The form and internal structure of the alkaline Kangerdlugssuaq intrusion, East Greenland

With Plate XIII

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Summary. The Kangerdlugssuaq intrusion (68′ 20′ N. 32′ 30″ W., roughly circular and 33 km across) is of Tertiary age, like the nearby Skaergaard intrusion. At the present level of erosion the outer part is of nordmarkite and inwards there are successive rings of transitional pulaskite (without quartz or nepheline), main pulaskite and, in the centre, foyaite. The different rock types are due to gradual changes in the amounts of certain of the minerals and there are no sharp junctions such as would be expected to result from successive injections.

Zones of inclusions of basalt, fallen from above, dip inwards at 30 to 60° and, in places, there is a platy parallelism of the tabular alkali feldspars dipping similarly inwards. The three-dimensional form of the intrusion is pictured as resembling a pile of saucers of decreasing size, the sequence of formation being from the outer saucer of nordmarkite to the inner, and smaller saucers of increasingly nepheline-rich syenites. Bottom accumulation of crystals is postulated to explain the disposition of the rock types, but the cause of the succession from quartz-bearing to felspathoidal syenites remains uncertain.

NEPHELINE-bearing syenites were found by the writer during the Watkins Expedition of 1930, on the west side of Kangerdlugssuaq fjord in east Greenland, about 20 miles from the layered basic complex which has since been named the Skaergaard intrusion. In 1932, accompanied by his brother, a further examination of the region was made and it was established that the nepheline-bearing rocks formed part of a large intrusion exhibiting a sequence of syenites from nordmarkites to pulaskites. In 1935–36, with the collaboration of W. A. Deer, the intrusion was mapped (1937, pp. 401 and 408) and shown to be a series of rings of considerable regularity, the outer being of nordmarkite which passes gradually into syenite, free from quartz, and then into syenite with increasing amounts of felspathoids, until an innermost foyaite is reached. Because of the gradualness of these changes, and the disposition of the various rock types, it was considered, at that time, that the change from a quartz syenite to an undersaturated nepheline–sodalite syenite was probably the result of crystal fractionation.

Much preliminary laboratory work was done in the 1940's by the present writer and by Professor W. A. Deer who analysed some twenty rocks and several of the rarer pegmatite minerals. However, before presenting the results, it seemed desirable to visit the intrusion again, and it was also decided that the responsibility for further investigation and description of the Kangerdlugssuaq intrusion should rest with the present writer while responsibility for the nearby Kap Edvard Holm intrusion, a basic layered complex with two large fayalite quartz-syenite masses intruding it, on which, until then, both of us had been collaborating, should become the responsibility of Professor Deer. In 1953, the alkaline intrusion was revisited; this confirmed previous field observations, and further material was collected. Because of Professor Tilley's deep interest in the origin of the alkali rocks, we have kept him generally informed of the progress of our investigations, and he has repeatedly exhorted us to give some account of the intrusion. It is thus a particular pleasure to present this preliminary account of an aspect of the Kangerdlugssuaq alkaline intrusion in a volume dedicated to him.

Field relations

The intrusion, which it seemed appropriate to call the Kangerdlugssuaq intrusion since it is the biggest Tertiary igneous complex in the neighbourhood of the fjord, is exposed as steep-sided mountains rising 500 to 1000 m out of fairly level ice fields at about 1000 m above sea-level except where the glaciers descend steeply to the sea (plate XIII, fig. 1). The intrusion is approximately circular and about 33 km in diameter. The outer nordmarkite ring is in contact on the north-east side with an earlier intrusion of layered basic rocks and fayalite-quartz syenite, called the Kaerven intrusive complex, an account of which by G. M. Brown and D. N. Ojha will shortly appear. On the south-west margin, basic rocks and syenites seem to form a part of another early intrusion called the January Nunatak complex, which has been largely replaced by the Kangerdlugssuaq intrusion. On the east side of the intrusion, various granitic rocks, called the Snout complex, have apparently been emplaced subsequently. All the intrusions post-date the late Cretaceous and early Tertiary lavas of the region and belong to the East Greenland Thulean igneous province.

