Layered Intrusions.

Notes on three lectures given to the Danish Geological Society in November 1952.

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Intrusions which show the features of such layered complexes as the Bushveld of South Africa and the Skaergaard of East Greenland are rare. It seems likely, however, that many other banded basic masses have been formed by essentially similar processes which were not carried so far or were made less regular by subsequent tectonic movements. Well layered intrusions are of interest in themselves; they also provide information on the composition of successive minerals produced by crystal fractionation and on the trend in composition of successive solid and liquid fractions resulting from this process. They contribute also to an understanding of the origin of banding in basic and ultrabasic igneous rocks.

When an account of the Skaergaard intrusion was given by W. A. DEER and I in 1939 (1) we could make some comparison with preliminary accounts of the Duluth, Bushveld, Stillwater and Bay of Islands complexes. There is more data now available for comparison, especially in the case of the Bushveld. In these lectures I propose first to summarise the features of the Skaergaard Complex, mentioning additional information gained since the original monograph, and then to make brief comparison with other definitely layered intrusions and with intrusions in Rhum and Skye which, as shown by recent work, have some of the features of layered masses. USSING's classic work on the alkaline intrusion of Ilimausak seems to show that this also is a layered intrusion, but attention will here be concentrated only on those related directly to basic magma.

The Skaergaard intrusion.

A *layered series of igneous rocks* may be defined as an igneous complex which can be separated by structural or mineralogical criteria into a succession of extensive sheets lying one above the other. In addition, a Skaergaard-type layered series should show cryptic layering, a name first used in the original Skaergaard paper (1, pp. 37, 65). Cryptic layering is made manifest by changes, related to height in the layered series, in the composition of the minerals, or in the number of separate primary mineral phases present. Cryptic layering may exist whether the rocks show the more ordinary banding (rhythmic layering) or not.

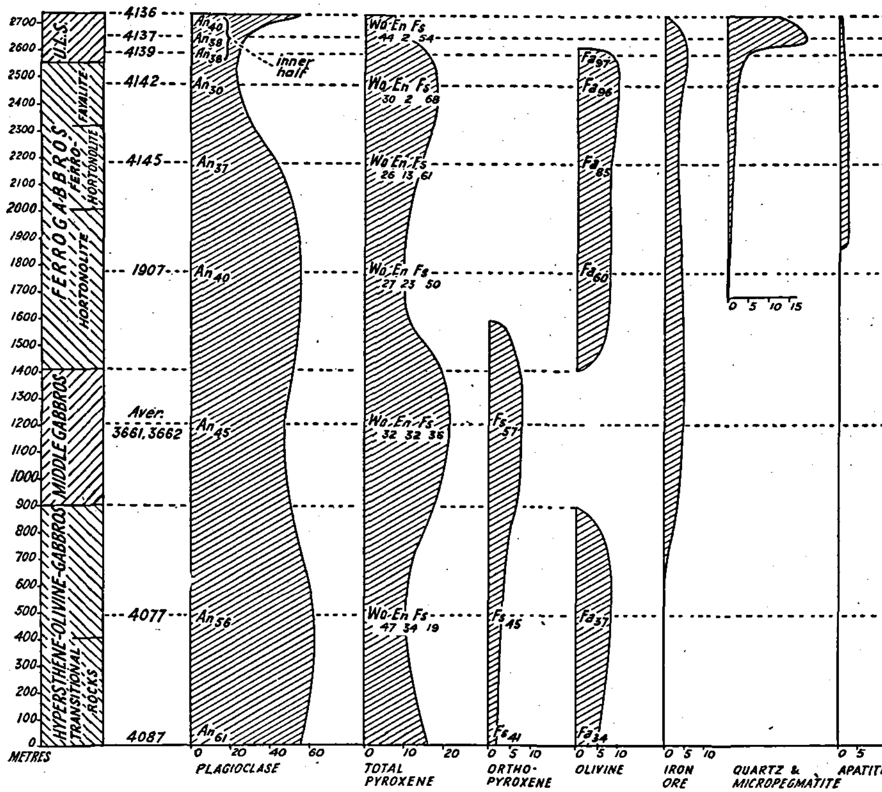


Fig. 1. Modal composition of average rocks of the layered series and the composition of certain of the minerals, plotted against the height in the intrusion (reproduced with permission from Meddel. om Gronland 1939 105).

The cryptic layering in the layered series of the Skaergaard intrusion is characterised by:

1. Steady change in the unzoned parts of the more important mineral phases, such as plagioclase, pyroxene and olivine, from high temperature to low temperature solid solutions during ascent.

2. Abrupt appearance and disappearance of crystal phases at certain levels in the layered series. These abrupt changes are grouped with the steady changes in the solid solution minerals because both are believed to be the result of crystal fractionation.

I should regard it as necessary for a layered series to show cryptic layering before describing it as of Skaergaard type.

For the Skaergaard intrusion chemical analyses supplemented by optical work provided the foundation for the description of the changing composition of the minerals and the results were summarised graphically (fig. 1). Additional work has since been done on the plagioclases (2, pp. 145–6) the pyroxenes (3) and the iron ores (2, pp. 153–9). Work on the iron ores

TABLE 1

Trace element composition as parts in million of clinopyroxenes and olivines from the Skaergaard intrusion.
A-F represent selected horizons in the layered series in ascending order.

