Types of Igneous Cumulates

by L. R. WAGER, G. M. BROWN, *and* W. J. WADSWORTH

Department of Geology and Mineralogy, Oxford, England

ABSTRACT

The term 'cumulate' is proposed as a group name for igneous rocks formed by crystal accumulation. After accumulation of the crystal precipitate, various ways of completing the crystallization process lead to differences in the rock finally produced. The various types of cumulates which have so far been distinguished are briefly described.

IN layered intrusions the lower levels contain minerals of presumed high-temperature crystallization and upwards the minerals are of progressively lower temperature type. This relationship, together with textural features, has led to the view that discrete crystals successively separated from the magma and accumulated, as a result of their greater density, at the bottom of the liquid, building up gradually to form a layered series. Crystal accumulation without remelting was advocated by Bowen for the origin of certain ultrabasic rocks (1928, p. 167), and the term 'accumulative rocks' has gradually appeared in petrological literature. Now that an origin by crystal accumulation has been widely accepted for certain eucrites, gabbros, and ferrogabbros as well as for various extreme rock types such as dunites, pyroxenites, and chromitites, it is convenient to have a single, short name for the group and we suggest the word cumulate[1] (Latin *cumulus*, a heap).

In the original description of the Skaergaard intrusion by Wager & Deer the initial accumulation of discrete crystals was called the primary precipitate and the surrounding contemporary magma, the interprecipitate liquid (1939, p. 127). The term 'primary precipitate crystal' may conveniently be replaced by the shorter term 'cumulus crystal', meaning a unit of the pile of crystals as originally precipitated from the magma before any modification by later crystallization. The liquid in the interstices of the cumulus may then be called intercumulus liquid and the crystalline material occupying this position, whether or not it has the same composition as the original liquid, may be called intercumulus material.

After the original accumulation of the crystal precipitate various ways of completing the crystallization process lead to differences in the rock finally produced. The various types of cumulates which have so far been distinguished are briefly described in this paper. The classification into types of cumulates has proved useful in describing Skaergaard, Rhum, and Bushveld rocks, and its use leads to clearer thinking about the details of the solidification processes involved.

[1] Among ourselves we had for some time used the term 'cumulite' for an accumulative rock, the ending 'ite' conforming to that of many rock names. Professor C. E. Tilley, however, suggested that 'cumulate' would be better and this we have gladly adopted since it is to be a general term for a group of rocks and is thus distinct from specific rock names which are the ones usually ending in 'ite'.

ORTHOCUMULATES

In the case of the Skaergaard complex it has been shown that the intercumulus liquid crystallized slowly, forming successive lower temperature zones round the primary precipitate (i.e. the cumulus crystals), and new mineral phases (Wager & Deer, 1939, pp. 127, 136). Crystallization of the intercumulus liquid presumably continued during a considerable fall in temperature, and by the time the bulk had crystallized, the thickness of the overlying pile of accumulated crystals must have been of the order of hundreds of feet.

This manner of crystallization of the intercumulus liquid is particularly well indicated in the bands consisting originally of only one cumulus mineral. Thus in certain felspar-rich bands having plagioclase as the only cumulus species, the intercumulus liquid crystallized to form lower temperature zones round the cumulus plagioclase, and extensive poikilitic pyroxene, olivine, and iron ore crystals enclosing many of the plagioclase crystals (Figs. 1A, 3A). It was postulated that while plagioclase material could be continuously deposited about the cumulus crystals, other minerals could only crystallize from the intercumulus liquid around relatively rare crystal nucleii which grew into large poikilitic pyroxenes, olivines, and iron ore by diffusion of the appropriate substance towards the growing crystal (Wager & Deer, 1939, Fig. 27, pp. 119–22). If this be the manner of origin of the poikilitic intercumulus crystals they should be zoned and this can sometimes be seen. Late stage minerals such as micropegmatite, representing a final residual liquid, may also be found, in rather widely separated interstitial patches. This texture is diagrammatically represented in Fig. 1A and an actual example is figured from the Skaergaard intrusion in Fig. 3A.

In the case of the Skaergaard plagioclase cumulates, the unzoned or only slightly zoned part of the plagioclase crystals is taken as the original cumulus and outside this are the impersistent zones of lower temperature plagioclase which have come from the intercumulus liquid. Despite the presumably very slow crystallization of the intercumulus liquid there was no complete making over of the first formed plagioclase crystals to compositions in equilibrium with the changing composition of the trapped magma. Had such equilibrium been fully maintained the crystals would have been homogeneous. The possibility of some making over of the plagioclase to lower temperature solid solutions cannot be excluded, but the extent of the process must have been slight. The making over of plagioclase to lower temperature solid solutions necessitates replacement of some of the Al by Si within the oxygen tetrahedra and such replacement would probably be difficult. Perhaps replacements in the pyroxenes and olivines, particularly of Fe^{2+} for Mg, take place more easily.

By taking the unzoned, well-shaped part of the plagioclase to represent the cumulus crystals, it is possible to get some idea of the proportion of cumulus crystals to intercumulus material in some of the rocks of the Skaergaard intrusion.