The small-scale map (fig. 1) shows the nordmarkite ring to be 11 km across on the west and narrowing to only 2 km adjacent to the Kaerven intrusion. The outer contact is outward dipping or vertical and the adjacent gneisses of the metamorphic complex are found to be only slightly metamorphosed. The inner rings of pulaskite and the central mass of foyaite are together 14 km in diameter and also asymmetric.

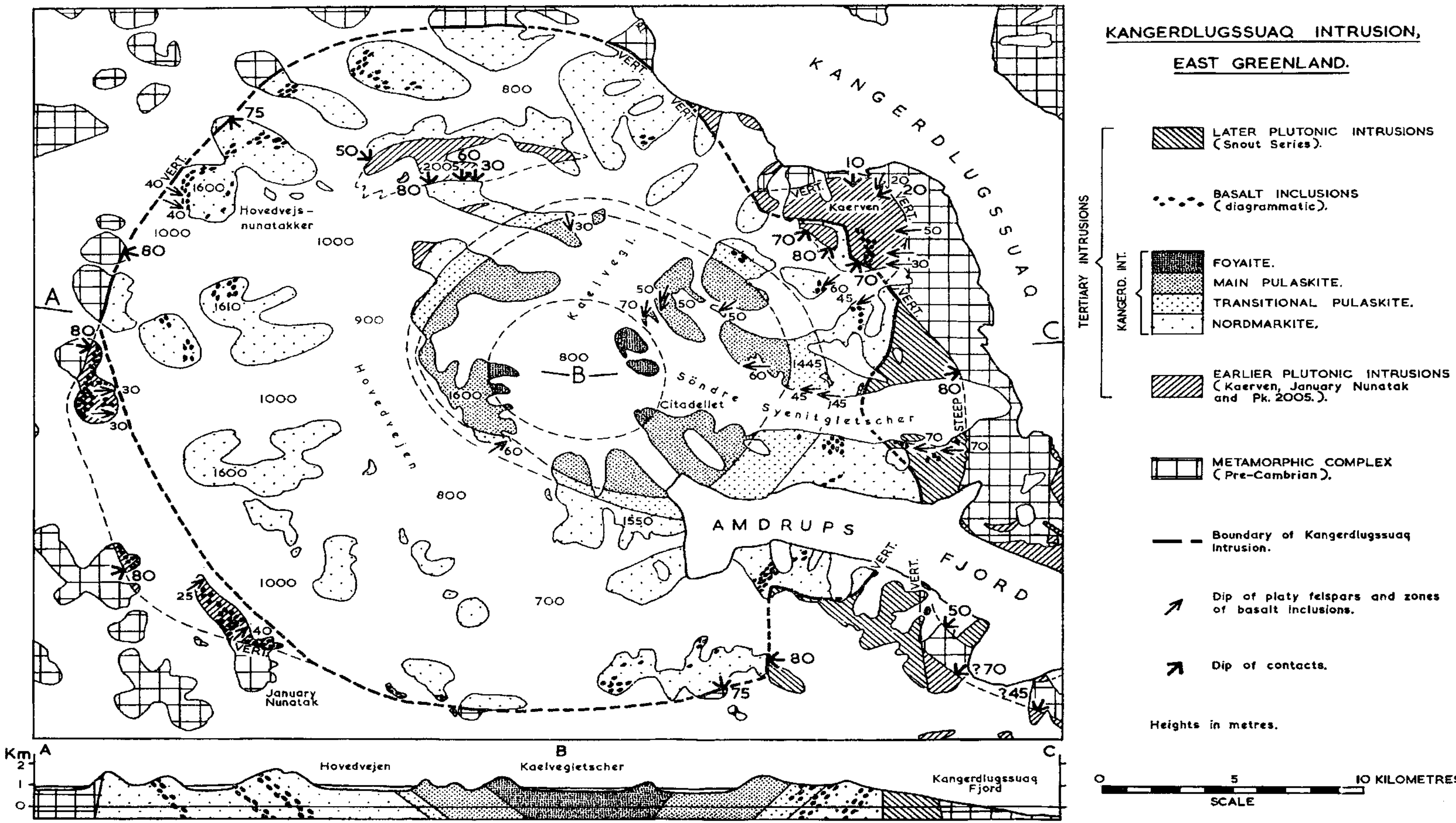

Fig. 1. Map and section of Kangerdlugssuaq intrusion, east Greenland.

