian River section, where pronounced differential weathering has emphasized the structures. The more resistant components are thin, slightly sinuous sheets of gabbro intruded into the layered cumulates of the Harris Bay series in a generally conformable fashion, although in some places they are seen to be slightly transgressive. As a result of this intrusion the cumulates are somewhat altered, so that they weather very easily and typically appear as soft, sandy layers containing spheroidal cores of unweathered rock.

Olivine is always the most abundant mineral in the cumulates of the Harris Bay series, usually comprising 40 to 45% by volume of the rocks. The olivines of the normal cumulates are especially characterized by their shape. They are approximately tabular on (010) and exhibit igneous lamination. However, the overall tabularity is considerably obscured by the development of parallel growth structures similar to those of the harrisitic olivines. In sections perpendicular to the layering (figure 22, plate 6) the olivines appear to be very elongate, as the ratio of length to thickness is about 5:1, and the embayments resulting from parallel growth are rather prominent and regular. In sections parallel to the layering the olivines are approximately rectangular in shape, with no very marked elongation, and the embayments appear far less regular. There is no lineation within the plane of layering. The harrisitic olivines are very similar to those in the Ard Mheall series in that they exhibit well-developed parallel growth structures (figure 17, plate 5), and tend to be orientated with (010) approximately perpendicular to the layering. However, the platy parallel growth structures, or branches, are thinner than in the Ard Mheall series so that the olivines have a particularly acicular appearance in sections perpendicular to (010). This is especially obvious in cases of pronounced upward growth where the olivines protrude like blades or tufts of grass into the overlying normal cumulate (figure 13, plate 4), but it is also characteristic of the less perfect harrisitic cumulates in which moderately elongate or platy olivines occur in rather haphazard orientation, and the resultant texture is dominated by radiating or sheaf-like aggregates of apparently acicular olivines. No zoning has been detected in the olivines.

The feldspars comprise between 30 and 40% by volume of the cumulates in the Harris Bay series, and they are typically of prismatic habit, with slight modification by intercumulus growth. In the normal cumulates there is a tendency towards a lineation of the feldspars parallel to the layering, but it is less marked than the igneous lamination of the olivines. The feldspars of the harrisitic cumulates are definitely of cumulus origin, and also tend to be prismatic in habit. Sections perpendicular to the layering show that many of the crystals are orientated with their length parallel to the olivine branches (figure 17, plate 5). In sections parallel to the layering they appear to be much more intricate in shape, as they have obviously been extended by intercumulus growth into the olivine embayments. In both the normal and the harrisitic cumulates the feldspars generally exhibit marginal zoning, which extends the composition range from An_{78} to approximately An_{50}.

Pyroxene is always a cumulus phase in the Harris Bay series, and is consistently present in quantities rarely encountered elsewhere in the layered series. It usually comprises between 15 and 20% by volume of each layer, and occasionally reaches 25%. The pyroxene crystals appear to be rather variable in shape, mainly because each one has been considerably modified by intercumulus additions, and there is usually a tendency towards a subpoikilitic habit as olivines and feldspars have been partially enclosed at the margins. Some rather patchy zoning has been detected in the pyroxenes. Individual pyroxene crystals are less numerous than the olivines or feldspars, and are correspondingly larger as the intercumulus material was distributed to fewer centres of growth. The pyroxenes of the harrisitic cumulates are even larger than those of the normal cumulates, but are similar in shape. Chrome-magnetite, like the other cumulus minerals of the Harris Bay series, is remarkably constant in amount, almost always comprising between 1 and 1·5% by volume of the cumulates, and consisting of small euhedral or rounded grains.

The moderate amount of feldspar and pyroxene zoning indicates that the cumulates of the Harris Bay series are essentially mesocumulates, unlike the remainder of the layered series in south-west Rhum, but comparable to the lowest units in the Hallival–Askival area (Brown 1956, p. 22). It seems likely that a greater rate of crystal accumulation, and hence more effective trapping of the intercumulus liquid, was operative during the formation of the Harris Bay series. A chemical and spectrographic analysis of a normal cumulate from the Harris Bay series is given in table 4.

The alteration of these cumulates is somewhat variable in type and extent, and seems to be the result of three distinct processes. First, there is often a small amount of amphibole, biotite, and chlorite, which probably formed by deuteric alteration, and as in the Ard Mheall series these secondary minerals are more common in the harrisitic than in the normal cumulates. Secondly, in the western part of the outcrop, particularly in the Glen Duian River section, the cumulates are more strongly altered, but in the same fashion, and they contain a relatively high proportion of biotite, green hornblende, and chlorite. Further, the feldspars are more strongly zoned (to An_{35}) and clouded; orthopyroxene is sometimes present; and the olivines contain numerous dendritic ore inclusions, as well as streaks of pale brown material. On the other hand, there is rarely any trace of schillerization in the clinopyroxenes. Most of these effects could be the result of a relatively high proportion of trapped liquid, but from the field evidence it would seem that the alteration is connected with the intrusion of the gabbroic sheets, which themselves are very coarse grained and pegmatitic in appearance. It appears that these sheets were injected before the cumulates had consolidated completely, and that they contributed to the interstitial alteration of the latter. Thirdly, close to the small outcrop of granophyre near the mouth of Abhainn Fiachanis, the alteration of the cumulates is quite distinct from that already described. The olivine usually has a reaction rim of orthopyroxene and is sometimes clouded with minute ore granules, but never contains dendritic ore inclusions; the feldspar is strongly clouded and the clinopyroxene schillerized; while biotite is unusually common and apatite occurs locally. These alteration effects diminish gradually with increasing distance from the granophyre, the clinopyroxene schillerization being the most persistent feature and only disappearing finally in the cumulates of the Transition series.

(*e*) *Transition series*

The Transition series is structurally and mineralogically intermediate between the eucritic cumulates of the Harris Bay series and the ultrabasic cumulates of the Ard Mheall series, and although its boundaries are somewhat gradational it is mapped as a distinct unit on account of certain petrological characteristics which are persistent throughout a thickness of 150 to 170 ft. The series is relatively resistant to weathering and forms a small scarp overlooking the low ground around Harris. This scarp can be traced from Glen Duian, south-east towards the junction of Lag Sleitir and Abhainn Rangail. Its base descends from 400 ft. above sea level in Glen Duian to about 100 ft. at its south-eastern limit, because the strike of the layering is not parallel to the scarp, and there is a small component of dip (5 to 7°) to the south-east in the scarp face itself. The layering in the Transition series is generally conformable to that of the Harris Bay series and the Ard Mheall series, although there are local discrepancies. The dip increases from an average of 15 to 20° in the north-west, to 30 or 35° in the south-east, and as the width of outcrop decreases the scarp also becomes less prominent.

The Transition series comprises olivine-feldspar (-pyroxene) adcumulates of both harrisitic and normal type. The proportion of olivine is always higher than in the Harris Bay series, while the proportion of feldspar is always higher than in the Ard Mheall series. The harrisitic cumulates are quantitatively more important than the normal cumulates, and they occur as massive coarse-grained layers, one or two of them reaching 20 to 30 ft. in thickness, and occasional layers containing exceptionally large olivines (figure 11, plate 4). In mineral proportions they are more like the harrisitic cumulates of the Harris Bay series than those of the Ard Mheall series, but texturally they exhibit intermediate characters, as the olivine branches are less platy and therefore appear to be less acicular than those of the underlying series. The orientation of the parallel growth structures, and the average grain size, both tend to be variable in the harrisitic layers, and the resultant texture is somewhat patchy. The intervening normal cumulates are often thin (averaging a few inches in thickness) and rather irregular, although at the top of the Transition series they reach some feet in thickness and exhibit quite regular rhythmic layering. They are distinct from the normal cumulates of the Harris Bay series in that they contain granular or tabular, rather than skeletal and platy, olivines; small anhedral grains rather than elongate prisms of feldspar; and large poikilitic crystals, rather than discrete grains of pyroxene. They are more feldspathic than the normal cumulates of the Ard Mheall series, and the small feldspar grains give the weathered surfaces a characteristically sugary appearance. The olivines of both the harrisitic and normal cumulates in the Transition series always contain numerous iron ore inclusions, which vary from tiny granules to large and intricate dendrites.

The base of the Transition series is best exposed in Abhainn Rangail, where typical dark-weathering cumulates of the Harris Bay series are overlain by olivine-feldspar cumulates which contain large poikilitic pyroxene crystals and exhibit honeycomb weathering. These cumulates are succeeded 50 to 60 ft. upstream by massive harrisitic cumulates, although the actual junction is rather gradational owing to the initially patchy appearance of the harrisitic texture. Unfortunately, the succession here is obscured as the harrisitic cumulates soon pass into a zone of igneous breccia. In the field, the boundary between the Harris Bay series and the Transition series was drawn at the junction of the laminated dark-weathering olivine-feldspar-pyroxene cumulates (9618–9621) and the olivine-feldspar cumulates with honeycomb weathering (9622–9623). This decision was confirmed by the mineralogical evidence (summarized in table 8, traverse *A*), although the changes are actually gradational over a few feet (9619–9622). Besides the modal and textural changes, the olivines become more magnesian, and the feldspars more calcic, upwards, and there is also a marked reduction of plagioclase zoning so that the rocks are adcumulates rather than mesocumulates. Along another traverse (table 8, traverse *B*) in the vicinity of the road, the changes in composition of the cumulus minerals take place above a massive layer of harrisitic cumulate (9636), which on field evidence is included within the Transition series, since it forms the lower part of the scarp and is texturally unlike the harrisitic cumulates of the Harris Bay series. The top of the Transition series is marked by a fairly distinct upward change from olivine-feldspar (-pyroxene) cumulates (9646) with grey-brown weathered surfaces, to olivine and olivine-feldspar cumulates with pale brown weathered surfaces, typical of the Ard Mheall series. This change is not accompanied by a sharp change in the composition of the cumulus minerals. The olivine, which remains at Fo_{86} throughout the Transition series, appears to grade to $Fo_{88\frac{1}{2}}$ within the lowest 100 ft. of the Ard Mheall series. The plagioclase shows no detectable change, mainly because it is so scarce in the Ard Mheall series.

TABLE 8. MINERALOGICAL AND MODAL VARIATIONS IN TRAVERSES FROM THE HARRIS BAY SERIES INTO THE TRANSITION SERIES

							olivine, plagioclase composition	
relative height	specimen	type of cumulate	olivine	plagioclase	pyroxene	chrome-magnetite	(Fo %)	(An %)
				Traverse *A*				
125 ft.	9623	o-f-p	71·3	8·7	19·4	0·6	86	84
25 ft.	9622	o-f	61·0	33·9	4·0	1·2	85	84
	9621	o-f-p	57·1	33·8	7·7	1·4	84	77 (zoned to 60)
20 ft.	9619	o-f-p	37·0	45·4	16·9	0·8	82	81 (zoned to 63)
0 ft.	9618	o-f-p	45·2	38·2	15·4	1·2	82	78 (zoned to 70)
				Traverse *B*				
170 ft.	9646	o-f	59·3	36·7	3·1	0·9	86	86
	9644	o-f-p	70·8	12·3	16·3	0·6	86	—
	9643	o-f-p	63·4	18·0	17·8	0·9	86	—
	9642	harrisitic	52·2	30·6	16·2	1·0	85	84
	9640	o-f	—	—	—	—	84	—
	9639	harrisitic	70·9	15·7	12·1	1·3	82	84 (zoned to 79)
	9638	o-f-p	44·2	34·3	20·9	0·6	82	80 (zoned to 53)
0 ft.	9636	harrisitic	56·5	19·8	22·9	0·9	82	—

(*f*) *Igneous breccia*

Two zones of a distinctive variety of ultrabasic rock have been mapped in the Harris area. The rock is brecciated in appearance, and consists of two principal components, namely the blocks, which appear to be fragments of olivine-rich cumulates, and the matrix, which is always more feldspathic than the blocks but in hand-specimen and thin-section also has the appearance of a typical ultrabasic cumulate. Harker (1908, p. 76) has described these rocks as 'peridotites...traversed by a network of more feldspathic veins', and he noted that the veins were similar to the typical allivalites or feldspathic peridotites of the area. He believed that the veins were distinctly later intrusions, and used the term 'intrusion breccia' to describe one particular occurrence of these rocks (Lag Sleitir), where he believed that the age relationships were clearly demonstrated. Harker (1904, p. 77) has also recorded similar rocks from Skye, and has used the term 'xenolithic structure' to describe the breccias there. In this account the descriptive term 'igneous breccia' is used, since it is believed that the mode of origin is not obvious merely from the general appearance of the rocks in the field.

The more westerly of the two zones of igneous breccia occurs in Lag Sleitir, and its outcrop is about three-quarters of a mile long and 400 to 500 ft. wide except towards its southern end where it tapers out. Its western margin is moderately sharp and steep, dipping eastwards at about 60°, and is transgressive towards the layered cumulates of the Ard Mheall series. The eastern margin is less steep, and the cumulates of the Dornabac series, dipping eastwards at about 40°, appear to rest on top of the igneous breccia.

The blocks vary in shape from rounded or irregular, to angular, the latter type generally being predominant, and in dimensions from one or two inches to a few feet. The proportion of blocks to matrix is also somewhat variable, but in general the blocks comprise between two-thirds and three-quarters of the total bulk (figure 28, plate 7). In the Lag Sleitir zone the blocks are always extremely rich in olivine, but in texture they range from normal cumulates, sometimes exhibiting igneous lamination of tabular olivines, to harrisitic cumulates. Individual blocks are usually uniform in texture and mineral proportions, but chrome-magnetite seams and other indications of rhythmic layering are sometimes present. From the exceedingly haphazard distribution of the different types of block, and the relative disorientation of the blocks as indicated by the layering or lamination, it is obvious that the original layered sequence, which probably comprised both harrisitic and normal cumulates has been thoroughly disrupted and mixed up in the process of brecciation, and not merely fractured and invaded *in situ*. However, as in many other parts of the layered series there are also some pyroxene-feldspar veins which are distinctly later than both components of the breccia.

Traced northwards, the Lag Sleitir zone of igneous breccia seems to die out to the west of An Dornabac summit, and is replaced laterally by more normal olivine-feldspar cumulates which exhibit streaky layering, and by a later intrusion of eucrite. Southwards the zone of breccia is reduced in width, and appears to be completely overlapped by the Ruinsival series between the Abhainn Rangail–Lag Sleitir stream junction and the shore near the mouth of Abhainn Fiachanis, where a small patch of similar breccia is encountered.

The study of thin sections of the blocks confirms the suggestion that the breccia was derived by the disruption of layered cumulates similar to those of the Ard Mheall series. In thin section the matrix material also has the appearance of a typical adcumulate, containing olivine grains which in size and shape are generally unlike those of the adjacent blocks, cumulus feldspars considerably extended by adcumulus growth, and intercumulus pyroxenes. The feldspars are also distinct in that they often enclose two or three olivine grains, and it is this characteristic which confirms the impression that the matrix is a typical cumulate, because layered cumulates containing the same type of feldspar and with similar modal proportions (9689, 9690, table 5) form the lowest part of the Dornabac series, overlying the breccia. There also seems to be a slight but distinct difference in composition between the olivines from the blocks (Fo_{88}) and those from the matrix (Fo_{86}). The former show affinities with the olivines of the Ard Mheall series, and the latter with those of the Dornabac series.

The other zone of igneous breccia is exposed on the western flanks of Ruinsival, from Loch Fiachanis south towards the coast between Rudha Sgor an t-Snidhe and Papadil. This zone is about a mile in length, and a few hundred feet wide, but it does not appear to be so sharply defined as the Lag Sleitir zone of breccia. The Ruinsival zone appears to be steep and transgressive to the layering in the Ruinsival series; it is exposed at a height of 600 to 700 ft. near Loch Fiachanis and also to the south of Ruinsival, but on the main north-west face of the mountain it is present at heights between 700 and 1400 ft. From the mapping there is some indication that the zone dips steeply towards the east, and this is confirmed by occasional streaky layering that dips in the same direction. To the north, across Abhainn Fiachanis, the zone appears to be replaced laterally by streakily layered and slumped cumulates (believed to form the top of the lower part of the Ruinsival series), dipping at about 40° to the east. The relationship between these cumulates and the breccia is rather obscure, but the two series comprise petrologically and mineralogically similar rock types. As in the Lag Sleitir zone of igneous breccia, the blocks of the Ruinsival zone were obviously derived from a series of olivine-rich cumulates, although they are more variable in their mineral proportions, and never appear to exhibit small-scale layering or harrisitic texture. The matrix is always more feldspathic than the adjacent blocks, but is not constant in modal composition throughout the zone (table 9). Generally the feldspars are smaller and more numerous than those of the Lag Sleitir zone, and sometimes exhibit slight marginal zoning.