When the original work was done the best estimate, using this principle, seemed to be 80 per cent of cumulus material and 20 per cent of intercumulus material (Wager & Deer, 1939, p. 127). In the bands containing only one cumulus mineral species, measurement of the poikilitic crystals gives a minimum value

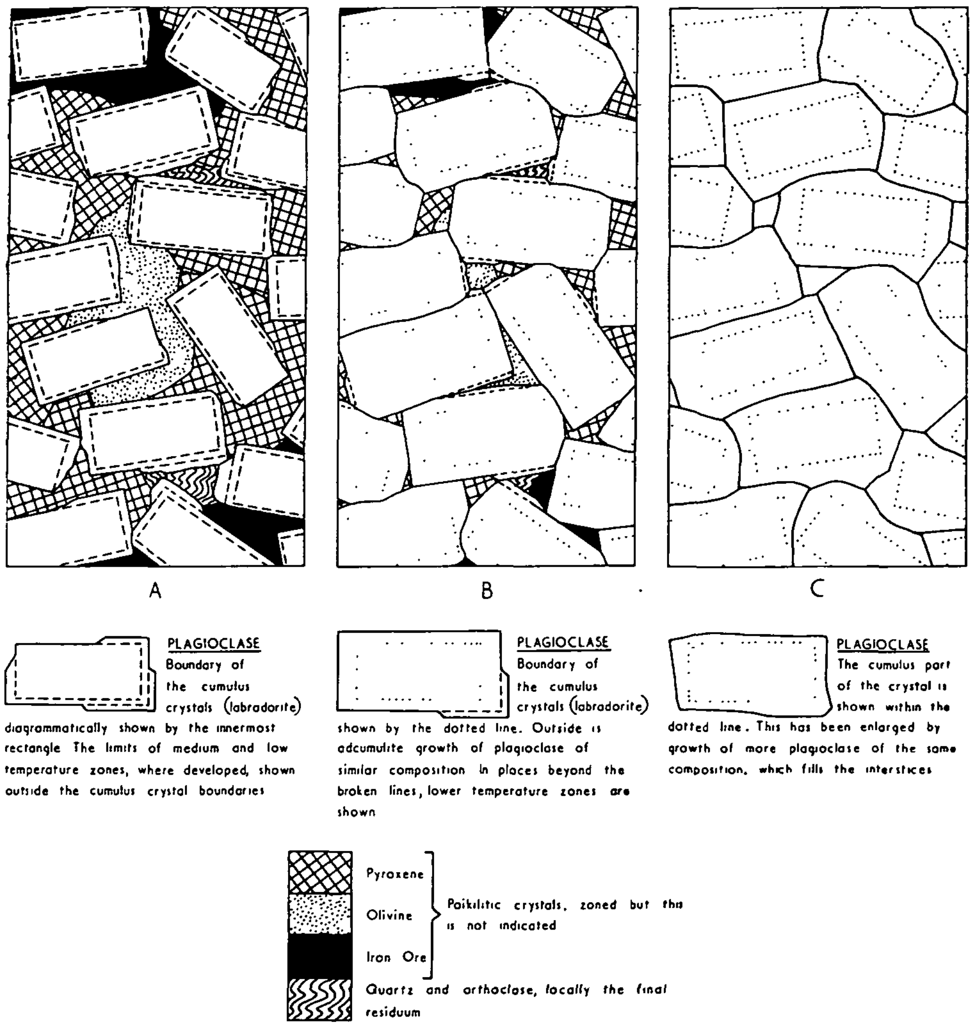

FIG. 1. Diagrammatic representation of plagioclase cumulates formed from a gabbroic magma. A, extreme plagioclase orthocumulate. B, plagioclase mesocumulate. C, extreme plagioclase adcumulate.

for the intercumulus material; to obtain a closer approach to the true value an estimate of the amount of the outer zone of the cumulus crystals, which also formed from the intercumulus liquid, would have to be included. Owing to the difficulty of deciding exactly the position of the boundaries between the unzoned and zoned parts of the crystals, there is no wholly satisfactory means of obtaining the true proportions of cumulus and intercumulus material. Simple packing experiments, in water, with aluminium tablets of a shape comparable with the cumulus felspars in the lower part of the Skaergaard intrusion have shown that, if loosely accumulated, the amount of the cumulus material is about 55 per cent and that shaking to improve the packing only increases the amount to about 65 per cent.

The name *orthocumulate* is here proposed for a cumulate consisting essentially of one or more cumulus minerals together with the products of crystallization of the intercumulus liquid, which necessarily has the composition of the contemporary magma. This is the definition of an extreme case, and is the simple concept originally used to explain the crystallization of the interprecipitate liquid in rocks of the layered series of the Skaergaard intrusion. Since that time study of other layered intrusions has shown that processes can occur which modify the over-all composition of the material crystallizing from the intercumulus liquid and we have found that some of these have operated in the case of the Skaergaard intrusion. So far as is known at present, examples of ideal orthocumulates are rare and it is suggested that the definition should be widened to include some degree of departure from the ideal (see below, p. 79).

There is the possibility in cumulates, as mentioned above, that the first formed cumulus crystals may be made over to lower temperature solid solutions by reaction with the intercumulus liquid, a process which Bowen called continuous reaction. If carried to completion such reaction would produce unzoned crystals. Thus, if a layer consisted of cumulus plagioclase with 50 per cent of the contemporary liquid, the ultimate composition of the plagioclase of the rock would be the average of the cumulus and the more acid plagioclase capable of forming from the intercumulus liquid. If, on the other hand, the cumulus at about the same horizon (i.e. with the same contemporary liquid) consisted of orthopyroxene only, the plagioclase ultimately formed in the rock would be all from the intercumulus liquid and would be more sodic than in the first case. This making-over process does not seem to have been of much importance in the small and high-level intrusions of the Skaergaard and Rhum. In some of the layered rocks of Rhum the primary precipitate crystals and the poikilitic crystals round them are unzoned but their composition is not what would be expected on the continuous reaction hypothesis and this case is considered later when the heterad type of cumulate is described.

