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SYMPOSIUM ON LAYERED INTRUSIONS

THE MECHANISM OF ADCUMULUS GROWTH IN THE LAYERED SERIES OF THE SKAERGAARD INTRUSION

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ABSTRACT

If we accept that the common feature of layered rocks is the bottom accumulation of crystals separating from a large body of magma, then there are three stages to be distinguished: (1) initial deposition of the cumulus crystals, (2) growth of the cumulus crystals while forming the top surface of the pile, (3) crystallization of trapped intercumulus liquid.

In the case of the Skaergaard intrusion the highly variable rhythmic layering is the result of the precipitation of different proportions of the possible cumulus phases. Convection currents, sometimes intermittent as Hess has postulated for the Stillwater, and sometimes continuous, though of variable velocity, account for many features of the rhythmic layering and igneous lamination.

Enlargement of the cumulus crystals during the brief time they formed the top surface of the precipitate is required to explain features of Rhum, Bushveld, Stillwater and, to a lesser extent, the Skaergaard layered series. In the latter case the amount of P_2O_5 in the rocks provides an indirect measure of the amount of adcumulus growth, and confirms the textural evidence. It is believed that the removal of heat to allow adcumulus crystallization cannot be downwards through the already deposited layered rocks but into the overlying magma which is, at certain times and places, supercooled. It is postulated that nucleation in the descending current probably occurred only after 5 or 10° C. of supercooling, that relatively few nuclei formed, and these grew slowly because of the slowness of diffusion. The crystal nuclei were probably so sporadically distributed that the magma, during the time it was flowing over crystals on the floor, did not become uniform, but was at the equilibrium temperature in the neighborhood of the growing crystals, while away from these it was supercooled.

The amount of trapped liquid depends largely on the extent of adcumulus growth; in the Skaergaard there was between 5 and 40 per cent, and its crystallization, giving lower temperature phases and zones, must have continued for many thousands of years.

Layered intrusions may be defined objectively as igneous complexes which, by structural or mineralogical critera, can be seen to be a succession of genetically related sheets, lying conformably one above the other, and showing no evidence of chilling between successive layers (*cf.* Wager 1953, p. 23). Such a definition, however, does not indicate the really significant characteristic of layered intrusions, which is their formation by accumulation of discrete crystals at the bottom of a magma, leading to the gradual building up of successive layers of rock. Such bottom accumulation of crystals cannot, of course, be directly observed, but it can be inferred in many cases from mineral compositions and textures, and it will be taken here as the fundamental characteristic of layered rocks.

When discrete crystals accumulate as a layer at the bottom of a liquid from which they are crystallizing, magma must initially have occupied the interstices betweeen the grains. Thus three stages in the production of a layered rock can usually be distinguished:

1. The initial deposition of the crystals (the cumulus crystals).
2. Growth of the cumulus crystals while forming the top of the pile (adcumulus growth).
3. Crystallization of the magma finally trapped between the cumulus crystals, due to the succeeding deposit. The material so formed is called the pore material.

The relative extent of the second and third processes vary inversely; in extreme cases there may be no adcumulus growth, all the intercumulus liquid becoming trapped and then crystallizing as cooling proceeds; in other cases adcumulus growth may be so extensive as to push out all the interstitial magma, leaving no trapped liquid to crystallize in the later stage. The terms used here have been more fully explained in a paper by Wager *et al.* (1960).

The rhythmic layering of layered intrusions is normally the result of precipitation of the possible cumulus minerals in different proportions at different times, and a major problem is to account for this variability. Some of the features of the rhythmic layering of the Skaergaard intrusion suggest the action of convection currents (Wager and Deer, 1939; Wager, 1952). At one stage in the development of the Skaergaard layered series, trough-banding structures provide evidence of the paths of former currents which passed radially across the floor of the intrusion from the margin towards the center (Wager and Deer, 1939, pp. 45–50, 262–77). Two

FIG. 1. Rhythmic layering; a thin gravity-stratified layer between uniform rock. Glaciated surface in the lower zone of the Skaergaard layered series, Uttentals Plateau.

contrasted types of layering (Fig. 1) seem to be due to precipitation of the cumulus crystals from two kinds of current; one a slow, steady current giving the uniform rock, and the other an intermittent current, as Hess has postulated for the Stillwater intrusion (1960, p. 113), giving the gravity stratified layers.