TABLE 9. MODAL ANALYSES OF ROCKS FROM THE ZONES OF IGNEOUS BRECCIA

specimen	description	olivine	plagioclase	pyroxene	chrome-magnetite
		Lag Sleitir zone			
9687	block	96·8	—	0·2	3·0
	matrix	68·5	29·2	0·6	1·7
		Ruinsival zone			
9751	block	70·0	17·6	10·8	1·6
	matrix	35·2	62·0	2·1	0·7
9757	block	98·3	—	tr.	1·7
9752	matrix	70·0	29·3	0·2	0·5

It has been shown that, in hand specimen and thin section, the matrix material of the igneous breccia exhibits the characteristic features of an ultrabasic adcumulate, and it is therefore presumed to have originated by crystal settling. However, it is necessary to consider whether brecciation took place before or after this accumulation, and in what way, if any, the present matrix was connected with the process of brecciation.

First, the breccia could have been formed by slumping after crystal accumulation and partial consolidation, the blocks representing the consolidated fraction and the matrix the overlying crystal mush. This may have happened periodically during the deposition of the Dornabac series, but in the case of the igneous breccia there is no evidence of the directional structures normally associated with slumping. A second possibility is that brecciation was effected by faulting and that the contemporaneous unconsolidated material was simultaneously distributed among the blocks to form the matrix. Again, the degree of upheaval necessary to account for the relative disorder of the blocks and the effective distribution of the matrix must surely have produced slump structures as well. It is evident therefore that the blocks were derived before they became associated with their matrix material, although it is unlikely that the accumulation of the latter occurred entirely after brecciation, as the cumulus olivine and feldspar crystals could not have settled directly into the deeper interstices. The distribution and field relationships of the igneous breccia, together with the high proportion of blocks to matrix, certainly seems to indicate that the brecciation was effected by faulting rather than slumping. It is suggested therefore that the blocks represent fragments of a previously consolidated part of the layered series, accumulated at the foot of a fault scarp, and that the matrix comprises olivine and feldspar grains of a new phase of crystallization, accumulating contemporaneously with the blocks. Only by such a mechanism could the blocks have been thoroughly mixed and disorientated before they became associated with the matrix. From the exposed thickness of igneous breccia, especially in the Ruinsival zone, it seems likely that the process may have been the result of successive movements along the fault, rather than one single disruptive phase. Intercumulus crystallization would ultimately weld the blocks and matrix into a coherent, but heterogeneous igneous rock. Similarly, the breccia as a whole would be welded against the fault scarp and the overlying cumulates of the Dornabac series or Ruinsival series, and there is certainly no evidence that the fault has been a line of weakness subsequently.

In considering the Lag Sleitir zone of igneous breccia in particular, it is suggested that the faulting and the formation of the breccia took place before the deposition of the Dornabac series, and that the present relative distribution of the various members of the layered series in this area is primarily the result of these movements. It is apparent from the mapping that the portion of the layered series to the east of the breccia zone was downthrown, and that the throw increased from north to south, reaching at least 2200 ft. (the combined thickness of the Harris Bay series, Transition series, Ard Mheall series, and Dornabac series) on the shores of Harris Bay where the lower members of the Ruinsival series are adjacent to the lowest exposed part of the Harris Bay series. It seems probable that the eastern block was actually depressed towards the south, if as is believed, the present dips of the Ard Mheall series and Dornabac series are essentially depositional features. The floor of the magma chamber must have sloped generally to the east in this part of Rhum (with some variation from E.N.E. to E. on Ard Mheall), but following the period of faulting, tilting, and brecciation, the surface on which the Dornabac series was deposited (to the east of the fault) acquired a slight southerly component of slope. The relatively steep dips of the exposed part of the Dornabac series are the result of its position directly on top of the steep wedge of plutonic fault scree. The tapering of the outcrops, both of the Dornabac series and the breccia, at the present level of erosion, is probably caused by progressive southward overlap by the Ruinsival series, which eventually came to rest against the fault itself. This overlap is not due to any essential discordance between the Ruinsival series and the underlying Dornabac series, but is the result of the gradual reduction of the irregularity caused by the wedge of breccia, as successive layers of the Dornabac series and Ruinsival series assumed the general dip and strike of the eastern fault block, rather than the local dispositions effective near the fault.

The structural relationships and implications of the Ruinsival zone of breccia are less obvious, but the breccia is again believed to represent an intraformational period of faulting. From the structural features observed, it seems probable that the downthrown side was to the east, but it is difficult to assess the amount of displacement that has occurred because of poor exposures to the west of the breccia zone and the lack of distinctive horizons in the layered series. It is possible that the total thickness of the Ruinsival series is considerably greater than the minimum estimated thickness of 2500 ft., since this figure was based on the assumption that the normal upward succession was approximately continuous.

4. The associated later basic intrusions

As in the Hallival–Askival area (Brown 1956, p. 39) the layered series of south-west Rhum is invaded by a number of eucrites and gabbros. All these intrusions are demonstrably younger than the layered series, since they typically send small offshoots and veins into the latter, and in some cases the eucrites contain blocks of the cumulates. However, there is never any indication of chilling, and it seems that intrusion took place soon after the consolidation of the layered rocks. Further, most of the later intrusions show mineralogical affinities with one another, and also with the ultrabasic cumulates, in that they contain plagioclase crystals with cores of calcic bytownite. It seems probable that the magma from which they crystallized was closely related to the parent magma of the cumulates.

(a) *Glen Harris eucrite*

Only part of the Glen Harris eucrite is exposed in the area mapped, to the west of the Long Loch fault in relatively low ground on either side of Abhainn Rangail. There is also a smaller mass of eucrite exposed in higher ground to the south, and this appears to be unconnected with the main mass, at the present erosion level at least. However, Harker's map indicates a link between the two, just to the west of the Long Loch fault, but this link is in fact a small body of quartz-gabbro, and is probably of later intrusion than the eucrite, although the field relationships are rather obscure. The principal junction of the Glen Harris eucrite with the ultrabasic rocks is well defined and appears to be approximately vertical, but there is no doubt about the age relationships as is shown by Harker's description (1908, p. 94): 'Not only does the newer rock near its border vein the older and enclose fragments of it to make a typical intrusion-breccia, but throughout the interior of the eucrite, over a breadth of 800 yards, there are abundant inclusions of peridotite, from small pieces to patches 200 yards long, all traversed by a network of eucrite veins.'

The eucrite is somewhat variable in grain size and mineral proportions (table 10) but never exhibits rhythmic layering. The only heterogeneity which can be observed in the field consists of occasional irregular streaks and patches of fine-grained eucrite enclosed in the typical coarse-grained variety. The plagioclase crystals are somewhat variable in size and shape, but are generally larger than the olivines, and form euhedral or subhedral prisms. They typically exhibit strong normal continuous zoning marginally, and there is often faint oscillatory zoning in the crystal cores. The composition of the cores varies between An_{81} and An_{85} (the oscillatory zoning is probably restricted within this range too), while the marginal zoning extends the compositional range to An_{65}. The olivine occurs as discrete grains, generally between 1 and 2 mm in dimensions, and somewhat irregular in shape as they have been marginally modified by interference with feldspar crystals during the later stages of crystallization. The olivines never contain dendritic ore inclusions or exhibit glide lamellae. The composition is Fo_{79-80} and no zoning has been detected. The clinopyroxene is generally poikilitic, although in some examples it occurs as clusters of discrete grains. Interstitial magnetite is typically present.

TABLE 10. MODAL ANALYSES OF THE TRANSGRESSIVE EUCRITES

specimen	olivine	plagioclase	pyroxene	iron ore
		Glen Harris eucrite		
9723	19·4	59·3	20·5	0·8
9792	4·5	60·3	33·9	1·3
9793	9·0	64·2	26·2	0·7
9794	14·8	77·8	6·1	1·4
9797	4·2	62·3	32·1	1·4
9798	11·7	65·5	19·9	2·9
		Fiachanis eucrite dyke		
9808	19·0	73·7	6·8	0·4
9811	22·3	69·5	8·0	0·2
9812	22·9	68·6	8·2	0·3
		Ruinsival eucrite		
9818	37·5	56·9	4·8	0·8
9819	12·8	39·5	47·1	0·6
9822	22·0	67·5	9·7	0·8
9825	26·9	45·8	26·9	0·5
		Papadil eucrite		
9827	10·1	57·9	30·9	1·1
*9828	22·5	63·7	12·5	1·2
		Gabbro of Rudha Sgor an t-Snidhe		
9833	14·5	63·1	20·8	1·7

* From the tongue of eucrite immediately to the east of the main Papadil eucrite.

(b) *Fiachanis eucrite dyke*

To the south of the Glen Harris eucrite, a rather similar rock forms a dyke-like mass, 20 to 30 yards wide. This can be traced southwards from a point just to the north of Loch Fiachanis, high on to the north face of Ruinsival where it bifurcates, one limb passing on to the main north-west face, and the other continuing up to the summit ridge. The main part of the dyke, and the more easterly limb, dip steeply (60 to 70°) towards the east. The more westerly limb is almost vertical, and itself bifurcates, the two parts so formed becoming intricately involved in a complex region of igneous breccia and intrusion breccia immediately to the west of the summit. This eucrite shows rather constant petrological features along the length of the dyke (see table 10 for modal proportions), and it is quite similar to the Glen Harris eucrite, except that the plagioclase rarely exhibits complex zoning (there is often a single reversal of zoning, but rarely oscillatory zoning), and the olivines are slightly more magnesian (Fo_{81-82}). The overall composition range of the plagioclase is precisely the same as in the Glen Harris eucrite, with cores of An_{85} and marginal normal continuous zoning to An_{65}.

(*c*) *Ruinsival eucrite*

Another distinct variety of eucrite outcrops in the top part of the main north-west face of Ruinsival. Although it exhibits streaky layering which is approximately conformable with the layering in the adjacent cumulates of the Ruinsival series, the eucrite can be distinguished from the latter in the field because of its dark weathered surface. Offshoots from the eucrite penetrate the ultrabasic rocks locally. The layering in the eucrite consists of variations in the mineral proportions (see table 10) and in the grain size. The plagioclase forms subhedral laths which are typically clouded (hence the characteristically dark weathered surfaces of the eucrite) and are often bent as the result of strain. Rather complex zoning, similar to that observed in the Glen Harris eucrite, is common and the composition is An_{82} (core) to approximately An_{65} (margin). The olivines occur as rather irregular discrete crystals, of composition Fo_{81}, while the clinopyroxenes vary in habit from subpoikilitic to discrete subhedral grains, and interstitial magnetite is typically present.

(*d*) *Papadil eucrite and neighbouring intrusions*

The part of the Papadil eucrite exposed to the west of the Long Loch fault comes within the area under investigation, and has been mapped and briefly studied. The eucrite has a steep, unchilled margin against the ultrabasic rocks, into which it sends small offshoots. The normal rock type is not unlike the Glen Harris eucrite in mineral proportions (table 10) and the complex zoning exhibited by the plagioclase crystals (composition An_{85} to An_{60}). However, the olivine is slightly more magnesian (Fo_{81}). Two other steep-sided tongues of eucrite penetrate the ultrabasic cumulates in the cliffs to the west of the Papadil eucrite. The more easterly of these shows close affinities with the Papadil eucrite, but the other is distinct in that it contains little or no olivine, numerous discrete clinopyroxene grains, and plagioclase which is zoned from An_{83} to approximately An_{50}. Quartz is sometimes present, and the associated feldspar is more strongly zoned than in the quartz-free varieties. Two or three very small masses of eucrite have been mapped within the ultrabasic cumulates on the southern slopes of Ruinsival, and they appear to be similar to the types described above.

Gabbro outcrops at the base of the cliffs just north of Rudha Sgor an t-Snidhe, and its junction with the ultrabasic rocks is steeply transgressive. The rock is an olivine-gabbro and is fairly constant in modal proportions (table 10), although its grain size is somewhat variable. The plagioclase, which exhibits very little zoning, has a composition of An_{62-64}, and the olivine composition is Fo_{76}. Apart from its generally coarser grain size, this gabbro is quite similar to the fine-grained olivine-gabbro of the Hallival–Askival area (Brown, 1956, p. 39).

(*e*) *Dornabac gabbro*

The Dornabac gabbro is also steeply transgressive to the layered series, and forms the steep-sided hill, An Dornabac, at the northern end of the long ridge in which the feldspathic cumulates of the Dornabac series are exposed. The gabbro is rather heterogeneous, comprising a dark, coarse-grained rock, intimately associated with streaks and lenses of a laminated feldspar rock, and also containing blocks of hornfels. The plagioclase crystals in the coarse gabbro occasionally contain small bytownite cores (An_{82}), but the bulk of the crystals are labradorite, and exhibit zoning from An_{66} to An_{50}. Sporadic grains of olivine occur, and are approximately Fo_{78} in composition. The feldspars are typically clouded in the basic rocks, and also in the neighbouring ultrabasic cumulates, and as a result it is very difficult to trace the junction between the two rock types, especially as they both exhibit rather streaky layering.

A dyke-like mass of eucrite is exposed just to the west of An Dornabac, and it forms a northward continuation of the western margin of the igneous breccia zone. Plagioclase of composition An_{76} is associated with olivine of composition Fo_{82}.

(*f*) *Glen Duian gabbro*

As has already been described (§ 3 (*d*)) the eucritic cumulates of the Harris Bay series have been intruded in an approximately conformable fashion by a number of thin gabbro sheets. The term gabbro is used because the rocks are composed of plagioclase, clinopyroxene, and magnetite, but the high degree of alteration of the feldspar precludes the precise determination of its composition. It seems probable that bytownite cores are sometimes present, but that the bulk of the crystals are labradorite. Secondary minerals such as epidote and chlorite are typically abundant.

Tomkeieff (1945) described these sheets as eucrite pegmatite, which, he believed, crystallized from the more fluid fraction of a flow-banded heterogeneous eucrite magma, at a slightly later stage than the associated fine-grained eucrite (now shown to be a cumulate). Clearly, the eucritic cumulates have been altered by the gabbro sheets and the type of alteration (see § 3 (*d*)) indicates that the two were closely associated in time, as well as in space, although this is not necessarily the result of such a close genetic relationship as implied by Tomkeieff's hypothesis.

However, the rocks of the Glen Duian section are more complex than this preliminary account indicates. Besides the cumulate layers and the gabbro sheets, horizons of hornfels also occur, and their relationships with the other rock types are obscure. Zeolite veins are locally common, and more than one generation of dykes seems to be represented. Further, the strong differential weathering has resulted in over-emphasis of the importance of the relatively resistant gabbro and hornfels sheets, and a corresponding neglect of the characteristic features of the heavily weathered cumulates.

(*g*) *Marginal gabbro*

Gabbro is locally encountered in the complex zone between the layered series and the Western granophyre. It forms a discontinuous belt, and is poorly exposed except on the shore near Harris Lodge where it forms a zone up to a few feet in width, with irregular offshoots transgressive to the layered cumulates. From Harris into Glen Duian it is more persistent and considerably wider, although the contact with the layered series is nowhere exposed. This marginal gabbro is characterized by feldspars showing strong normal continuous zoning from sodic bytownite centres to andesine or oligoclase margins, and is generally similar to the marginal gabbro of the Hallival–Askival area (Brown 1956, p. 41).

Towards the granophyre the gabbro gradually assumes a hybrid character, with the incoming of quartz and alkali feldspar, and the occurrence of more sodic plagioclase. However, there is always a sharp but unchilled contact with the main granophyre.

5. The margin of the layered series

The junction between the Western granophyre and the rocks of the layered series is generally vertical or very steep, except where tongues of acid rock penetrate the layers horizontally, and it has a roughly arcuate outcrop in the Harris area. Because of the topography and the steepness of the junction, the granophyre is adjacent to successively higher members of the layered series, from the lowest exposed part of the Harris Bay series on the shore near Harris Lodge, to the higher members of the Ard Mheall series exposed less than 100 ft. below the summit of Ard Mheall. The actual junction is rarely a straightforward one between the granophyre and the cumulates. More typically there is a complex zone comprising gabbro, hybrid rocks, and hornfelsed basic blocks set in an acid matrix, between the two.