If cumulates occur in which the cumulus crystals were made over by continuous reaction to homogeneous, lower temperature solid solution, then these would form a distinct type. The making-over process is one which would be greatly favoured by shearing stress acting on the crystal mush, a possibility alluded to in a recent address (Wager, 1958, pp. 10–11). It is there suggested that an effect of this sort, really a form of metamorphism, might well occur in very thick piles of rapidly accumulated primary precipitate as there would be an excess weight in the column of crystals over that in the column of liquid, giving a tendency for the crushing down of the lower part of the crystal column.

ADCUMULUS GROWTH

Studies of the Stillwater layered intrusion by Hess (1939, and a paper in the press) and of the Rhum layered intrusion by Brown (1956) have shown that the simple conception of an intercumulus liquid crystallizing round the cumulus crystals does not satisfactorily account for certain of the rocks in these intrusions. In explaining some of the Stillwater rocks Hess (1939, p. 431) indicated in a preliminary way the need to postulate some degree of enlargement of the original cumulus crystals, at the same temperature as their original formation. It was suggested that this was effected by diffusion of substances from the overlying reservoir of magma through the intercumulus liquid to the growing crystals in the top layers of the precipitate, with a simultaneous diffusion of the unwanted material in the other direction. Hess considered certain changes in composition could be 'correlated with the rate of accumulation of crystals. Where accumulation is slow, diffusion of material from the magma above, into and out of the interstitial liquid in the crystal mush on the floor, will tend to allow crystallization in it of minerals having almost exactly the same composition as the settled crystals' (Hess, 1939, p. 431). This diffusion mechanism was used by Brown (1956, pp. 14, 49) to explain various features of the layered series of Rhum, especially certain thin bands consisting of 99 per cent plagioclase, all essentially unzoned, which occur at or near the top of some of the rhythmic units.

The exact way in which the cumulus crystals became enlarged by material of similar composition is still not certain, but it must have taken place at the same temperature as the formation of the cumulus crystals because of the similarity in the solid solution composition. By such growth the intercumulus liquid would gradually be pushed out. It would be expected that the enlargement of the top crystals of the pile would take place before those below and that such growth would eliminate the intercumulus liquid in the top layer and so prevent diffusion of material to lower levels. It seems probable that extension of the cumulus crystals at constant composition can only have taken place while they formed the uppermost layer of the pile; thus thick layers of such rocks must have formed very slowly. The term 'adcumulus' growth is proposed for the extension of the original cumulus crystals by material of the same composition, to give unzoned crystals. The adcumulus process, which gradually reduces the intercumulus liquid by mechanically pushing it out, may sometimes reduce the amount to vanishing point. Any part of the intercumulus liquid which is eventually trapped by further accumulation of crystals is here distinguished as the *trapped liquid.* When this has crystallized it will be described as the *pore material.* The trapped liquid will necessarily have had the over-all composition of the contemporary magma and thus the composition of the pore material must also be that of the contemporary magma.

ADCUMULATES AND MESOCUMULATES

If adcumulus growth largely or completely eliminates the intercumulus liquid there will be little or no pore material, and it is suggested that the rock produced in this way with, say, less than 5 per cent. of pore material, be called an *adcumulate*. Some of the rocks in the layered series in Rhum, e.g. the analysed allivalite