The various rock types grade into each other and the boundaries between the successive rings as given on the map, mark only the general position of gradational boundaries. On the last visit to the area in 1953, further attempts were made to find if there were any evidence for successive injection of different magmas but, despite the good exposures, none was found.

Clusters of basalt inclusions occur sporadically in the quartz nordmarkite and to a lesser extent in the transitional pulaskite, but are absent in the inner, more alkaline syenites. These inclusions must clearly come from the thick spread of Thulean basalts which is still preserved to the north-west, north, east, and south-west of the intrusion (see map in Wager, 1947, plate 6). Although the Kangerdlugssuaq intrusion, at the present level of erosion, is nowhere in contact with the basalts but only with the basement metamorphic complex and other Tertiary intrusions, it is apparent that the intrusion penetrated a considerable way into the originally overlying lava series. The basalt inclusions, varying from hundreds of metres across to small fragments, tend to occur in zones in which basalt is more abundant than the surrounding syenite. The zones of inclusions dip inwards at 40 to 50 degrees (plate XIII, fig. 2) and dips of some of the better defined zones are shown on the map. This structural peculiarity is interpreted as the result of the sinking inclusions coming to rest on solidified syenite, the temporary top surface of which had an inward dip of about 40–50°.

Although the majority of rocks of the intrusion show no obvious directional structures, strong parallelism of tabular feldspars is found at certain places especially in the north-east sector. For example along the north side of Söndre Syenitgletscher most of the rocks show inward dips of the parallel feldspars of 30–60°. Slight to marked parallelism of tabular feldspars is also found in the northern and south-western sectors of the pulaskite rings although the greater part of the rocks show no obvious igneous lamination. The directional structures shown by the feldspars have a similar disposition to the zones of basalt xenoliths and they are believed to result, either from the laying down of tabular feldspars on the successive inwardly inclined top surfaces of already solid material, or by flow of the magma containing primocryst feldspars parallel to such a surface, or by a combination of these processes.

The chief rock types

The earliest and most abundant rock type is the *nordmarkite* of the outer ring. This is a grey to fawn-coloured, fairly coarse-grained rock which is usually slightly miarolitic. The outer part of the nordmarkite ring has about 10 % of modal quartz and this decreases steadily inwards to a vanishing point which is taken as the inner limit of the nordmarkite. Alkali feldspar forms 75–95 % by volume of the rock and is largely perthite and cryptoperthite with fringes of sodic plagioclase. In some rocks there are sporadic, large, dark cryptoperthites which are regarded as porphyroblastic rather than porphyritic. They contain small inclusions of pyroxene and hornblende which are not the alkaline types properly belonging to the rock. Large cryptoperthites with similar inclusions are seen to have developed as porphyroblasts in many of the altered basalt inclusions and it seems virtually certain that the complete disintegration of the inclusions is the reason for the scattered large cryptoperthites found in many parts of the nordmarkite, particularly the inner part. Less definite and smaller patches of cryptoperthite, somewhat different from those just described, are widespread from the outermost nordmarkite to the beginning of the main pulaskites. They do not seem to have been derived from basalt inclusions and it is suggested tentatively that they formed during the metasomatism of inclusions of the grey gneiss from the metamorphic complex.

The chief ferromagnesian mineral of the nordmarkites is alkali amphibole. There is sometimes subsidiary aegirine and biotite, the latter being noticeably commoner near the inner limit of the nordmarkite ring. Iron-ore, apatite, and, rarely, sphene are the chief accessories.

Inwards from the inner limit of the nordmarkite there is a ring of *pulaskite* which varies steadily in character and composition centripetally. The outermost part, described as the transitional pulaskite, is a felspathoid-free syenite and, with the incoming of a trace of nepheline, this passes gradually into the main pulaskite. The amount of nepheline increases inwards until at about 5 % nepheline by volume we have drawn the arbitrary limit of the pulaskite, the rock further inwards being called foyaite.

The different rock types shown on the map and used for descriptive purposes are simply arbitrary divisions of a systematically varying assemblage of minerals. Thus the quartz in the nordmarkite becomes gradually reduced in amount centripetally until, on a square yard of a glaciated surface, when scrutinized closely, only one or two interstitial fragments can be seen. A little further inwards none is found, and for a distance of a kilometre or so the rock is free from both quartz and felspathoids. The incoming of felspathoids is equally gradual; thus inwards from the felspathoid-free syenite, nepheline or its interstitial alteration products, makes its first appearance in sporadic traces, and from there inwards increases steadily in amount.