After the accumulation of crystals at the bottom of the liquid there is usually evidence of some further growth of the crystals at the same temperature as that at which they originally formed. This phenomenon, which has been called adcumulus growth (Wager *et al.*, 1960, pp. 77–79) is easily noticed when it is developed in extreme form, as in certain rocks of the Stillwater and Rhum intrusions (Hess, 1960, p. 113; Brown, 1956, p. 37). On the other hand it is not usually obvious in the Skaergaard intrusion where the effects of the crystallization of trapped liquid, during the protracted period of cooling, are particularly conspicuous. The layered rocks of the Skaergaard intrusion, when originally described in 1939, seemed to be adequately accounted for by assuming accumulation of discrete crystals at the bottom of the liquid, surrounded by about thirty per cent of magma (underestimated at the time) which crystallized slowly as the whole mass cooled. The evidence for this is the lower temperature, outer zones surrounding the essentially unzoned, cumulus crystals, and the additional, lower temperature mineral phases, commonly poikilitic in habit, which have also crystallized from the intercumulus liquid. Rocks having these features have since been called orthocumulates (Wager *et al.*, 1960, pp. 74–76). A feldspar orthocumulate is diagrammatically represented in Fig. 2 (left-hand column); the unzoned, cumulus plagioclases of the first stage of accumulation are indicated as rectangles; around them are lower temperature zones of plagioclase, together with olivine, pyroxene, iron ore and finally dregs of micropegmatite, all formed from the intercumulus liquid. Photomicrographs of different examples of orthocumulates from a low horizon in the Skaergaard layered series have previously been presented (Wager *et al.*, 1960, fig. 3A & B; Wager, 1961, Pl. XIX).

The phenomenon of adcumulus growth, diagrammatically illustrated in Fig. 2, became apparent during Hess's early work on the Stillwater and was briefly mentioned by him (1939, p. 431); later it was further described by G. M. Brown from Rhum (1956, p. 37) and subsequently discussed by Wager *et al.* (1960). The lower units of the layered series of eastern Rhum are orthocumulates, but the higher units include allivalites and thin bands of plagioclase rock (Brown 1956, Pl. V, Fig. 38) in which the plagioclase crystals are unzoned. It is clear that the closest possible natural packing of cumulus plagioclases would still leave space for 20 per cent or so of intercumulus liquid, which should crystallize to lower temperature material. Various hypotheses, none of which were proving satisfactory, were being considered to account for the absence of such low temperature material in certain Rhum rocks when Hess pointed out that he had suggested an explanation, expressed in a sentence in one of his early papers on the Stillwater complex (1939, p. 431). This is the now well-known hypothesis of the growth of the crystals by the diffusion of the appropriate substances from the overlying liquid while the crystals lie at, or near the top surface of the pile; as a result of this growth there is mechanical expulsion of some, or all of the intercumulus liquid from between the crystals. The hypothesis has been more fully considered in the Stillwater memoir (Hess, 1960, p. 113), in which it is also noted that for the diffusion effect to be important, there must be plenty of time or, in other words, the rate of accumulation of crystals at the bottom of the liquid must be relatively slow.

For adcumulus growth of the crystals at the temporary top of the pile of cumulus crystals, heat must be lost to the surroundings in some way. During the formation of the higher Skaergaard layered series, which is the only part now accessible to observation, there must have been many kilometres of