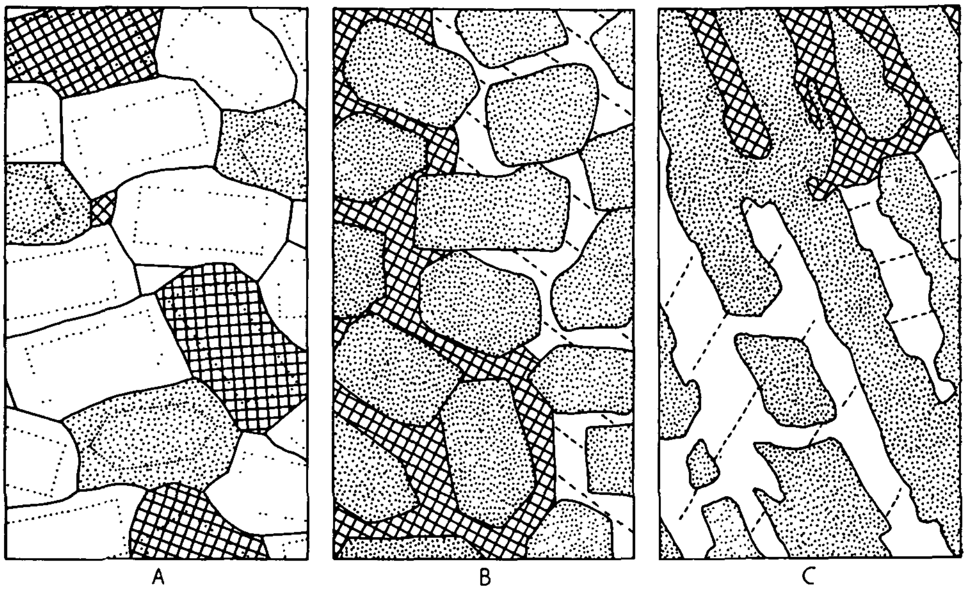

FIG. 2. Diagrammatic representation of an adcumulate, heteradcumulate, and harrisitic cumulate formed from gabbroic magma. Plagioclase, white; olivine, stippled; pyroxene, cross-hatched. A, plagioclase–olivine–augite adcumulate in which the three types of cumulus crystals are considered to have been enlarged by the adcumulus process until all the intercumulus liquid has been eliminated (cf. Fig. 1C). The boundaries of the cumulus crystals of plagioclase, olivine, and pyroxene are indicated diagrammatically by dotted lines. The material inside and outside the dotted lines has the same composition. B, olivine heteradcumulate. Large poikilitic augite and plagioclase crystals, essentially unzoned, are shown surrounding cumulus olivines. Adcumulus growth of the olivines is not indicated on the diagram. In this diagram it is assumed that there was no trapped liquid. C, olivine harrisitic cumulate. All olivine shown has the same orientation and is essentially unzoned. The surrounding plagioclase and pyroxene are also essentially unzoned and are considered to have been formed as in the heteradcumulates.

and the felspar rock (Brown, 1956, p. 47 and Fig. 37; p. 37 and Fig. 38) and probably many of the rocks of the Bushveld complex, are adcumulates. As it will often be difficult to decide with any precision on the amount of the trapped liquid which eventually crystallized round the adcumulus crystals, it is suggested that the term 'orthocumulate' be used for those rocks in which adcumulus growth is not conspicuous and that the term 'mesocumulate' be used for rocks showing small amounts of pore material, while the term 'adcumulate' be used for those in which the pore material is inconspicuous or absent. A plagioclase mesocumulate formed from a gabbro magma is diagrammatically shown in

Fig. 1B and may be compared with the extreme orthocumulate of Fig. 1A; both are shown as having the same amount of cumulus plagioclase. An extreme plagioclase adcumulate formed from gabbro magma, in which there has been complete elimination of intercumulus liquid, is shown diagrammatically in Fig. 1C. In this case there is no zoning of the plagioclase, and augite, olivine, iron ore, &c., are absent because of the complete pushing out of the intercumulus liquid. Another case (Fig. 2A) which could well be a band adjacent to the previous example, is equally an extreme adcumulate, but the cumulus crystals were of three different kinds—plagioclase, olivine, and pyroxene. Again there is no zoning of the cumulus minerals, nor is there any iron ore or micropegmatite from any trapped liquid because, again, the intercumulus liquid is assumed to have been completely eliminated by the adcumulus growth. A photomicrograph of an actual example of this type of adcumulate, having three different cumulus phases, is shown in Fig. 4A.

It has proved useful to have a name for the extreme type of cumulate such as orthocumulate or adcumulate. Rocks may then be described as approaching a pure orthocumulate or pure adcumulate in character. It is likely, however, that the pure types will be rare. There is some indirect evidence, for instance, that the lower layered rocks of the Skaergaard (Figs. 3 A, B) are not pure orthocumulates but have some adcumulus growth and certainly many of the Skaergaard upper layered rocks are mesocumulates, showing considerable reduction in the amount of pore material, although this was not realized in the original description. The formation of orthocumulates will be favoured by fast bottom accumulation of crystals. Adcumulus growth, on the other hand, must be favoured by relatively slow accumulation of the bottom precipitate, allowing time for enlargement of the crystals as they formed the top layer of the crystal pile.

HARRISITIC CUMULATES AND HETERADCUMULATES

In the layered series of Rhum certain olivine-rich rocks have been interpreted as the result of upward growth of cumulus crystals of olivine as they lay at the bottom of the magma, forming the temporary floor (Wager & Brown, 1951; Brown, 1956, p. 10; Wadsworth, thesis, 1958). These rocks, described as having a harrisitic structure, consist of upstanding elongated olivines often exhibiting parallel growth and with scarcely zoned plagioclase and augite crystals in poikilitic patches between them (Brown, 1956, Fig. 42 and diagrammatically shown here in Fig. 2C). Upward growth of cumulus crystals has been detected at one or two horizons in the Bushveld, and a rather similar structure, the so-called perpendicular felspar rock, occurs in the Border Group of the Skaergaard intrusion (Wager & Deer, 1939, pp. 144–50) and in certain gabbros of Kungnat described by Upton (thesis, 1958). Enlargement of cumulus crystals but without the development of upward growth occurs in all adcumulates, and thus there is a close genetic connexion between the latter and the harrisitic cumulates.

