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On the magmatic evolution of the alkaline igneous province of South Greenland

by

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In 1938 E. Wegmann divided the rocks of southern Greenland into and old basement and a younger formation. The basement consists of the remains of a mountain chain for which Wegmann introduced the name the Ketilides. The younger rocks, which are separated from the Ketilidian orogeny by a long period of denudation, were grouped in the Gardar formation.

The Gardar "formation" comprises supracrustal rocks, a great number of dykes and a limited number of plutonic bodies. In this article an outline of the geology and the magmatic evolution of the Gardar province will be given.

The Ketilidian basement

The basement is made up of supracrustal sediments and volcanics and of infracrustal gneisses, crystalline schists, migmatites and granite. Gabbro-anorthosites are locally of great importance in the gneissic basement. At least two periods of folding have been distinguished. A later reactivation of the basement rocks was accompanied by the formation of a number of bodies of intrusive calc-alkaline granites, which are locally rich in fluorite.

Isotopic age determinations of the basement rocks have given values between 2710 and 1590 million years. The young granites are about 1600 million years old. A summary of the geology of the basement is given by Noe-Nygaard and Berthelsen (in press) and a summary of the isotopic age data is presented by Bridgwater (1965).

The Gardar supracrustals

Supracrustal rocks of Gardar age occur in a small area around Tunugdliarfik fjord. They rest on a peneplained and weathered surface of basement rocks and comprise a 3000 m thick series of continental sandstones, lava flows and sills.

The lower part of the succession is made up mainly of sandstone, while lavas predominate in its upper part. The beginning of volcanic activity is marked by a strong development of volcanic breccias.

Basaltic rocks are most prominent among the volcanics; they may be of trachybasaltic affinity (Ussing, 1912), but a closer study is difficult because of the intense alteration of the rocks. One trachyte flow has been distinguished; in addition there are a few trachyte sills. A study of these volcanic rocks has now been completed by J. W. Stewart(Ph. D. thesis, University of Durham).

Gardar dykes

The region between Kap Farvel to the south and Frederikshåb to the north is intersected by a great number of dykes, the majority of which are considered to be of Gardar age. The excellent exposure has made it possible to establish a detailed chronological sequence of the dykes. The general order of emplacement of the dykes is: lamprophyres and trachytes; three to five generations of dolerites and olivine dolerites; granophyres; alkali microgranites and microsyenites; trachytes and tinguaites.

Dykes are most numerous in three ENE-striking zones through Ivigtut, Nunarssuit and Ilímaussaq respectively. Of the various types the dolerites are by far the most numerous and the largest; the alkali dykes are generally thin, and are largely confined to the Ivigtut and Ilímaussaq zones, which are also the site of undersaturated plutonic centres.

In two of these zones giant dykes occur. The Nunarssuit zone contains five such dykes situated to the NE of the Nunarssuit intrusion. They are up to 500 m wide and of late Gardar age. The dykes are composite having marginal gabbro and central saturated or slightly oversaturated augite-biotite syenite. According to D. Bridgwater (personal communication) the gabbro has intruded without dilation of the structures in the country rocks which indicates emplacement by stoping. The syenite intruded into the gabbro while the latter was still hot and partly unconsolidated.

The second area of giant dykes is Tugtutôq island to the SW of Ilímaussaq (Upton,1962 and 1964). The number of dykes in this zone is so large that more than 20% of the ground is occupied by dykes. Most of the dykes strike NE-SW, that is towards the Ilímaussaq intrusion. The oldest giant dyke is 500-600 m wide and composite with marginal gabbro (displaying a chilled zone at its contact with the country rocks) and central syenite (which is coarse-grained and pegmatite-rich adjacent to the gabbro). A hybrid zone is developed between gabbro and syenite indicating that the syenite intruded while the gabbro was still hot and partly unconsolidated. The syenite varies from a slightly undersaturated ferroaugite syenite in the west to a strongly undersaturated nepheline syenite in the east. The rocks in the west carry fayalite, biotite and barkevikitic hornblende, but the most nepheline-rich rock contains only slight amounts of biotite and hornblende, no fayalite, and a clinopyroxene more sodic than that farther to the west. The marginal gabbro is slightly alkaline being composed of plagioclase (An_{57-44}), Fe-rich olivine, cryptoperthite and accessories.