	Pyroxene						Olivine					
	A	B	C	D	E	F	A	B	C	D	E	F
Ga^{+3}	3	3	*	5	10	10	*	3		5	5	5
Cr^{+3}	3000	350	*	*	*	*	20	*	Olivine	*	*	*
V^{+3}	300	250	100	30	*	*	*	*	absent.	*	*	*
Mo^{+4}	*	3	5	*	*	*	3	10		10	10	30
Li^{+1}	3	2	*	*	2	50	2	3		5	5	15
Ni^{+2}	200	140	50	*	*	*	2000	325		10	*	*
Co^{+2}	60	50	60	40	30	15	150	125		100	50	20
Cu^{+2}	*	35	100	300	1000	100	20	20		300	400	20
Sc^{+3}	80	30	50	150	80	80	*	*		*	*	*
Zr^{+4}	30	50	30	50	*	*	*	*		*	*	*
Y^{+3}	*	*	*	*	*	500	*	*		*	*	*
La^{+3}	200	*	*	*	150	300	*	*		*	*	*
Sr^{+2}	10	*	20	80	30	100	10	10		100	100	20
Pb^{+2}	*	*	*	*	*	*	*	*		*	*	*
Ba^{+2}	*	7	10	10	*	60	*	7		10	10	10
Rb^{+1}	*	*	*	*	*	50	*	*		*	*	*
Generalised composition from optics or chemical analysis (Wt percentages)	En 42 Fs 17	En 34 Fs 19	En 32 Fs 36	En 23 Fs 50	En 13 Fs 61	En 6.5 Fs 68	Fo C.70	Fo 64		Fo 41	Fo 20	Fo 3

is at present being carried further by the separation and analysis of the ore minerals.

To increase our knowledge of the steadily varying composition of the various mineral phases, spectrographic determinations of trace elements in the chief minerals of the layered series have also been made (2). Like the major constituents the trace elements change systematically in amount but in some cases they show much stronger variation than the major constituents. As examples may be given the variation in the trace element composition of the clinopyroxenes and olivines (Table 1). These two ferromagnesian minerals are rather similar in some of their trace element characteristics, for example Ni, Co and Cu, but they differ markedly in others, for example Cr, V and Sc. In both there may be strong changes in amount of an element as the layered series is ascended; thus, in the pyroxenes, Cr, V and Ni fall from high to very low values while in olivine, Ni falls rapidly from very high to very low values. Table 1 gives only a small selection from much data available for the minerals of this intrusion.

The other phenomena included in the concept of cryptic layering, namely the abrupt appearance or disappearance of particular crystal phases is well shown by the behaviour of the iron ores and apatite (see also fig. 1). Small amounts of these are present in the rock in the earlier stages; it is the incoming in quantity as a primary precipitate (see below) which is significant. Magnetite and ilmenite appear approximately together but more work is needed before the full story, involving, apparently, a ferrous titanium spinel, can be given. The disappearance of olivine for a time in the Middle Gabbro and its return in the ferrogabbros is another example of abrupt change in the primary minerals. Although in the Middle Gabbro olivine is absent as a primary precipitate it forms as a reaction rim round iron ore, and this olivine is an iron-rich type like that occurring high up in the ferrogabbros.

The layered series of the Skaergaard intrusion shows rhythmic banding or layering which is a more conspicuous, though less significant feature than the cryptic layering. It is produced by a variation in the proportions of the three or four chief mineral phases and in this fundamental respect it is the same as much of the usual banding of basic igneous rocks, for example, that described at an early date by GEIKIE and TEALL in the Skye gabbros (4). Changes in proportions of the light and dark minerals give the most conspicuous rhythmic banding and frequent repetition of the changes are characteristic. In the Skaergaard intrusion rhythmic banding is well developed up to 1900 m. on the arbitrary height scale. Accurate measurements of the dip and strike of the layers can be made when the rhythmic banding is good and the original form has been established as saucer-shaped (fig. 2). The particular type of rhythmic layering known as gravity stratification is a usual feature of the layered series up to about 1600 m.; the gravity statified layers have a rather definite base consisting largely of the heavier and darker minerals and this gradually gives place upwards to a more felspar-rich material, or in extreme cases to an almost pure felspar rock; after this there is a sudden return to melanocratic material and the rhythm is repeated. In the middle of the ferrogabbros, high in the layered series,