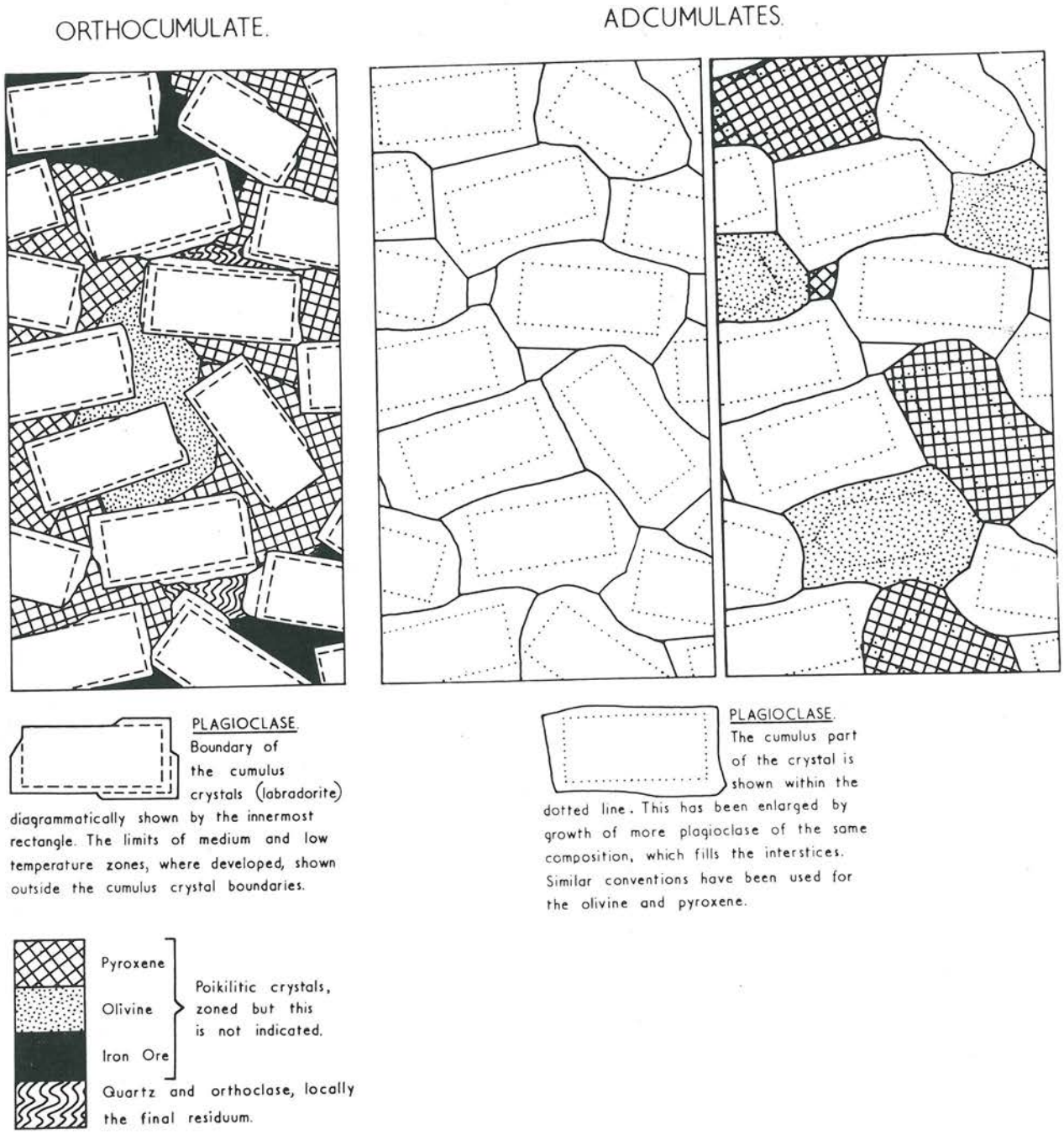

FIG. 2. Diagrammatic representation of 1) plagioclase orthocumulate, 2) extreme plagioclase adcumulate, 3) extreme plagioclase-olivine-pyroxene adcumulate.

already deposited material below, between the crystals of which there would often be intercumulus liquid requiring a considerable reduction in temperature for its complete crystallization. To produce appreciable adcumulus crystallization, heat loss from the neighborhood of the crystals lying at, or near, the surface of the pile must be relatively rapid, since it has to occur before the crystals are too deeply buried by further deposition. Qualitatively, it seems clear that heat loss downwards from the top layer of the accumulated crystals would be far too small to produce adcumulus crystallization, and Professor Hess (personal communication) states that a calculation of the relative heat losses through the floor and