Some of the higher olivine cumulates on Askival and Hallival in Rhum

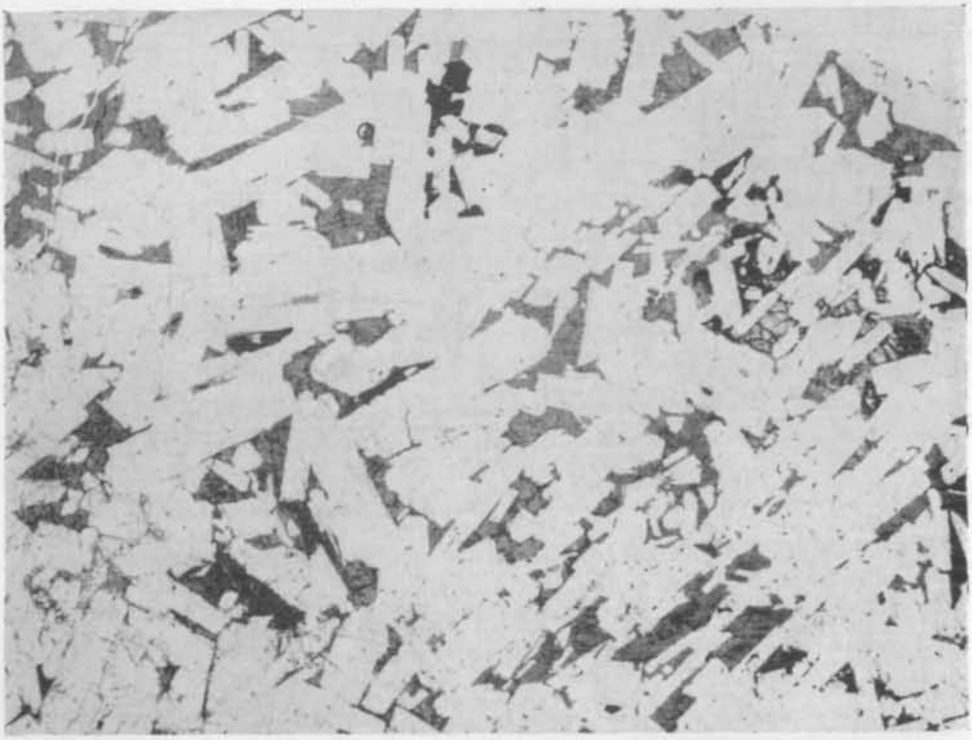

FIG. 3A. Plagioclase orthocumulate, lower layered series, Skaergaard intrusion. Intercumulus minerals include olivine, pyroxene, and iron ore. The cumulus plagioclase has been extended by lower temperature zones, only apparent in cross-polarized light. Magnification ×7.

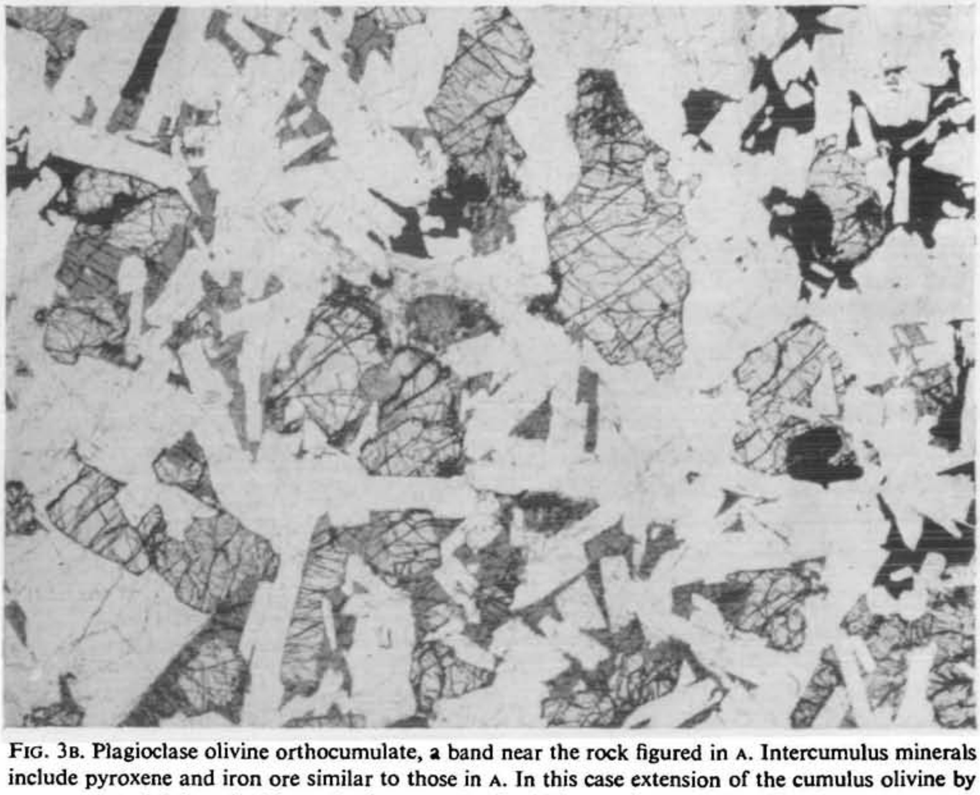

FIG. 3B. Plagioclase olivine orthocumulate, a band near the rock figured in A. Intercumulus minerals include pyroxene and iron ore similar to those in A. In this case extension of the cumulus olivine by material deposited from the intercumulus liquid is conspicuous. Magnification ×7.

