INTERNAL STRUCTURES AND GEOLOGICAL SETTING OF THE THREE AGPAITIC INTRUSIONS — KHIBINA AND LOVOZERO OF THE KOLA PENINSULA AND ILIMAUSSAQ, SOUTH GREENLAND

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Abstract

The sites of the three large intrusions of agpaitic nepheline syenites, Ilímaussaq, South Greenland (*ca.* 1000 m.y.) and Khibina and Lovozero, Kola Peninsula (*ca.* 300 m.y.) are first of all determined by intersecting fault systems and by discordances separating peneplaned Precambrian metamorphic complexes from overlying penecontemporaneous supracrustal rocks, including lavas. Ilímaussaq is associated with a rift zone. The three massifs represent the latest stages of intrusive activity in the two alkaline provinces, which explains their character as products of consolidation of residual melts derived from primary alkali basaltic magmas. The intrusions are of permitted discordant type. Khibina is a ring intrusion, Lovozero and Ilímaussaq are stratified intrusions which were at least partly emplaced by stoping. All three intrusions are composite, the individual complexes often display rhythmic layering. The intrusions are mineralogically, petrologically and geochemically related. The three intrusions may be interpreted as representatives of three stages of evolution of an agpaitic magma with Khibina representing the first stage, Ilímaussaq the second and Lovozero the third.

Introduction

In the alkaline magmatic provinces of the Kola Peninsula and of South Greenland there are large intrusions dominated by agpaitic nepheline syenites. These are the Khibina Intrusion measuring 1327 km^2, the Lovozero Intrusion measuring 650 km^2 in Kola and the Ilímaussaq Intrusion measuring about 100 km^2 in South Greenland.

The term agpaitic was introduced by Ussing (1912, p. 341) for nepheline syenites having $\frac{Na_2O + K_2O}{Al_2O_3} \geqq 1.2$ (as molecular proportions). Fersman (1929) widened the group of agpaitic nepheline syenites to cover all peralkaline nepheline syenites, *i.e.* all having an agpaitic coefficient higher than 1. The present author (Sørensen 1960) has emphasized the importance in this rock group of complex Zr-Ti-silicates such as eudialyte and rinkite. The use of the term should therefore be restricted to those peralkaline nepheline syenites containing complex rare-metal silicates. The mineralogy of the agpaitic rocks indicates that crystallization took place under high volatile pressures. Agpaitic phonolites are consequently rare (Azambre & Girod 1966).

Agpaitic rocks are of rather rare occurrence and are in some alkaline provinces confined to late pegmatites in complexes built up of more usual nepheline syenites; examples are the Oslo Province of Norway and the Igaliko composite intrusion in South Greenland.

THE PALEOZOIC ALKALINE PROVINCE OF THE KOLA PENINSULA

There are numerous occurrences of alkaline rocks in the Kola Peninsula, ranging in age from 2420 m.y. to about 300 m.y. (*cf.* Kukharenko *et al.* 1965, and Gerassimovsky *et al.* 1966 and in preparation). Only the intrusions of Paleozoic age will be considered in this paper (see table I and fig. 1).

The alkaline province is made up of a group of small ultramafic intrusions, the two large agpaitic intrusions of Khibina and Lovozero, suites of thin dykes, and small occurrences of Paleozoic volcanic rocks (with associated sediments) in Kandalaksha Fjord and in xenoliths in the Lovozero and Kontozero Intrusions.

The sediments are mainly conglomerates and sandstones which by means of plant fossils have been dated to the upper Devonian or lower Carboniferous. The Lovozero series of volcanic rocks is made up of porphyritic picrite, augite porphyrite, alkali basalt, trachyte and phonolite. On the Turij Peninsula there are also melilite-bearing basalts. Volcanic rocks may have covered large parts of the Kola Peninsula in upper Paleozoic times, since dykes of alkali basalt, *etc.* are fairly widespread.

The ultramafic intrusions are all composite and measure up to a few km in diameter. They are made up of two groups of rocks, an older composed of ultramafic rocks (peridotite, pyroxenite and nepheline pyroxenite) and a younger of urtite-ijolite-melteigite. The ultramafic rocks often form the cores of the intrusions while the ijolite series form marginal rings and also veins. These ring intrusions may have the shape of inverted cones. There are, furthermore, young veins of nepheline syenite, melilite-bearing rocks, magnetite-rich rocks and carbonatites. The average composition of these intrusions is close to that of melilitite. According to Bogdanov & Sorokina (1967) these intrusions may be 20-200 km deep.

TABLE 1. THE PALEOZOIC ALKALINE INTRUSIONS OF THE KOLA PENINSULA

Name of intrusion	Major rock types	Age (m.y.)	Method	Reference
Sebljavr	pyroxenite, ijolite, carbonatite	383	K/Ar (phlogopite)	1
Salmagorsk	peridotite, pyroxenite, ijolite, melilite-rocks	375	He	2
Pezotchnaja	peridotite, pyroxenite, urtite			
Ozernaja Varaka	pyroxenite, melteigite, ijolite, carbonatite	338	He (schorlomite)	3
Afrikanda	pyroxenite, melteigite	249-358	He (knopite)	3
		391-426	K/Ar (phlogopite)	1
Lesnaja Varaka	peridotite, pyroxenite, ijolite, carbonatite			
Kovdor	peridotite, pyroxenite, ijolite, melilite rocks, carbonatite	370	He (schorlomite)	2
Turij Peninsula	dykes of alkali basalt, nephelinite, nepheline syenite, turjaite, etc.	294-393	K/Ar (biotite)	1
Kandalaksha Islands	alkali basalt, lamprophyre			
Kovdozero	ijolite-melteigite			
Vuorijarvi	peridotite, pyroxenite, ijolite, carbonatite	380-402	K/Ar (phlogopite)	1
Sallanlatvin	ijolite-urtite, carbonatite, vermiculite			
Kontozero	nepheline syenite, ijolite-melteigite, lava	330-410	Whole rock K/Ar	1
Soustova	syenite, nepheline-analcime syenite			
Khibina	nepheline syenite, urtite, ijolite	280	He (loparite)	3
		300	K/Ar (alkali feldspar)	1
Lovozero	lujavrite, nepheline syenite, urtite, lava	231-266	He (loparite)	3
		298-303	U-Th (loparite)	3

1. Polkanov & Gerling (1960) ;
2. Kucharenko *et al.* (1965) ;
3. Gerassimovsky *et al.* (1966).

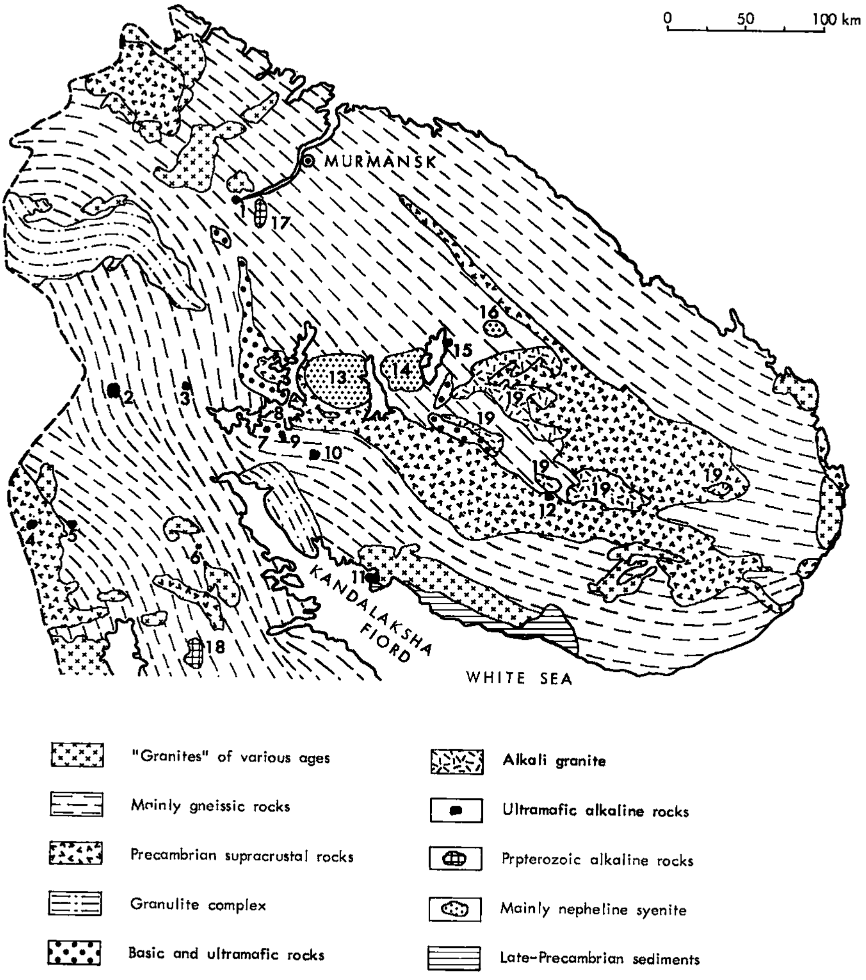

FIG. 1. Simplified geological map of the Kola Peninsula, based partly on map published by Kukharenko *et al.* (1965). The alkaline intrusions are indicated by numbers: 1. Sebljavr; 2. Kovdor; 3. Mavrgubinsky; 4. Sallanlatvin; 5. Vuorijarvi; 6. Kovdozero; 7. Afrikanda; 8. Ozernaja Varaka; 9. Lesnaja Varaka; 10. Salmagorsk; 11. Turij Peninsula; 12. Pezotchnaja; 13. Khibina; 14. Lovozero; 15. Kurga; 16. Kontozero; 17. Gremjacha-Vurmes; 18. Yeletozero; 19. Keivy alkali granites.

THE PRECAMBRIAN ALKALINE GARDAR PROVINCE OF SOUTH GREENLAND

The alkaline province of South Greenland is made up of numerous dykes, lavas (with associated sandstones) and of a number of composite intrusions (table 2 and fig. 2). The rocks formed during this cratogenic period were named the Gardar formation by Wegmann (1938). This time interval is consequently termed the Gardar period (*cf.* Sørensen 1965 and Watt 1966).

TABLE 2. THE PRECAMBRIAN ALKALINE GARDAR PROVINCE OF SOUTH GREENLAND

Name of intrusion	Major rock types	Age (m.y.)	Method	Reference
Ivigtut	alkali granite, pegmatite, cryolite	1260	Rb/Sr (whole rock)	1
		1160-1210	Rb/Sr (biotite)	1
Grønnedal-Îka	nepheline syenite, carbonatite	1170-1210	K/Ar (biotite)	2
Nunarssuit	syenite, granite, alkali granite, gabbro	1128	K/Ar (biotite)	1
		1150	Rb/Sr (biotite)	1
Kûngnât	syenite, alkali gabbro	1170	Rb/Sr (biotite)	1
Puklen	syenite, alkali granite			
Tugtutôq	syenite, alkali granite			
Narssaq	pyroxenite, gabbro, syenite, alkali granite			
Igaliko	nepheline syenite, syenite			
Klokken	alkali gabbro, syenite			
Ilímaussaq	syenite, alkali granite, nepheline syenite, agpaitic nepheline syenite	1012-1030	Rb/Sr (Li-mica)	1

1. Bridgwater (1965) ;
2. Larsen (1968).

A series of continental sandstone, 1500 m thick, overlain by a sequence of basalt, at least 1500 m thick, is only preserved in a down-faulted area around the Ilímaussaq intrusion. The basalts display alkaline tendencies but this may be due to contact alteration caused by the Ilímaussaq intrusion.