Although a detailed investigation of these complex junction relationships is still in progress, certain conclusions which have a bearing on the origin and emplacement of the layered series may be drawn at this stage. Of primary importance is the age of the granophyre intrusion. Because the Harris Bay series, which was originally regarded as a eucrite intruded at the base of the ultrabasic mass, is penetrated by offshoots from the granophyre, Geikie (1897) and Harker (1908), followed later by Tomkeieff (1945), naturally concluded that the latter was younger than the basic and ultrabasic rocks. However, a more detailed study of the junction, and of the time sequence of Tertiary igneous activity as indicated elsewhere on the island, has led to the conclusion that the Western granophyre was intruded before the emplacement of the layered series in its present position, but that it was locally remelted when the latter event took place.

The most obvious evidence is that of certain dolerite dykes, which cut the granophyre but do not penetrate the layered cumulates, and have also been thermally metamorphosed where they approach the latter. The modifications of the granophyre close to the layered series are somewhat variable, but the most constant is the development of a quartz mosaic or sieve-texture in the large plagioclase crystals. This feature is believed to indicate reheating of the feldspars, as it is characteristic of acid rocks invaded by basic magma (Emeleus 1956, p. 156). Also significant is the presence of inverted tridymite in these marginal rocks. Obvious examples of quartz paramorphs after tridymite are not very common, but the groundmass of the granophyre frequently exhibits a type of intergrowth texture in which criss-crossing thin lamellae of quartz are dominant, and it has been shown that in the rather similar groundmass of the Coire Uaigneich granophyre of Skye (Wager, Weeden & Vincent 1953) the quartz is clearly a paramorph of tridymite. Unlike its distribution in the Coire Uaigneich granophyre, however, inverted tridymite is not present throughout the bulk of the Western granophyre of Rhum, but only in close proximity to the basic and ultrabasic rocks. This fact supports the suggestion that the granophyre has been locally remelted, presumably as the result of its contact with hot basic material. Inverted tridymite also occurs locally in the Torridonian sandstone adjacent to the ultrabasic cumulates (Harker 1950, p. 68).

Indirect evidence bearing on the age relationships at the junction under consideration is provided by the lavas of Rhum. Black (1952) confirmed Judd's assertion that the basalt outlier of Orval rests uncomformably on the Western granophyre. Further, the conglomerates interbedded with basalts in a faulted outlier to the west of Minishal have been re-investigated, and are found to contain pebbles of a granophyre closely resembling the Western granophyre, but no pebbles of basic or ultrabasic rocks similar to the types present in the Rhum intrusion (a few pebbles of olivine-gabbro were found, but these could not be closely matched with any of the Rhum gabbros).

The most significant feature of the layered cumulates near the junction with the Western granophyre is the total absence of any of the structural or mineralogical modifications which are normally associated with the margins of layered intrusions. This suggests that the present margin is not the original one, but is probably the result of faulting. Brown (1956) has already suggested that the layered series was emplaced from below as a plug of hot consolidated, or almost consolidated, cumulates, probably representing only a part of the whole intrusion. He explained the absence of any marked marginal folding and fracture, which might be expected to accompany such an upheaval, as the result of the lubricating action of the marginal gabbro, and this hypothesis applies equally well to south-west Rhum, especially in view of the similarity between the marginal gabbros of both areas. Further, it is suggested that the emplacement of a hot, but essentially solid, mass of cumulates, accompanied by the injection of basic magma, resulted in the marginal remelting of the granophyre, the thermal metamorphism and disruption of earlier doleritic intrusions, and the production of hybrid material as basic magma assimilated acid rock or mixed with regenerated acid magma. The movement also caused differential displacement of the lubricating basic magma, so that along parts of the junction gabbro and hybrid rocks are absent, and the layered cumulates are in contact with the acid material containing fine-grained basic blocks, or with homogeneous granophyre. Even where the cumulates are adjacent to granophyre there is no sign of faulting at the contact, probably because any fracturing that occurred was annealed following the marginal remelting of the granophyre. In this connexion it is interesting to note that the shearing which locally affects the granophyre is not found very close to the contact, but some feet away, probably in granophyre that was never remelted.

6. THE FORMATION AND EMPLACEMENT OF THE LAYERED SERIES

(a) *The possible nature of the parent magma*

No new evidence concerning the composition of the parent magma of the Rhum layered series has been forthcoming in the Harris area, and the estimate made by Brown (1956, p. 44) is probably the best attainable. The inferred composition is close to the high-alumina basalt type (Tilley 1950; Abelson 1957; Kuno 1960), and although an abundance of early formed plagioclase is characteristic of rocks in this group it is clear that olivine began to crystallize before plagioclase in each unit of the Rhum layered series. However, the later basic intrusions, in which plagioclase is very abundant and generally seems to have preceded olivine, may have crystallized from the same magma under somewhat different physical conditions.

(*b*) *The origin of the major layering*

Ultrabasic cumulates of a comparable thickness to those on Rhum form the lower parts of the Bushveld and Stillwater complexes, but they are overlain by many thousands of feet of later differentiates. This implies either that the exposed cumulates on Rhum have been brought up from a very considerable depth and the overlying differentiates removed by erosion, or that the residual magma did not crystallize in the magma chamber where its early crystal fraction was deposited. Brown (1956, p. 44), although postulating some uplift, favours the latter view, and has suggested that 'the layered rocks were deposited in a sub-crustal magma 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 process would also account for the major layering, and each unit in the Hallival–Askival area is believed to represent a fresh influx of basic magma. The absence of overall cryptic layering substantiates this hypothesis and indicates that successive portions of the parent magma had approximately the same composition. The absence of cryptic layering within each unit indicates that the temperature drop during the deposition of 150 to 200 ft. of cumulates was not sufficient to produce detectable changes in the composition of the cumulus minerals. That there was slight cooling is shown in each unit by the crystallization sequence of the cumulus minerals, whereby olivine and chrome-magnetite appeared first and were later joined by feldspar and finally by pyroxene, although Wager (1959) has suggested that the same sequence might be produced without a significant temperature drop, as the result of differential powers of crystal nucleation.

The pattern of major layering in south-west Rhum is in many respects similar to that in the Hallival–Askival area. Although the succession is less obviously continuous than in the latter area, three complete, or almost complete, units have been recognized above the Harris Bay series, which itself may represent the top of another unit. These units are very much thicker than those of the Hallival–Askival area, but each one shows the same crystallisation sequence with the incoming of cumulus feldspar and, later, pyroxene. Cryptic layering occurs within two of these thicker units, as with a longer period of crystal accumulation the magma cooled enough for detectably lower temperature members of the solid solution series to be precipitated. The repetition of the crystallization sequence and the cryptic layering in south-west Rhum provides strong confirmatory evidence of the successive replenishment hypothesis postulated by Brown.

Of particular importance in this connexion is the progression from the top of the Harris Bay series, through the Transition series, to the lower part of the Ard Mheall series. The structural position of the Harris Bay series is anomalous in that these eucritic cumulates must have been deposited from a magma considerably less basic than that which gave rise to any of the overlying cumulates. This composition difference might have been in some way connected with the original derivation of the magma, or it might have been accidental, perhaps the result of contamination with granophyre. It might also have been the result of pronounced crystallization differentiation of the normal parent magma, during the formation of a very thick unit, of which the Harris Bay series is the top. Unfortunately, the exposed thickness of the Harris Bay series is only about 400 ft., and nothing is known of the underlying rocks. However, the significant feature in this context is not merely the anomalous composition of the cumulates, but the nature of the transition from the Harris Bay series to the Ard Mheall series. As has already been shown (§ 3 (*e*)) the Transition series does not exhibit a gradual change of mineralogy and petrology throughout its thickness, but in fact comprises a distinct group of rocks with characteristics intermediate between those of the underlying and overlying cumulates. It is difficult to see how this variation could be explained except on the successive replenishment hypothesis, since the Transition series must have been deposited from a magma intermediate in composition between the parent magma of the exposed part of the underlying Harris Bay series (less basic) and that of the overlying Ard Mheall series (more basic). Therefore it is suggested that the former magma was not completely replaced by the latter in a single phase of extrusive activity and replenishment, but that some mixing of the two occurred, and for a certain period of time before a new inrush of magma finally replaced the less basic variety the cumulates of the Transition series were deposited. This is the only known example of such mixing at the junction of two major units in Rhum.

(*c*) *The origin of the rhythmic layering*

Any explanation of the rhythmic layering in the Rhum intrusion must account for the development of the remarkable harrisitic layers which are so characteristic of the Harris Bay series, Transition series, and Ard Mheall series. As was first mentioned by Wager & Brown (1951) the field evidence clearly indicates that the controlling factor in the formation of the harrisitic cumulates was the upward growth of olivine from the temporary top of the crystal pile. The significant features are the large size and the near-vertical parallel growth structures of the harrisitic olivines in comparison with the small granular or tabular olivines of the intervening layers, which are believed to have formed by normal crystal settling. It is apparent that the upward-growing olivines were periodically smothered by showers of discrete grains, and these in turn formed layers from which further phases of harrisitic growth were initiated.

At first, this growth would take place from all the grains at the top surface of the pile, but the textural evidence shows that the growth was competitive and some grains were preferentially enlarged while others were suppressed. It is known that olivine has a tendency to develop a tabular habit parallel to (010) (Drever & Johnston 1957), and it is suggested that settling grains which came to rest with (010) close to vertical would have an advantage over other grains if uninterrupted growth was possible for a sufficiently long time. If small equidimensional olivine grains formed the base of a harrisitic layer, comparatively few of them would be orientated with (010) vertical, and if the base was composed of tabular olivines exhibiting igneous lamination, then (010) would be horizontal for the majority of the crystals. But probably more important than the actual orientation with respect to the floor would be the orientation of each grain in relation to its immediately adjacent neighbours. Even a slight advantage here would probably be sufficient to ensure a relatively greater component of growth in an upward direction, and not only would the favoured crystal be better situated to receive material from the magma, but it would also be free to expand laterally, probably by budding to form parallel growth structures, so that it would effectively obstruct the growth of the neighbouring grains.

Initially then, successful upward growth might take place from grains showing a wide range of orientations, but as the competitive process continued there would be a tendency to approach the situation where only the most favourably orientated crystals could survive. Attainment of this advanced stage was delayed or prevented altogether in the majority of harrisitic layers because crystal settling rarely ceased completely. Although the sinking grains were too infrequent to prevent upward growth, they continually interrupted it by providing new centres of crystallization, so that none of the harrisitic olivines was able to grow for long enough to dominate the structure by virtue of a relatively favourable orientation. Thus, a vertical section through most harrisitic layers shows a series of only moderately large and embayed olivines with no strongly preferred orientation. However, in a few cases, generally when a new major phase of crystal settling was delayed for an exceptionally long time, the magma was cleared of sinking crystals and the competitive process went to completion, so that the upper parts of these layers consist of very large olivines, with (010) vertical, and showing well-developed parallel growth structures.

It seems likely that the feldspars (and the clinopyroxenes in the Harris Bay series) of the harrisitic cumulates are generally of cumulus origin too, and like the olivines each optically distinct crystal probably represents a single settled grain that has increased in size by growth from the floor. However, it is obvious that the olivines controlled the resultant texture, presumably because of their relatively rapid growth rate. The extension of the cumulus feldspars and clinopyroxenes would thus be partly upwards and partly into the interstices and embayments of the surrounding olivines.

One way in which rhythmic layering can be produced is by periodic current action in the magma, as postulated by Wager & Deer (1939) for the Skaergaard intrusion, and generally accepted as applicable to other layered intrusions as well (Brown 1956, p. 45 and Hess 1960, p. 134). However, in Rhum there is certainly no evidence of pronounced current action. A more satisfactory hypothesis is that the necessary periodicity was developed as an intrinsic part of the nucleation process, and it is believed that this would be the case if supercooling of the magma was necessary to initiate nucleation. At some stage the supercooling would be relieved by the spontaneous formation of many nuclei (labile state), and following growth to a requisite size, with concomitant return towards the equilibrium crystallization temperature of the magma, the crystals would sink. No further nucleation could occur until the necessary degree of supercooling was developed again, and thus there would be an interval during which the only possible crystallization would be the upward extension of grains on the floor. Then spontaneous nucleation would initiate a fresh cycle, and in this way crystal settling would be periodic. It is believed that the interval between successive phases of nucleation and crystal settling was normally too short for detectable upward growth to occur, but slight rhythmic layering would be produced as each shower of crystals was sorted by the action of gravity, especially if there had been preferential nucleation of the structurally simpler (and denser) minerals, as suggested by Wager (1959). The occurrence of harrisitic layers is taken to indicate conditions of exceptional tranquillity, when relief of supercooling was liable to be delayed for long enough to allow prominent upward growth. Such conditions obviously held throughout the formation of the Harris Bay series, Transition series, and Ard Mheall series, where harrisitic layers are common, but even then the interval between successive crystal showers was very variable. Sometimes it was too short for any upward growth to occur, while at other times harrisitic layers, which might be any thickness from less than an inch to many feet, were formed. Clearly nucleation was very easily triggered off even under the most favourable conditions for prolonged supercooling.

If supercooling occurs in a basic magma, then this mechanism of periodic nucleation may be as important as variable current action in producing rhythmic layering. In this connexion it is significant that harrisitic layers are developed in cumulates over a range of composition from eucritic (Harris Bay series) to ultrabasic (Ard Mheall series), so that supercooling must have occurred over an equivalent range of magma composition.

(*d*) *The structural relationships of the layered cumulates in south-west Rhum and in the Hallival–Askival area*

The structural relationships of the cumulates in south-west Rhum and those in the Hallival–Askival area are of considerable importance in connexion with the emplacement of the layered series. Although the two series are now exposed at approximately the same height, there is a certain amount of evidence to suggest that they were originally deposited at different times, and therefore probably at different levels, in the magma chamber. The average thickness of the units is very different in each area, and there are also petrological differences, particularly the remarkable development of harrisitic cumulates in south-west Rhum. These differences might be merely the result of lateral variation, but this seems unlikely in view of the absence of transitional types, or any sign of lateral changes within the areas concerned. More important is the fact that the earliest olivines of each unit in south-west Rhum are slightly more magnesian than olivines of similar occurrence in the Hallival–Askival area (Fo_{88-89} instead of Fo_{86-87}), and the Ni/Co ratio is slightly higher in the adcumulates of the former area. These are the only hints of overall cryptic variation in the Rhum intrusion, and suggest that there may have been slight fractionation of the magma in the main reservoir. Thus it seems likely that the 4500 ft. (approximately) of cumulates in south-west Rhum represents a distinctly lower level of the original layered intrusion than the 2600 ft. of cumulates in the Hallival–Askival area. That the thickness of cumulates originally deposited between the Ruinsival series and unit 1 of the Hallival–Askival area may have been considerable is suggested by their dissimilarity. The upper part of the Ruinsival series is a thick unit of olivine-feldspar (-clinopyroxene) adcumulates, while unit 1 is very much thinner, and consists of ortho- or mesocumulates containing orthopyroxene.

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

It has been suggested that the thick pile of Rhum cumulates was pushed into its present position from below as an essentially solid mass, with basic magma, now the marginal gabbro, acting as a lubricant. The size of the original intrusion cannot be estimated, but there is no particular reason for assuming that it was much bigger than the exposed portion, or that it was very deep-seated. It is more likely that the magma chamber was of intermediate situation between a volcanic vent and a deeper source of basic magma.

The relative displacement of the eastern and western parts of the intrusion probably occurred during emplacement from below. These two parts are separated by a belt of cumulates in which igneous breccia and slump structures are common, indicating that there was considerable disturbance in this region, even during the period of accumulation. The transgressive eucrites (in particular the Glen Harris, Ruinsival, and Papadil eucrites), and gabbros are also characteristic of this zone, and were probably intruded as differential uplift of the two parts took place. Later faulting has also added to the complexity of the region. The Long Loch fault is the most prominent, and truncates the layered series of south-west Rhum to form the western margin of the disturbed zone. To the east, important faults in the Barkeval region separate this zone from the layered series of the Hallival–Askival area.