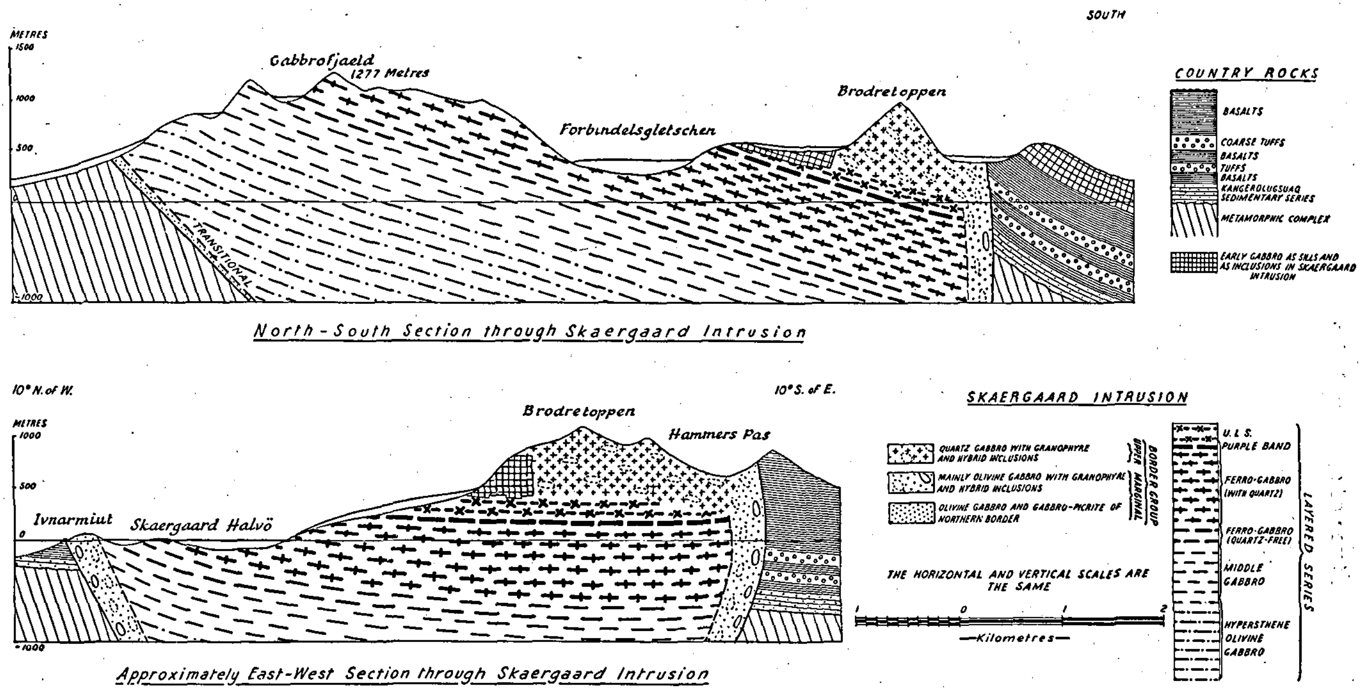


Fig. 2. Sections across the Skaergaard intrusion showing the layered series within the envelope of the marginal and upper border groups (reprinted with permission from Meddel. om Gronland, 1939 105).

a rather specialised type of small scale layering is developed, some layers being strongly gravity stratified and others uniform. At this horizon also the peculiar trough banding is sporadically developed (1, pp. 45–50) while still higher rhythmic layering ceases.

Besides cryptic and rhythmic layering the rocks of the layered series may also show parallelism of those minerals which have a platy or bladed habit. Thus in the hypersthene olivine gabbros, low in the layered series, the felspars are thin, square plates and these may be arranged almost parallel to each other and to the extent of the layering, giving rise to good igneous lamination. In adjacent layers with equally platy felspars there may be no parallelism of the plates. Igneous lamination has, indeed, proved to be oddly sporadic in the main part of the layered series, and in the top 200 m., which still shows a sort of cryptic layering, igneous lamination is absent and the rocks have been separated off as the unlaminated layered series.

In the Skaergaard intrusion the layered series lies within an envelope formed by the marginal and upper border groups (fig. 2). These contribute useful data towards an explanation of the mechanism of formation of the layered series but they will not be described except to point out that there is some variation in the composition of the rocks, which, to some extent, is the same as that of the layered rocks but due mainly to the changing composition of successive residual magmas. Changes resembling the upward sequence of the layered series are found in the marginal border group when passing in from the margin and, in the upper border group, when passing downward.

The Bushveld and some other layered complexes.

The Bushveld complex of South Africa has a different order of size from the Skaergaard intrusion (fig. 3), yet many features are surprisingly similar. The descriptions of WAGNER (5), HALL (6), LOMBAARD (7) etc. show that there is an approach to cryptic layering but the steady change in composition is periodically interrupted. From the published work of LOMBAARD and his students (7, 8, 9, 10), the variation in composition of the felspars may be generalised as shown in plate VIII. One reversal in the trend of composition of the felspars is indicated but several others have been established in different parts for both the felspars and the rhombic pyroxenes. The rocks show rhythmic layering on a much more impressive scale than is the case with the Skaergaard intrusion, especially in the so called Critical Zone where bands may be traced over great distances. Igneous lamination or pseudo-stratification is also well developed. In a private communication LOMBAARD has said:

"The present, enlarged picture of the petrography of the Bushveld is remarkably like that of the Skaergaard —most of the rocks, structures, etc., can be matched almost exactly by Bushveld examples, including pure fayalite-bearing types".