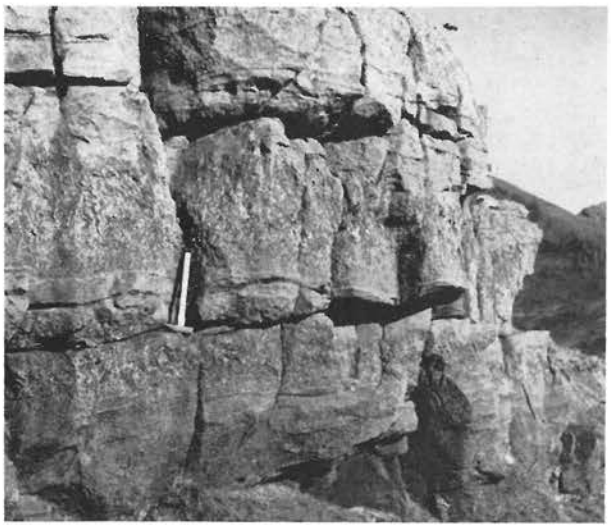

FIG. 3. Harrisitic and equigranular textures in peridotites of Rhum. The rock face shows layers of elongated, upward-growing olivines alternating with fine-grained layers of olivines. (Photograph by W. J. Wadsworth.)

the roof of the Stillwater complex provides supporting evidence for this.

It is the main purpose of this paper to suggest that the loss of heat to allow adcumulus growth is not downwards through the crystal mush but is into supercooled liquid lying above the pile of crystals. Some degree of supersaturation is needed to produce nucleation in a liquid free from seed crystals, and certain features of layered intrusions provide evidence for such non-equilibrium conditions. Thus, in the layered intrusion of Rhum, Wadsworth (1961) has described in detail the harrisite structure of the peridotites (Fig. 3). Olivines, much elongated along the *a* axis and flattened parallel to 010, have grown upward into the liquid from the top surface of an accumulation of fine-grained olivines. After some time, such upward growth was interrupted by a further deposit of fine-grained, equigranular olivines. Wadsworth accounts for the periodicity by assuming that a considerable degree of supercooling is necessary to produce nucleation. He stated that with steady loss of heat from the stationary magma

"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."

A hypothesis of this kind is basically similar to Ostwald's explanation of Liesegang's rings (for a convenient discussion, see Van Hook, 1961, pp. 12–19).

In the Skaergaard intrusion, evidence of supercooling is available from the marginal border group (Brown, 1957, p. 530; Wager, 1961, pp. 359–60). These examples are related to marginal cooling, but they are useful in showing that some 5° or 10° C. of supercooling had sometimes to occur before nucleation of pyroxene and plagioclase took place. An explanation of certain types of layering in the Bushveld complex has also been tentatively ascribed to the order in which different crystals nucleate from a supercooled magma (Wager, 1959).

Supersaturation of magma is usually considered to result simply from loss of heat into the surroundings, as when a magma intrudes cool rock. Another possible cause of supersaturation is the transfer of saturated magma, without gain or loss of heat, from a region of low to high hydrostatic pressure. The effect of increasing pressure on the common rock-forming minerals is to raise their melting point and thus, if saturated magma be transferred from a region of low to high hydrostatic pressure, it will be supersaturated in its new environment. In the Skaergaard intrusion, rhythmic layering and other phenomena suggest that convection currents occurred in the magma. In the descending part of these currents there will be an opportunity for supersaturation to occur.

In the original paper on the Skaergaard intrusion, it was suggested that convection currents, like the wind, would be variable in velocity and that, in a general way, this accounted for the rhythmic layering (Wager and Deer, 1939, pp. 272–73; Wager, 1952, pp. 345–48). It is now realized that variation in velocity of a current will, however, not produce the alternating uniform and gravity stratified bands commonly occurring in the layered series (Fig. 1). To account for rhythmic layering of this kind it is believed, as mentioned earlier, that two different sorts of currents existed simultaneously; one, a gentle and fairly continuous convective circulation from which the uniform rocks were deposited, and another, an intermittent, dense current of relatively small volume which periodically plunged down along the outer margin of the liquid and came to rest on the temporary floor, where a gravity stratified layer was deposited. The intermittent currents are similar to those postulated by Hess as having been in action during the formation of the Stillwater layered series

(Hess, 1960, p. 113). Possible velocities of the currents in the Skaergaard intrusion at a late stage in the formation of the layered series are given in Fig. 4. Both types of current are due to thermal convection.