consist of olivine grains surrounded in one place by poikilitic plagioclase and in another, only a centimetre away, by poikilitic augite (Brown, pp. 36–37). The poikilitic plagioclase and augite crystals, 2 or 3 cm across and alternating throughout the rock, clearly formed between the olivine grains; one or two thousand olivines may be enclosed in a single poikilitic crystal. The case is diagrammatically shown in Fig. 2B and an actual example in Figs. 5A, B. It is found that the poikilitic plagioclase and augite crystals are virtually unzoned and that their composition is essentially the same as that of the plagioclase and augite occurring as cumulus crystals in the layers just above or below. If the poikilitic plagioclase of this rock had resulted from the crystallization of trapped liquid as in orthocumulates or mesocumulates, it would have been more zoned and, on average, considerably richer in soda. If, on the other hand, the original cumulus olivine had been extended by the adcumulus process, then a pure olivine rock would have been formed, which seems to be the origin of the dunites of the Isle of Skye. Some new mechanism, therefore, has operated in the formation of the poikilitic crystals and we suggest that they have grown between the cumulus crystals, while they were at or near the top of the pile, as a result of diffusion of material to relatively rare crystal nuclei developed in the intercumulus liquid. The material for the growth of the poikilitic crystals must have come from the main bulk of the magma and not from trapped liquid as the crystals are unzoned and of the composition of the cumulus crystals in adjacent layers. Since plagioclase and pyroxene crystals do not occur as part of the cumulus, which is here only olivine, the material required for the growth of the poikilitic crystals could diffuse for a few centimetres without any tendency to be precipitated on crystals on the way. This case, therefore, differs from that of the adcumulates where enlargement of the cumulus crystals is regarded as having taken place while they actually formed the top surface of the pile. The diffusion mechanism suggested here results in the continued growth of both cumulus and poikilitic crystals at constant temperature until little or no pore liquid remains. The term 'heteradcumulate', implying a complex form of adcumulus process, is proposed for this type of cumulate formation and the material formed by this process will be described as heterad material. A heteradcumulate may have the same composition as an adcumulate with the appropriate variety of cumulus crystal phases, and thus a name linking this cumulate type to the adcumulates is appropriate. In the case figured (Fig. 2B) the composition of the final rock and, indeed, the texture, would have been much the same if among the cumulus olivine there had been evenly scattered a few cumulus plagioclase and pyroxene crystals about which adcumulus growth took place. One of the reasons for not accepting this as the origin of the Rhum examples is the textural one that there is a regularity about the centres of growth of the poikilitic heterad material which would be unlikely if the centres were discrete crystals laid down among the abundant cumulus olivines.

The example from Rhum chosen to illustrate the conception of a heterad-

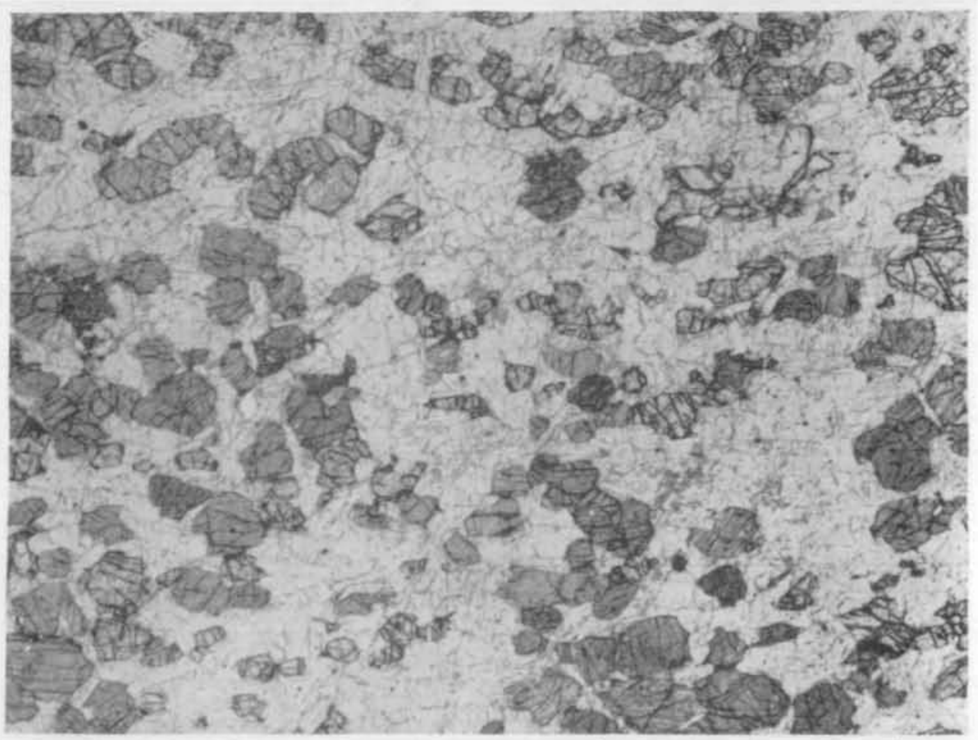

FIG. 4A. Plagioclase olivine augite adcumulate from unit 10 of the ultrabasic layered series of Rhum. In contrast to the orthocumulates A and B, intercumulus iron ore is absent. The cumulus plagioclase (as also the olivine and augite) has been extended by adcumulus growth and in cross-polarized light no zoning can be detected. Magnification ×12.