The size of the Bushveld is so great that nothing like a full story is yet available, but it seems that the vertical sequences, although broadly sim-

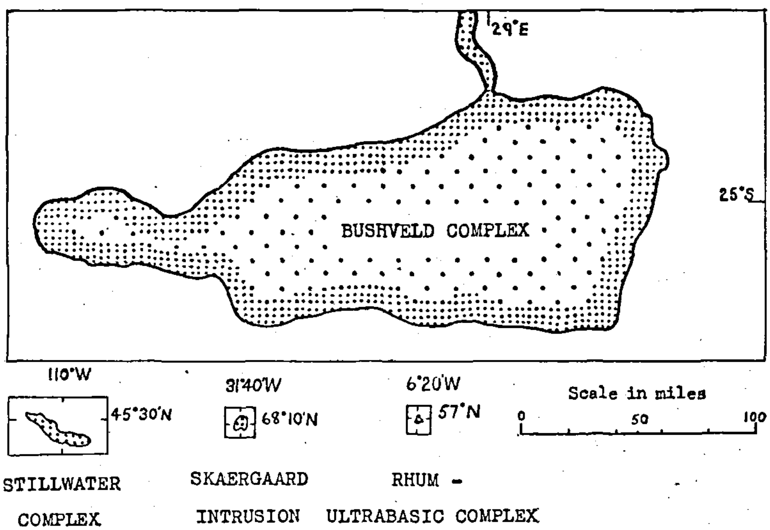


Fig. 3. Relative size of certain layered intrusions.

ilar, differ somewhat in different parts, and it also appears that the cryptic layering is interrupted at intervals. LOMBAARD and others suggest that this is due to influx of fresh magma, but another possibility will be mentioned below when the mechanism of the Skaergaard intrusion is discussed.

The Stillwater complex is known from the work of PEOPLES and HESS (12, 13, 14). It has close similarity with the lower part of the Bushveld (Plate VIII). The composition of the pyroxenes is known from separation and analysis (15) and the broad results are given in fig. 4, in combination with the new data for the Skaergaard pyroxenes provided by MUIR (3). It is hoped that HESS will soon furnish more data on the other minerals of this interesting complex.

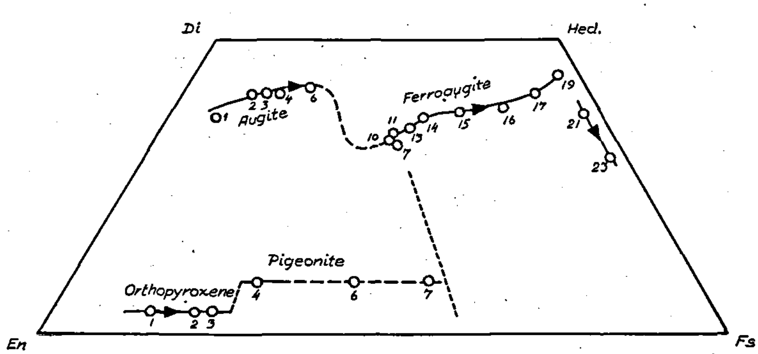


Fig. 4. Trend in composition of pyroxenes from the Stillwater complex (1–4) and the Skaergaard intrusion (6, 7, 10, 11, 13–17, 19, 21, 23) after HESS (15) and MUIR (3). In many cases the original pyroxenes have undergone exsolution. Pyroxenes 21 and 23 from the Skaergaard were originally iron wollastonite.

Other layered basic intrusions such as the Duluth and Bay of Islands complexes on which more work is urgently needed will not be considered here, but mention will be made of the apparently incomplete and considerably modified examples of layered intrusions from the Tertiary igneous province of Great Britain. The Cuillin gabbro of Skye described by GEIKIE and TEALL (4) and HARKER (16) is a classic example of a banded intrusion. Recently gravity stratification was found in the Cuillin gabbro and this suggested the probability of it being a layered intrusion (17). Since then J. M. CARR has studied a sector of the Cuillin gabbro and has shown that, despite many complications, cryptic layering is indicated by the change in composition of the felspars and other features (Plate VIII). Analyses of some of the rocks for trace elements by R. L. MITCHELL strongly suggest the same thing. More work is in progress especially on the ultrabasic rocks which BOWEN (18) as long ago as 1928 maintained were the result of crystal sorting during the cooling of a pool of basic magma.

Banding in the hypersthene gabbro of the Centre II ring dyke complex of Ardnamurchan was described by RICHEY and THOMAS in the original memoir. More work on this gabbro by M. K. WELLS (19) suggests, though as yet not very clearly, that this again is part of a layered intrusion.

The small island of Rhum in the Inner Hebrides (cf. fig. 3) displays well a complex consisting of sheets of peridotite and allivalite (olivine and basic plagioclase rock, approximately $An/_{90}$). The successive layers having roughly horizontal outcrops round the mountains of Allival and Askival, were considered by HARKER (20) to be the result of successive sill-like injections of peridotite and allivalite. A recent preliminary examination (21) showed that the sheets were not due to successive injection but to a peculiar type of layering resulting from the repetition of units, sometimes 100 ft. thick, varying gradually from olivine-rich rocks at the bottom to felspar-rich rocks at the top. Only 2000 ft. of layered rocks have so far been identified and in these no cryptic layering has been proved, but there seems no doubt that the pile is due to bottom accumulation which, as shown below, is the essential feature of the Skaergaard type of layering.

Textural features of layered rocks.