Volcanic rocks may have covered large areas in South Greenland as is seen from xenoliths in the Tugtutôq, Nunarssuit and Kûngnât intrusions (Watt 1966, p. 14) and from numerous swarms of parallel dykes mainly of

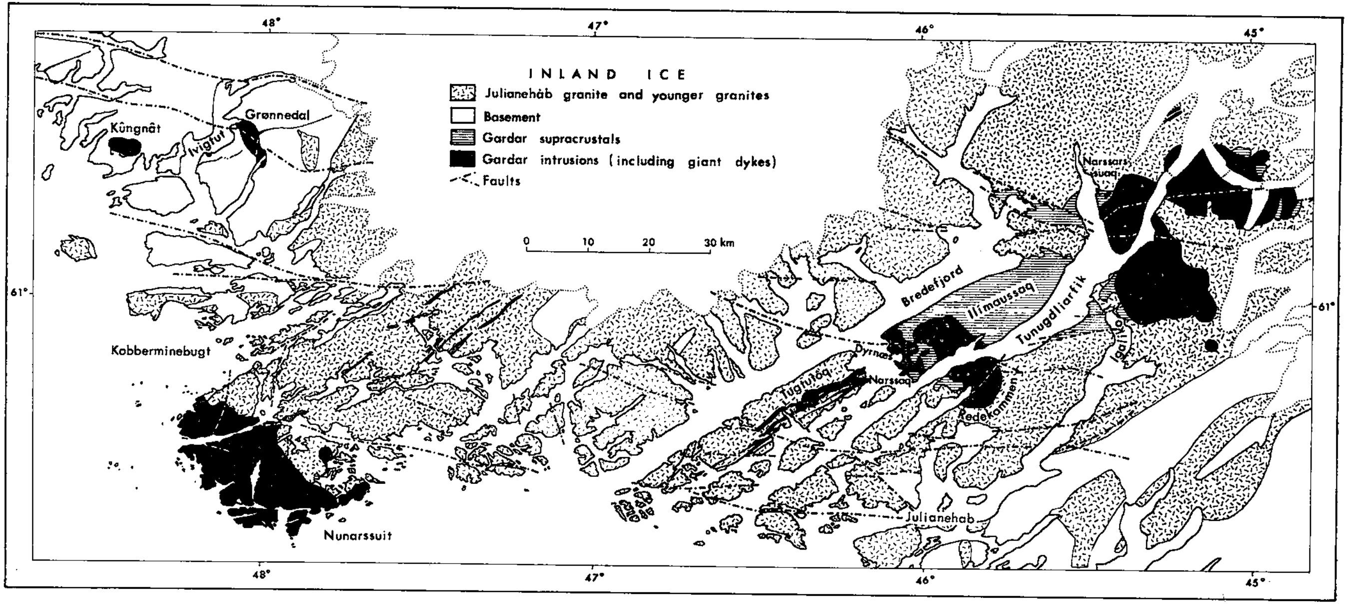

FIG. 2. Simplified geological map of the Gardar alkaline province, South Greenland based on the maps of the Geological Survey of Greenland.

olivine dolerite. Dykes are especially numerous in NE-directed zones around Ivigtut, Nunarssuit and Ilímaussaq. In the two last-named zones there are composite giant dykes composed of marginal olivine gabbro and syenite or nepheline syenite.

Bridgwater (1965) and Bridgwater & Harry (1968) have suggested the following chronological evolution of the Gardar period :

Early Gardar : sandstone, lava, the Grønnedal-Íka nepheline syenite intrusion, a nepheline syenite-gabbro giant dyke of Tugtutôq, dykes of lamprophyre, gabbro and carbonatite, possibly the first intrusive phases of the Igaliko intrusion. Augite from dolerite and biotite from lamprophyre have given K/Ar-ages of 1435 (excess Ar?) and 1275 m.y., respectively (Bridgwater 1965 ; Larsen & Møller 1968).

Mid Gardar : several generations of olivine dolerite dykes, sometimes as giant dykes with syenitic or granitic centres ; thin composite syenite-dolerite dykes with centres of dolerite, dykes of microsyenite, comendite, phonolite, small intrusions of gabbro, syenite and alkali granite at Narssaq. Xenoliths of anorthosite are numerous in the basic dykes from this period (Bridgwater & Harry 1968).

Late Gardar : emplacement of the major intrusions of Nunarssuit, Kûngnât, Tugtutôq, Ilímaussaq, Puklen, the youngest phases of Igaliko, and perhaps Ivigtut. Few thin dykes of syenite, tinguaite etc.

The petrochemistry of the Gardar province is discussed by Watt (1966) and Upton (in preparation).

GEOLOGICAL SETTING OF THE KHIBINA AND LOVOZERO INTRUSIONS

The Kola Peninsula is made up mainly of Precambriam gneisses, granites and schists (Polkanov 1937 ; Polkanov & Gerling 1960). There is a basement of gneiss, schists, gabbro-anorthosite, basic intrusive rocks and granites. According to Gerling *et al.* (1968) these rocks give K-Ar ages of 2600-3600 m.y.

Overlying this basement there are schists and metamorphosed volcanics, now preserved in narrow north-west-striking synclinorial belts, the Keivy belt made up mainly of kyanite gneisses and schists and the Petchenga-Imandra-Varsuga belt made up mainly of volcanic rocks. These supra-crustal rocks were folded and metamorphosed during the Karelian orogenic episode and are cut by granites giving K-Ar ages of 1700-1900 m.y. The alkaline intrusions Gremjacha-Vurmes and Eletozero and the alkali granites of Keivy give K-Ar ages of 1600-1800 m.y. (Gerassimovsky *et al.* 1966 and in preparation ; Kukharenko *et al.* 1965).

Zhdanov (1968) suggests that the rocks of the Petchenga trough are of lower Paleozoic age and that deformation of these rocks and their adjoining rocks is of Caledonian age. He also suggests that the "granite" layer of the crust is lacking under parts of the Petchenga trough and under parts of the "granulite formation" (see fig. 1). The latter also contains norite and gabbro anorthosite.

The partly reactivated rocks of the gneissic basement now form anticlinorial belts between the above-mentioned synclinorial belts and are also preserved along the north coast of the peninsula and to the south on both sides of the White Sea (the Belomoridian zone).

In Paleozoic times the Kola Peninsula was foreland to the Caledonian mountain belt. The marginal part of the shield (platform) of Precambrian rocks was intersected by faults along which the alkaline intrusions were emplaced (Vorobieva 1960; Sheynmann *et al.* 1961).

The small ultramafic intrusions are found mainly in the Belomoridian complex at the intersections of NW-SE faults (or boundaries of Precambrian complexes) and E-W faults (Kukharenko *et al.* 1965).

The Lovozero Intrusion is situated at the intersection of a NE-SW zone within which Paleozoic supracrustals have subsided and N-S tectonic zones containing the lakes Umpozero and Lovozero. The intrusion is located in a zone of weakness between the basement and a cover of Paleozoic supracrustals.

The Khibina Intrusion is located in the contact zone between the Karelian Imandra-Varsuga synclinorium and an anticlinorium of Belomoridian gneisses. Xenoliths of volcanic rocks may represent Proterozoic volcanic rocks or rocks of the Lovozero volcanic series. In the latter case the intrusion may as the Lovozero Intrusion be located at the contact between a basement of Precambrian rocks and a cover of Paleozoic volcanics.

Geophysical data indicates that the Khibina and Lovozero intrusions are not connected at depth (Shablinsky 1963). Kandalaksha Fjord is considered to be a graben zone bounded by NW-SE faults.

Volotovskaya (1967) and Kukharenko (1967) point out that the alkaline rocks of the Kola Peninsula are situated in a graben-like zone. This northeasterly trending zone of deep faulting is in Kola marked by a sudden change in depth of the Mohorovičić discontinuity and also by the gravitational and magnetic anomaly contours. Paleozoic supracrustal rocks are confined to this zone.

The zone may be traced towards the southwest through Finland and Sweden to the Oslo graben. The alkaline rocks of Sweden and Finland

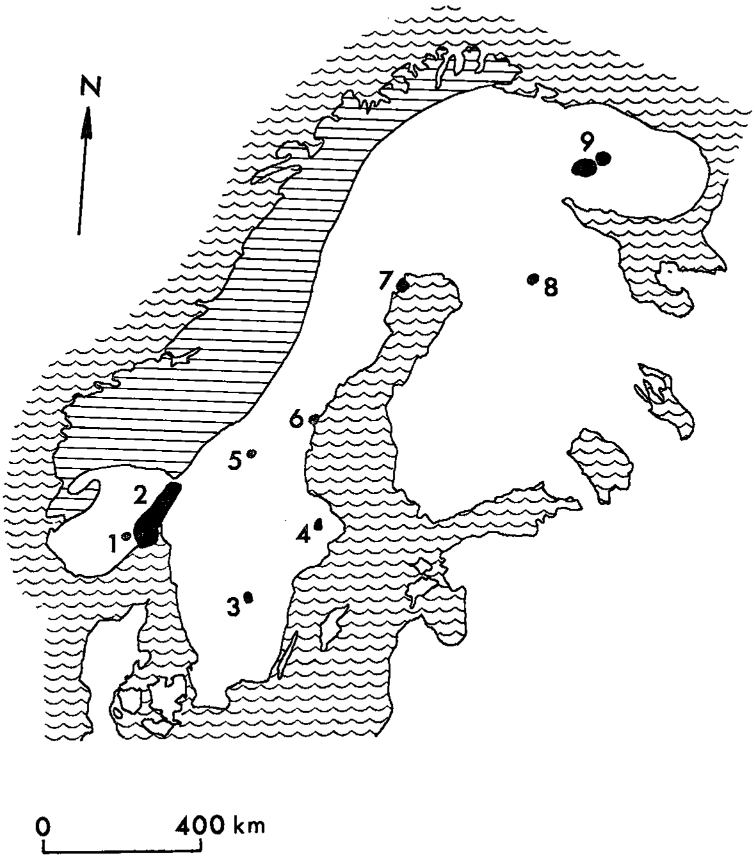

FIG. 3. Sketch map of Scandinavia indicating the known occurrences of alkaline rocks and the marginal thrust zone of the Caledonian mobile belt. (Horizontal Ruling: Caledonian belt; 1. Fen; 2. Oslo; 3. Norra Kärr; 4. Almunge; 5. Särna; 6. Alnö; 7. Kalix; 8. Iivaara; 9. Kola).

are situated in this zone which parallels the marginal thrust zone of the Caledonides of Scandinavia (fig. 3).

GEOLOGICAL SETTING OF THE ILÍMAUSSAQ INTRUSION

South Greenland is made up of the deep zones of a mobile belt termed the Ketilides by Wegmann (1938). The Ketilidian supracrustal series is more than 6000 m thick and is composed of a lower group of sediments and an upper group of basaltic lavas. In the northern part of the map area (fig. 2) the pre-Ketilidian basement is made up of gneisses with layers of gabbro anorthosite. This basement gives K/Ar-ages of 2500 m.y. or more (Pulvertaft 1968). Towards the south, the boundary between basement and supracrustals has been obliterated, tectonically or migmatically, during several periods of deformation. The basement can therefore not be distinguished in the southern part of the area of fig. 2. The Ketilidian rocks give ages of 1800-1500 m.y. (Pulvertaft 1968).

The central part of the map (fig. 2) is made up of the so-called Julianehåb granite which covers an area of 125 x 50 km between Kobberminebugt and Igaliko. Parts of this granite formed by granitization during the Ketilidian folding. This older granite was reconstituted or mobilized during a later plutonic episode. The bodies of young granite have longitudinal axes parallel to the regional structures and their emplacement was probably controlled by the pre-existing structures. In cases the granites appear to have originated in antiformal structures (Allaart 1967), as for instance between Julianehåb and Igaliko. The granitization involved considerable homogenization and much of the granite originated by anatexis of the basement (Allaart 1967, p. 119).

Walton (1965) suggests that the Julianehåb granite formed by granitization in the root zone of the Ketilidian belt. During epeirogenic uplift of the root zone, a suite of basic "appinitic" intrusions and the bodies of reactivated granite were formed. The granitic rocks give K/Ar-ages of 1640-1500 m.y. (Brigdwater 1965).

Ilímaussaq and the other major Gardar intrusions are located in the region made up of fairly homogeneous Julianehåb granite, or just north of this region. The fact that Ketilidian supracrustals are preserved both to the north and south of this region, but not in the Julianehåb granite, may indicate an "arching" of the section occupied by the granite. This arching may be responsible for the alkaline magmatism of the region (*cf*. Bailey 1964 and in preparation and Bailey & Schairer 1966, p. 152).