The abundant alkali feldspars of the pulaskites are perthites, the size of which is on average greater than that of the nordmarkites. In fact, away from a narrow, chilled, marginal zone of the intrusion, the average size of the perthites increases centripetally reaching a maximum in the main pulaskite (about double the size of those in the outer nordmarkite) and then decreasing in the foyaite. Rather indefinite porphyroblastic cryptoperthites occur in the outer pulaskite but disappear before the foyaites are reached. Aegirine and biotite equal, or exceed, in amount the alkali amphibole in the main pulaskite. The nepheline is interstitial and so also is the small amount of sodalite which is found mainly in the north-east sector. Sphene is an abundant accessory.

Where the amount of felspathoidal minerals in the pulaskites reaches about 5 % we have placed the boundary between them and the *foyaites.* Although the foyaite area is largely ice covered and evidence limited, the amounts of nepheline and sodalite increases inwards, and typically the foyaites have thirty or forty per cent. of felspathoids. Sodalite tends to occur as small well-shaped crystals. Nepheline is in larger units than in the pulaskites and is more idiomorphic in habit. The dominant ferromagnesian mineral is zoned aegirine, but melanite, astrophyllite, and alkali amphibole, rather different in type from that in the rocks of the outer rings, also occur. The rock is heterogeneous due to the development of indefinite pegmatitic streaks.

A wide range of pegmatites and contemporary veins cut all the rocks of the intrusion. They will not be described here but it may be noted that the quartz-bearing aplitic and pegmatitic veins are confined to the nordmarkite. Alkaline pegmatites, usually nepheline bearing and tending to occur as rather flat and outward dipping sheets of several different kinds, are commonest in the pulaskites but can occur in all the rocks, one example was even found in the metamorphic complex outside the intrusion.

The petrology of the graded series of rocks developed in the Kangerdlugssuaq intrusion will be more fully described after the completion of an investigation of the mineralogy which is at present being undertaken by Mr. D. R. C. Kempe at Oxford.

The three-dimensional disposition of the rock types and its petrogenetic implications

The outer contact of the intrusion against the intermediate and acid gneisses of the Pre-Cambrian metamorphic complex is well seen in many places and is vertical or dips outwards, and as has been mentioned, the contact is sharp. Apparently the intrusion was developed by stoping, and clear evidence of some stoping action, at a late stage, is shown by the basalt xenoliths. In the cross-section (fig. 2) the unconformity between metamorphic complex and basalts is assumed to have been about 2 km above sea-level, for which there is evidence from the general

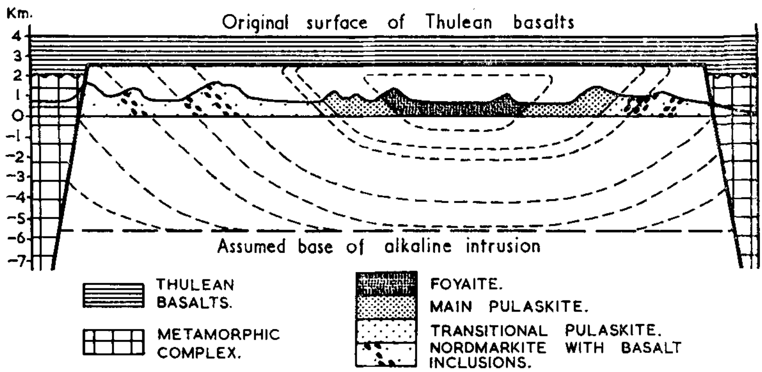

Fig. 2. Hypothetical section of the Kangerdlugssuaq intrusion. The height of the unconformity between the basalt lavas and the metamorphic complex is known from the evidence of the surrounding mountains. The former thickness of the basalt has similarly been estimated as 2–3 km. The alkaline magma is postulated as having stoped 0·5 km into the basalt. There is no direct evidence at present for the depth of the base of the alkaline intrusion; it is here assumed to be 5·5 km below sea-level so that the total thickness of the intrusion is assumed to have been 8 km.

structure and geomorphology of the region (Wager, 1947, pp. 31 and 38, and fig. 8); the intrusion is pictured as having stoped half a kilometre into the basalts which formerly lay above the gneisses.