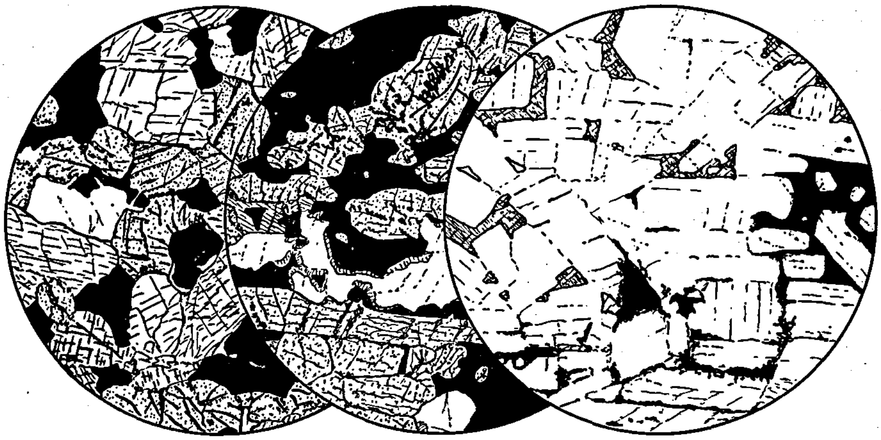
The two types of variation included under the heading of cryptic layering are exactly those which would result from the accumulation, on the floor of a magma chamber, of successive crystal fractions formed during steady cooling of the magma. This hypothesis of bottom accumulation for the origin of the Skaergaard layered rocks, which was put forward in the original memoir (1, pp. 125–7) was also found to provide an explanation of certain textural features. An accumulation of discrete crystals collected tranquilly at the bottom of a magma pool would necessarily have a considerable amount of liquid occupying the space between the crystals of the precipitate and, as the whole complex cooled, this interstitial magma would itself slowly crystallize. In some of the rocks there is good evidence for this two-fold nature of the material making up the layered rocks. To simplify the discussion the presumed original precipitate, accumulated as discrete crystals at the bottom of the magma, may be called the primary precipitate and the material formed from the interprecipitate magma may be called the interprecipitate material, as was done in the original memoir (1, pp. 127–32). The interprecipitate magma will partly crystallize as an outer fringe to the existing minerals and partly as additional mineral phases which have an interstitial situation. In the case of the plagioclases the interprecipitate part is usually to be seen as strong zoning at certain points round the circumference of the crystals. For the layered series of the Skaergaard intrusion, the primary precipitate minerals and the additional minerals of the interprecipitate material are listed in the table below.

TABLE II.

	Height in layered series	Primary precipitate minerals	Additional minerals of the interprecipitate material
Ferro-gabbros	2350–2500 m	Plagioclase, olivine, iron-wollastonite, iron ore, apatite	Quartz and perthite
	1850–2350 m	Plagioclase, olivine, clino-pyroxene, iron ore, apatite	Quartz and perthite
	1700–1850 m	Plagioclase, olivine, clino-pyroxene, iron ore	Apatite, quartz
	1600–1700 m	Plagioclase, olivine, clino-pyroxene, iron ore	Apatite
	1400–1600 m	Plagioclase, olivine, clino-pyroxene, orthopyroxene, iron ore	Apatite
Middle gabbros	Ca. 1200–1400 m	Plagioclase, clinopyroxene, orthopyroxene, iron ore	Olivine, apatite
	900–ca. 1200 m	Plagioclase, clinopyroxene, iron ore	Orthopyroxene, olivine, apatite
Hyper-sthene-Olivine-gabbros	Ca. 700–900 m	Plagioclase, olivine, clino-pyroxene, iron ore	Orthopyroxene, apatite
	Ca. 400–ca. 700 m	Plagioclase, olivine, clino-pyroxene	Orthopyroxene, iron ore, apatite

Note: Iron ore includes magnetite, ilmenite and perhaps a ferrous titanium spinel.

In some of the strongly banded rocks the primary precipitate consists only of felspar. As the interprecipitate liquid crystallized the felspathic part was deposited on the primary precipitate felspars slightly extending these, but the pyroxene, depositing from the interprecipitate magma, developed as skeleton poikilitic crystals spreading extensively through parts of the crystal pile containing two or three hundred of the primary precipitate felspars (fig. 5). Iron ores and olivine behave in essentially the same way, forming poikilitic crystals. It is clear that only a few pyroxene, iron ore and olivine crystal nucleii were formed in the interstitial liquid and that during slow crystallization of the liquid, the appropriate material diffused to the growing crystals over distances up to a centimetre or so and produced in one place poikilitic pyroxene, in another poikilitic iron ore or olivine. In melanocratic bands adjacent to the felspar-rich bands,



1924 2569 2568

Fig. 5. Extreme rhythmic layering in ferrogabbro. 1924 & 2569 — Melanocratic bands, consisting of primary precipitate clinopyroxene, plagioclase and iron ore. Interprecipitate material has crystallized on the primary minerals and no special textures are seen. 2568. — Leucocratic band adjacent to 2569. The only primary precipitate mineral is plagioclase. Interprecipitate pyroxene, olivine (now decomposed) and iron ore have a poikilitic habit.

in which pyroxene, olivine, iron ore and occasional plagioclase crystals occur as primary precipitates, there is no poikilitic development of pyroxene or other crystals because the interprecipitate liquid was able to crystallize on the varied primary precipitate crystals (fig. 5).