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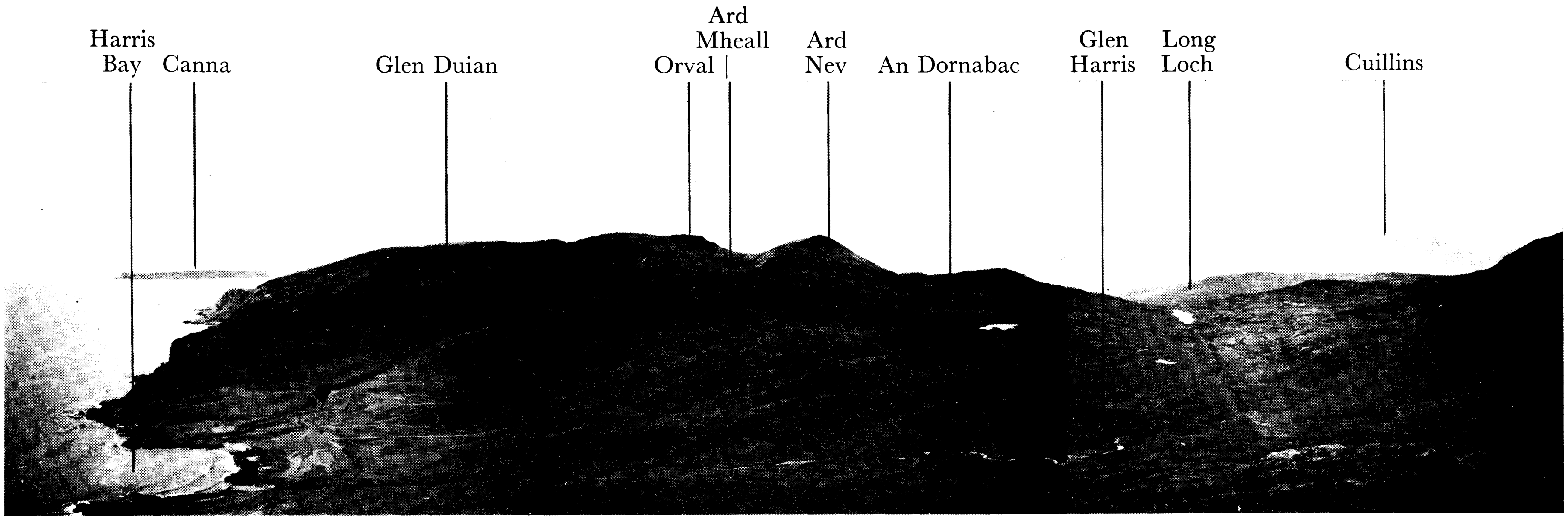

FIGURE 5. Panorama of south-west Rhum, from the summit of Ruinsival.

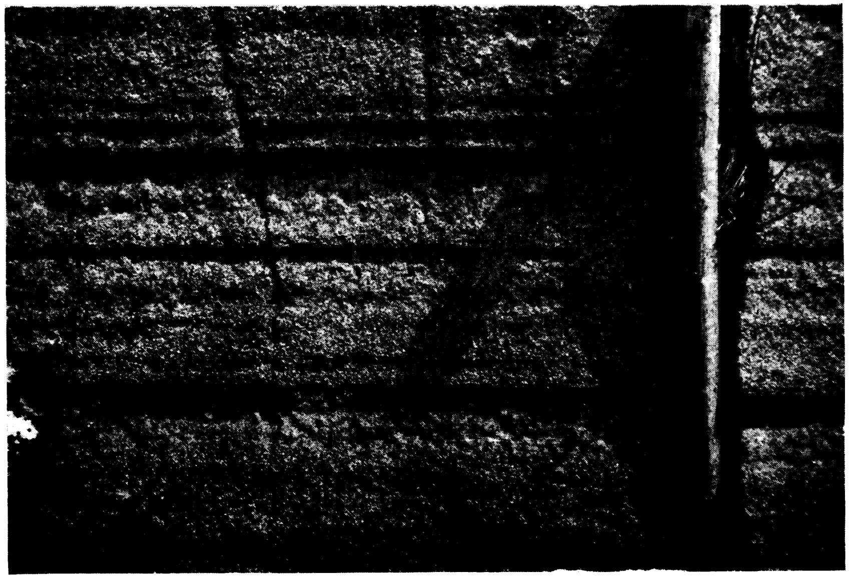

FIGURE 6. Rhythmic layering in the normal cumulates of the Ard Mheall series. Terraces $\frac{1}{2}$ mile south-west of Ard Mheall summit.

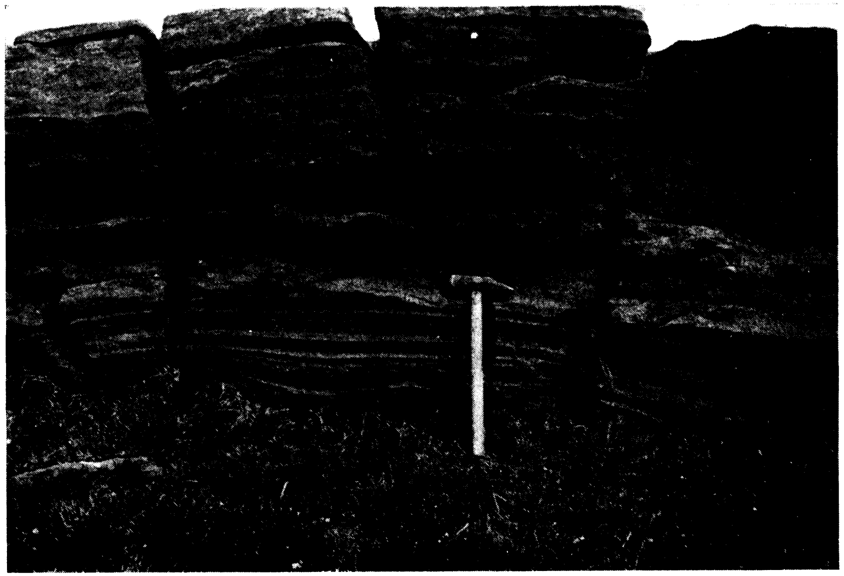

FIGURE 7. Slight irregularities in the rhythmic layering of the normal cumulates, Ard Mheall series (strike section). Same locality as figure 6.

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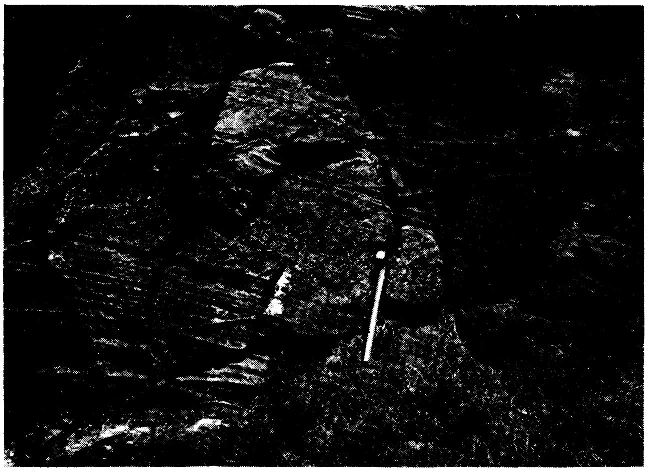

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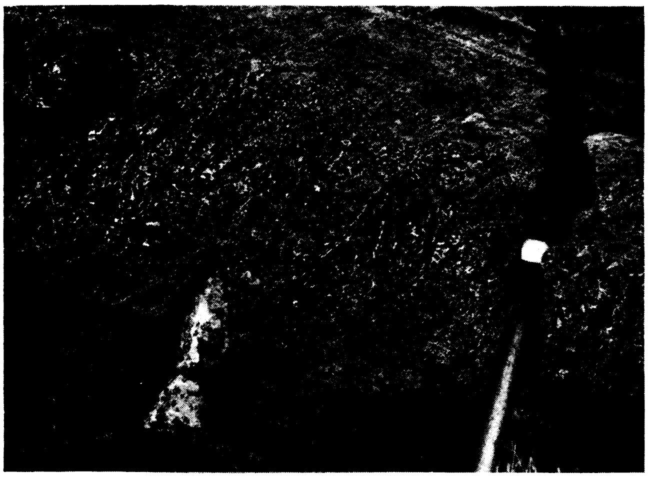

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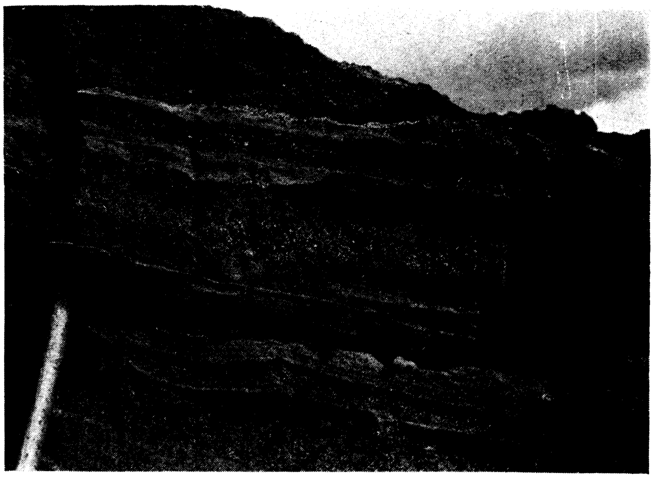

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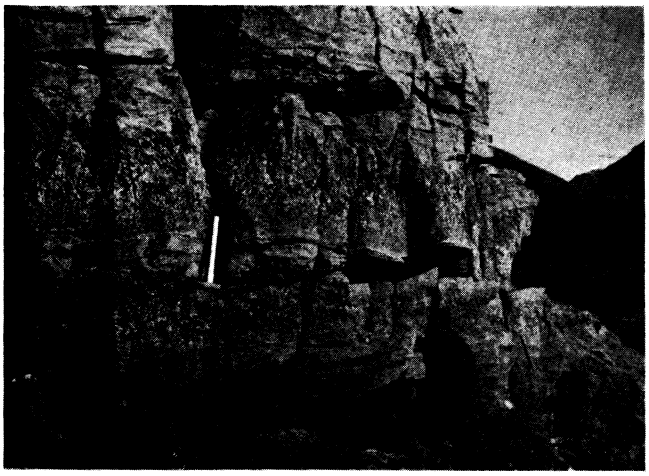

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Description of plate 4

Figure 8. Rhythmic layering involving harrisitic layers. Ard Mheall series. Terraces, $\frac{1}{2}$ mile south-west of Ard Mheall summit. Dip section.

Figure 9. Close-up of part of figure 8, showing the typical textural features of a harrisitic layer; particularly the upward increase in grain size, the preferred orientation of the olivines (emphasized by the interstitial feldspar) and the irregular top of the layer. Note that the irregularity is gradually reduced in the normal cumulates above.

Figure 10. Two harrisitic layers, showing extremely large olivines at the top of the upper layer. Ard Mheall series, above road, $\frac{1}{2}$ mile north of Harris Lodge.

Figure 11. Part of a thick layer of exceptionally coarse harrisitic cumulate in the Transition series. Above road, $\frac{1}{2}$ mile north of Harris Lodge.

Figure 12. Rhythmic layering involving numerous thin harrisitic layers. Ard Mheall series, from the eastern face of Ard Mheall.

Figure 13. Harrisitic layers in the Harris Bay series, showing the acicular nature of the olivines. Shore, $\frac{1}{2}$ mile south-east of Harris Lodge.

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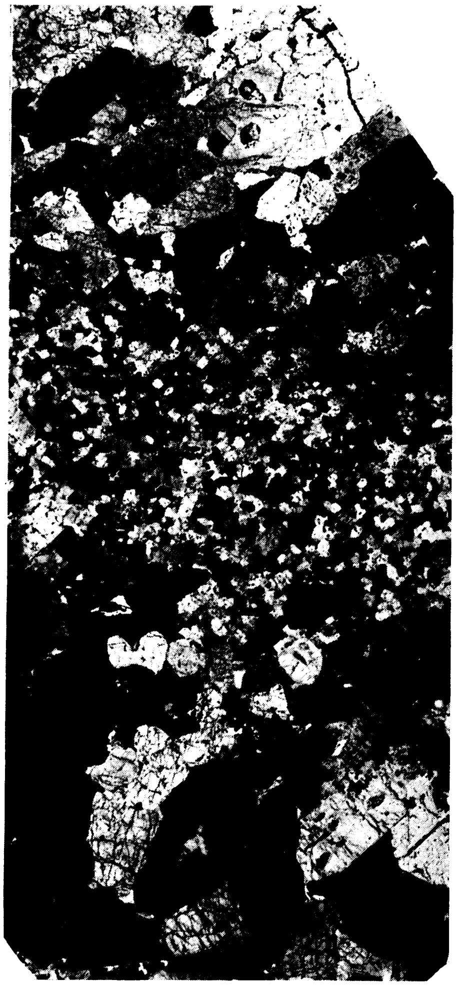

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DESCRIPTION OF PLATE 5

FIGURE 14. Photomicrograph of 9651 (Ard Mheall series). Part of a single harrisitic olivine, with well-developed parallel growth structures; (010) vertical and perpendicular to the plane of the photograph. Section orientated perpendicular to the layering. (Magn. × $1\frac{1}{2}$, crossed polars.)

FIGURE 15. Photomicrograph of 9651. The same olivine as in figure 14, but sectioned parallel to (100). (Magn. × $1\frac{1}{2}$, crossed polars.)

FIGURE 16. Photomicrograph of 9670, showing the top two harrisitic layers and the intervening normal cumulate, from the 'perched block' of figure 12. Section orientated perpendicular to the layering. (Magn. × $1\frac{1}{2}$, crossed polars.)

FIGURE 17. Photomicrograph of 9607. Harrisitic cumulate from the Harris Bay series. Note the parallel growth structure of the olivine, with slight relative disorientation of the two branches. Section orientated perpendicular to the layering. (Magn. × 8, crossed polars.)

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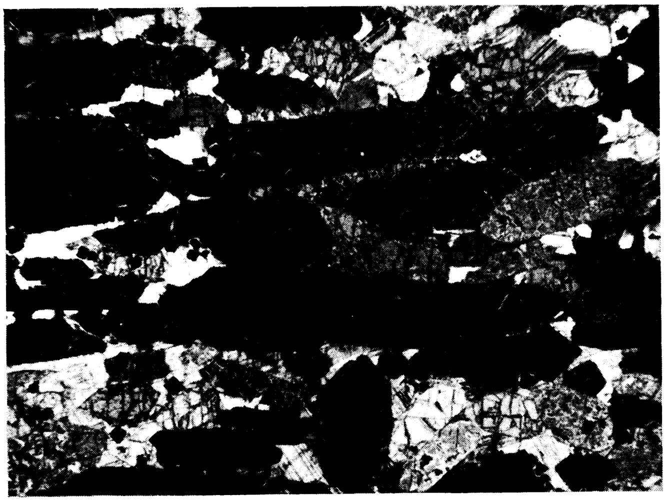

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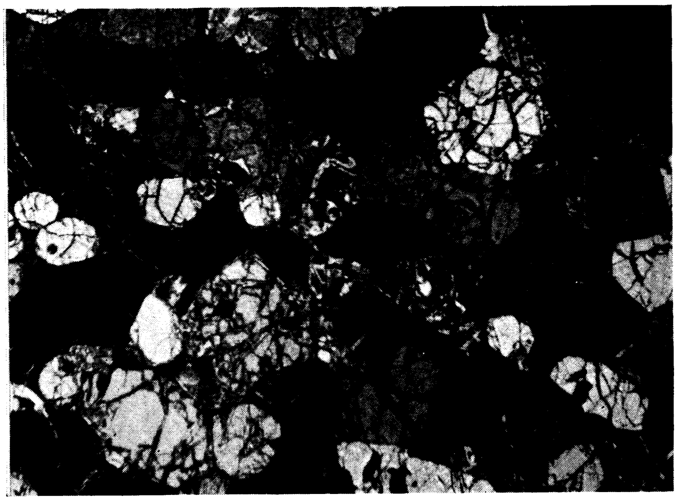