The inward dipping accumulations of basalt xenoliths in the nordmarkites and outer pulaskites, and the similarly orientated igneous lamination, due to the parallel arrangement of the tabular feldspars, are regarded as indications of the disposition of the gradational junctions between the successive rock types. Observations in the field occasionally indicated the probable run of the junctions between rock types and they either confirmed, or did not preclude, the view that they had an inward dip. Thus the somewhat unexpected conception is reached of an internal structure in which the junctions between the different rock types dip inwards at 30–60°. In drawing the simplified and extrapolated cross-section given in fig. 2, an average inward dip of 45° has been assumed.

It has been remarked earlier (p. 489) that the basalt xenoliths must have accumulated on inward dipping surfaces of already solidified material, and that the igneous lamination equally implies a similarly inclined solid–liquid interface. Since cooling must be due to loss of heat upwards, it would at first be expected that solidification would be from the top downwards. However, until the time of formation of the main pulaskite the evidence from the occurrence of basalt blocks shows that the magma was stoping upwards; it would not, at the same time, be solidifying against the roof.

Evidence of the order of solidification of the different parts of the intrusion is also available from the distribution of the aplitic and pegmatitic veins; thus the nordmarkites are cut by nepheline-bearing pegmatites, presumably derived from the pulaskite and foyaite stages of the magma, while the inner, nepheline-bearing syenites are not found to be intruded by the quartz-bearing aplites and pegmatities. This provides confirmatory evidence that the nordmarkites solidified before the nepheline-bearing syenites. In what follows it will be assumed that solidification of the intrusion proceeded centripetally from the lower, outer parts consisting of nordmarkites, to the pulaskites, and finally to the foyaites at the centre.

The three-dimensional picture of the intrusion makes it clear that the volume of the nordmarkites must be much greater than that of the quartz-free syenites. The relative proportions will depend on the thickness of the intrusion. There is direct evidence for the initial height of the top surface since it lay within the overlying basalts but the position of the base of the syenites is at present unknown. In the cross-section given in fig. 2 the floor of the alkaline intrusion is arbitrarily placed $5\frac{1}{2}$ km below sea-level which makes the intrusion 8 km thick. With these assumptions the proportions of the various rock types may be estimated as approximately:

Nordmarkite	5700 km^3 or 88 % of the whole
Transitional pulaskite	250 km^3 or 3·9 % ,, ,, ,,
Main pulaskite	430 km^3 or 6·7 % ,, ,, ,,
Foyaite	90 km^3 or 1·4 % ,, ,, ,,

These proportions suggest that the average composition of the Kangerdlugssuaq intrusion corresponds to a quartz-poor nordmarkite. The initial magma would have had this composition also, unless gains or losses of constituents took place during solidification, a possibility mentioned below.

From the beginning of the pulaskite stage, the sequence of rock types is of the kind to be expected to result from crystal fractionation. Since the same process of side and bottom solidification occurred during the formation of the whole intrusion it is tempting to suppose that the whole

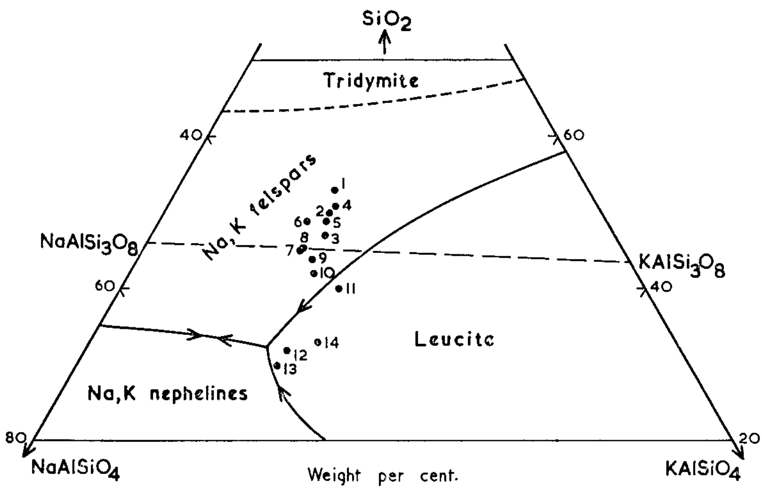

FIG. 3. Equilibrium diagram for part of the system $NaAlSiO_4$–$KAlSiO_4$–SiO_2 taken from Schairer (1950) on which are plotted, the normative proportions of fourteen analysed Kangerdlugssuaq syenites. The rocks are numbered in order from the margin to the centre, 1–6 are nordmarkites, 7 and 8 are transitional pulaskites, 9–11 are main pulaskites, 12–14 foyaites.