In seeking an explanation of adcumulus growth, the hypothesis of a steady convective circulation will be used. During the circulation of the magma it may be that neither the loss of heat to the country rocks, nor the effect of increasing hydrostatic pressure during descent, is sufficient to cause nucleation. In the circumstances a supersaturated liquid, free from crystals, will sweep over the floor; the top crystals of the pile will have an opportunity to grow, and an adcumulate or, in extreme cases, a rock with harrisitic texture, will result. On the other hand, it may be that during circulation the heat loss and the effect of increasing hydrostatic pressure are sufficient to cause some nucleation, so that by the time the current turns horizontally across the floor, some crystals will be present in it. If the horizontal current has laminar flow, those suspended crystals which are denser than the liquid (and this is probably all of them) will sink steadily through the current to the floor, giving a uniform rock. At first sight it might seem that if crystals were present in the magma, then equilibrium conditions would exist, and no adcumulus growth would be possible. However, since the crystals are suspended in a moving current, there is only limited time available for the attainment of equilibrium. It is possible that equilibrium

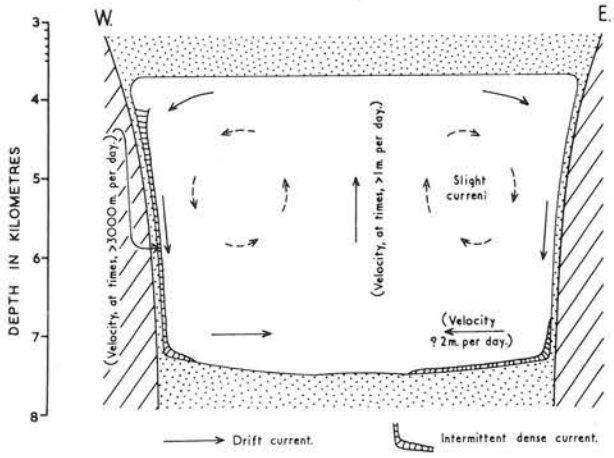

FIG. 4. Suggested conditions in the Skaergaard liquid at the beginning of the observed layered series, showing 1) the gentle, steady, convective circulation, with a velocity of the order of 2 m per day, 2) intermittent, dense, convection currents descending along the walls with high velocity, undercutting the gentle current, and coming to rest on the floor.

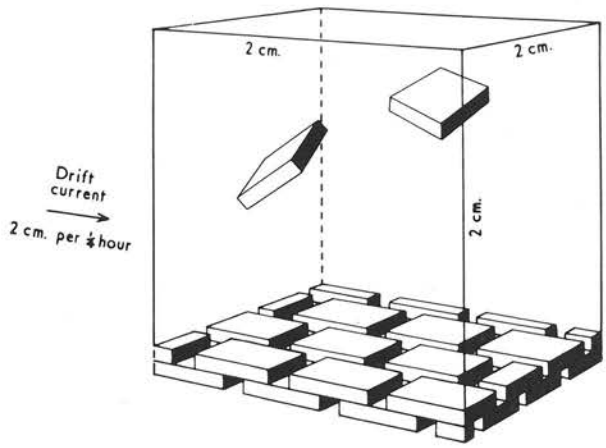

FIG. 5. Suggested conditions for adcumulus growth from the steady convection currents of the Skaergaard magma during the period of formation of the lower zone. The cumulus is considered to consist of crystals 0.5×0.5×0.1 cm in size, and a new layer assumed to take 3 days to form. In a 2 cm cube of liquid it is estimated that 1) there are only two crystals at any one time, and 2) 288 of the 2 cm cubes of liquid plus crystals pass over 4 square cm of floor in the three days required for the formation of a new layer of crystals.

conditions are not attained, and this becomes more probable the more spaced-out the crystals are in the suspensions. In a thin suspension of crystals, the liquid could be at equilibrium temperature in the neighborhood of the suspended crystals and supersaturated further away. If such a liquid passes slowly over a crystal precipitate, it should deposit occasional crystals and, at the same time, it should produce adcumulus growth, the latent heat of crystallization passing into the supercooled part of the liquid. The conditions are diagrammatically indicated in Fig. 5. The overall rate of heat loss from the Skaergaard intrusion is assumed to have been of the same order as for the Stillwater complex, which has been estimated by Hess to be such that 10 cm of layered series are accumulated per year. The velocity of the convection current is taken as 2 m per day, a reasonable figure in the light of Shimazu's (1959) calculations. It is also a velocity sufficient to transport large feldspars upwards at the center, and this seems to be required for the formation of the upper border group of the Skaergaard intrusion. The amount of suspended crystals in the magma must be small, and has been estimated to be about 0.1%. The conditions illustrated are believed to represent those occurring in the Skaergaard intrusion during adcumulus growth from the steady drifting current. Some evidence for the numerical quantities assumed