The location of the intrusions within this arched zone may in part be determined by the boundary surface between basement and Gardar supracrustals. But fault zones have determined the exact position of the intrusions, as has been emphasized by all students of the province in recent years (*cf*. Berthelsen 1962; Berthelsen & Noe-Nygaard 1965; Harry & Pulvertaft 1963; Sørensen 1965; Watt 1966; and Bridgwater & Harry 1968).

According to these authors, the Gardar province is situated in a 60-100 km wide zone bounded by WNW-ESE faults which mainly show transcurrent sinistral movement but also vertical movement. An instance of this is seen south of Igaliko, where the base of the Gardar sandstone is down-faulted at least 1000 m. The big intrusions of Nunarssuit and Ilímaussaq straddle these faults and post-date them. Other intrusions such as Grønnedal-Íka, Narssaq and parts of Igaliko are cut by the faults. This E-W zone, which more or less coincides with the distribution of the Julianehåb granite, may represent a deep section through a rift zone, in which arching was succeeded by rifting (*cf.* Bailey 1964). The intrusions are situated at the intersections of the E-W faults and NE-SW faults in directions paralleling the fjords. The rift zone may be contemporaneous with the development of the Grenville Belt in Canada (Berthelsen 1961; Bridgwater 1967).

A significant combination of factors is the general lack of radial dykes, the existence of swarms of dykes parallel to the NE-SW zones of movement and the fact that the composite giant dykes of Isortoq and Tugtutôq are directed respectively towards the Nunarssuit and Narssaq-Ilímaussaq intrusions; these factors indicate the existence in Gardar times of long, deep and narrow magma reservoirs which were tapped intermittently to produce the dykes and the central intrusions (Berthelsen & Noe-Nygaard 1965, p. 138). This tapping took place during periods of tension; in the intervening periods of compression (which resulted in the transcurrent faulting), gases were held back in the subjacent magma reservoirs, which permitted differentiation to take place (for instance by liquid fractionation, see Bridgwater & Harry 1968).

The Ilímaussaq intrusion combines all the features mentioned above in being situated at the boundary surface between Julianehåb granite and Gardar sandstone, at the intersection of E-W and NE-SW zones of movement and on a line with the composite giant dykes of Tugtotôq. According to Ussing (1912, p. 289), the intrusion is situated in the deep part of a down-faulted block. As pointed out by Bridgwater & Harry (1968), xenoliths of anorthosite are especially numerous in the gabbro dykes around Ilímaussaq, which indicates strong fractionation of the magma in the subjacent magma reservoirs at these places. Xenoliths of anorthosite have also been found in the syenites of the Ilímaussaq intrusion (Hamilton 1964; Nielsen 1967, Bridgwater & Harry 1968, and Sørensen *et al.* 1969).

CONTACT RELATIONS OF THE KHIBINA, LOVOZERO AND ILÍMAUSSAQ INTRUSIONS

All three intrusions are distinctly discordant, intersecting the structures of all country rocks. They all form mountainous regions intersected by deep valleys, which allows a direct study of thicknesses of rocks of more than 1000 m.

The Khibina Intrusion (Galakhov 1961 ; Zak 1963, and personal observations) displays generally steep contacts dipping mainly towards, but in places also away from, the centre of the intrusion (fig. 4). According

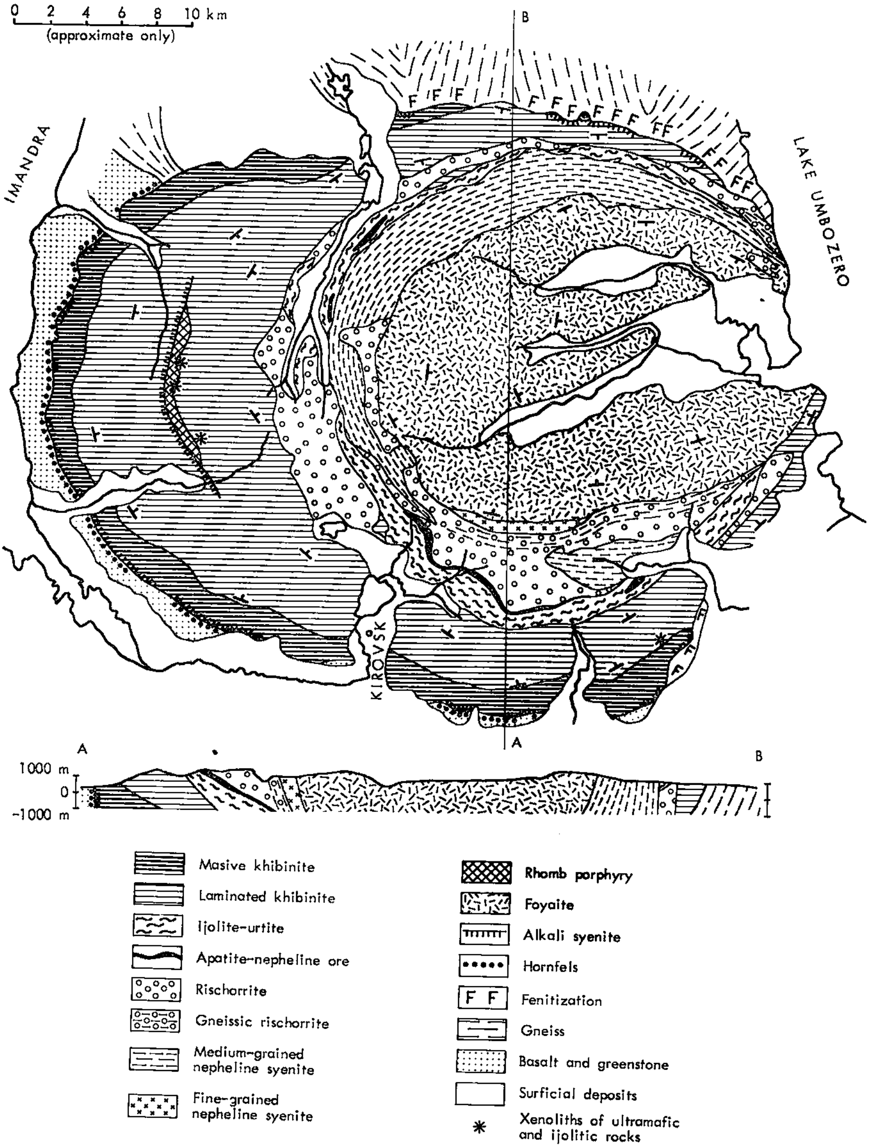

FIG. 4. Geological map of the Khibina intrusion based mainly on map published by Zak (1963).

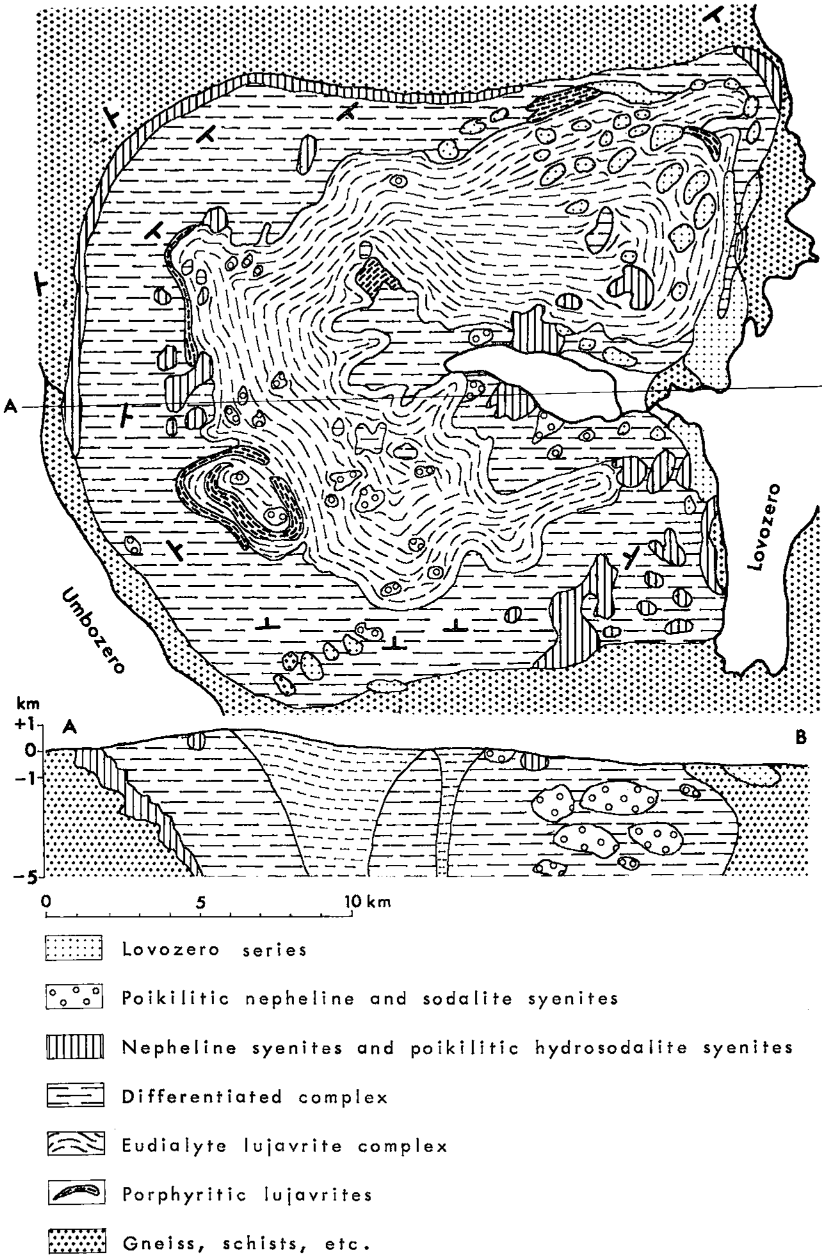

FIG. 5. Geological sketch map of the Lovozero intrusion based mainly on Bussen & Sakharov (1967).

to geophysical data the west contact is steep and the intrusion is at least 7 km deep but the central part may have a flat floor at a depth of 4-5 km.

The marginal nepheline syenite (massive khibinite) veins the country rocks and there are chill zones a few cm wide in both the main body and apophyses. There are numerous xenoliths of the country rocks in the marginal zone which is enriched in pegmatitic patches. Pegmatitic veins also penetrate into the country rocks. A number of small satellite bodies of nepheline syenite occur in the adjacent country rocks.

The gneisses in contact with the northernmost part of the intrusion are fenitized. Between the fenitized gneisses and the khibinite there is a zone, 200 m wide, made up of the alkali syenite termed umptekite by Ramsay & Hackman (1894). This rock veins the gneisses and may be a contaminated nepheline syenite or a mobilized fenite. Xenoliths of umptekite occur in the khibinite. The spilitic lavas of the west contact are altered into hornfels in a 300-600 m thick zone containing diopside, hypersthene and cordierite. The altered volcanics may be enriched in pyrrhotite. The roof of Khibina is unknown ; xenoliths of altered lavas may represent Precambrian lavas as well as rocks from the Lovozero series.

The Lovozero Intrusion (Atamanov *et al.* 1961, Gerassimovsky *et al.*, 1966 and in preparation ; Bussen & Sakharov 1967) intersects basement gneisses and granites and the high-alumina gneisses of the Keivy series (fig. 5). These rocks are fenitized in a zone up to 400 m wide and are cut by veins of nepheline syenite and by zones of albitization. Geophysical data indicates that the intrusion has the shape of a laccolith with a thick stem which is at least 7 km deep and which may be concentrically zoned. The north contact has a steep southern dip.

Remnants of the roof are preserved as xenoliths in the upper part of the intrusion. They consist of sediments and lavas of the Lovozero series. These rocks are strongly altered into hornfels in contact with the nepheline syenites.