Two giant dykes of troctolitic gabbro up to 800 m thick intersect the above-mentioned composite dyke. The gabbro at Narssaq (Ussing's essexite), to the NE of Tugtutôq, may be the eastern continuation of these dykes. These gabbros are mainly composed of plagioclase (An_{65}) and olivine (Fa_{30-40}). One fo the dykes contains a small body of alkali gabbro composed of plagioclase, cryptoperthite, Fe-rich olivine, biotite and clinopyroxene; and a body of quartz syenite composed of antiperthite, fayalite, augite, biotite, amphibole and accessories. Between this syenite and the main gabbro a hybrid alkali gabbro of the same type as the one just mentioned is developed. Apparently contemporaneous with the giant gabbro dykes is the emplacement of small masses of titanium-rich pyroxenite at Narssaq (Ussing, 1912).

Xenoliths are abundant in the Gardar dykes, comprising anorthosite, gabbro-anorthosite and nepheline syenite.

The anorthosite xenoliths are very widespread and may make up 80% by volume of the dykes. The xenoliths vary in size from small cleavage fragments of crystals of plagioclase to masses up to over 100 m wide and several km long. The anorthosite xenoliths occur in the dykes over a 12,000 square km large area (Bridgwater, 1965, p.16). The anorthosite is composed of andesine-labradorite in very large crystals and subordinate amounts of augite, olivine and magnetite. Uralitization is widespread. The xenoliths often recall igneous cumulates and they are quite different from the gabbro anorthosites found in the basement.

Faulting

Faulting has played an important role during the Gardar period. A detailed study of one of the major WNW-ESE fault zones (Henriksen, 1960) has shown that faulting took place along this zone already in pre-Gardar times and that it continued intermittently during Gardar time, which is demonstrated by comparing the relative displacements of successive generations of Gardar dykes.

Three prominent directions of fault zones have been distinguished (see Berthelsen, 1962). One system of major wrench faults strikes WNW-ESE. These faults delimit large fault blocks, for instance the one in which Ivigtut, Grønnedal-Íka, Ilímaussaq and Igaliko are situated. Another system, the ENE-trending fault and crush zones, is especially pronounced in the dyke-rich zones through Ivigtut and Ilímaussaq. A third important system of faults trends N-S, and is prominent in the Nunarssuit and Ivigtut regions.

Plutonic bodies

With the exception of the Grønnedal-Íka intrusion and possibly some units of the Igaliko intrusion, all the Gardar plutonic bodies are of mid- or late Gardar age, since they are intersected by very few Gardar dykes and they themselves intersect Gardar dykes (and the Gardar supracrustals).

The predominant rocks of the intrusions are augite syenite, alkali granite and nepheline syenite; calc-alkaline granite and gabbro are more subordinate.

The intrusions were apparently emplaced by cauldron subsidence or stoping and they are all composite having been formed by two or more pulses of magma. They all show chilled zones in contact with the country rocks. Igneous layering is developed in most massifs, but will not be treated in the present paper (a review of the layering has been published by Ferguson and Pulvertaft, 1963).

1. The Grønnedal-Íka intrusion: The major rock types have been described by Callisen (1943), and a detailed geological map and a description to the map published by Emeleus (1964). The intrusion is made up of a great number of types of nepheline syenite (foyaite, ditroite, ijolite, malignite, pulaskite) and to a lesser extent of other syenites. Contacts between the rock types are generally transitional in the field.

The rock-forming minerals are microperthite, ægirine augite, nepheline, biotite, hornblende and minor sodalite, that is a typical miascitic assemblage.