The peridotite layers of Rhum are sometimes markedly poikilitic. These rocks were formed as an accumulation of discrete olivine crystals surrounded by interprecipitate liquid which has now crystallized to form extensive poikilitic pyroxene or plagioclase crystals, a single poikilitic pyroxene or felspar being often 3 cm. across and containing something of the order of 10,000 discrete olivine crystals. In explaining the structures shown by some of the Skaergaard rocks we had to postulate that the discrete units which accumulated at the bottom of the magma were in some cases composite, consisting of clusters of pyroxene and felspar. This texture is particularly clear in certain Rhum rocks in which olivine-felspar or pyroxene-felspar clusters, together with separate tabular felspars, formed the primary precipitate material, the reality of the composite units of the precipitate being shown by the way the felspars wrap round them tangentially. Other textural problems still await a solution; one difficulty is the almost pure felspar and olivine rocks found in Rhum and Skye respectively, in which the interprecipitate liquid seems to have been reduced to very small amounts by some kind of filterpress action, the nature of which is not yet clearly understood[1].

The mechanism of layered intrusions.

The result of the sinking of crystals through basic magma under the influence of gravity is clearly seen in sills such as the Palisade Sill of New Jersey (22), and an appreciable sinking of crystals in a melt in the laboratory may be observed to take place in short periods of time (cf. for instance the sinking of diopside described by Bowen (23)). Cryptic layering and the special textural features due to primary precipitate and interprecipitate minerals might also be explained by direct sinking, to the bottom of a pool of magma, of crystals produced by cooling at the upper surface of the magma, provided there was sufficient stirring to keep the magma tolerably homogeneous.

Some sinking of crystals through magma under the influence of gravity seems to be an essential part of any hypothesis of formation of layered intrusions, but for the Skaergaard intrusion, the existence of convection currents which move bodily certain already formed crystals, have been postulated as a contributory factor. Enrichment in heavy crystals near the margin of the layered series compared with the same horizon nearer the centre (1, pp. 40 & 263), is a feature not to be explained by vertical sinking. Also the average size of the plagioclase at any one horizon increases from the margin towards the centre of the intrusion (1, pp. 71 & 263) and there seems no reason for this if only vertical sinking were in-

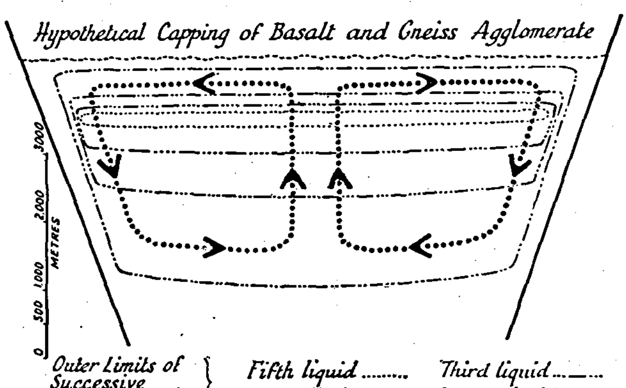


Fig. 6. Section of the Skaergaard intrusion showing the suggested arrangement of the convection currents at a middle stage in the solidification corresponding to the so called second residual liquid.

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[1]) Since writing this Professor H. H. Hess of Princeton, U. S. A., has suggested a different, and highly likely explanation which he is adopting for certain rocks of similar type found in the Stillwater Complex.