The Ilímaussaq Intrusion (Ussing 1912 ; Ferguson 1964 and 1967 ; Sørensen *et al.* 1969 ; and personal observations) intersects Julianehåb granite overlain by Gardar sandstone and lava (fig. 6). The bottom of the intrusion is unknown ; the roof is preserved in places. The marginal contacts are steep, generally with outward dips. The adjacent sandstone and lava generally dip towards the intrusion (fig. 7).

The Julianehåb granite is fenitized in a zone which is up to 50 m wide, the sandstone is recrystallized and bleached adjacent to the intrusion and the lavas are strongly recrystallized, often containing albite, arfvedsonite and analcime. In the northernmost part of the intrusion the re-

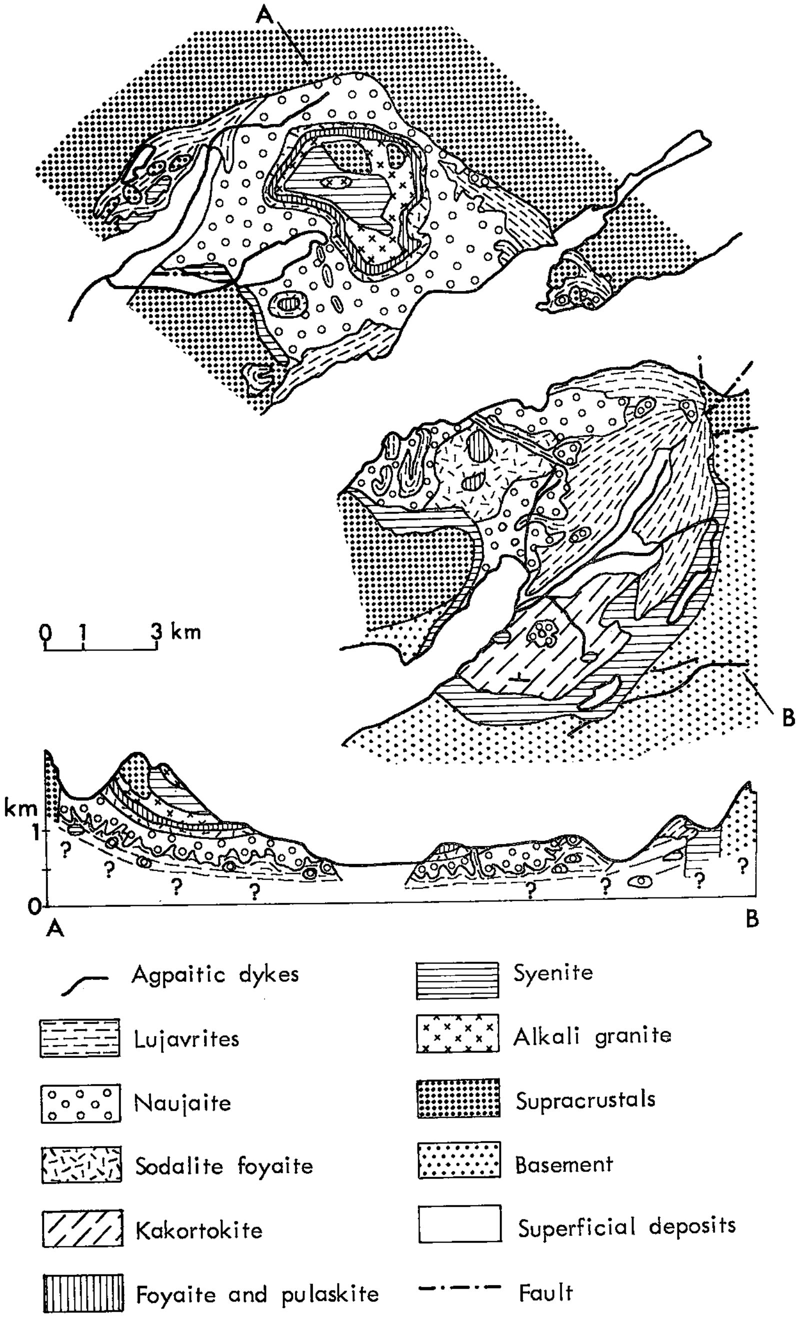

FIG. 6. Geological map of the Ilímaussaq intrusion based mainly on Ferguson (1964).

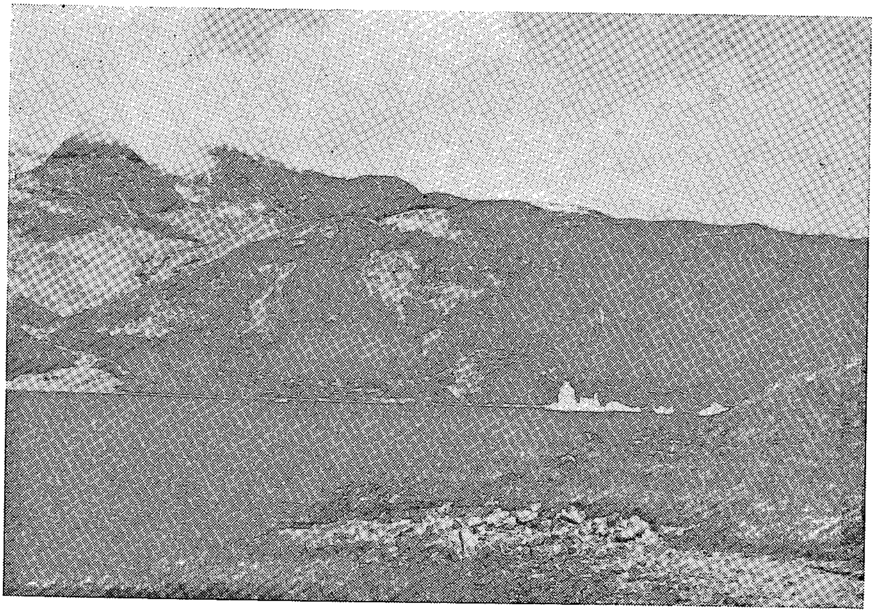

FIG. 7. Eastern contact of Ilímaussaq. The lavas (on the right) dip towards the intrusion. The nepheline syenites (grey) are overlain by cappings of lava.

crystallized lavas are enriched in minerals containing Nb, Th and U (Sørensen *et al.* 1969).

The augite syenite and alkali granite of Ilímaussaq are chilled in the contact zone and the naujaite is also finer-grained at these places. The rocks are often rich in pegmatites near the contacts.

Apophyses of syenite, granite, naujaite and lujavrite vein the country rocks. There are xenoliths of sandstone and altered lava in the marginal parts of the intrusions. The presence of large xenoliths of recrystallized sandstone in the augite syenite of the southwest contact of the intrusion is especially remarkable. They occur at sea level where the country rock is Julianehåb granite; even at altitudes of 800 m this rock type is without a cover of sandstone, indicating that blocks of sandstone have sunk at least 800 m in the syenite magma (Ussing 1912).

INTERNAL STRUCTURES OF THE KHIBINA, LOVOZERO AND ILÍMAUSSAQ INTRUSIONS

Khibina is a ring intrusion while Lovozero and Ilímaussaq are layered intrusions. They are all composite.

The Khibina Intrusion (Galakhov 1961, Zak 1963, personal observations) is composed of successive horseshoe-shaped intrusions opening towards the east and surrounding a core of foyaite. The intrusive phases (complexes) wedge generally out towards the east (fig. 4).

There is no general agreement on the order of succession of the intrusive phases. In the following discussion the rock types are presented by starting with the marginal types and working inwards. This sequence also coincides with the views of some authors regarding the order of intrusion (tables 3 and 4).

The major part of the periphery of the intrusion is made up of the *massive (or granitoid) khibinite*. It is leucocratic and is rather heterogeneous as to grain size and structures. On the inner side of the massive khibinite follows the *laminated (trachytoid) khibinite*. The contact is steep and sharp and there are xenoliths of the massive type in the laminated rocks. The laminated khibinite is coarse but finer-grained than the massive variety. The two varieties of khibinite are mineralogically identical apart from a constant content of eudialyte in the laminated type. Between the two complexes of khibinite there is in places a body of *rhomb porphyry* which may represent a recrystallized zone.

The planar structures of the innermost part of the laminated khibinite is cut by the complexes of rischorrite and ijolite-urtite. The contacts with these rocks are steep to moderately steep.

The rischorrite complex consists of massive, laminated or gneissic rocks which are characterized by a pronounced poikilitic texture; small crystals of nepheline are enclosed in larger plates of alkali feldspar. The complex is composed of several rock types, namely mica rischorrite, mica-aegirine rischorrite and aegirine rischorrite, and was formed during two almost continuous intrusive stages : 1) massive rischorrite in ring fault between khibinite and the foyaitic core of the intrusion ; 2) incomplete ring of massive, laminated and gneissic rocks with steeply dipping planar structures (Galakhov 1959 and 1961). The second ring is situated along the inner side of the southern part of the first formed ring and was probably formed by subsidence of the central part of the intrusion. This displacement continued after consolidation of the rischorrite as is seen from zones of crushing containing albite, astrophyllite, etc., and in the gneissic structure of parts of this complex.

The ijolite-urtite-malignite-apatite complex forms a ring between khibinite and rischorrite, especially in the southern part of the intrusion. The contacts of this complex have steep to flat dips towards the centre of the intrusion. This complex may have been formed during two stages : 1) ijolite-urtite with the apatite-nepheline ore body along the hanging

TABLE 3. THE MAJOR ROCK TYPES OF THE KHIBINA INTRUSION

	Massive khibinite	Laminated khibinite	Rischorrite
Grain size	coarse	coarse	coarse
Structure	massive (rarely laminated)	laminated, in part rhythmically layered	poikilitic; massive, laminated or gneissic
Essential minerals	alkali feldspar nepheline aegirine-augite Na-amphibole aenigmatite biotite	alkali feldspar nepheline aegirine-augite	alkali feldspar nepheline aegirine-augite lepidomelane aenigmatite arfvedsonite aegirine
Minor minerals	apatite sphene (eudialyte) lamprophyllite	eudialyte alkali amphibole astrophyllite aenigmatite sphene apatite	apatite astrophyllite eudialyte ilmenite sphene
Agpaitic coefficient	1.01	1.10	1.05

	Ijolite-urtite	Apatite-nepheline ore	Medium-grained aegirine-nepheline syenite	Foyaite
Grain size	coarse	medium to coarse	medium	coarse
Structure	massive, layered	massive, spotted, layered, brecciated	massive	massive, laminated or layered
Essential minerals	nepheline aegirine-augite	apatite nepheline	alkali feldspar nepheline aegirine alkali amphibole	alkali feldspar nepheline Na-pyroxene Na-amphibole biotite
Minor minerals	apatite sphene titanomagnetite	eudialyte sphene	aenigmatite sphene astrophyllite apatite biotite	astrophyllite sphene eucolite
Agpaitic coefficient	1.04	0.86	0.98	0.97

Table 4. Order of Intrusion of Different Complexes of the Khibina Intrusion

V.I. Vlodavetz (1935)	V.M. Kupletsky (1937)	N.A. Eliseev, I.S. Oginsky & E.N. Volodin (1939)	A.V. Galakhov (1961)	S.I. Zak (1963)
	4. late dykes	7. late dykes	late dykes	late dykes
5. khibinite		6. fine-grained mica-aegirine-hornblende nepheline syenite, foyaite, medium-grained aegirine-nepheline syenite	(age relations of medium-grained aegirine-nepheline syenite, foyaite and fine-grained nepheline syenites are uncertain, may be younger than ijolite-urtite)	b. foyaite (cone) III
4b. apatite-nepheline ore 4a. ijolite-urtite	3. ijolite-urtite and apatite-nepheline rock	5. ijolite-urtite and apatite-nepheline rock	5. ijolite-urtite	a. medium-grained aegirine-nepheline syenite (ring)
4. mica-nepheline syenite 3. poikilitic nepheline syenite	2. aegirine-, hornblende-, mica- and fine-grained nepheline syenites (rischorrite)	4. rischorrite	4. rischorrite	b. ijolite-urtite-apatite (cone) II a. rischorrite (ring)
2. hornblende nepheline syenite	1a. foyaite and laminated khibinite	3. laminated khibinite	3. laminated khibinite	b. laminated khibinite (cone)
1. foyaite and khibinitic foyaite	1. khibinite and umptekite	2. massive khibinite 1. umptekite, etc.	2. massive khibinite 1. umptekite	I a. massive, khibinite (ring)

wall in contact with the rischorrite; 2) veins of ijolite-urtite and malignite cutting and brecciating the apatite body and the rischorrite. The apatite-nepheline ore forms a 35 km long, arcuate body which dips 25-40° towards the centre of the intrusion. The ore body passes gradually into the underlying urtite and intersects and veins the overlying rischorrite.