A few small bodies of carbonatite intrude the syenites. They are associated with fault zones and carbonatite dykes form intrusion breccias in the syenites. The carbonatite is rich in calcite and siderite, but has a very low content of rare minerals

2. Ivigtut: The cryolite deposit at Ivigtut is situated in a granitic stock which intruded the country rocks with the formation of a distinct intrusion breccia. The granite is sodic, containing ægirine augite and soda hornblende in addition to biotite. It is altered into greisen adjacent to the cryolite mass and inclusions of granite and greisen occur in the cryolite. The cryolite is considered to have been formed through reactions of volatiles trapped in the upper part of the granite stock with the already consolidated granite (Sørensen, 1951 and Berthelsen, 1962).

3. Kûngnât: This small intrusion has been described in great detail by Upton (1960).

The complex is made up of three steep-sided syenite bodies which were intruded with progressive easterly shift of centre. Later is a ring dyke of alkali gabbro.

The first-formed part of the intrusion is the south-western quartz syenite which contains fayalite, ægirine augite, soda hornblende and biotite.

The second intrusion of syenite is divided by a gneiss raft into a lower and an upper part which apparently crystallized independently after the sinking of the raft. A considerable degree of fractionation had taken place before the raft settled. The upper syenite contains less Mg, Fe, Ca, Sr and Ba than the lower one. After the separation of the magma chamber into two parts, fractional crystallization caused each to become lighter in colour and richer in quartz passing upwards. Both parts contain fayalite, pyroxene in the range augite to ægirine augite, and biotite. The lower syenite contains hastingsite, the uppermost one riebeckite. In both parts of the second intrusive phase there are late dykes and sheets of alkali granite containing one or more of the minerals riebeckite, ægirine and astrophyllite. Pegmatites are numerous in the peripheral parts of the second syenite intrusion; in these riebeckite, fluorite, siderite, zircon, tæniolite, astrophyllite and molybdenite have been found.

The easternmost syenite belonging to the third intrusive phase is more basic than the two first syenite intrusions in the complex. It contains fayalite, relatively Mg-rich pyroxene and Ca-rich feldspar. Hornblende and biotite are normally present. This syenite is accompanied by late intrusive bodies of quartz microsyenite and microgranites which however are less alkaline than those in the western centre, hornblende and biotite being the predominant mafic minerals. There is an irregular fringe of pegmatites around this intrusive phase which contain feldspar, quartz, hornblende and minor siderite and zircon.

The fourth intrusive phase, the gabbro ring dyke, was emplaced later than the syenites but prior to the emplacement of the late acid differentiates of the second and third phases. The gabbro is alkaline, being made up of plagioclase, alkali feldspar, Fe-rich olivine, titanium augite and accessories.

4. The Nunarssuit intrusion: A general description is provided by Harry and Pulvertaft (1963). The intrusion is younger than the Gardar dykes but older than some of the faults. It is composed of a number of rock types:

a. The Alángorssuaq gabbro in the northern part of the intrusion is an olivine gabbro with a small amount of alkaline residuum. The gabbro is heavily uralitized and hybridized at the contact with the granites of the massif.

b. The Helene granite, in the west part of the massif, contains perthite, quartz, hornblende, soda hornblende, green clinopyroxene, fayalite and biotite. Pegmatites are very rare.

c. The Kitsigsut syenite forms the western part of the massif and is made up of perthite, plagioclase, augite, fayalite, green amphibole and subordinate quartz.

d. The Biotite-granite forms the northern part of the intrusion and is composed of quartz, perthite, soda plagioclase, biotite, hornblende and accessories. Quartz veins, aplites and pegmatites are common, the last contain green mica, fluorite, zircon and beryl.

e. The Nunarssuit syenite is the predominant rock of the intrusion and makes up its southeastern part. It is very homogeneous and is composed of perthite, plagioclase, ferroaugite with green margins, green hornblende, fayalite, biotite and minor quartz, soda hornblende and aenigmatite. There are late stage laccoliths and veins of soda granite containing soda pyroxene and amphibole, hornblende, biotite, aenigmatite, fluorite and astrophyllite. Pegmatites are common and contain soda amphibole, ægirine, fluorite, zircon, galena and monazite; albite is the predominant feldspar.