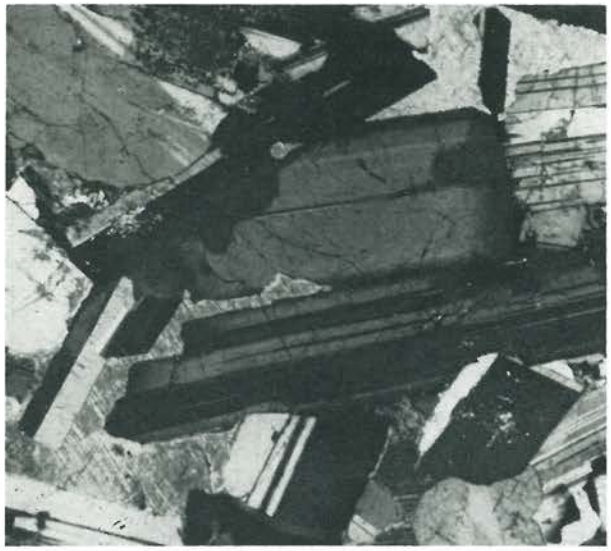

FIG. 6. Typical zoning of plagioclase in a plagioclase orthocumulate of the Lower Zone of the layered series (EG. 5109, ×23).

in Figs. 4 and 5 are derived by an overall consideration of the formation of the layered series and, as already mentioned, a paper on this is in preparation.

In the lower observable rocks of the Skaergaard layered series there is usually evidence of a considerable amount of pore material, that is, material formed by crystallization of trapped liquid. Thus interstitital magnetite is present which, at this level, is only an intercumulus mineral. Apatite in small, interstitial, subophitic crystals is found sporadically and, at this stage, it also is only an intercumulus mineral, being 1600 m below the level of its appearance as a cumulus phase. The zoning of the feldspars also indicates the effect of the trapped liquid. Thus the feldspars in a plagioclase cumulate from 110 meters in the layered series (Fig. 6) show essentially homogeneous cores,[1] representing the original cumulus crystals, surrounded by successively lower temperature zone where contact with other grains has not prevented their development. In the upper layered rocks the zoning in the plagioclases is less, or non-existent. Thus in the ferrogabbro at 1800 m (Fig. 7), zoning is only to be seen in the large crystal at the top left-hand corner of the photomicrograph, and even this amount of zoning is rarely seen. In this rock there was much adcumulus extension of the feldspars, and presumably, of the other cumulus minerals also. If, under the microscope, it were possible to define the boundary between the adcumulus material and the lower temperature zones formed from the trapped liquid, then a micrometric analysis could be made which would give the proportion of the various minerals in the pore material, and from this an approximate composition for the trapped liquid could be obtained. In practice, such a micrometric estimate is found to be difficult or impossible; usually all that can be done is to estimate whether there was much, or little trapped liquid and from this to decide, in general terms, whether the rock should be described as an orthocumulate, mesocumulate or adcumulate.

However, in the layered series below the horizon at which apatite becomes a cumulus phase, the phosphorus content of the rock may be used to decide with more precision the amount of trapped liquid. Since the cumulus minerals (plagioclase, olivine, pyroxene and iron ores) are essentially free from phosphorus, the phosphorus found by the analysis of the whole rock must be in the pore material formed from the trapped liquid. If, at a particular horizon, one rock has twice as much phosphorus as another, it is inferred that it also had twice the amount of trapped liquid. Furthermore, insofar as the amount of phosphorus in the successive residual liquids is known (Wager, 1961, pp. 378–81), the

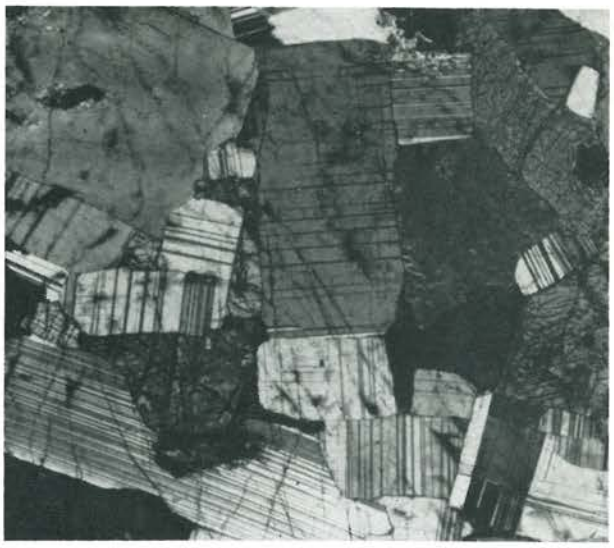

FIG. 7. Typical, almost unzoned, plagioclase crystals in a plagioclase-augite-olivine-magnetite mesocumulate from Upper Zone b of the layered series. (E.G. 5181, ×23).