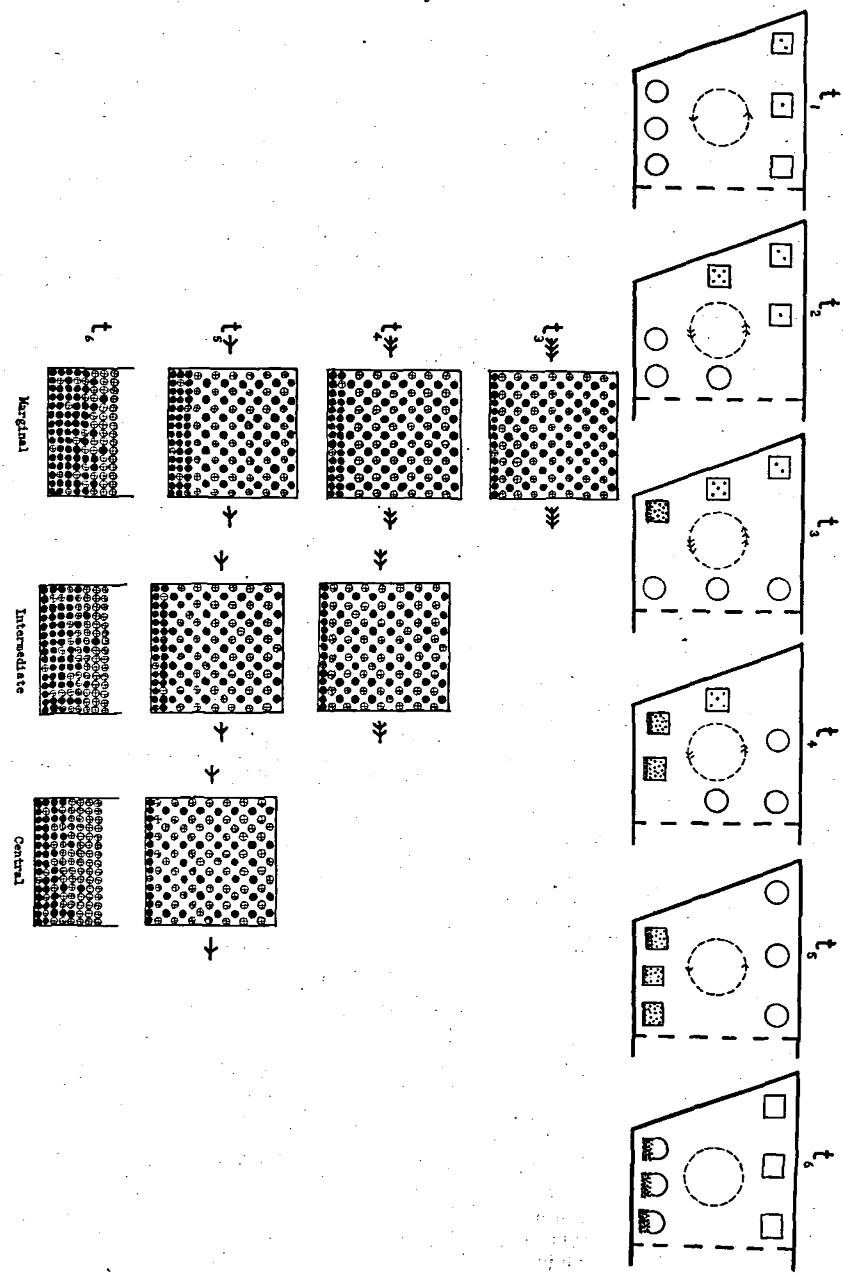

Fig. 7. Suggestion for mechanism of formation of a gravity stratified layer as the result of a convective half turn over of the magma. The top row of the diagram shows vertical cross sections of half the Skaergaard magma pool at six successive

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volved. In the original monograph these phenomena and others such as igneous lamination and trough banding were considered to indicate the existence of significant currents in the magma (1, pp. 262–89).

Convection currents, as diagrammatically shown in fig. 6, descending near the margin and rising near the centre, are postulated to have existed over much of the period of deposition of the Skaergaard layered series. Crystals would begin to form due to cooling in the upper part of the magma and would continue to form during descent in the convection current as a result of increasing pressure. As the current moved, with varying velocity, across the floor of the magma pool the crystals are considered to have settled, under the influence of gravity, a short distance through the magma to accumulate on the floor of the intrusion. In the original paper (1, pp. 272–3) we postulated that variation in the velocity of the currents would cause variation in the proportion of the heavy and light constituents deposited at any particular place, thus giving rise to the rhythmic banding. Pulsatory variation in the velocity of convection currents seems to be one of their characteristic features, and in these pulsatory changes in velocity there seems to be a factor as variable as rhythmic banding itself.

In an attempt to illustrate the conception of the origin of the rhythmic layering by convection currents the diagram, fig. 7, has been prepared. It represents the supposed conditions during the formation of the layered series below the trough banding horizon, where the layers form extensive and roughly plane surfaces and where there is a feeble, gravity stratified, rhythmic layering such as illustrated in the original paper (1, Plates 6 & 7). A single gravity stratified layer is considered to be produced during a half turn over of the magma, when the convection currents vary from low or zero velocity to relatively high velocity and back to low or zero again. Mainly heavy crystals are precipitated during the time of more vigorous movement and more are precipitated near the margin than towards the centre. Then when movement ceases, or is much reduced all the crystals which are denser than the bottom layer of liquid in which they are suspended, sink and eventually come to rest on the floor of the intrusion. The

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stages, the relative velocities of the convection currents being indicated diagrammatically by the number of arrows on the inner circle. Three cooling units of magma at the top of the intrusion are shown (squares) and three warming up units at the bottom (circles). A few crystals form in the top units due to cooling and the number and size of the crystals increase during descent because of the increasing pressure. Deposition of crystals takes place during t_3–t_6 stages, and details are shown in the lower part of the diagram. At t_3 stage heavy crystals (black circles) and light crystals (light circles) are shown in suspension in the liquid with some crystals, mainly the heavy ones, already deposited. In t_4 and t_5 stages deposition of mainly heavy crystals continues near the margin and spreads inwards. At t_6 stage with reduced, or zero current the remaining crystals in the lower layer of liquid are deposited, the heavier crystals being more abundant in the first precipitate and light crystals, later. The thickness of material deposited is the same near the margin as near the centre, the form of the layering being adjusted so that this is possible, but the marginal part of the layer is more melanocratic than the central. Whether near the margin or near the centre the layer shows gravity stratification, but in both situations the material of a layer is shown as deposited under two slightly different sets of conditions, a point which has not yet been demonstrated in the field.

rate of sinking of the heavier crystals is faster than the light so that the layer of crystal precipitate is gravity stratified. Circulation of the magma then begins again, or speeds up and the cycle is repeated. If the fluctuations in velocity of the convection currents be small, then rhythmic layering will be less well marked, and a more or less uniform rock will result from steady velocities, the crystals sinking uniformly through the lower part of the liquid on to the temporary floor.

At the middle ferro-gabbro stage, just below and during the formation of the trough banding, the rhythmic layering is at times extreme. Examples of this which were much photographed and can be collected in reasonable-sized specimens are not typical of the banding in most of the intrusion. This extreme rhythmic layering may be formed in a manner generally similar to the usual type considered above, but perhaps other factors such as a winnowing action by the currents were also involved and were responsible for the strong differentiation into almost pure melanocratic or leucocratic primary precipitates.