Table 1. Chemical analyses of Gardar syenites

Компо-ненты	1	2	3	4	5	6	7	8	9	10	11
SiO_2	55,79	53,5	57,5	53,71	56,53	61,17	60,64	61,33	62,98	55,92	57,09
TiO_2	1,81	1,6	1,1	3,40	1,29	1,04	0,99	0,57	0,38	2,18	1,58
Al_2O_3	15,76	16,2	17,1	15,37	16,61	16,10	15,37	15,87	16,45	14,22	13,52
Fe_2O_3	1,60	3,7	1,8	3,28	1,66	2,00	1,36	1,09	1,07	1,60	1,60
FeO	7,56	6,3	6,9	5,72	7,10	4,37	5,49	5,56	3,73	10,36	7,12
MnO	0,14	0,2	0,2	0,14	0,19	0,16	0,15	0,13	0,09	0,29	0,19
MgO	0,41	2,0	0,9	1,58	0,83	0,66	0,42	0,28	0,11	0,75	1,26
CaO	3,70	4,6	1,9	5,20	3,41	2,69	3,05	2,98	2,52	3,83	4,06
Na_2O	7,72	5,8	5,8	6,84	5,98	5,40	5,15	5,66	5,94	4,98	5,15
K_2O	4,34	4,7	5,1	4,11	5,22	5,60	5,35	5,86	6,09	4,86	5,13
H_2O^+	0,18	0,5	0,5	0,45	0,94	0,74	0,71	0,58	0,40	0,54	0,37
H_2O^-	0,34			0,33	0,08	—	0,12		0,26	0,13	
P_2O_5	0,36	0,4	0,4	0,52	0,36	0,34	0,20	0,09	0,05	0,54	0,49
Сумма	99,71	99,5	99,2	100,65	100,20	100,27	99,00	100,00	100,07	100,20	97,56

1. Augite syenite, Ilímaussaq. C. Winther, anal. (Ussing, 1912, p. 190).
2. Chilled augite syenite, Ilímaussaq. Average of 3 analyses. E. Hamilton anal. (Ferguson, 1964, p. 32).
3. Coarse augite syenite, Ilímaussaq. E. Hamilton anal. (Hamilton, 1964, p. 27).
4. Augite syenite, Igaliko. C. Winther anal. (Ussing, 1912, p. 243).
5. Syenite, W end of first generation giant dyke, Tugtutôq. (Upton, 1964, p. 10).
6. Nunarssuit syenite. B. Borgen anal. (unpublished).
7. Syenite, E end of second generation giant dyke, Tugtutôq. E. Godijn. anal. (Upton, 1964, p. 10).
8. Mean of two quartz syenites from 2nd intrusive phase from Kûngnât. (Upton, 1964, p. 10).
9. Quartz-fayalite syenite from lower part of 2nd intrusive phase, Kûngnât. B. Collett anal. (Upton, 1960, p. 93).
10. Syenite from lowermost part of 2nd intrusion phase, Kûngnât. B. Collett anal. (Upton, 1960, p. 92).
11. Approximate analysis of syenite from 3rd intrusive phase, Kûngnât. B. Upton anal. (Upton, 1960, p. 92).

f. The Malenefjeld granite occurs to the east of the Nunarssuit syenite from which it is separated by a narrow zone of country rocks. It contains microcline vein perthite, albite, quartz, soda pyroxene and amphibole, pseudomorphs after olivine, aenigmatite, zircon, Li-mica and astrophyllite. Zoned pegmatites contain agpaitic microcline, zircon, bastnäsite, ægirine, fluorite, astrophyllite, ilmenite and other minerals