[1] In some cases there are slight, patchy variations in the extinction of the core (not shown in the figure) implying differences in composition; this is a second order effect, which may be due to the crystal having formed under varying hydrostatic pressures and temperatures during movement in a convection current.

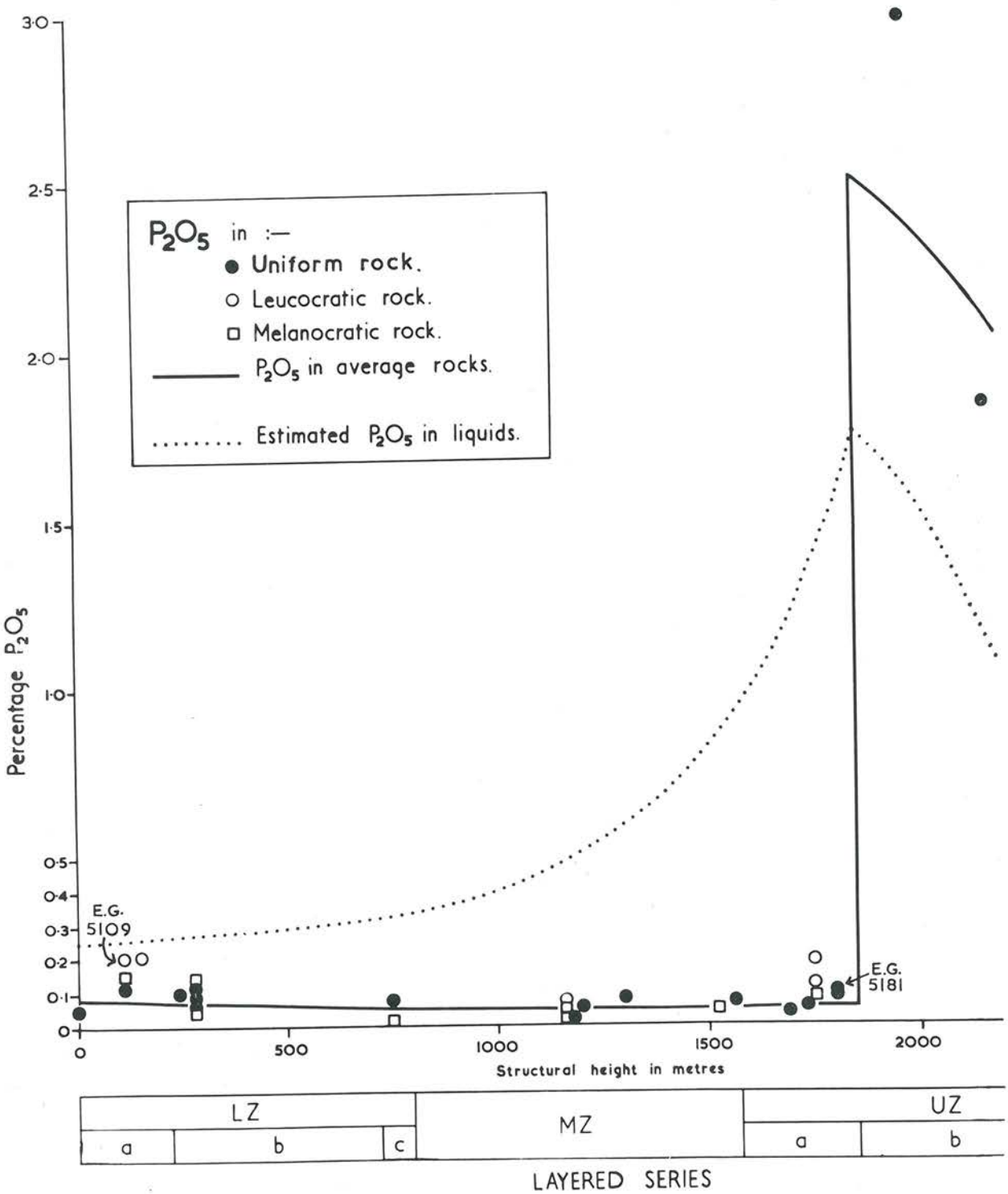

FIG. 8. P_2O_5 content of Skaergaard rocks plotted against height in the intrusion. Positions of EG. 5109 of Fig. 6 and of EG. 5181 of Fig. 7 are indicated.