sequence, from quartz-bearing syenites to felspathoidal syenites, is also the result of crystal fractionation. During the field-work in 1935–36 and for long afterwards, this seemed the most likely hypothesis although there was little support for such a view from other studies of alkaline intrusions or from the relevant experimental work on the system: SiO_2–$NaAlSiO_4$–$KAlSiO_4$ done by Schairer (1950).

The chemistry of the intrusion is known from some twenty analyses by Professor Deer. These will not be presented until a more detailed account of the intrusion can be published but normative data from the fourteen analyses of the chief rock types have been superimposed on Schairer's SiO_2–$NaAlSiO_4$–$KAlSiO_4$ phase diagram (fig. 3). The numbers 1 to 14 refer to rocks in order of SiO_2 percentage, 1 to 6 being nordmarkites, 7 and 8 transitional pulaskite, 9 to 11 main pulaskite, and

12 to 14 foyaites. The analyses show a trend in the compositions of the rocks away from the quartz corner. If consideration is confined to those normative constituents shown on the diagram, the nordmarkites (1–6) plot appropriately in the alkali feldspar–quartz area, the transitional pulaskite (7 and 8) plots on the alkali feldspar-join, and the pulaskites and foyaites plot in the alkali feldspar–feldspathoid area. The Kangerdlugssuaq magma was certainly not anhydrous, in view of the presence of hydrous minerals, and direct comparisons with the experimental results for the dry system would be of doubtful value except that later work by W. S. Mackenzie, referred to by Tilley (1957, p. 330 and fig. 8, and the paper by Hamilton and Mackenzie in this volume), has shown that the presence of water under pressure does not radically alter the relationships observed in the dry system, apart from causing a marked contraction of the leucite field. In particular, at water-vapour pressures of up to 1000 kg/cm^2 at least the feldspar thermal barrier between the low-temperature granite and foyaite sinks remains. As a first approximation, therefore, the sequence of rocks of the Kangerdlugssuaq intrusion can be considered in relation to the anhydrous system, apart from the acceptance of a contracted leucite field.

From the transitional pulaskite (anal. 7 and 9) onwards the sequence of compositions roughly follow down the alkali feldspar surface to the nepheline–alkali feldspar sink (assuming the shrinkage of the leucite field). Such a sequence could be the direct result of crystal fractionation. On the other hand, the trend from the early nordmarkites to the pulaskites is up the alkali feldspar surface, which cannot occur as the result of crystal fractionation alone. It may be that the presence of the other components of the natural magma so modify the equilibria from those of the dry, three-component system that the feldspar thermal barrier disappears, in which case fractional crystallization could lead from quartz syenite to nepheline syenite. If this is not the case then it may be that other processes have caused desilication of the magma at the same time as crystal fractionation was proceeding. In the Kangerdlugssuaq intrusion, it is possible that desilication took place as a result of the magma reacting with the abundant basalt xenoliths; on the other hand it may be the result of the loss of silica from the intrusion along with water vapour,[1] a possibility suggested by Tilley for his Group B Alkaline Complexes (1957, p. 334), or possibly it may be due to the addition of elements from below of a kind which would reduce the concentration

[1] Experimental evidence indicating the possibility of this has been mentioned by Mackenzie (1960, pp. 383–384).

of silica in the magma relative to alkalis.[1] In this preliminary paper no attempt will be made to decide between these various possible petrogenetic hypotheses.

Throughout the whole period of crystallization of the Kangerdlugssuaq intrusion alkali feldspar was the dominant mineral forming, and all the rocks seem, from the textures, to have passed through a stage of being dominantly an accumulation of alkali feldspar crystals with some interstitial magma between them. In the nordmarkites the interstitial liquid crystallized to give chiefly more feldspar together with alkali amphibole and quartz. In the pulaskites it may be that the initial mush of crystals, although mainly alkali feldspar, included some ferromagnesian minerals and sphene, and the surrounding liquid of the mush crystallized to give more of these minerals and some felspathoids. In the foyaite, the mush of crystals seems likely to have consisted of an assemblage of alkali feldspars, ferromagnesian minerals, and probably nepheline and sodalite, and the surrounding liquid crystallized to give more of these minerals.