The gabbro is definitely the oldest rock of the intrusion. The Kitsigsut syenite is older than the Biotite-granite, which again is most probably younger than the Helene granite. The Helene granite and the Nunarssuit syenite are apparently contemporaneous, the syenite being the youngest to the north, and being veined by the granite to the south where, furthermore, inclusions of syenite are found in the granite. The Malenefjeld granite recalls the late acid differentiates of the Nunarssuit syenite and contains inclusions and local marginal rims of augite syenite. It is therefore considered by Harry and Pulvertaft to be younger than the Nunarssuit syenite.

5. The Puklen intrusion (Pulvertaft, 1961): A few km to the east of the Nunarssuit intrusion a small ring intrusion apparently of the same age as the Nunarssuit intrusion occurs. It is composed of an outer ring of augite syenite and quartz syenite and a central stock of alkali granite and granophyre. Pulvertaft regards the syenites as older than the granites. The rocks are closely related to the Nunarssuit syenite and the Malenefjeld granite.

6. The central intrusion of Tugtutôq (Upton, 1962, 1964): The giant dykes of Tugtutôq are intruded by a small ring complex made up of a number of ring intrusions of saturated syenites and alkali granite succeeded by a stock of coarse-grained perthosite. There are very many xenoliths of basalt, quartzite, olivine gabbro and microsyenite in the members of the intrusion indicating a former larger extension of the supracrustal Gardar rocks.

The rock-forming minerals are: alkali feldspar, hornblende and soda amphibole, hedenbergite - ægirine augite - ægirine, fayalite, quartz and biotite. In pegmatites zircon, astrophyllite and Li-mica have been found. The latest members of the intrusion are most rich in low temperature minerals and contain astrophyllite, aenigmatite and fluorite.

7. The Ilímaussaq "batholith" has been described by Ussing (1912), Wegmann (1938), Sørensen (1958), Hamilton (1964) and Ferguson (1964).

The "batholith" may be divided into two separate intrusions, the western Narssaq intrusion composed of alkali gabbro (Ussing's essexite), quartz and pyroxene syenites and alkali granite (Ussing, 1912, and J.W. Stewart, unpublished observations), and the eastern Ilímaussaq intrusion. The Narssaq intrusion is intersected by a great fault which in turn is cross-cut by the Ilímaussaq intrusion and is thus older than the latter.

According to Ussing the Ilímaussaq intrusion proper was formed in two stages: 1) intrusion of augite syenite and alkali granite, 2) emplacement of a stratified complex made up of (from the top downwards): alkali granite, quartz syenite, pulaskite, foyaite and the agpaitic rocks sodalite foyaite, naujaite, lujavrite and kakortokite. The bottom of the intrusion is unknown, hence Ussing's term "batholith". The stratified complex intruded into and partly replaced the older rocks.

Wegmann (1938) considered the rocks of Ilímaussaq to be partly of metasomatic origin.

Sørensen (1958) advanced the view that the intrusion was formed during one main magmatic phase followed by late- and post-magmatic phases. During the first phase an augite syenite magma enriched in volatiles crystallized to form augite syenite and the agpaitic rocks. The upper quartz syenite and alkali granite were considered to be formed through reactions with the roof of the intrusion. The lujavrites were the latest rocks to form and were considered partly to be late- or post-magmatic rocks.

According to Ferguson (1964) two magmas were involved in the evolution of Ilímaussaq. First an augite syenitic magma was injected and crystallized to form syenite and foyaite. Then small stocks and sheets of alkali granite and quartz syenite intruded the syenite and foyaite. After this interruption the crystallization of the augite syenitic magma continued with the formation of the agpaitic rocks. A high content of volatiles was responsible for this evolution.

Hamilton (1964) proposes a formation of the intrusion in three stages: 1) augite syenite and foyaite, 2) the agpaitic rocks which are considered to have developed by extreme fractionation of augite syenite magma, and 3) the acid rocks.