ratio of trapped liquid to cumulus crystals can be obtained for any analyzed rock. The amount of phosphorus in the rocks of the lower and middle zones of the Skaergaard layered series is small, and ordinary methods of determination of P_2O_5 were unsatisfactory; Dr. E. A. Vincent has obtained more precise data, using radioactivation methods. In Fig. 8 newly obtained P_2O_5 values for various layered rocks are plotted against height in the intrusion. Three different types of cumulates are distinguished:

(1) the uniform rock, considered to have been deposited by the steady, drifting current, (2) the feldspar cumulates from the upper part of gravity stratified layers, and (3) the melanocratic cumulates from the base of gravity stratified layers.

The average phosphorus content of the layered rocks below the UZb horizon remains low, or even decreases, with height, *i.e.* with increasing fractionation. Before these measurements were made it was anticipated that the phosphorus content would rise, because the amount in the magma must have increased over this range. The fact that the P_2O_5 of the rocks does not increase is apparently due to the decreasing amount of trapped liquid at successively higher horizons. Confirmation of this is provided by examination of the rocks in thin section, but had not been appreciated until the phosphorus data were obtained. A small amount of trapped liquid implies either good initial packing of the cumulus crystals, or much adcumulus growth, or both. The effect on the phosphorus content of variation in the initial packing is considered slight, compared with the effects of adcumulus growth. The phosphorus analyses, therefore, provide clear evidence of an overall increase in adcumulus growth with increasing height in the layered series, up to the time when apatite became a cumulus mineral. Above this level the phosphorus content, obviously, is no longer a measure of the amount of intercumulus liquid, but because of the scarcity of zoning in the plagioclase it is clear that much adcumulus growth persisted almost to the top of the layered series.

Although the data on the phosphorus content of the Skaergaard layered series are, as yet, not abundant, they suggest that adcumulus growth is important in the formation of the uniform rocks, believed to have formed from the drift current (Fig. 8). The leucocratic and melanocratic parts of the gravity stratified bands have contrasting amounts of adcumulus growth, as judged by the few determinations of the phosphorus content available. The leucocratic plagioclase cumulates which are believed to be the result of the settling out of plagioclase from the intermittent, dense currents when they finally came to rest, show the least amount of adcumulus growth, probably because they accumulated quickly from a dense suspension of crystals. The thin melanocratic rocks at the base of the gravity stratified units have usually little phosphorus, implying considerable adcumulus growth. It is believed that the heavy crystals forming these layers fell to the floor through a turbulent current, and that the turbulence provided opportunities for the supersaturated parts of the magma, even if proportionally only small in total amount because of the density of the suspension, to come into contact with the deposit of heavy crystals.

The higher layered rocks, showing much adcumulus growth, suggest considerable supersaturation in parts of the liquid at the time they were forming. It is also interesting to note that the only clear case, in the Skaergaard intrusion, of harrisitic texture, which is taken to imply supersaturation, is within 200 m of the top of the layered series. With increasing depth in the observed layered series the rocks pass, on the average, from adcumulates or mesocumulates into meso- or ortho-cumulates, and it is thought probable that the hidden zone consists largely of orthocumulates. With increasing descent, the convecting magma perhaps would tend to become increasingly supersaturated, causing so much nucleation that no part of the magma was far from seed crystals, and less time would be required for diffusion of heat and substance to produce equilibrium conditions; thus, little or no adcumulus growth occurred. If this hypothesis is applicable to the layered rocks of Rhum, then the magma from which the adcumulates and harrisites formed should have been of no great thickness. On the other hand, this hypothesis is not directly applicable to the Bushveld and Stillwater layered rocks which include many adcumulates, apparently formed from bodies of liquid several kilometers thick.

Acknowledgments

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