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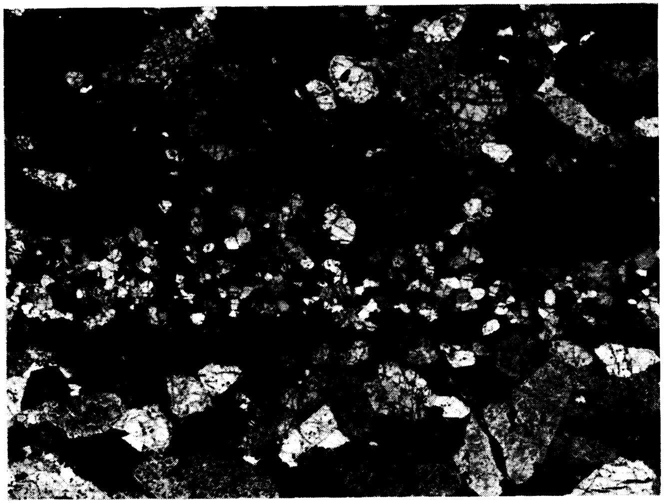

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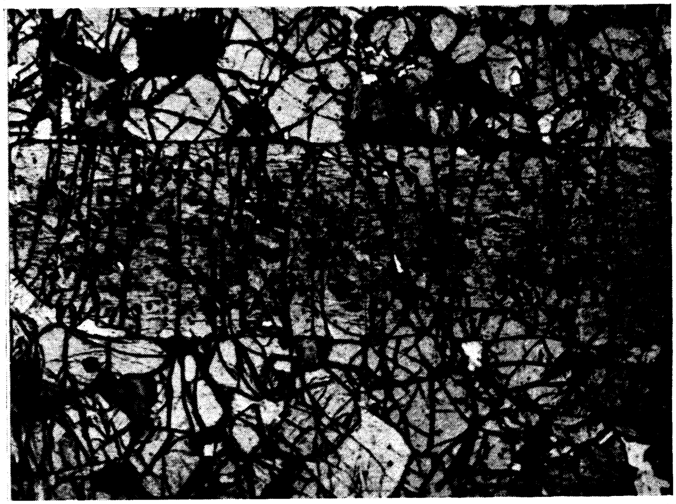

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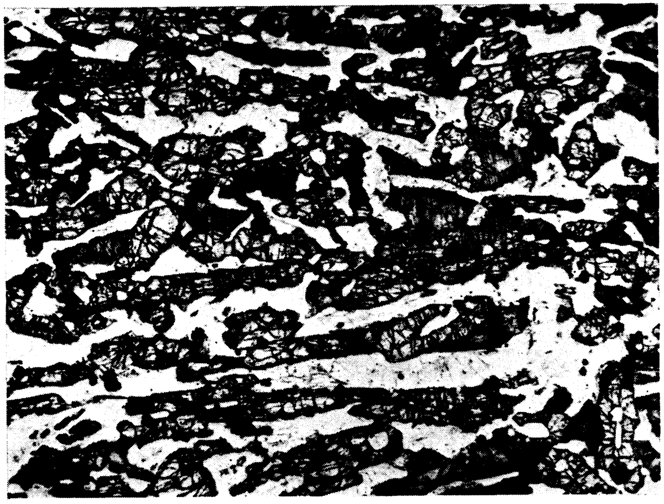

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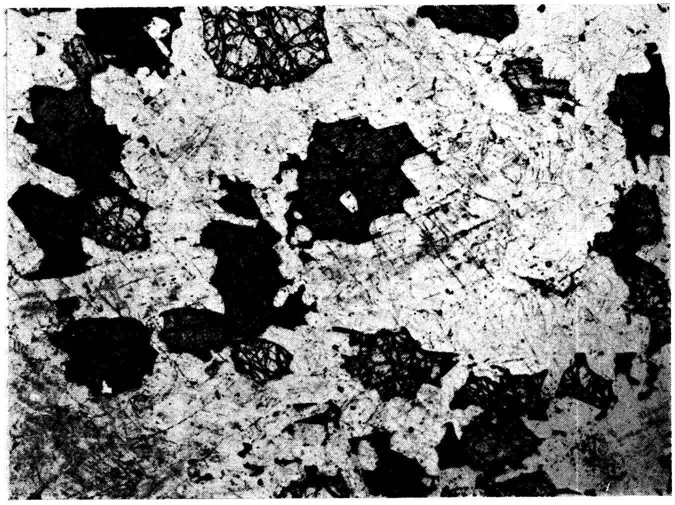

Description of plate 6

Figure 18. Photomicrograph of 9656B. Olivine-feldspar cumulate from the Ard Mheall series, showing igneous lamination of tabular olivines, a small amount of cumulus plagioclase, and relatively numerous chrome-magnetite grains. Section orientated perpendicular to the layering. (Magn. × 8, crossed polars.)

Figure 19. Photomicrograph of 9656A. Olivine cumulate from the Ard Mheall series (adjacent layer to 9656B), showing very few chrome-magnetite grains. (Magn. × 18, crossed polars.)

Figure 20. Photomicrograph of 9662, showing rhythmic layering in cumulates of the Ard Mheall series. Section orientated perpendicular to the layering. (Magn. × $2\frac{1}{2}$, crossed polars.)

Figure 21. Photomicrograph of 9677, showing a (100) section through a large tabular olivine in the Ard Mheall series. Note the orientated dendritic inclusions, and the associated small granular olivines free from inclusions. (Magn. × 18.)

Figure 22. Photomicrograph of 9605. A typical olivine-feldspar-pyroxene mesocumulate from the Harris Bay series, showing igneous lamination of the olivines and feldspars. Section orientated perpendicular to the layering. (Magn. × 8.)

Figure 23. Photomicrograph of 9698. A typical feldspar-olivine-pyroxene adcumulate from the upper part of the Dornabac series. There has been considerable marginal modification of the discrete olivines and pyroxenes by intercumulus crystallization. (Magn. × 12.)

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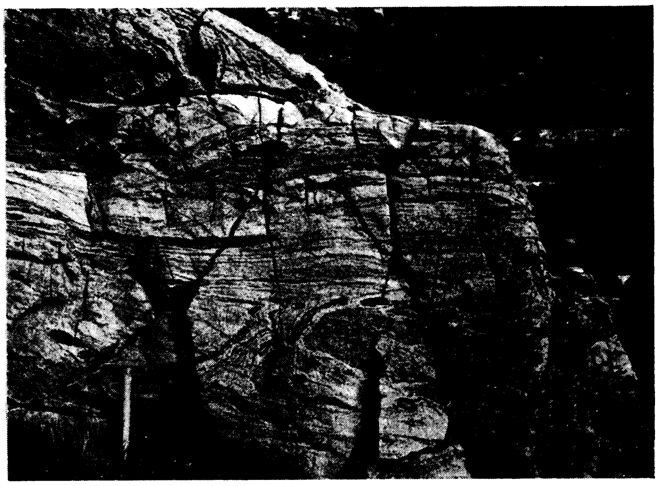

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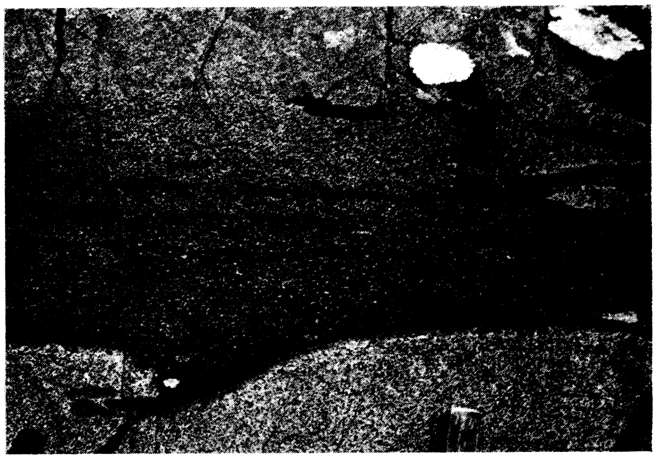

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Figure 24. Typical irregular banding in the Dornabac series. Dip section.

Figures 25 and 26. Slump structures in the Dornabac series.

Figure 27. Gravity stratification in the Dornabac series.

Figure 28. Igneous breccia, Lag Sleitir.

Figure 29. Streaky banding, due to slumping, in the lower part of the Ruinsival series. $\frac{1}{8}$ mile west of Loch Fiachanis.

FIGURE 2. Geological map of the Harris area, south-west Rhum.

FIGURE 5. Panorama of south-west Rhum, from the summit of Ruinsival.

FIGURE 6. Rhythmic layering in the normal cumulates of the Ard Mheall series. Terraces $\frac{1}{2}$ mile south-west of Ard Mheall summit.

FIGURE 7. Slight irregularities in the rhythmic layering of the normal cumulates, Ard Mheall series (strike section). Same locality as figure 6.

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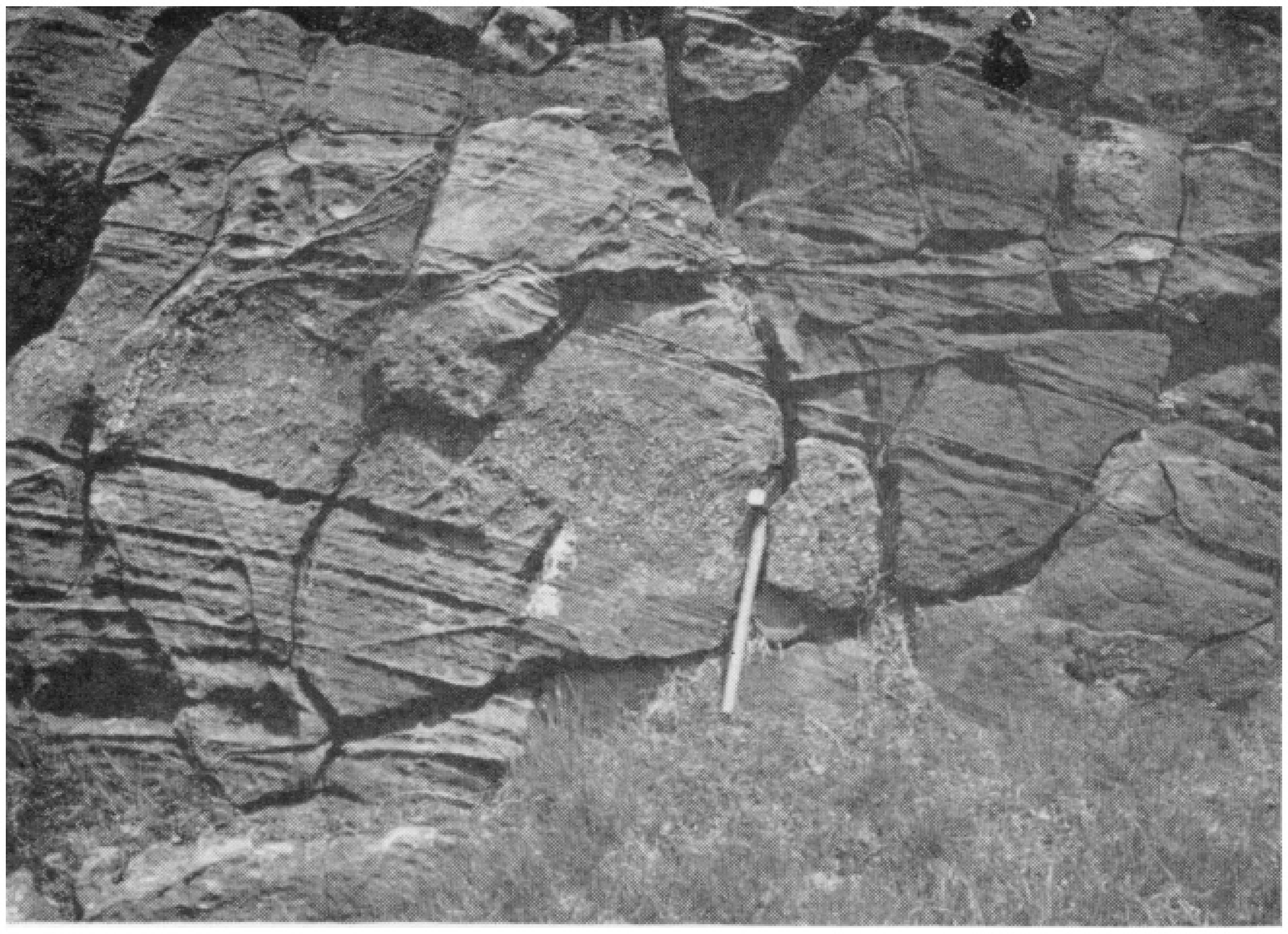

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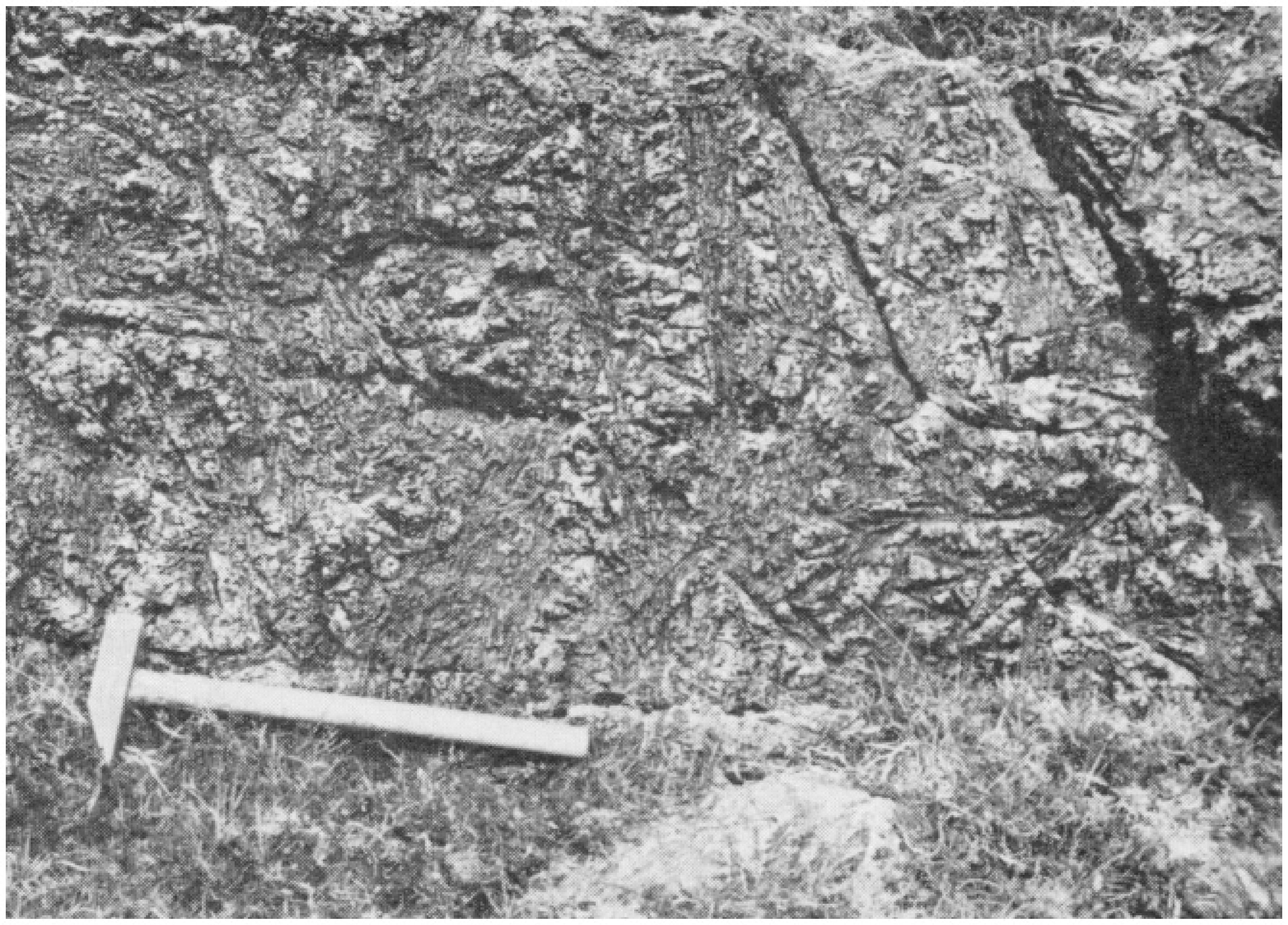