Between the rischorrite and the foyaite of the core there is a zone made up of *medium-grained aegirine-nepheline syenites* (fig. 8). The

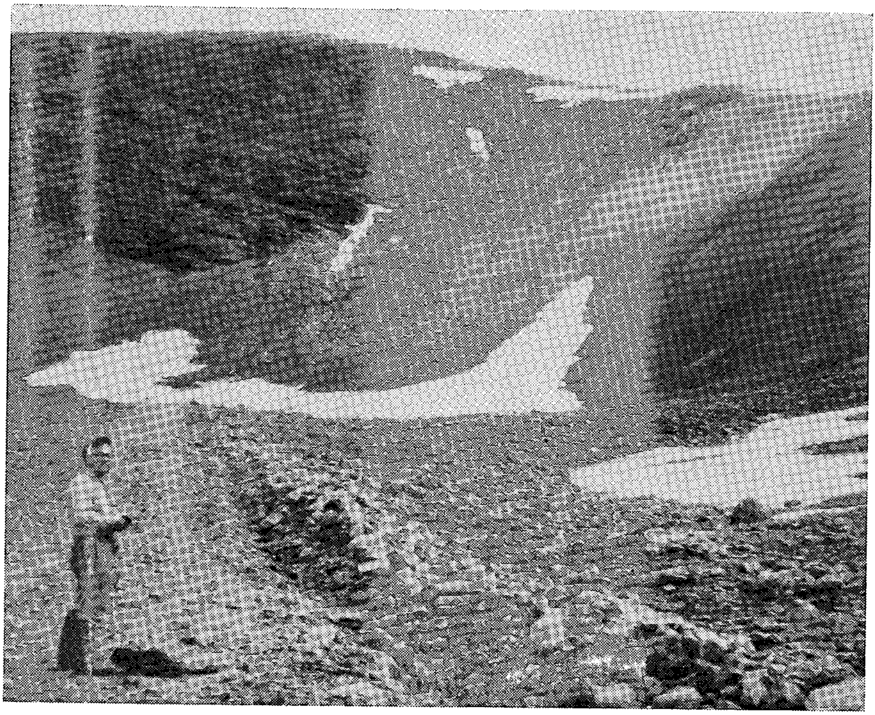

FIG. 8. Contact between rischorrite (right) and gneissic nepheline syenite (left). Hackman valley, the Khibina intrusion.

contacts of the zone dip 60-70° inwards. These rocks are heterogeneous with respect to grain size and modal composition and recall in some places khibinite, in others foyaite. According to Galakhov (1961) the rocks of this zone were formed successively during an interval of time. They appear to be younger than the rischorrite since there are xenoliths of this rock type and since veins of nepheline syenite cut the rischorrite ring. They are also younger than the ijolite-urtite and cut the planar structures of this complex.

In the same zone are bodies of *fine-grained mica-aegirine-hornblende-nepheline* syenites, also found around xenoliths of country rocks enclosed in the foyaite.

The core of the intrusion is made up of *foyaite*. The marginal part of this complex is strongly laminated with inward directed dips ranging from steep to flat. The central part is more massive. The body may be funnel-shaped. In places there is a rapid alternation of rock types. Xenoliths of hornfels are distributed more or less at one level. The foyaite complex is made up of two main types of rocks, the one is rich in aegirine, the other in amphibole. The foyaite is clearly younger than the khibinite as it contains xenoliths of that rock and also veins the laminated khibinite. The age relation to the rischorrite is unsolved.

As mentioned above, most rock types display igneous lamination, at least in restricted areas. Apart from the rischorrite in which the planar structures are near vertical, the planar structures of all other rocks have inward directed dips. In the inner part of the massive khibinite and in the wide parts of the ring of laminated khibinite, the lamination has low dips, but in regions of thinning out of the ring of laminated khibinite the dips are 75-80°. In contact with the outer ring of massive khibinite the laminated type displays near horizontal rhythmic layering with mineral graded units. The layered part of the complex passes upwards into unlayered laminated khibinite. In the ijolite there is lamination and layering with steep dips in the lower part and low dips (20-30°) in the upper part.

Chemically the rocks of Khibina are weakly agpaitic, as seen from the co-existence of miaskitic minerals such as biotite, iron ore, sphene and apatite with minerals such as aegirine, Na-amphibole, eudialyte and rinkolite (Galakhov 1967*b*; Gerassimovsky 1967; Gerassimovsky *et al.* in preparation).

According to Zak (1963), the Khibina intrusion is made up of ring complexes of massive khibinite, rischorrite and medium-grained aegirine-nepheline syenite, and of conical complexes of laminated khibinite, ijolite-urtite and foyaite. The ring complexes have vertical to steep inward dips. The lower parts of the cone intrusions have inward dips of 60-70°, while the upper parts have lower dips of 20-30°. The centres of successive intrusions shift from west to east so that only the latest phase, the foyaite, is well preserved. There are radial fractures in the different complexes marked by albitization, oxidation, *etc.* Ring faults appear as mylonite zones in the surrounding gneisses.

Galakhov (1967*a*) reports the discovery of xenoliths of ultramafic and ijolitic rocks in the nepheline syenites of the intrusion, that is, rocks of the type found in the small "Caledonian" intrusions (p. 307).

The Lovozero Intrusion (Vlasov *et al.* 1959; Atamanov *et al.* 1961; Gerassimovsky *et al.* 1966 and in preparation; and Bussen & Sakharov 1967) is made up of an upper funnel-shaped complex of eudialyte lujavrite, resting on the differentiated complex of lujavrite-foyaite-urtite (table 5). The available geophysical data (Shablinsky 1963) indicate that the central part of the intrusion is pipe-like with almost vertical marginal

TABLE 5. THE MAJOR ROCK TYPES OF THE LOVOZERO INTRUSION
(based mainly on Gerassimovsky *et al.*, 1966)

	Nepheline and hyprosodalite syenites	Poikilitic hydrosodalite syenite	Eudialyte lujavrite	Poikilitic sodalite syenite
Grain size	fine to coarse	coarse	medium to coarse	coarse
Structure	massive, layered, porphyritic	poikilitic	laminated, layered	massive, poikilitic
Essential minerals	alkali feldspar nepheline hydrosodalite Na-bearing pyroxene arfvedsonite	alkali feldspar nepheline hydrosodalite pyroxene	alkali feldspar nepheline sodalite eudialyte aegirine arfvedsonite	sodalite nepheline alkali feldspar aegirine arfvedsonite
Minor minerals (in part in pegmatites)	sphene apatite ore minerals biotite lamprophyllite wöhlerite låvenite	sphene apatite ore minerals	lamprophyllite lovozerite ramsayite murmanite neptunite pectolite rinkolite	villiaumite eudialyte murmanite lamprophyllite loparite pectolite rinkolite
Agpaitic coefficient	0.96 — 1.22	1.00 — 1.24	1.12 — 1.75	1.17 — 1.60

	Te differentiated complex		
	Lujavrite	Foyaite	Urtite
Grain size Structure	medium laminated	medium to coarse massive, pegmatoid, poikilitic, trachytoid	medium to coarse massive
Essential minerals	alkali feldspar nepheline aegirine arfvedsonite sodalite eudialyte	alkali feldspar nepheline sodalite aegirine arfvedsonite eudialyte	nepheline alkali feldspar sodalite aegirine eudialyte
Minor minerals (in part in pegmatites)	loparite lamprophyllite rinkolite apatite sphene murmanite ramsayite Mn-ilmenite aenigmatite villiaumite	murmanite lamprophyllite ramsayite loparite aenigmatite Mn-ilmenite astropyllite villiaumite	apatite aenigmatite arfvedsonite Mn-ilmenite loparite ramsayite murmanite lamprophyllite
Agpaitic coefficient	1.09 — 1.95	0.90 — 1.72	0.90 — 1.35

contacts which may dip towards the centre of the intrusion. The stem measures 12 x 16 km. Remnants of the roof of basic and alkaline volcanites of the Lovozero series occur as xenoliths in the upper part of the intrusion.

The intrusion is considered by the Russian investigators to be made up of separate intrusive phases but there is no general agreement on the number or order of phases (table 6).

TABLE 6. ORDER OF INTRUSION OF THE DIFFERENT COMPLEXES OF THE LOVOZERO MASSIF ACCORDING TO INVESTIGATIONS BY VARIOUS AUTHORS

N.A. Eliseev & E.E. Fedorov (1953)	I.V. Bussen & A.S. Sakharov (1958)	K.A. Vlasov, M.V. Kuz'menko & E.M. Es'kova (1959)	V.I. Gerassimovsky and others (1966)
4. Complex of young vein rocks.	5. Complex of veins of alkaline rocks.		4. Complex of alkaline lamprophyres.
	4. Complex of eudialyte and porphyritic lujavrites.	3. Vein rocks.	3a. Complex of eudialyte lujavrite and syngenetic poikilitic sodalite syenite and tawite. 3b. Porphyritic lujavrite.
3. Complex of eudialyte lujavrite.	3. Differentiated complex of urtite-foyaite-lujavrite.	2. Complex of poikilitic syenite	
2. Differentiated complex of urtite-foyaite-lujavrite.	2. Complex of porphyritic and poikilitic nepheline syenite.		
1. Complex of alkali and nepheline syenite; poikilitic nepheline and sodalite syenite; urtite juvite and foyaite.	1. Complex of metamorphosed alkaline rocks, nepheline syenite, porphyry and rhombporphyry.	1b. Differentiated complex of urtite-foyaite-lujavrite. 1a. Complex of eudialyte lujavrite.	2. Differentiated complex of urtite-foyaite-lujavrite and syngenetic poikilitic sodalite syenite. 1. Equigranular nepheline syenite; nepheline-hydrosodalite and poikilitic hydrosodalite syenites and metamorphosed nepheline syenite.

Equigranular or porphyritic nepheline syenites, poikilitic hydrosodalite syenites and *various types of altered nepheline syenites* occur as a continuous zone, 150-200 m wide, along the NW-contact of the intrusion. This zone dips at a low angle under the intrusion and may therefore play a major role in the invisible part of the intrusion.

The rocks of this group contain sphene, apatite and biotite, and are partly miaskitic. They recall the nepheline syenites of Khibina and correspond closely to members of the volcanic Lovozero series. They are cut by veins of agpaitic nepheline syenites and, as they also occur as xenoliths in the rocks of the visible part of the intrusion, they are considered by most investigators to represent the first intrusive phase. These rocks make up 5% of the volume of the accessible part of the intrusion.

The rocks of *the differentiated complex* occur in the lowermost visible part of the intrusion and make up about 77% of its volume. In drill holes it has been proved to be at least 1500 m thick. It displays a pronounced rhythmic layering. The layers vary in thickness from a few centimetres to several tens of metres. They are persistent throughout the complex (except for a narrow, pegmatite-rich contact zone), and are almost horizontal. Most of the complex is dominated by lujavrite and foyaite but in certain horizons there is a striking repetition of three-layer units which in ascending order are urtite-foyaite-lujavrite. The lower contact of each unit is abrupt while there are gradational internal contacts. Xenoliths of volcanic rocks and of poikilitic syenites are wrapped by the layering. This complex outcrops along the periphery of the intrusion.