Using the evidence from the internal structure of the intrusion, and without going into detail on the mineralogy or petrology, it is possible to offer a broad picture of the mechanism of formation of this beautifully symmetrical complex of rocks. The intrusion has the internal structure of a succession of saucers of decreasing size, packed one within the other; the outer saucer was the first formed and then successively, those lying within. The intrusion, in fact, shares with layered intrusions a fundamental characteristic, namely, solidification from the sides, inwards, and from the bottom, upwards. The explanation recently given of the manner of formation of basic layered intrusions (Wager, 1963) can perhaps be applied, with suitable modifications, to the Kangerdlugssuaq intrusion. The most significant feature, common to the basic layered intrusions and to certain alkaline ones, is that the crystals formed or accumulated at the bottom of the liquid and not at the top where the heat loss must mainly have taken place. Had the magma solidified without movement of the magma or crystals then the solidification would undoubtedly have taken place from above, downwards. That this was not the manner of cooling of the basic layered intrusions or of

[1] This possibility is mentioned because, in considering the source of the original nordmarkitic magma of the Kangerdlugssuaq intrusion, it is thought likely that it was derived mainly by melting of the rocks formerly occupying the present position of the intrusion. These former rocks were the intermediate to acid gneisses of the metamorphic complex and these would require some sort of alkali metasomatism, as well as heat, to produce a magma of nordmarkitic composition.

the Kangerdlugssuaq alkaline intrusion seems to imply that a convective circulation developed in these intrusions, the currents rising at the centre and descending at the margins. In a circulating magma, crystals would begin to form either at the top, as a result of cooling, or during descent, as a result of increasing hydrostatic pressure. Wherever they may have formed the crystals had apparently a tendency to sink, produring a crystal mush, the top surface of which had a saucer-shape. In the case of the Kangerdlugssuaq intrusion, the only parts which can be seen are the edges of the saucers, dipping inwards at about 45°, the floor unfortunately not being exposed. The extent to which the crystals on the inclined floor were there as a result of sinking, or of growth in place is, at present an open question but it is believed that the internal structure of the alkaline Kangerdlugssuaq intrusion is to be explained by a mechanism of bottom accumulation similar in essentials to that postulated for basic layered intrusions.

Acknowledgements. Looking back to the early field work I wish to record my grateful thanks to Professor W. A. Deer for his very pleasant collaboration and subsequently for his help with the laboratory study, especially the analytical work. I also thank Dr. G. M. Brown for his helpful suggestions about the manuscript, and Dr. W. S. Mackenzie who, at a late stage in the writing of this paper, told me of his recent work on the system $NaAlSi_3O_8$–$KAlSi_3O_8$–$NaAlSiO_4$–$KAlSiO_4$–H_2O, published in this volume.

References

HAMILTON (D. L.) and MACKENZIE (W. S.), 1964. Min. Mag., this volume, p. 214.
MACKENZIE (W. S.) 1960. Liverpool–Manchester Journ. Geol., vol. 2, p. 369.
SCHAIRER (J. F.) 1950. Journ. Geol., Chicago, vol. 58, p. 512.
TILLEY (C. E.) 1957. Quart. Journ. Geol. Soc., vol. 113, p. 323.
WAGER (L. R.) 1937. Geograph. Journ., vol. 90, no. 5, p. 393.
—— 1947. Medd. om Grønland, vol. 134, no. 5, p. 5.
—— 1963. Min. Soc. Amer., Special Paper 1, p. 1.

EXPLANATION TO PLATE

PLATE XIII

FIG. 1. Looking south across the upper part of Söndre Syenitgletscher at the Citadellet formed of pulaskites.

FIG. 2. Cluster of basalt inclusions in nordmarkite dipping inwards at 40°, Hovedvejsnunatakker, NW. side of the intrusion. The locality is the more northerly of the 40° dip arrows. The photograph gives the impression of a higher dip for the zone of inclusion than is actually the case.

1

2

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