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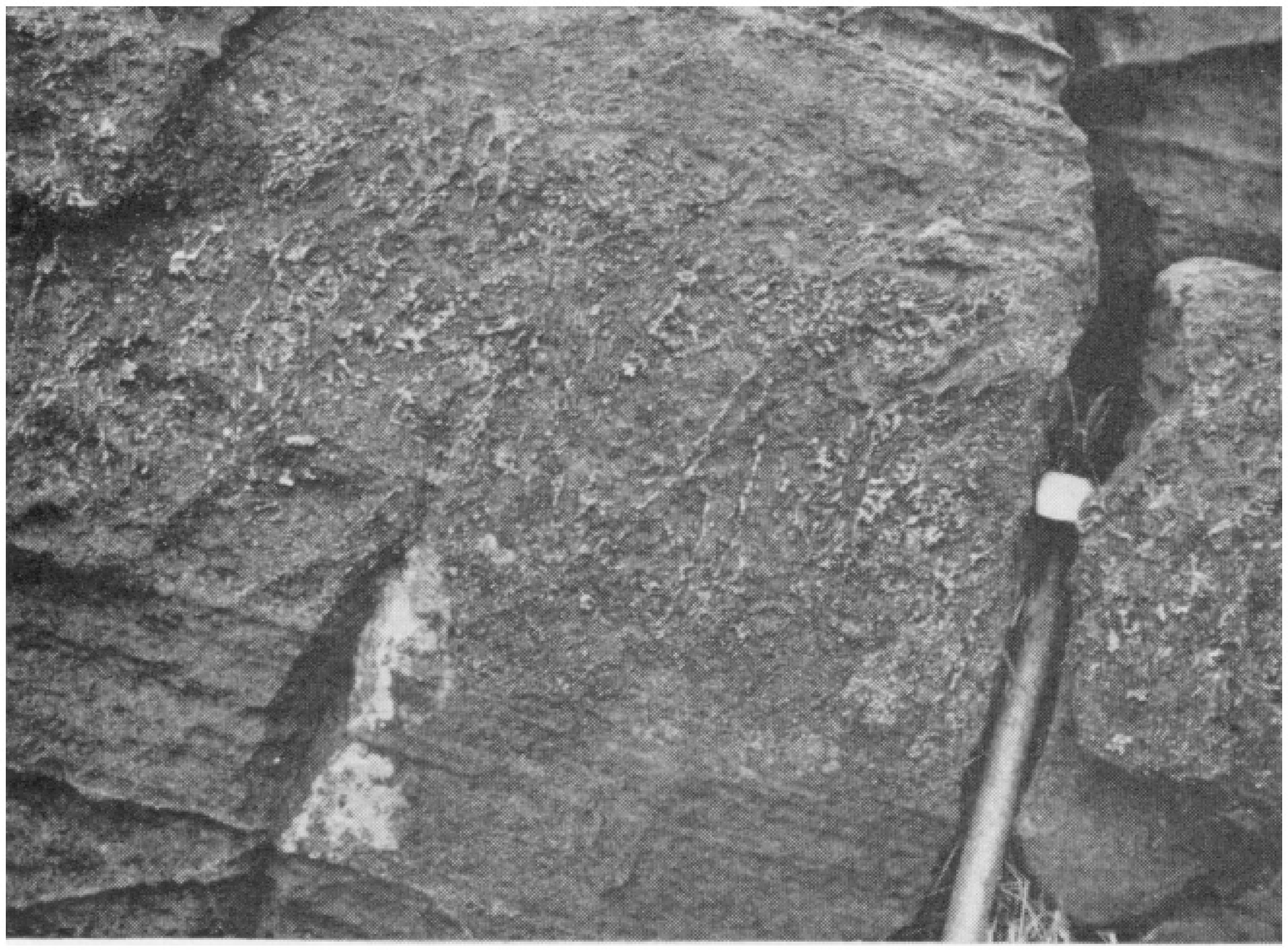

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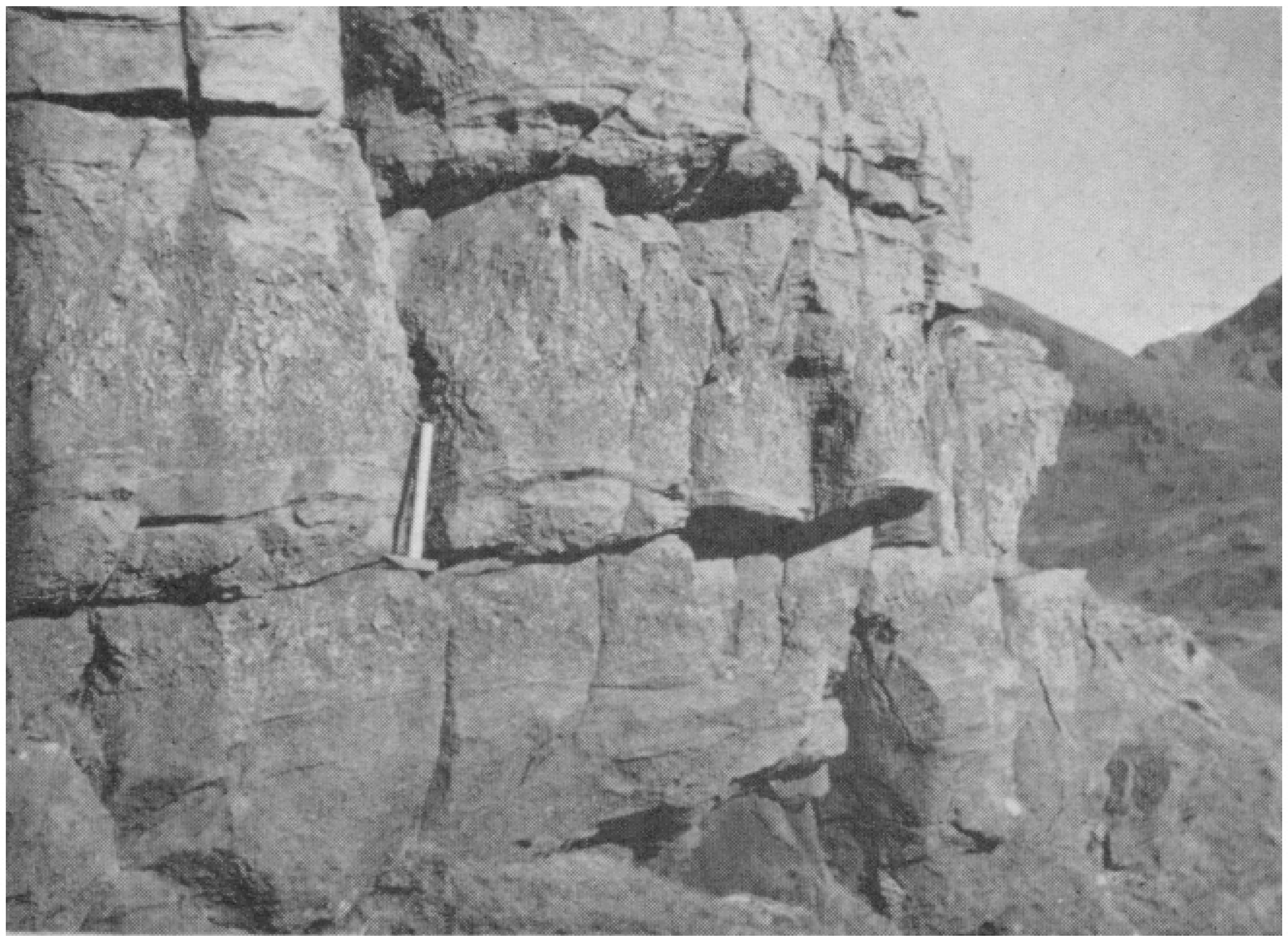

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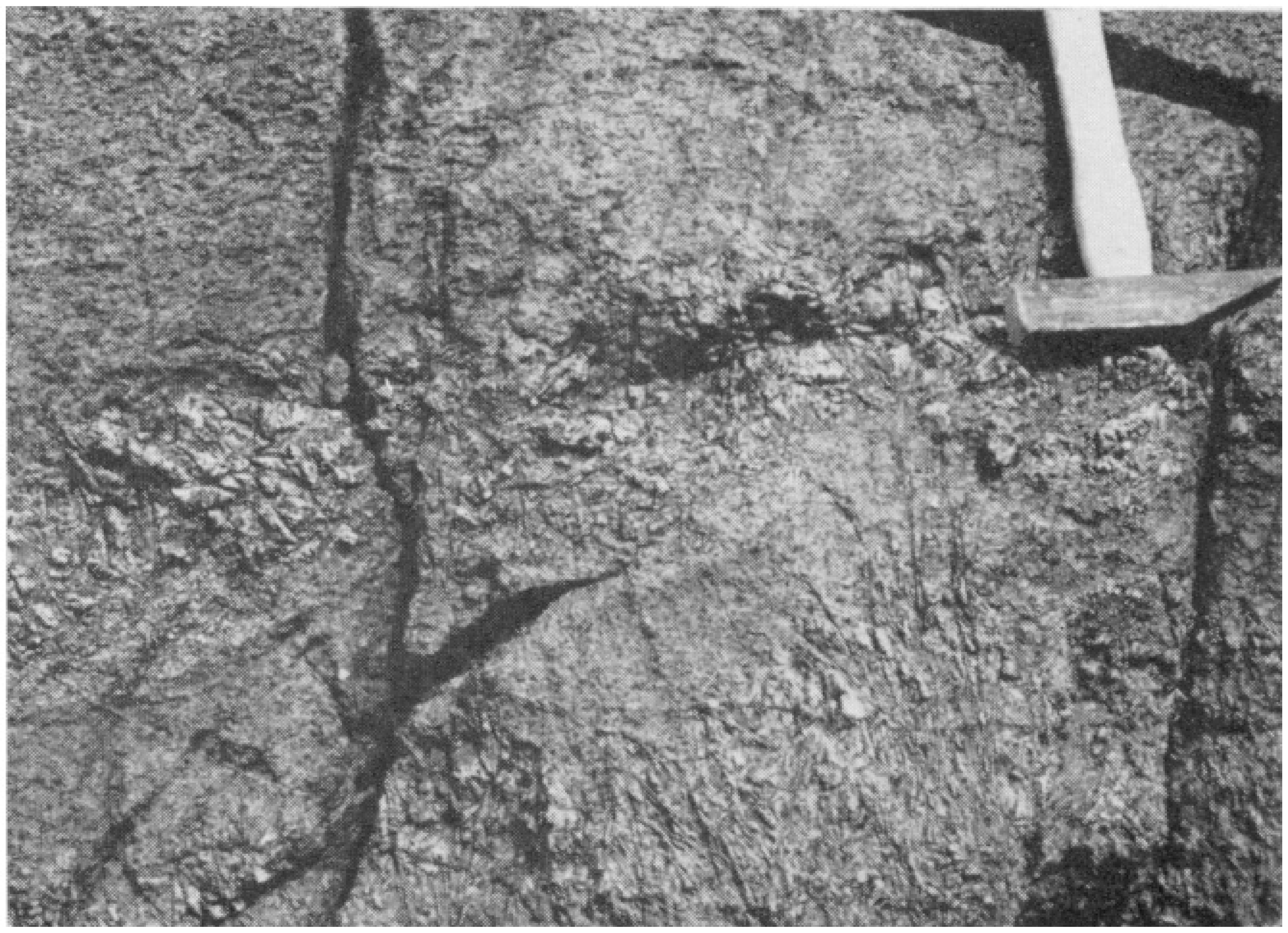

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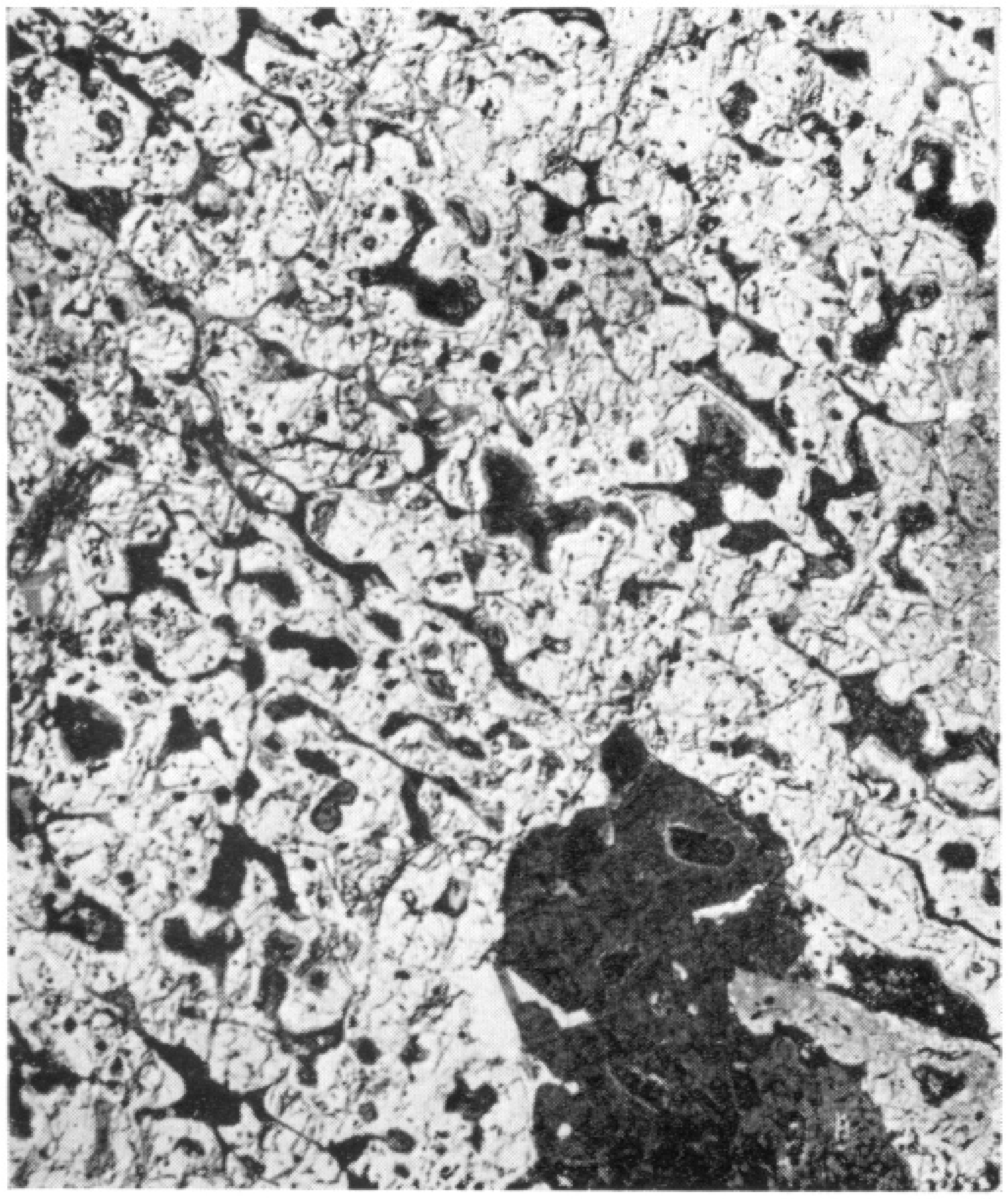