The uppermost part of the intrusion is made up of the *eudialyte lujavrite complex* which appears to be funnel - or mushroom-shaped and up to 450 m thick. This complex is composed of slightly stratified lujavrites which are characterized by euhedral eudialyte. The layering is due to an alternation of dark and light-coloured layers of lujavrite. The layers often wedge out after short distances ; contacts between layers are mainly gradational. The eudialyte lujavrites intersect the layering of the differentiated complex and are therefore younger than this complex (Bussen & Sakharov 1958). This is contrary to the views of Vlasov *et al.* (1959), who consider the eudialyte lujavrite complex to be the earliest part of the intrusion. The contact of these two units is an eruptive breccia containing xenoliths of rocks belonging to the differentiated complex. There are also xenoliths of the early nepheline syenites and of supracrustal rocks. In this zone there are lenses and veins of feldspar-porphyritic lujavrite which is considered to be a late phase. Also developed in the contact zones are veins enriched in rare minerals such as lovozerite and murmanite. The lujavrite in contact with xenoliths of volcanic rocks is enriched in sphene and amphibole.

Sharply bounded, equidimensional lenses of *poikilitic sodalite syenite* occur in the eudialyte lujavrite complex and in the differentiated complex. The lenses are confined to lujavritic hosts. The size of these bodies varies from a few centimetres to several hundred metres. They are conformably enclosed by the lamination or layering of the host rocks. No feeder channels have been found. The largest rare mineral pegmatites are associated with these rocks. The adjacent lujavrites may be enriched in sodalite and aegirine. As seen from table 6, these rocks have been variously described as xenoliths, intrusives and bodies formed by liquid immiscibility.

The Ilímaussaq Intrusion (Ussing 1912; Sørensen 1958, 1968, 1969; Ferguson 1964, 1967; Hamilton 1964) : Ussing (1912) divided the "Ilímaussaq batholith" into an older unstratified part made up of augite syenite, essexite, alkali granite and alkali syenite, and a younger stratified part made up, from top to bottom, of alkali granite, quartz syenite, pulaskite, foyaite, sodalite foyaite, naujaite, a "breccia zone" of lujavrite with inclusions of naujaite, and kakortokite. Ferguson (1964) divided this "batholith" into the Narssaq intrusion, comprising most of the unstratified part, and the Ilímaussaq intrusion, consisting of the stratified part plus the augite syenite. Most of the rocks of the latter intrusion are agpaitic nepheline syenites (table 7).

As the field relations of the alkali granite are still not solved and as this rock has no equivalents in Khibina and Lovozero the granite will not receive further treatment. It should be pointed out, however, that this rock forms two sheet-like bodies below the roof of the intrusion and that the lower sheet passes gradually into the underlying quartz syenite and pulaskite.

All investigators consider the augite syenite as the first formed rock in the visible part of the intrusion (see table 8). It is confined to the marginal parts of the intrusion.

The stratified intrusion is made up of saucer-shaped zones in such a way that there is generally a gradual transition from the uppermost zone of pulaskite through several zones into the naujaite (see fig. 6). The upper zones of pulaskite, foyaite and sodalite foyaite are fairly thin and believed to be results of *in situ* crystallization from the roof downwards. The underlying naujaite, which is a few hundred metres thick, is considered to be a flotation cumulate in which small crystals of sodalite are poikilitically enclosed in large anhedra of the other rock-forming minerals. Simultaneously with the formation of these rocks, the layered series of kakortokite was formed by bottom accumulation of crystals at lower levels

Table 7. The Major Rock Types of the Ilímaussaq Intrusion
(based on Ussing (1912), Ferguson (1964 and 1967) and personal observations)

	Augite syenite	Alkali granite	Pulaskite	Foyaite
Grain size	medium, coarse	medium, coarse	medium, coarse	coarse
Structure	massive, layered	massive	massive	massive, layered
Essential minerals	alkali feldspar titanaugite	alkali feldspar quartz arfvedsonite aenigmatite	alkali feldspar nepheline Na-pyroxene	alkali feldspar nepheline Na-pyroxene Na-amphibole fayalite
Minor minerals	fayalite nepheline iron ore biotite apatite amphibole	aegirine zircon elpidite pyrochlore fluorite narsarsukite epididymite	Na-amphibole aenigmatite fayalite biotite apatite fluorite iron ore	aenigmatite iron ore apatite fluorite biotite sodalite eudialyte
Agpaitic coefficient	0.98	1.50	1.25	0.9 — 1.3

	Sodalite foyaite	Naujaite	Kakortokite	Lujavrite
Grain size	coarse	coarse	medium	fine - medium
Structure	massive	poikilitic	laminated, layered	laminated, layered
Essential minerals	alkali feldspar nepheline sodalite Na-pyroxene Na-amphibole aenigmatite	sodalite alkali feldspar nepheline aegirine arfvedsonite eudialyte	alkali feldspar nepheline aegirine arfvedsonite eudialyte	microline albite nepheline aegirine arfvedsonite eudialyte analcime natrolite naujakasite
Minor minerals	eudialyte fayalite iron ore fluorite rinkite biotite astrophyllite	aenigmatite rinkite biotite fluorite pyrrhotite stannite Li-mica villiaumite	aenigmatite biotite fluorite rinkite sodalite	sodalite steenstrupine sphalerite monazite britholite lovozerite ussingite Li-mica pyroclore villiaumite
Agpaitic coefficient	1.32	1.34	1.49	1.40

TABLE 8. ORDER OF INTRUSION OF THE DIFFERENT ROCKS OF THE ILÍMAUSSAQ MASSIF ACCORDING TO INVESTIGATIONS BY VARIOUS AUTHORS

N.V. Ussing (1912)	J. Ferguson (1964)	E.I. Hamilton (1964)	H. Sørensen (1965 & 1968)
2c. quartz syenite, pulaskite, foyaite (reaction products with granite ?)	1c. lujavrite	3. quartz syenite and alkali granite	2d. lujavrite
	1b. kakortokite (bottom) and naujaite (top)	2c. lujavrite and kakortokite	2c. naujaite (top) and kakortokite (bottom)
2b. Sodalite foyaite			
2a. naujaite (top) kakortokite and lujavrite (bottom)	2b. quartz syenite and pulaskite (products of reaction).	2b. pulaskite (reaction product)	2b. sodalite foyaite (top)
1b. alkali granite (assimilation product ?)	2a. alkali granite	2a. sodalite foyaite and naujaite	2a. pulaskite and foyaite (top)
1a. augite syenite (perhaps also pulaskite)	1a. augite syenite and foyaite (heterogeneous syenite)	1. augite syenite and foyaite	1. augite syenite and alkali granite

(*cf*. Ussing 1912; Sørensen 1958 and 1969; Ferguson & Pulvertaft 1963). The layering of the kakortokite is near horizontal but wavy (fig. 9). The dip is generally towards the centre of the intrusion. The zones of naujaite and kakortokite are not in direct contact but are separated by a zone of lujavrite rich in xenoliths of naujaite.

The augite syenite is intruded by kakortokite, lujavrite and naujaite which do not show chilling effects. No chilling is seen in the veins of lujavrite found in naujaite, sodalite foyaite and kakortokite.

The structural relations indicate that the sequence of saucer-shaped zones of pulaskite, foyaite, sodalite foyaite, naujaite and kakortokite was formed under fairly tranquil conditions of crystallization of one body of magma. The lujavrites may represent the residual magma from this crystallization or a later injection of magma in connection with subsidence of parts of the already consolidated rocks (Ussing 1912; Sørensen 1958 and 1969.

A COMPARISON OF THE KHIBINA, LOVOZERO AND ILÍMAUSSAQ INTRUSIONS

The rocks composing the three large intrusions discussed in this paper are mainly of agpaitic type and made up of practically the same minerals,

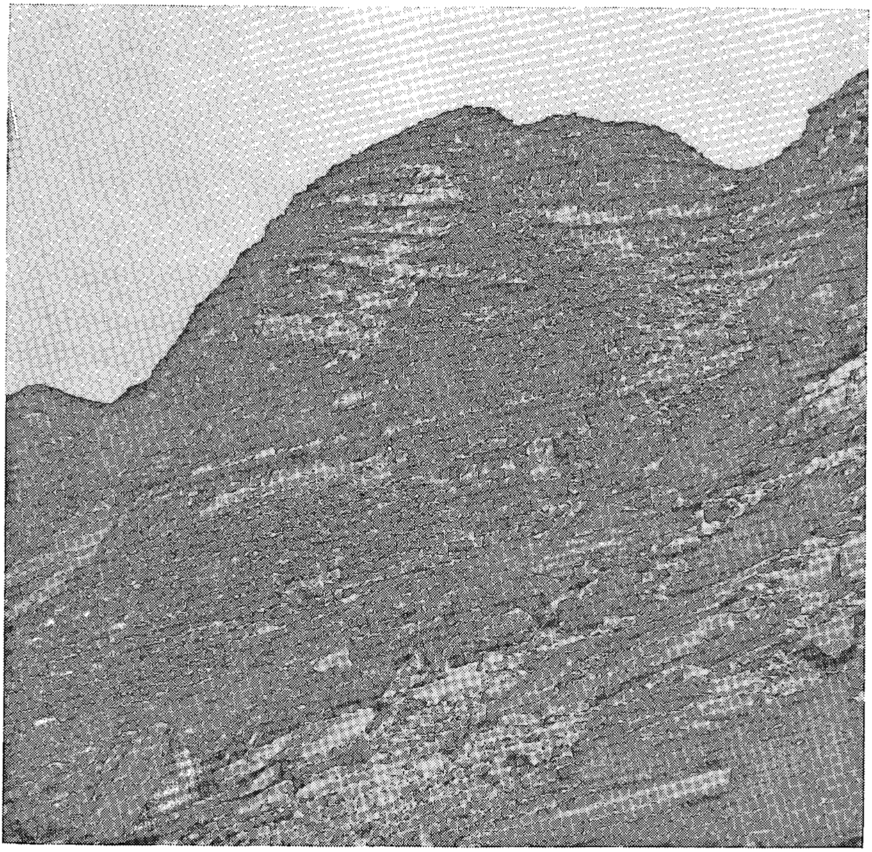

FIG. 9. Section through the layered series of kakortokite. Note the mineral-graded layering and the conformably enclosed inclusion of syenite (left side of photo). South coast of Kangerdluarssuk. The Ilímaussaq intrusion.

namely nepheline, sodalite, alkali feldspar of a special type confined to agpaitic nepheline syenites and alkali granites (Sørensen 1962, p. 225), aegirine, arfvedsonite, aenigmatite and eudialyte. The rocks of Khibina contain a high percentage of miaskitic minerals, such as sphene, apatite and biotite; Lovozero is poorer in these minerals, while they are present in insignificant amounts in Ilímaussaq.

The rocks of Ilímaussaq are poor in Ti and P while the rocks of Khibina and Lovozero are rich in these elements (*cf*. Gerassimovsky 1968). This is reflected in the accessory minerals which are generally rich in Ti in the Kola rocks, while those of Ilímaussaq are rich in Nb. Thus minerals such as lamprophyllite, astrophyllite, murmanite, sphene, ramsayite, loparite, etc. are widespread in the agpaitic rocks of Kola, while epistolite, pyrochlore and igdloite (lueshite) are widespread in Ilímaussaq. Apart from these differences there are pronounced geochemical similarities between the agpaitic rocks of the three intrusions. These relations will not be further discussed here since this paper is devoted to the field relations of the rocks of these intrusions.

Geological setting: The site of all three intrusions is determined first of all by intersecting fault systems or major geological boundaries, but also by first order discordances separating supracrustal rocks penecontemporaneous with the intrusions from worn-down crystalline basements of Precambrian age. Ilímaussaq appears to be situated in a rift zone which possibly occupies an arched region of older granites. The relation of the Kola intrusions to such structures is less clear. Ilímaussaq is clearly younger than the faulting.

Association: The isotopic ages indicate that Ilímaussaq is the latest intrusion in the Precambrian Gardar alkaline province, while Khibina and Lovozero are the latest intrusions in the Paleozoic Kola alkaline province.