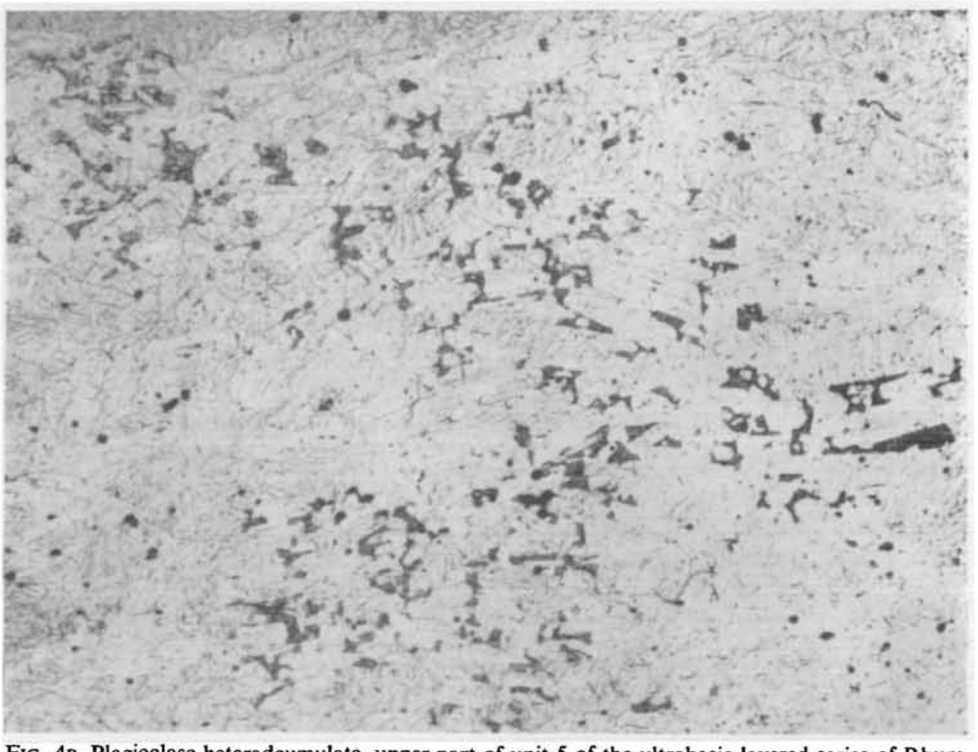

FIG. 4B. Plagioclase heteradcumulate, upper part of unit 5 of the ultrabasic layered series of Rhum. In contrast to A there is no poikilitic augite or iron ore present, but only poikilitic olivine of heterad character and composition close to, or the same as, that of cumulus olivine in layers immediately above and below. The plagioclase is unzoned and in places in the same slide forms a plagioclase adcumulate like that illustrated in Fig. 1C. Magnification ×12.