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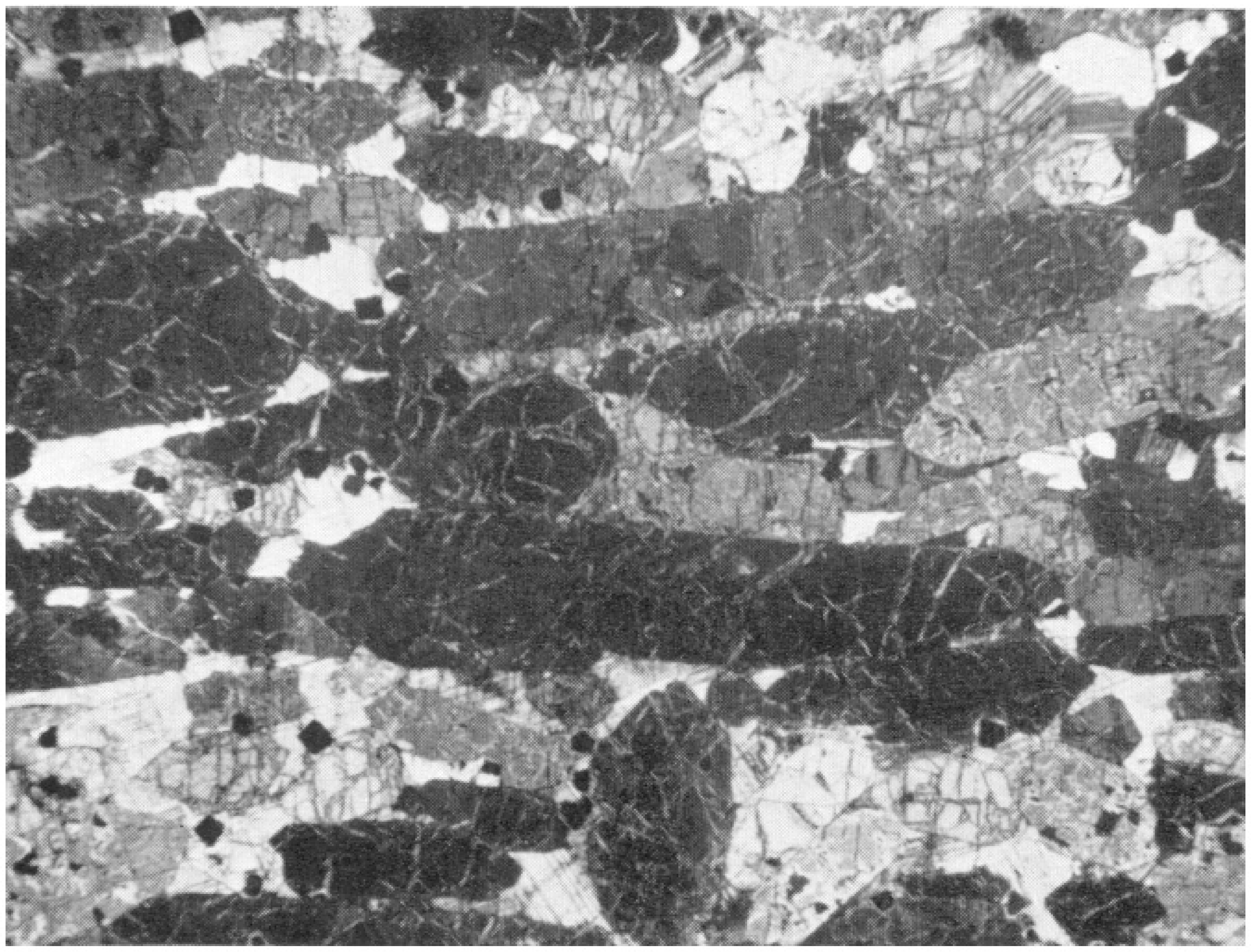

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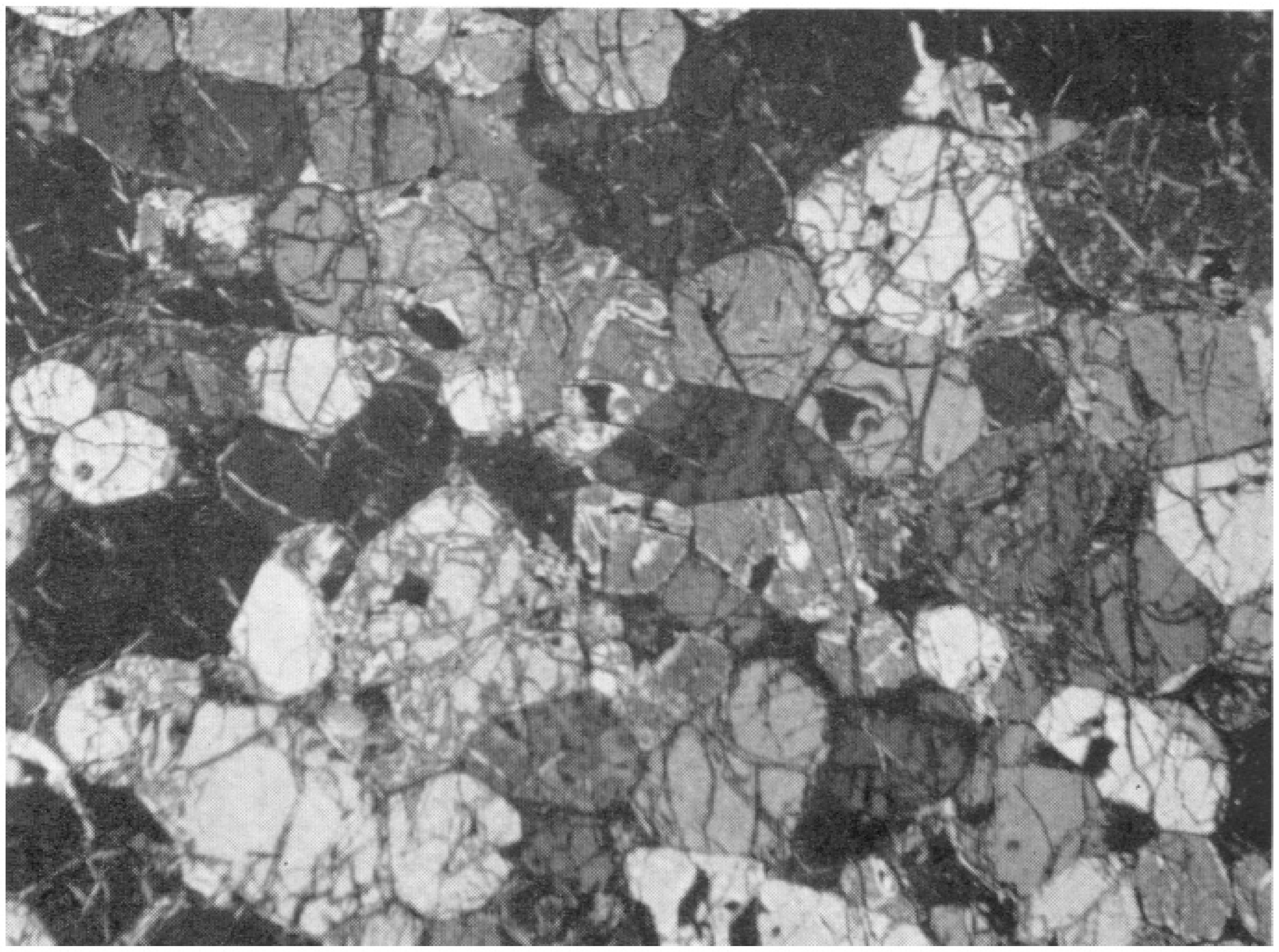

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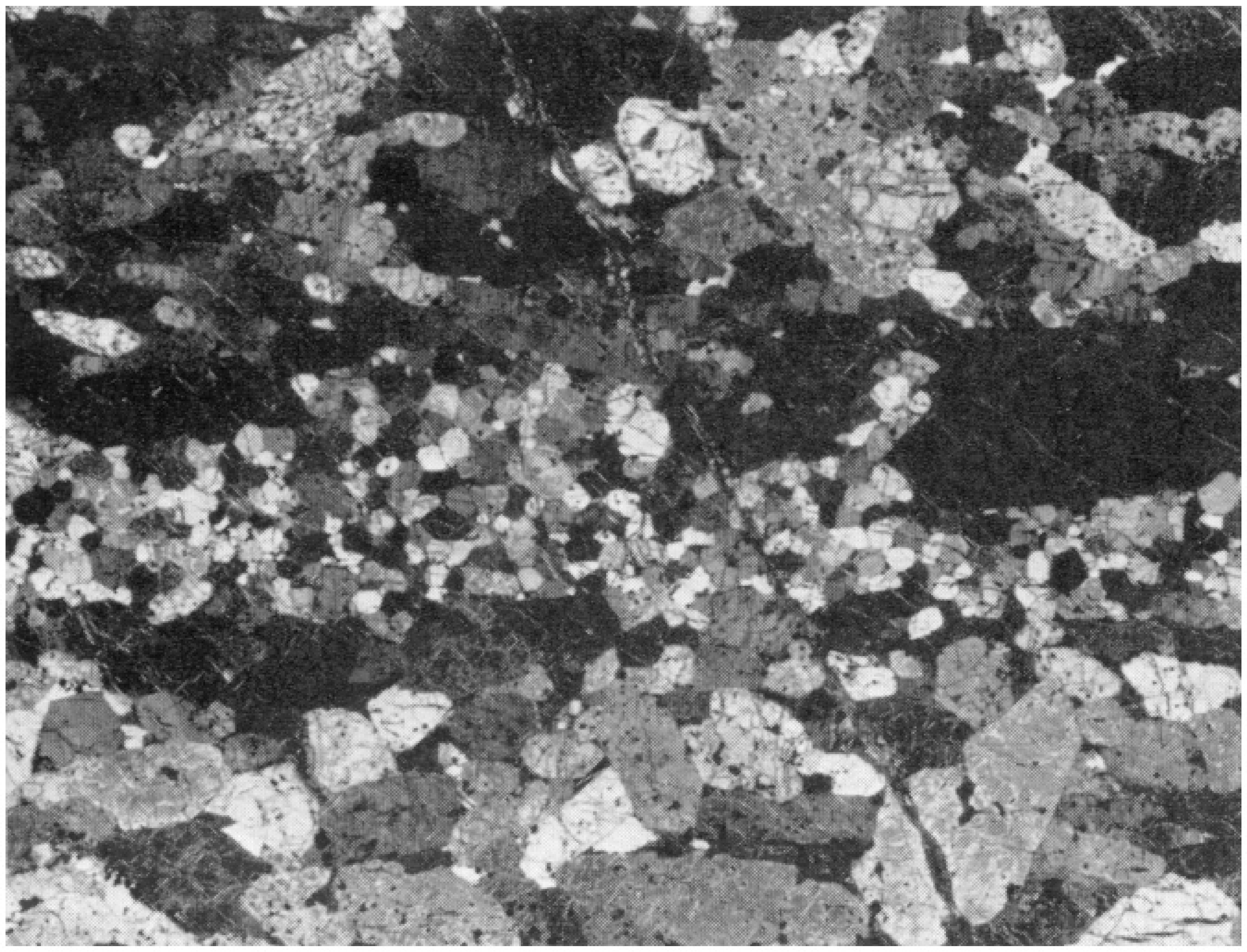

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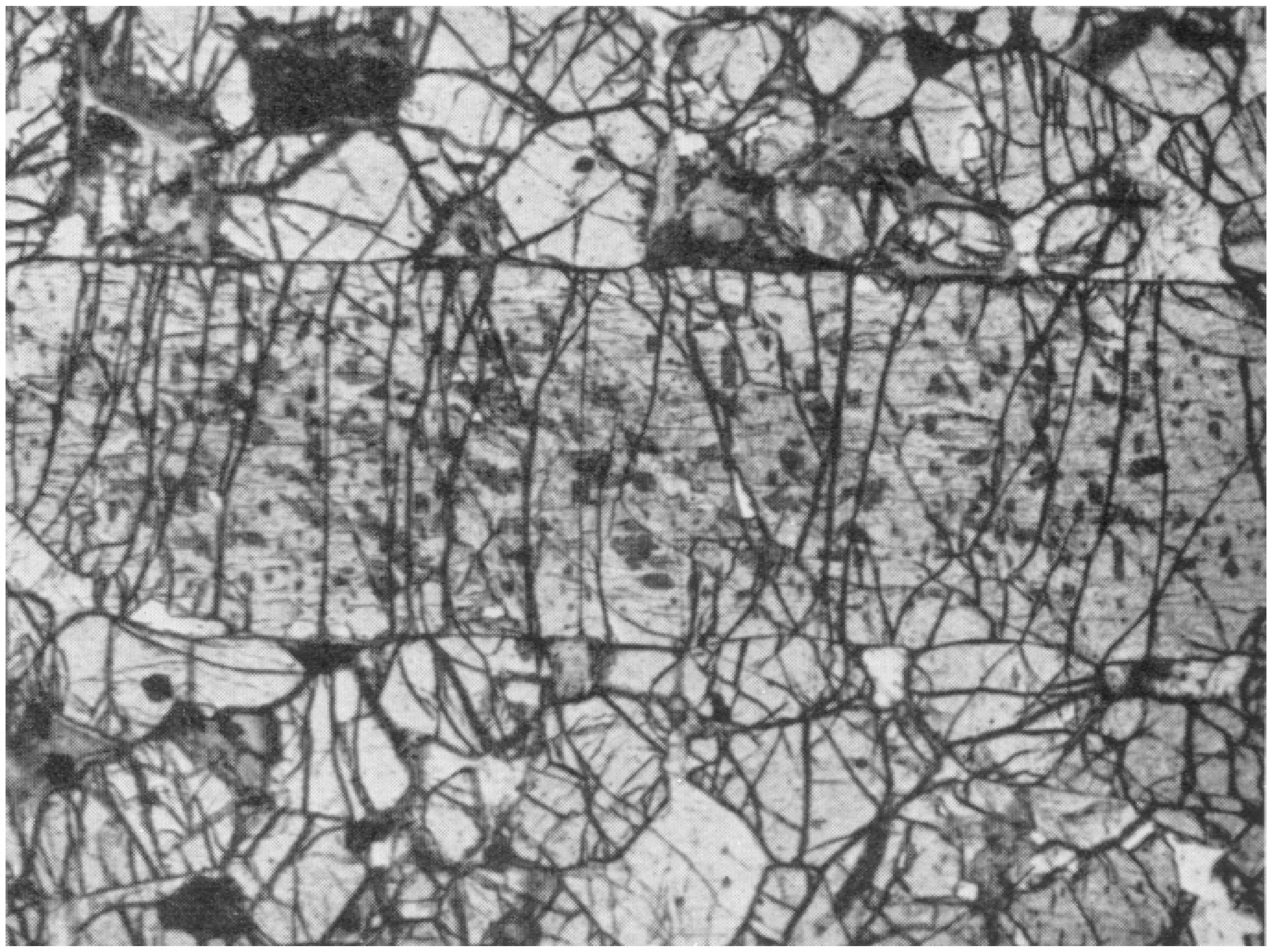

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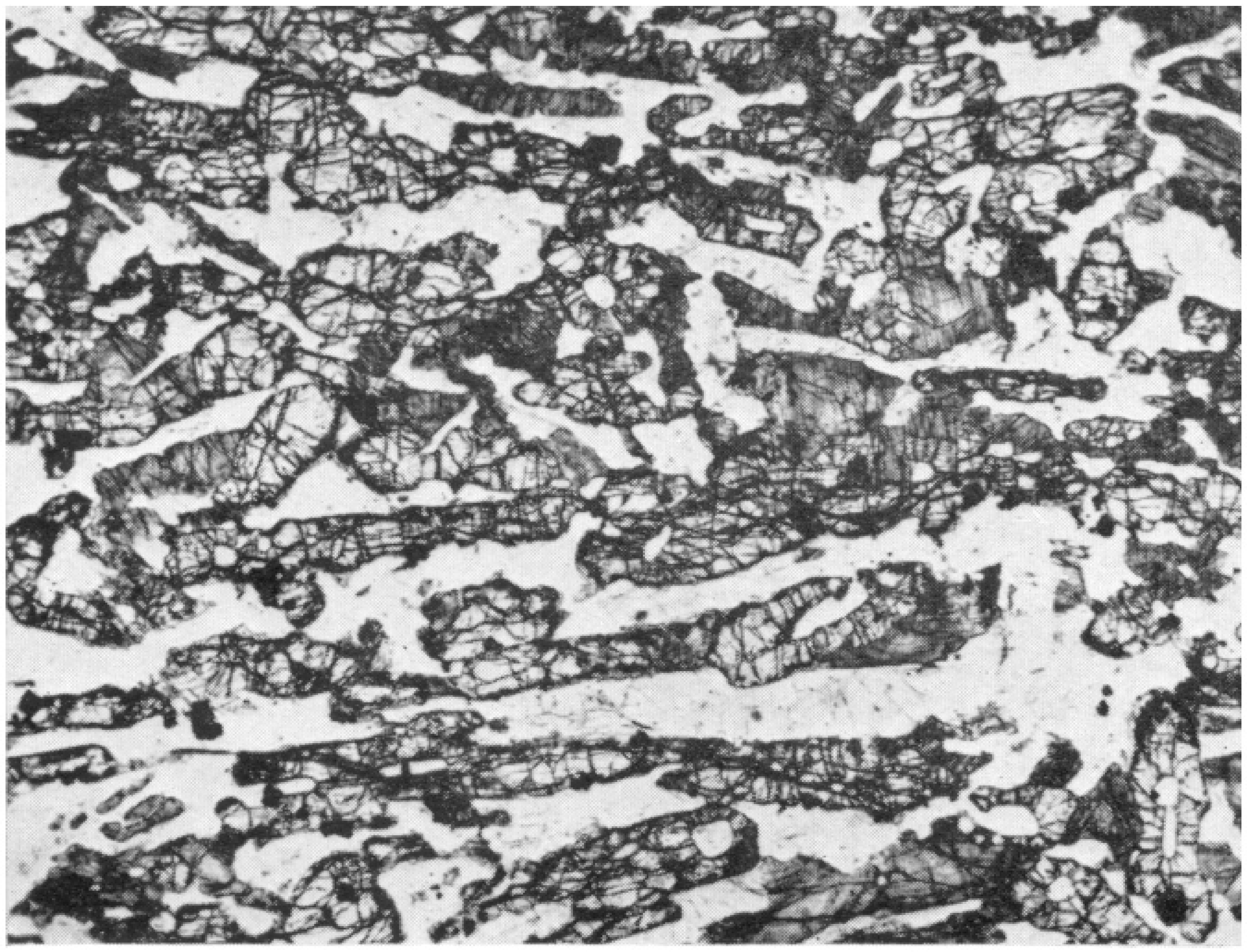