Ilímaussaq is a medium-sized Gardar intrusion. The agpaitic rocks of this intrusion occupy about 6% of the area covered by Gardar intrusions (Watt 1966). Gabbro makes up about 13%, syenite 31.5%, miaskitic nepheline syenite 35% and granite 13%. The figure given for gabbro is on the low side since the numerous thin dykes of dolerite have not been included. The figures for the areas are consistent with the view that the agpaitic rocks are true members of the Gardar alkaline province and that all these rocks may be co-magmatic.

The sizes of the Khibina and Lovozero intrusions are, however, quite out of proportion with the exposed areas of the other igneous rocks of the province.

As mentioned on p. 309, the diversity of rocks in the Gardar province may derive from long, narrow and deep magma chambers striking NE-SW. Thus the giant dykes and many thin dykes are composite, the former having marginal zones of gabbro and cores of syenite, the latter having the opposite distribution of these rocks. The agpaitic rocks of Ilímaussaq (and some pegmatites of the Igaliko intrusion) are considered to be late differentiates of gas-rich syenite magmas. The syenites may be derived from primary alkali basaltic magmas by crystal and liquid fractionation (Upton 1960, Sørensen 1965, and Bridgwater & Harry 1968).

The small intrusions of the Paleozoic alkaline province of the Kola peninsula are dominated by ultramafic alkaline rocks, the large intrusions by (agpaitic) nepheline syenites. Alkali basalts and nephelinites occur mainly as thin dykes. Melilite-bearing rocks are also found. The close similarity of the rocks of the ultramafic intrusions to some of the lavas of the Lovozero series and many thin dykes indicates a genetic connection between these rocks. Gerassimovsky *et al.* (1966 and in preparation) suggest that the ultramafic intrusions and the agpaitic nepheline syenites are both derivatives of an alkali basaltic magma. The agpaitic residual liquids may develop by fractionation of olivine-melilite-nephelinite and of diopside enriched in the Tschermak "molecule".

Emplacement: There is no evidence of forceful injection of the magmas of the three agpaitic intrusions. They all appear to be discordant permitted intrusions.

Xenoliths of the country rocks are present in all three intrusions. In *Ilímaussaq* they are confined to the roof zone and the marginal contact zones. The stratification of the sandstones, and lavas of the country rocks generally dips towards the intrusion. Ussing (1912, p. 299) suggested that the emplacement took place by stoping. The rarity of xenoliths of country rocks in the intrusion may be accounted for by the low specific gravity of the magma, which facilitated the sinking of the roof blocks. The chemical composition of the exposed agpaitic rocks speaks against a significant assimilation of subsided blocks of sandstone and lava.

Apart from the xenoliths of sandstone in the marginal augite syenite of Ilímaussaq (see, p. 314), there is little indication of the mode of emplacement of this rock. More evidence is available concerning the emplacement of the agpaitic rocks. In the contact zone between augite syenite and kakortokite, it is seen that blocks of syenite, loosened along near vertical faults and mylonite zones, have fallen into the kakortokitic magma, which is enriched in pegmatites in these places. Large and small blocks of syenite, foyaite and naujaite are widespread in the layered series of kakortokite, indicating a subsidence of blocks from higher levels. There are no blocks of lava enclosed in the presently exposed kakortokite which may mean that the "upper border group" of naujaite, *etc.* had effectively shielded the magma chamber at this stage of crystallization. Blocks of lava may exist at deeper levels in the earliest members of the kakortokite series. Xenoliths are practically lacking in the sodalite foyaite and naujaite, partly because of the *in situ* growth of these rocks from the top downwards and partly because of the low density of the gas-rich magma which gave rise to these rocks. The lujavrites along the roof and marginal contacts of the intrusion are rich in xenoliths of augite syenite, lava and other roof rocks, and the country rocks are intimately veined by the lujavrite. This is evidence of fracturing and subsidence at this stage of crystallization.

As pointed out on p. 000, the Ilímaussaq intrusion was formed during three periods of consolidation : 1) augite syenite ; 2) main body of agpaitic nepheline syenites by in situ consolidation of the uppermost parts of the magma to give the stratified succession : pulaskite, foyaite, sodalite foyaite and naujaite, and by bottom accumulation of crystals at lower levels to give the layered series of kakortokite ; 3) subsidence (basining) of parts of the already consolidated rocks, accompanied by emplacement of the lujavrites.

The Lovozero intrusion may be envisaged as a further stage in the development of the Ilímaussaq intrusion. The differentiated complex of Lovozero may be compared structurally with the kakortokite of Ilímaussaq (Sørensen 1969), and is probably formed by accumulation of crystals in the lower part of the magma chamber. Petrologically the overlying eudialyte lujavrites correspond more closely to the kakortokite. The xenoliths of poikilitic sodalite syenite and tawite in the uppermost part of the intrusion are enclosed partly in the rocks of the differentiated complex and partly in the overlying complex of eudialyte lujavrite ; these may represent remnants (partly as subsided blocks) of an upper horizon of poikilitic rocks corresponding to the naujaites of Ilímaussaq. There are also xenoliths of the roof in this part of the intrusion.

Vlasov *et al.* (1959) maintain that the poikilitic syenites are intrusive in the lujavrites. The evidence produced in support of this (*op. cit.*, p. 23) is the presence of apophyses branching out into the lujavrite from the poikilitic rocks ; these may as well be considered as products of backveining, as has been demonstrated for similar veins in Ilímaussaq (Sørensen 1962, p. 159).

Thus the Lovozero intrusion may have been composed of horizons of layered rocks overlain by an horizon of poikilitic rocks. This picture was disturbed by the subsequent intrusion of eudialyte lujavrites corresponding to the phase of lujavrites in Ilímaussaq.

The nepheline syenite, in part miaskitic, found along the western contact and as xenoliths in the agpaitic rocks of Lovozero corresponds approximately to the uppermost pulaskite and foyaite of Ilímaussaq and also to some of the rocks of Khibina. The fact that the contact zone dips under the differentiated complex has led Atamanov *et al.* (1961) to suggest that the hidden part of Lovozero is made up of such rocks.

The Khibina intrusion is clearly made up of individual ring — or cone-shaped complexes. Each subsequent complex cuts across the layering, *etc.* of the preceding one, and may contain xenoliths of the earlier complexes. The general lack of contact modifications such as chilling indicates that the successive intrusive phase followed one another at short intervals. The gneissic rischorrite is evidence of subsidence of parts of the intrusion during the crystallization of this rock.

The khibinites, medium-grained nepheline syenites and foyaites of Khibina recall the early stages of Lovozero (first phase) and Ilímaussaq (pulaskite and foyaite). The poikilitic rischorrite is reminiscent of the poikilitic rocks of these two intrusions, with the only exception that nepheline and not sodalite occurs as inclusions in the other minerals. This may indicate a crystallization at lower vapour pressures corresponding to an earlier stage of crystallization. Another possibility is that early nepheline has been substituted by sodalite in the poikilitic rocks of Ilímaussaq and Lovozero. Hamilton (1964, p. 42) has pointed out that much of the poikilitic sodalite at Ilímaussaq forms prismatic grains of hexagonal cross section. However, much evidence supports the view that the sodalite of the naujaite is the liquidus phase of that rock (Sørensen 1969).

The ijolite-urtite-apatite complex of Khibina has no exact counterparts in the other two intrusions, with the possible exception of the urtite of the differentiated complex of Lovozero. The genesis of the ijolite-urtite-apatite complex is still unsolved (*cf.* Minakov *et al.* 1967). The experimental studies of Bailey & Schairer (1966, p. 156) in the system Na_2O — Al_2O_3–Fe_2O_3–SiO_2 at 1 atm indicate that ijolite-like compositions in this system may constitute a low-temperature residuum for at particular range of undersaturated rocks. Furthermore, similar bulk compositions containing potential sodium silicate may, under other conditions of crystallization, have a phonolitic low temperature residuum. This means that the ijolite-urtite-complex may represent a residual melt formed under special conditions of P, T. It should also be pointed out that ijolite is a common member of the small ultramafic intrusions of Kola and that nephelinite is present in dykes; in both cases, however, the quantities involved are exceeded by those of the ijolite-urtite-apatite complex of Khibina. Galakhov (1967*b*) points out that the average chemical composition of the rocks of the Khibina massif is close to that of average nepheline syenite calculated by Daly and Nockolds. The average content of phosphorus in this huge massif is large enough to account for the amount of phosphorus of the apatite ores.

Atamanov *et al* (1961) have suggested that the hidden stem of Lovozero is made up of a core of foyaite surrounded by rims of poikilitic nepheline syenite, ijolite-urtite, khibinite *etc.*, that is, a structure like that found in Khibina. The geophysical data indicate that the specific gravity of the rocks of the feeder increases from the centre towards the periphery. Gerassimovsky *et al.* (1966, p. 12) interpreted the geophysical data of Schablinsky (1963) in the following way: a core of foyaite (sp.g. = 2.60-2.62), an inner ring of foyaite and minor lujavrite (sp.g. = 2.66-2.68) and an outer ring of lujavrite and minor foyaite (sp.g. = 2.72-2.74, i.e. the average specific gravity of the exposed part of the intrusion). The rings open to the east.

According to this interpretation, the magmas of Lovozero, like those of Khibina, have ascended along ring and conical fracture systems, perhaps accompanied by cauldron subsidence. The magma spread out under the roof to form the central foyaite of Khibina and the rocks of the exposed part of Lovozero. The source of these magma injections is then to be found in subjacent magma chambers.

Derivation of the agpaitic magmas: Khibina is only slightly agpaitic while the smaller Lovozero intrusion displays pronounced agpaitic properties. In South Greenland the large composite Igaliko intrusion contains agpaitic pegmatites, while the adjacent smaller Ilímaussaq intrusion is strongly agpaitic. The early members of Lovozero and Ilímaussaq recall those of Khibina and Igaliko, that is the agpaitic magmas developed from miaskitic nepheline syenite magmas through enrichment in volatiles and rare elements. In Khibina and Igaliko, conditions did not permit the development of strongly agpaitic rocks, or, if they were present, then they occurred at high levels which are now removed by erosion. The problem of the derivation of the agpaitic magmas in the two provinces is thus simplified to a problem of derivation of nepheline syenite magmas of rather usual types; these occur in other provinces as independent intrusions the large volume being quite out of proportion to the amount of rocks of established "primary" magmas. Bailey & Schairer (1966, p. 158) have suggested that alkaline magmas may form by partial melting of basaltic source materials in the deep crust under rift arches. The accompanying nephelinites, *etc.* are then formed by partial melting of melilite basaltic sources in the mantle. Both types of magma rise to higher levels along ring faults and may be caught under first order discordances to develop aberrant types such as the Lovozero intrusion.

The amount of nepheline syenite and syenite in the two provinces by far surpasses the amount of gabbro in the present erosional level. This may indicate that the different magmas originated independently by partial crustal and mantle anatexis. The diversity of rocks of the Gardar alkaline province, may, however, be convincingly explained by fractionation of a primary alkali basaltic magma in deep elongated crustal magma chambers (see p. 000). By analogy, the Khibina and Lovozero rocks may be products of similar processes even if the present erosional level does not provide much evidence in favour of this idea. The volatile-rich syenite magma may have been able to move by nature of its low density and low viscosity to higher crustal levels than achieved by the more dense primary magmas.

REFERENCES

ALLAART, J.H. (1967) : Basic and intermediate igneous activity and its relationships to the evolution of the Julianehåb granite, South Greenland. *Meddr Grønland*, **175**, 1, 1-136.

ATAMANOV, A.V., LUGOV, S.F. & FEYGIN, YA.M. (1962) : New results on the geology of the Lovozero massif. *Int. Geol. Rev.* **4**, 570-577.

AZAMBRE, B. & GIROD, M. (1966) : Phonolites agpaïtiques. Bull. Soc. fr. Minér. Cristallogr. **89**, 514-520.

BAILEY, D.K. (1964) : Crustal warping — a possible tectonic control of alkaline magmatism. *J. geophys. Res.*, **69**, 1103-1111.

——— in preparation: Continental rifting and alkaline magmatism. In Sørensen, H. (ed.) : *The alkaline rocks*. Interscience Publishers.