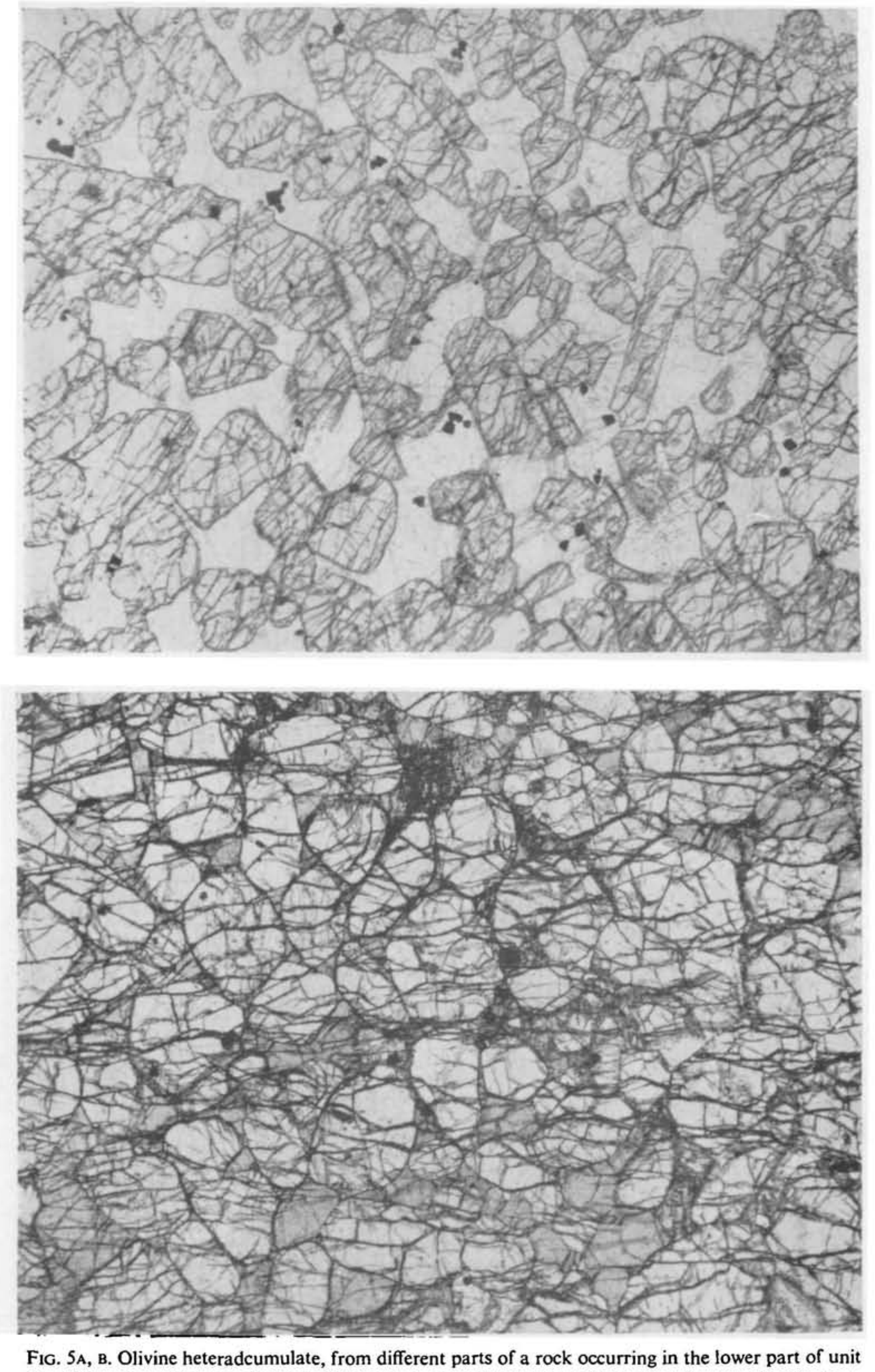

FIG. 5A, B. Olivine heteradcumulate, from different parts of a rock occurring in the lower part of unit 12, of the ultrabasic layered series of Rhum, an example corresponding to the diagram Fig. 2B. In A, the cumulus olivine is surrounded by plagioclase which is almost unzoned and from optical determination has essentially the same composition as cumulus plagioclase of nearby layers. In B, which is from another part of the same thin section, the cumulus, olivine is surrounded by pyroxene. Magnification ×14.

cumulate is a common type in which the cumulus phase is olivine. In nearby rocks, however, the cumulates consist of plagioclase and rare chromite while olivine has developed as the heterad material (Fig. 4B). In the lower part of the Bushveld complex plagioclase heteradcumulates are present with ortho- and clinopyroxenes as the poikilitic crystals.

In the harrisitic cumulates of Rhum the material between the elongated crystals consists in some cases of unzoned high-temperature crystals of plagioclase and augite and is thus essentially heterad in character.

A variant in the crystallization of the heterad material has been noted at two or three levels in Rhum. In an olivine cumulate layer with poikilitic plagioclase and pyroxene, upward tapering crystals of poikilitic augite are found (Brown, 1956, p. 33, and Figs. 20, 21). These provide visual evidence of the heterad upward growth postulated above.

If we are right in our explanation of the heteradcumulates it is clear that, in the case considered, the olivine, plagioclase, and augite are all in equilibrium with the liquid. This is at variance with the previous suggestion by one of us (Brown, 1956, pp. 42–48) that a cumulus consisting only of olivine had formed because at this stage the temperature for the formation of plagioclase and pyroxene had not been reached. It seems likely that cumulus olivines without plagioclase and augite, were precipitated because of the easier nucleation of olivine (cf. Wager, 1959). Although in the main body of the liquid plagioclase and augite were not forming, the phases nevertheless developed in the intercumulus liquid, and some supplementary hypothesis to account for their nucleation is required. It may be that nucleation occurred in the confined space of the intercumulus liquid because considerable supersaturation of plagioclase and pyroxene resulted from the further growth of the cumulus olivine. Whether this be the explanation or not, once centres of heterad crystallization were established, growth continued by diffusion of the appropriate substances from the main body of magma to the site of crystallization.

THE APPARENTLY ORDINARY TEXTURES OF SOME CUMULATES

The fewer the number of different cumulus minerals in a rock, the greater the likelihood that its texture will reflect its origin: several of the illustrations in this paper have been in fact of cumulates consisting of only one cumulus mineral. With increasing numbers of different cumulus minerals, unusual textural features are less likely to be found. Thus, if an orthocumulate formed from a gabbroic liquid consisted of cumulus plagioclase, olivine, augite, and magnetite the crystallization of the intercumulus liquid would simply enlarge each of these crystals by zoning, and a normal gabbro texture would result. In the case of an adcumulate consisting of several different cumulus phases (Figs. 2A, 4A) the obvious textures will not suggest its especial origin unless the significance of the absence of zoning is appreciated.

NOMENCLATURE OF CUMULATES

In rhythmically layered rocks, the assemblages of cumulus minerals in adjacent bands are often strongly contrasted and there is little to be gained by using for such rocks the more recondite names given by petrographers in the past who were not then in a position to understand their genesis. We suggest that it is preferable to name rocks which are cumulates by listing the cumulus minerals in order of decreasing abundance. Thus the lower layered rocks of the Skaergaard intrusion may be broadly described as gabbros or gabbroic cumulates and particular bands in them may be described as labradorite cumulates, labradorite-olivine-cumulates, olivine-pyroxene cumulates, labradorite-olivine-pyroxene cumulates, and so on. Such names do not replace general names like gabbro, olivine-gabbro, felspar-rich gabbro, norite, anorthosite, &c., but may be used to give greater precision when the rocks are known to be cumulates.

Cumulates of general gabbroic composition must have formed from a magma of general dioritic composition, and similarly eucritic cumulates must have formed from gabbroic magma. Useful generalizations can be made about the composition of the magma which gives rise to bytownite, labradorite, and andesine cumulates. The composition of the other crystal phases in equilibrium, such as olivine and pyroxene, can be linked with the varying composition of the plagioclase. The composition of cumulates forming from various types of basic magma at successive fractionation stages will be considered in a subsequent paper.

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