The agpaitic rocks will not be further considered at this point. Instead a few remarks will be made about augite syenite and alkali granite.

The augite syenite is composed of alkali feldspar, augite (with green rims), fayalite, iron ore, apatite, lepidomelane, nepheline and hornblende. The amounts of nepheline, ægirine and amphibole increase from the chilled contact zones inwards. The augite syenite occurs along the major part of the margin of the intrusion and is also found at the roof of the intrusion. Inclusions of augite syenite occur in the agpaitic rocks and veins of the latter intersect the syenite. The agpaitic rocks do not show chilling against the augite syenite; on the contrary pegmatitic zones are often developed at the contact.

The alkali granite is composed of alkali feldspar, quartz, arfvedsonite, ægirine, aenigmatite, elpidite, zircon and astrophyllite. The acid rocks occur exclusively in the upper part of the intrusion and vein the overlying supracrustals. A minor amount of similar granite is found around quartzitic xenoliths in augite syenite.

8. The Igaliko intrusion (Ussing, 1912): Recent unpublished work by W. T. Harry and C. H. Emeleus has demonstrated that this large intrusion is a composite one, being composed of several central intrusions. Augite syenite is common in the marginal zones, the central parts of the intrusion being made up of various types of miascitic nepheline syenites.

The augite syenite is composed of alkali feldspar, augite, hornblende, biotite, apatite, iron ore and local nepheline and olivine. In this syenite there are at Narssarssuk several drusy pegmatites rich in rare minerals and quartz (see Ussing, 1912).

9. The Klokken intrusion southeast of Igaliko is a small stratified intrusion made up of syenogabbro and augite syenite (K. Ellitsgaard-Rasmussen, personal communication).

Mineralizations

Mineralizations are most pronounced in the two NE-trending dyke zones through Ivigtut and Ilímaussaq. The cryolite deposit at Ivigtut is a special type of mineralization, but in addition there are numerous small mineralizations on joints and in crush zones in the Ivigtut region. There are green ægirine-rich veins containing galena and sphalerite, and rusty zones composed of iron ores, chlorite, carbonates, sulphides, barytes, apatite, brannerite? and thorogummite? (Buchwald et. al., 1960).

Inside the Ilímaussaq intrusion numerous mineralized veins occur (Sørensen, 1962). In addition there are, to the northeast of the Ilímaussaq intrusion, mineralized zones containing ægirine, albite, chlorite, carbonates, quartz, iron ores, sulphides, fluorite, apatite, monazite, bastnäsite, thorite?, zircon and other minerals (J. Hansen, personal communication).

Isotopic age determinations on Gardar rocks

The following ages are taken from a review prepared by Bridgwater (1965).

A mid-Gardar dolerite dyke 1435 m.y. (augite, K/Ar); biotite granite, Nunarssuit 1150 m.y. (biotite, Rb/Sr); biotite from Kûngnât 1170 m.y. (Rb/Sr); biotite from the Nunarssuit syenite 1128 m.y. (K/Ar); biotite from pegmatite in the Ivigtut granite 1160-1210 m.y. (Rb/Sr and K/Ar); Li-mica from an agpaitic pegmatite in Ilímaussaq 1012-1030 m.y. (Rb/Sr). Biotite and augite from an anorthosite inclusion in the Narssaq gabbro gave an age of 1025 m.y. (K/Ar), that is the age of the adjacent Ilímaussaq intrusion.

Relationships between tectonism and magmatism

The emplacement of the plutonic bodies was undoubtedly, as emphasized by Berthelsen (1960) and Harry and Pulvertaft (1963), connected with the faulting of the region. Thus the Ilímaussaq, Igaliko, Nunarssuit and Grønnedal-Íka intrusions are situated on WNW-trending fault zones, and they are located where those faults are intersected by ENE dyke zones (see plate 1).