In the case of the Bushveld some sinking of crystals is generally postulated but a serious attempt to work out the implications of a convection current hypothesis has not yet been made although I believe it will prove of value. While the general sequences over the whole Bushveld area seem fairly constant there are significant differences in different sectors. Because of the great lateral extent of the Bushveld compared with its thickness no single system of convection currents would be established but instead a series of convection cells should form whose boundaries might well not be constant. If this were the case then the sequence of crystals deposited in the different cells would probably not be identical, although generally similar. Furthermore lateral migration of the convection cell walls might well produce results similar to a new influx of magma, which is a hypothesis frequently adopted by investigators of the Bushveld complex.

The characteristics of the Skaergaard type of layered series have been given above as objectively as possible in terms of such ideas as cryptic layering and primary precipitate and interprecipitate minerals. When the observational data are further generalised with a view to deciding what is the fundamental characteristic of a layered series, it appears that it is the way in which they are built up, from the bottom to the top, by successive precipitation of discrete crystals or clusters of crystals. This seems to be an alternative definition of a layered series but one which can obviously only be used when the work on any particular intrusion has gone far enough to enable such an origin to be effectively established. Moreover, in practice, the fact that no layered rock is ever entirely composed of primary precipitate minerals, but always includes a proportion of interprecipitate material, complicates the interpretation of the mineralogical, chemical and textural features.

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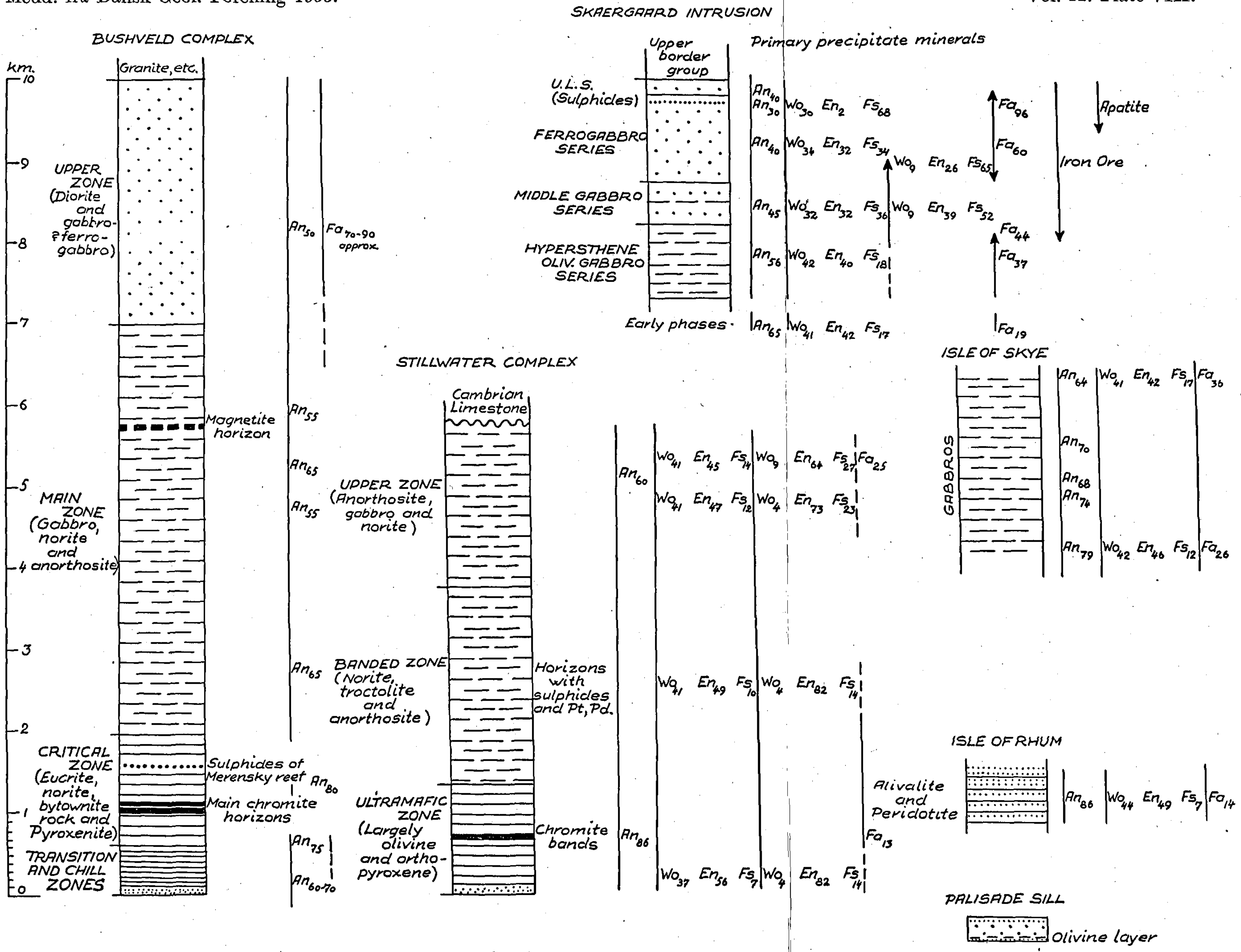

Comparative vertical sections of certain layered intrusions with an indication of the composition of some of the minerals. (Much of the data on thicknesses and mineral compositions are highly generalised).

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Færdig fra trykkeriet den 18. august 1953.