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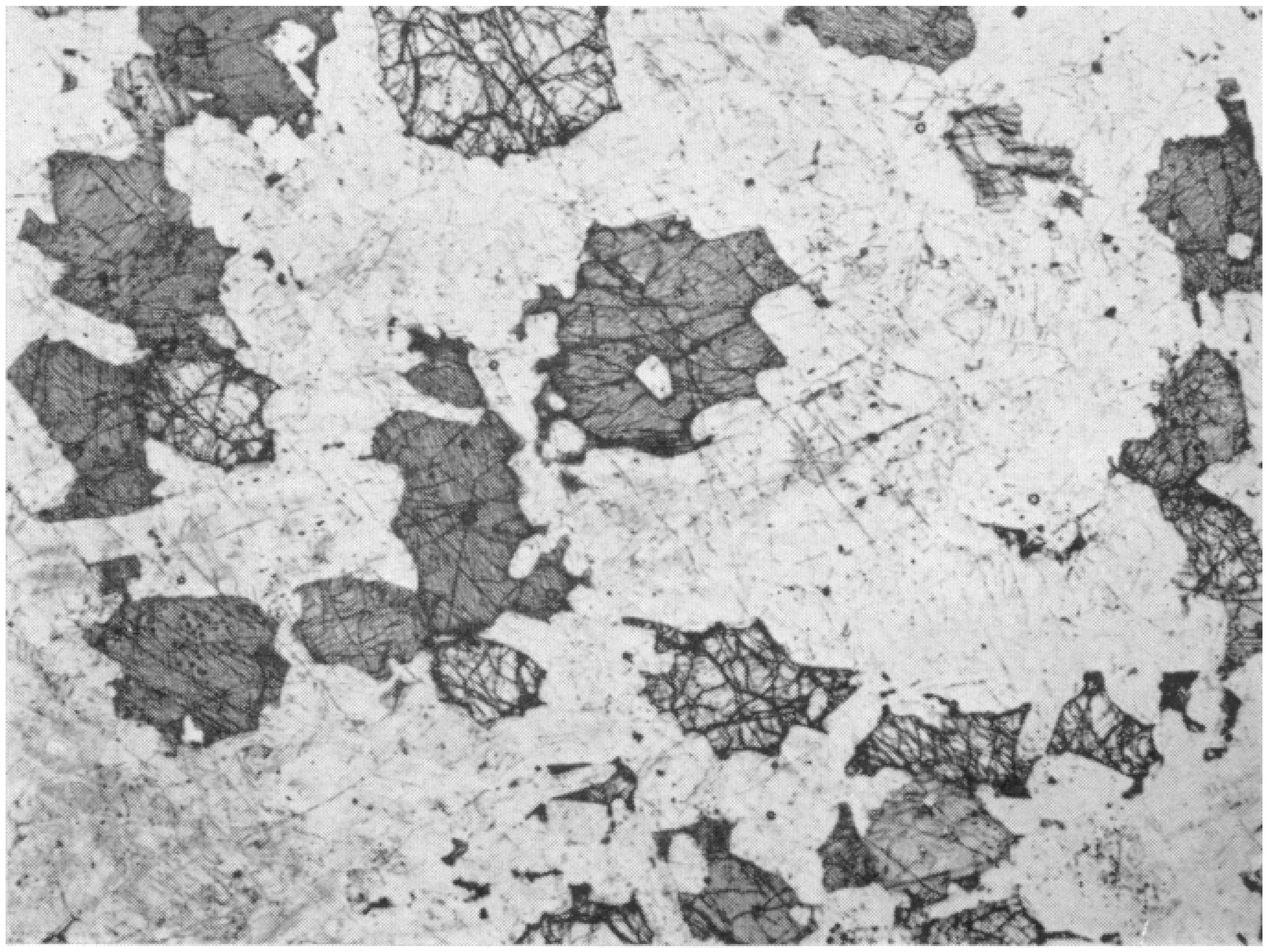

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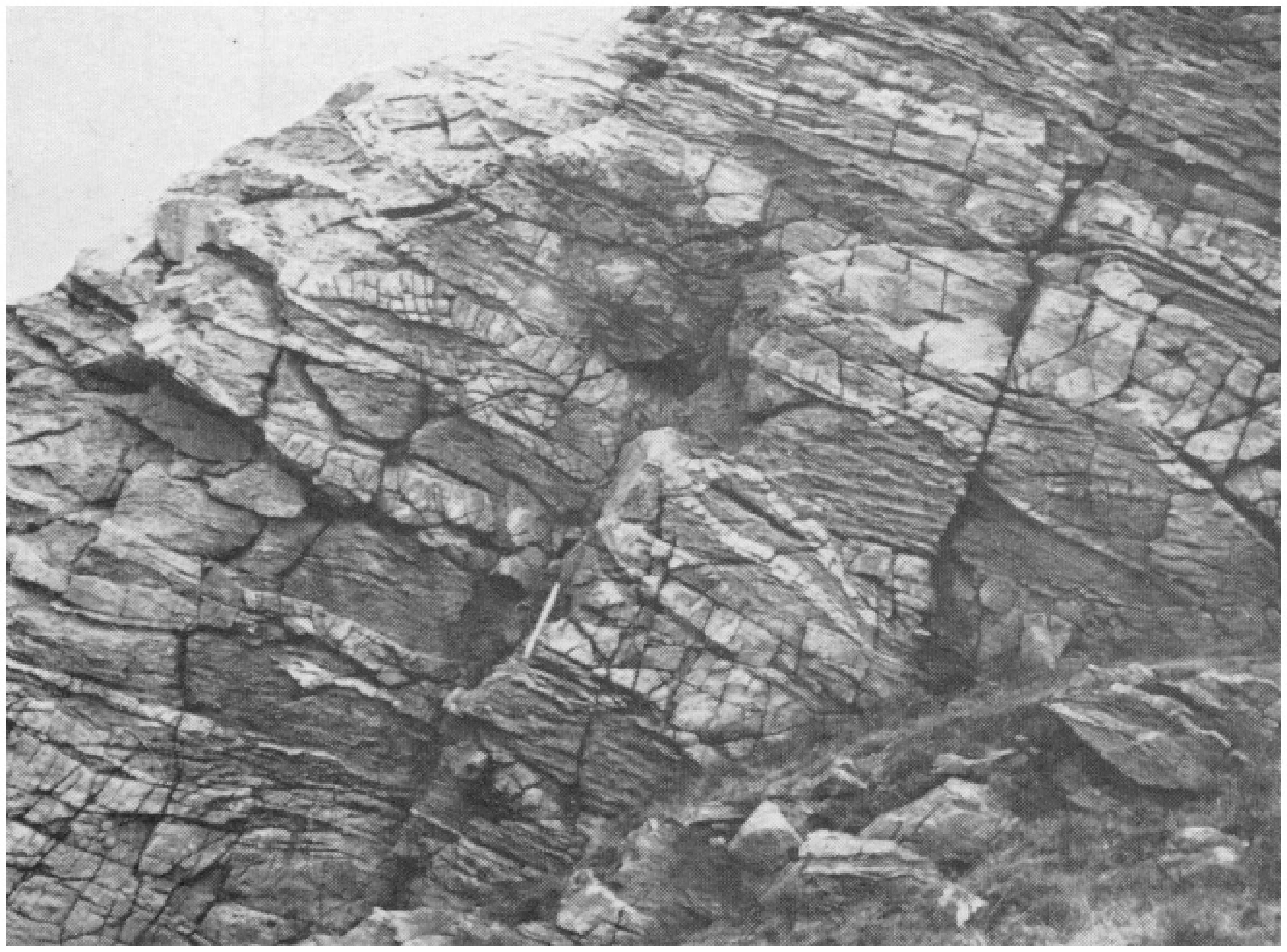

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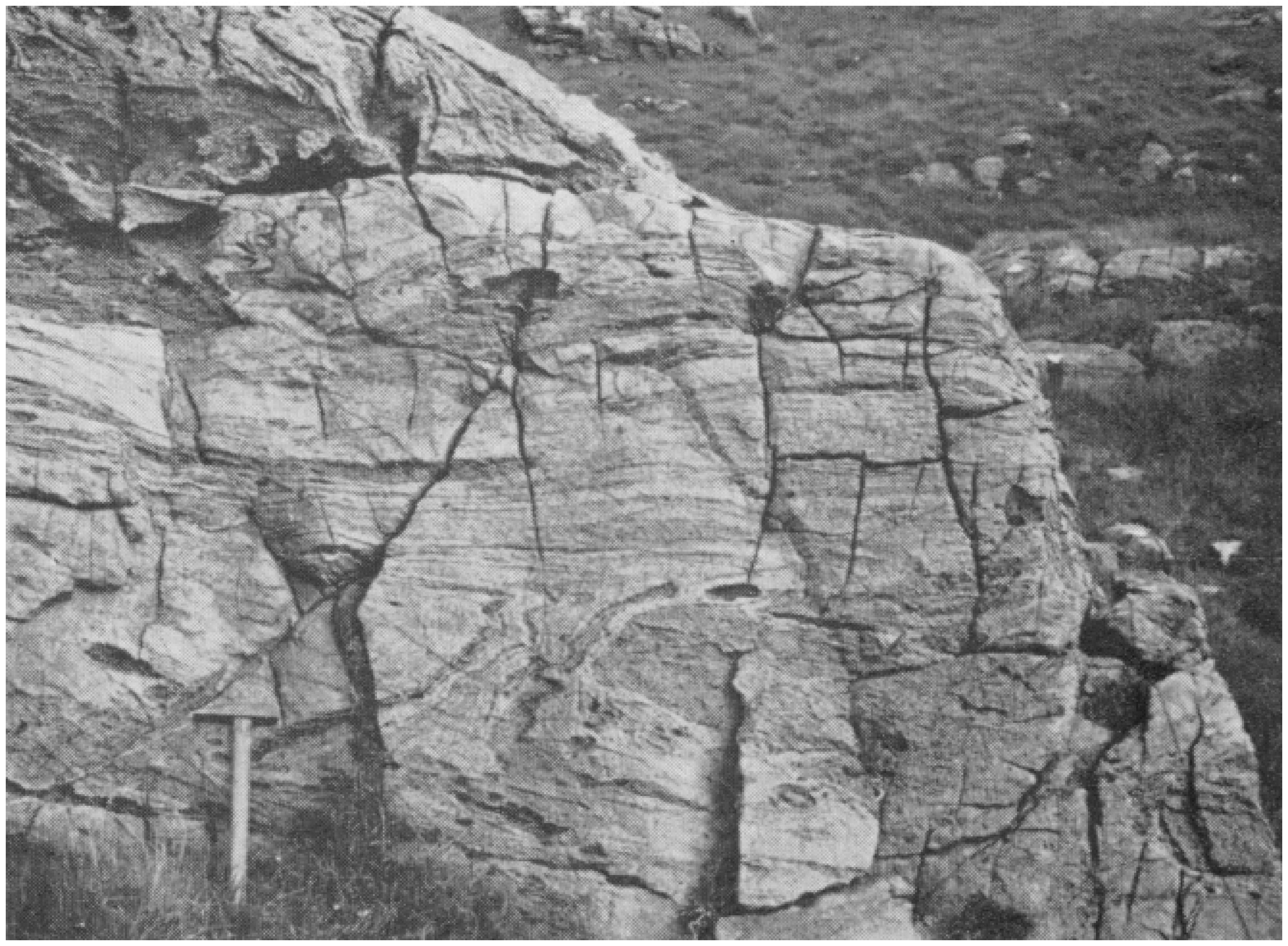

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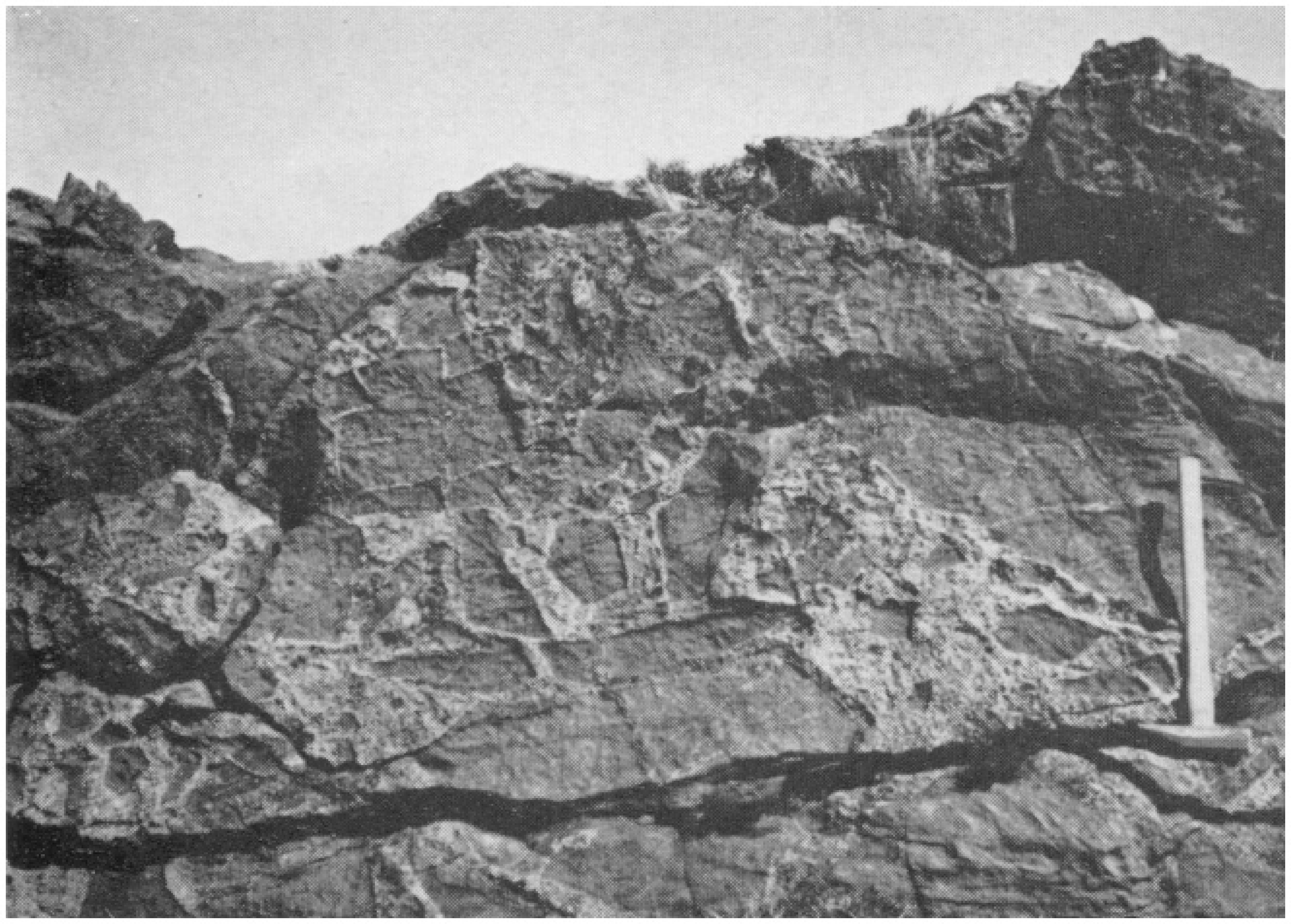

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