The distribution of the plutonic bodies and the dykes does not favour the view that the Gardar magmatic province has developed from an extensive regional magma reservoir, but rather that the magma reservoirs responsible for the Gardar volcanism were very long, relatively narrow and of a very great vertical extension (Noe-Nygaard and Berthelsen, in press). This is inferred from the presence of the giant dykes pointing towards plutonic bodies and from the sub-parallel regional dyke swarms which are without any radial grouping around plutonic centres.

The relationships between dykes and faults indicate that periods of tension alternated with periods of compression (and transcurrent faulting) during Gardar time. During the periods of tension basaltic magma injected the fractures; during the periods of compression, the magmas were trapped in the deep and narrow reservoirs and the volatiles held back so that fractionation of the basaltic magma could take place. In subsequent periods of tension the reservoirs were tapped successively from different levels. This may explain the great variety of dyke rocks and the location of the composite plutonic bodies in the ENE dyke zones, below which the reservoirs very probably were situated (Noe-Nygaard and Berthelsen, op. cit.).

On the magmatic evolution of the Gardar province

Four distinct rock types make up a majority of the Gardar intrusions and dykes, namely (alkali) gabbro, syenite, nepheline syenite and (alkali) granite. Intermediate types are rare or absent. Only in the Kûngnât intrusion does there appear to be a rather gradual transition from gabbro through syeno-diorite and basic syenite into quartz syenite. The order of intrusion is from the most acid to the most basic rocks. Upton (1960) suggests that this may be due to expulsion of magma fractions from the top downwards from a deeper-lying somewhat differentiated large body of alkaline olivine basalt. During a long undisturbed evolution volatiles accompanied by silica and alkalis, accumulated in the upper part of the magma chamber and reactions with the acid roof rocks increased the acidity of the uppermost part of the magma. It should however be pointed out that the intermediate rocks in this intrusion may have been formed through reactions between gabbroic magma and syenitic magma or rocks.

In all other plutons and in the composite dykes there are distinct compositional breaks between the successive pulses of magma. This is especially well seen in the giant dykes, where a restricted development of transitional rock types is clearly due to hybridization (see Upton, 1962).

The presence of basaltic lavas and dykes, and early gabbroic members in the composite giant dykes, and in the Nunarssuit and Narssaq intrusions, suggests that the Gardar province belongs to the gabbroic-alkaline association, discussed by Sheinmann et. al. (1961); there are no indications that the Gardar rocks belong to the ultrabasic or granitic-alkaline associations.

It might then be considered that the Gardar rocks have developed by fractionation of an alkaline olivine basalt magma as suggested by Upton (1960) for the Kûngnât intrusion. This evolution may have taken place in very deep crustal or sub-crustal reservoirs. The early crystallized plagioclase and some olivine and augite accumulated to form horizons of (gabbro) anorthosite, which resulted in a depletion in Ca, Al and Mg in the uppermost part of the reservoir. This separation of plagioclase also changed the Al/Si ratio in the upper part of the magma, but apparently did not give rise to a depletion in silica, possibly because of gas transfer of silica (and alkalis) to the upper parts of the magma and reactions with the roof. The general lack of rock types intermediate between gabbro and syenite may be explained as a result of this separation of the magma reservoir into a lower horizon of olivine gabbro (with concentrations of anorthosite) and an upper syenite magma. This recalls the separation of granophyric or granitic masses in the upper parts of tholeiitic sheet intrusions.

Vorob´eva (1963) has suggested a similar mechanism of formation of alkaline magmas as derivatives from a "pure line" basaltic magma in sub-crustal magma reservoirs. In this explanation liquation processes are involved.

The formation of alkali gabbro and syenite by crystallization of a basaltic magma may also be explained in accordance with the proposal by Wyllie (1963), namely that the liquidus path of the system has two "shelves", one at basalt and one at syenite, where small temperature changes cause much crystallization, while these two "shelves" are separated by a steep slope, where large temperature changes cause little crystallization and small compositional changes; this explains why only a very limited amount of intermediate rocks is formed.