BAILEY, D.K. & SCHAIRER, J.F. (1966) : The system Na_2O–Al_2O_3–Fe_2O_3–SiO_2 at 1 atmosphere, and the petrogenesis of alkaline rocks. *J. Petrology* **7**, 114-170.

BERTHELSEN, A. (1961) : Canada-Grønland, en geologisk sammenligning. *Meddr dansk geol. Foren.* **14**, 363-373.

——— (1962) : On the geology of the country around Ivigtut, SW-Greenland. *Geol. Rdsch.* **52**, 269-279.

BERTHELSEN, A. & NOE-NYGAARD, A. (1965) : The Precambrian of Greenland. In K. Rankama (ed.) : *The geologic systems — The Precambrian* **2**, 113-262. Interscience Publishers.

BOGDANOV, V.I. & SOROKINA, I.I. (1967) : An estimate for the variation in density of crystalline rocks of the crust with depth in the vicinity of the Kovdor alkaline and ultrabasic rock mass (Kola Geophysical Polygon). *Dokl. Acad. Sci. U.S.S.R.* (English translation), **173**, 9-11.

BRIDGWATER, D. (1965) : Isotopic age determinations from South Greenland and their geological setting. *Meddr Grønland* **179**, 4, 1-56.

——— (1967) : Feldspathic inclusions in the Gardar igneous rocks of South Greenland and their relevance to the formation of major anorthosites in the Canadian shield. *Can. J. Earth Sci.* **4**, 995-1014.

BRIDGWATER, D. & HARRY, W.T. (1968) : Anorthosite xenoliths and plagioclase megacrysts in Precambrian intrusions of South Greenland. *Meddr Grønland* **185**, 2, 1-243.

BUSSEN, I.V. & SAKHAROV, A.S. (1958) : Structure of Lovozero alkaline massif. (In Russian). *Rec. Russ. miner, Soc.* no. 1.

——— & ——— (1967) : Geology of Lovozero Tundra. (In Russian). *Izd. "Nauka", Moskva*, 1-125.

ELISEEV, N.A. & FEDOROV, E.E. (1953) : The Lovozero pluton and its deposits. *Trudy Labor. Precambrian Geol. Leningrad*, **19**, 1-38.

ELISEEV, N.A., OGINSKY, I.S. & VOLODIN, E.N. (1939) : Geological map of the Khibina tundra. (In Russian). *Trudy Len. Geol. Upr.* **19**.

FERGUSON, J. (1964) : Geology of the Ilímaussaq alkaline intrusion. South Greenland. Part 1. Description of map and structure. *Meddr Grønland* **172**, 4, 1-81.

——— (1967) : The alkaline igneous intrusion of Ilímaussaq, South Greenland. *Unpublished Ph.D. thesis, University of the Witwatersrand, Johannesburg. (Meddr Grønland,* **186**, *5).*

FERGUSON, J. & PULVERTAFT, T.C.R. (1963) : Contrasted styles of igneous layering in the Gardar Province of South Greenland. *Miner. Soc. America. Special Paper* **1**, 10-21.

FERSMANN, A.E. (1929) : Geochemische Migration der Elemente und deren wissenchaftliche und wirtschaftliche Bedeutung. I. Teil. Chibina Tundren. *Abh. prakt. Geol. u. Bergwirtsch.* **18,** 1-73.

GALAKHOV, A.V. (1959) : The rischorrites of the Khibina alkaline massif. (In Russian). *Izd. Akad. Nauk,* 1-169.

———(1961) : Geological and petrographical features of the Khibina alkaline massif and problems for further scientific investigation. (In Russian). in *Questions of geology, mineralogy and petrography of the Khibina Tundra,* 6-21.

GALAKHOV, A.V. (1967*a*) : Alkalic-ultrabasic igneous activity in the Khibiny tundras (Kola Peninsula). *Dokl. Acad. Sci. U.S.S.R.* (English transl.) **170,** 85-87.

——— (1967*b*) : Chemical composition of rocks in the Khibiny alkalic massif. *Dokl. Acad. Sci. U.S.S.R.* (English transl.) **171,** 225-227.

GERASSIMOVSKY, V.I. (1967) : Chief geochemical characteristics of nepheline syenites of Kola Peninsula. (In Russian). *Geochimija* **11,** 1320-1327.

——— (1968) : Geochemistry of agpaitic nepheline syenites. *Rep. 23rd Int. Geol. Congr., Praha,* **6,** 259-265.

GERASSIMOVSKY, V.I., VOLKOV, V.P., KOGARKO, L.N., POLYAKOV, A.I., SAPRYIKINA, T.V. & BALASHOV, YU.A. (1966) : Geochemistry of Lovozero alkaline massif. (In Russian). *Izd. "Nauka",* 1-395.

GERASSIMOVSKY, V.I. & KUZNETSOVA, S.YA. (1967) : Chemical composition of the rocks of the Ilímaussaq alkaline massif. (In Russian). *Geochimija,* **3,** 274-283.

GERASSIMOVSKY, V.I., VOLKOV, V.P., KOGARKO, L.N. & POLJAKOI, A.I. (in preparation) : The alkaline rocks of Kola Peninsula. In Sørensen, H. (éd.) : *The alkaline rocks* Interscience Publishers.

GERLING, E., KRATZ, K. & LOBACH-ZHUCHENKO, S. (1968) : Precambrian geochronology of the Baltic Shield. *Rep. 23rd Int. Geol. Congr., Praha,* **4,** 265-273.

HAMILTON, E.I. (1964) : The geochemistry of the northern part of the Ilímaussaq intrusion, S.W. Greenland. *Meddr Grønland,* **162,** 10, 1-104.

HARRY, W.T. & PULVERTAFT, T.C.R. (1963) : The Nunarssuit intrusive complex South Greenland. *Meddr Grønland.* **169**. 1-136.

KUKHARENKO, A.A. (1967) : Alkaline magmatism of the eastern part of the Baltic Shield. (in Russian). *Rec. Russ. miner. Soc.,* **96,** 547-566.

KUKHARENKO, A.A., ORLOVA, M.P., BULACH, A.G., BAGDASAROV, E.A., RIMSKAJA-KORSAKOVA, O.M., NEFEDOV, E.I., IL'INSKII, G.A., SERGEEV, A.S. & ABAKUMOVA, N.B. (1965) : Caledonian complex of ultrabasic-alkaline rocks and carbonatites of the Kola Peninsula and Northern Karelia. (in Russian). *Izd. "Nedra", Moskva* 772 pp.

KUPLETSKY, V.M. (1937) : Petrographical description of the Khibina Tundras. In Fersmann, A.E. (ed.) : *Minerals of the Khibina and Lovozero Tundras,* Acad. Sci. Press, Moskva, 11-19.

LARSEN, O. (1968) : K/Ar determinations. *Rep. Geol. Surv. Greenld.,* **19,** 62-67.

LARSEN, O. & MØLLER, J. (1968) : Potassium-argon age studies in West Greenland. *Can. J. Earth Sci.,* **5,** 683-691.

MINAKOV, F.V., KAMENEV, YE. & KALINKIN, M.M. (1967) : Initial composition and evolution of ijolite-urtite magma of the Khibiny alkalic massif. *Geochem. Int.* **4,** 738-753.

NIELSEN, B.L. (1967) : Anorthositforekomsterne på Kvanefjeldet. *Dissertation. University of Copenhagen.*

POLKANOV, A.A. (1937) : Pre-quaternary geology of the Kola Peninsula and Karelia or of the easternmost part of the Fennoscandian crystalline shield. *Rep. 23rd Int. Geol. Congr.,* 25-56, Moskva.

POLKANOV, A.A. & GERLING, E.K. (1960) : Application of K-Ar and Rb-Sr methods in determination of the ages of the Precambrian rocks of the Baltic Shield. (In Russian). *Trudy Labor. Precambrian Geol.* **9,** 7-41.

PULVERTAFT, T.C.R. (1968) : The Precambrian stratigraphy of Western Greenland. *Rep 23rd Int. Geol. Congr.* **4**, 89-107. Praha.

RAMSAY, W. & HACKMAN, V. (1894) : Das Nephelinsyenitgebiet auf der Halbinsel Kola. I. *Fennia,* **11**, 2, 1-225.

SHEYNMANN, YU.M., APEL'TSIN, F.R. & NECHAYEVA, YE.A. (1961) : Alkaline intrusions, their mode of occurrence, and associated mineralization. (In Russian). *Gosgeoltechnizdat, Moskva,* 177 pp.

SHABLINSKY, G.N. (1963) : Seismic investigation of abyssal structures of the alkaline massives of the Kola Peninsula. (In Russian). *Zap. Leningrad Gorn, Inst.* **16**, 2.

SØRENSEN, H. (1958) : The Ilímaussaq batholith, a review and discussion. *Meddr Grønland* **162**, 3, 1-48.

——— (1960: On the agpaitic rocks. *Rep. 21st Int. Geol. Congr. Norden* **13**, 319-327.

——— (1962) : On the occurrence of steenstrupine in the Ilímaussaq massif, Southwest Greenland. *Meddr Grønland* **167**, 1, 1-251.

——— (1965) : On the magmatic evolution of the alkaline province of South Greenland. (in Russian). In "Problemy Geochimiji". *Izd. "Nauka", Moskva* 338-349. (English translation: *Rep. Geol. Surv. Greenld.* **7**).

——— (1968) : Über die Paragenese einiger alkalischer Gesteine in Südgrönland. *Freiberger Forschungshelft.* **C 230**, 177-186.

——— (1969) : Rhythmic igneous layering in peralkaline intrusions. *Lithos* **2**, 261-283.

SØRENSEN, H., HANSEN, J. & BONDESEN, E. (1969) : Preliminary account of the geology of the Kvanefjeld area of the Ilímaussaq intrusion, South Greenland. *Rep. Geol. Surv. Greenld.* **18**, 1-40.

UPTON, B.G.J. (1960) : The alkaline igneous complex of Kûngnât fjeld, South Greenland. *Meddr Grønland* **123**, 4, 1-145.

——— (in preparation) : The alkaline rocks of South-West Greenland. (in Sørensen, H. (ed.) : *The alkaline rocks.* Interscience Publishers.

USSING, N.V. (1912) : Geology of the country around Julianehåb, Greenland. *Meddr Grønland* **38**, 1-376.

VLASOV, K.A. KUZMENKO, M.V. & ESKOVA, E.M. (1959) : The Lovozero alkaline massif. (In Russian). *Izd. Akad. Nauk. S.S.S.R.*, 624 p. (English translation : *The Lovozero alkali massif.* Oliver & Boyd, Edinburgh, 1966).

VLODAVETZ, V.I. (1935) : Pinuajvchorr — Yukspor — Rasvumchorr. (In Russian). *Trudy Arctic Inst.* **23**, 5-58.

VOLOTOVSKAYA, N.A. (1967) : New data on the distribution patterns of Hercynian alkalic rocks in the eastern Baltic Shield. *Dokl. Acad. Sci. U.S.S.R.* (English transl.), **173**, 48-49.

VOROBIEVA, O.A. (1960) : Alkali rocks of the U.S.S.R. *Rep. 21st Int. Geol. Congr. Norden.*, **13**, 7-17.

WALTON, B.J. (1965) : Sanerutian appinitic rocks and Gardar dykes and diatremes, north of Narssarssuaq, South Greenland. *Meddr Grønland* **179**, 9, 1-66.

WATT, W.S. (1966) : Chemical analyses from the Gardar igneous province, South Greenland. *Rep. Geol. Surv. Greenld.* **6**, 1-92.

WEGMANN, E. (1938) : Geological investigations in Southern Greenland. I. On the structural divisions of Southern Greenland. *Meddr Grønland* **113**, 2, 1-148.

ZAK, S.I. (1963) : Tectonics of Khibina alkaline massif. (In Russian). In "Magmatism and Geology of the Kola Peninsula". *Gosgeoltechizdat., Moskva,* 9-15.

ZHDANOV, V.V. (1968) : Two types of crust without "granitic" layer in northern Baltic Shield. *Int. Geol. Rev.*, **10**, 1138-1145.