The very great amount of Gardar syenite compared with the rather small amounts of gabbro in the plutonic bodies of the province may indicate that not only basalt magma, but also syenite magma was formed by partial fusion of sub-crustal (or crustal) rocks. This kind of "zone melting" (Vinogradov, 1961) has been proposed by Barth (1954) in order to explain the formation of two series of rocks in the Oslo province, the series of Oslo essexites and the larvikite series. In the Oslo region, the origin of the biotite granite (Drammens granite) falls outside these lines of evolution, as does the formation of the Biotite-granite and perhaps the Helene granite in the Nunarssuit intrusion (Harry and Pulvertaft, 1963).

Finally the associations syenite - nepheline syenite and syenite - alkali granite in the Gardar province should be considered.

The field relations at Kûngnât, Nunarssuit, Puklen, the central intrusion of Tugtutôq, the Narssaq intrusion and part of the Ilímaussaq intrusion indicate that small masses and sheets of alkali granite were formed as late differentiates of the common syenite magma. This process has been discussed by Upton (1960, 1964), Pulvertaft (1961) and Harry and Pulvertaft (1963). The formation of late peralkaline acid differentiates is in excellent agreement with experimental data and these may represent the crystallization products of a residual magma formed in the presence of volatiles, possibly in connection with retrograde boiling. The model proposed by Wyllie (op. cit.) can also explain this magmatic evolution.

The nepheline syenites of Grønnedal - Íka, the first generation giant dyke of Tugtutôq, Ilímaussaq and Igaliko are all associated with slightly undersaturated syenites, which contain only small amounts of nepheline. This in contrast to the syenites of Kûngnât, Nunarssuit, Puklen and the central intrusion of Tugtutôq, which are saturated or slightly oversaturated. Thus differences in chemical composition of the syenites may explain the formation of acid associates in some intrusions, while strongly undersaturated rocks accompany the syenites in others. This has been discussed by Upton (1960) in relation to the system $NaAlSiO_4$ - FeO - SiO_2 and could also be demonstrated with reference to the system $NaAlSiO_4$ - $KAlSiO_4$ - SiO_2 in which the over- and undersaturated regions are separated by a high temperature barrier.

In Ilímaussaq the crystallization of the augite syenite magma gave birth to augite syenite and foyaite which were both intruded by alkali granite (and quartz syenite). In this case undersaturated, as well as oversaturated, rocks are associated with the slightly undersaturated augite syenite. This association may be explained in at least two ways: either by changes in potentials of acid volatiles as discussed by Ryabchikov and Kogarko (1963), or by assimilation of sandstone in the alkaline augite syenite magma as discussed by Ussing (1912).

Ferguson's field observation that the emplacement of the alkali granite of Ilímaussaq occurred in between the emplacements of augite syenite and the agpaitic rocks, in the opinion of the author supports the view expressed by Ussing, that the Ilímaussaq intrusion was formed in two stages: 1) augite syenite, foyaite and alkali granite, and 2) the agpaitic rocks.

The agpaitic rocks of Ilímaussaq clearly crystallized from a strongly fractionated magma enriched in rare elements and in a gas phase rich in water vapour and chlorine and fluorine compounds. This magma was most probably derived from an augite syenitic magma, just as the well-known Langesundsfjord pegmatites in the Oslo region, which display a distinct agpaitic affinity, may be regarded as formed from residual liquids derived from the larvikitic and the closely related lardalitic magmas (see Barth, 1945). This interpretation partly bridges the gap between the apparently contradicting views on the origin of the agpaitic rocks of Lovozero; on petrographical evidence Vorob´eva (1963) regards these rocks as derivatives of a basaltic magma formed deep under the crust, while Gerasimovskii (1963) by means of geochemical data has demonstrated a relation between acid magmas and the agpaitic rocks of Lovozero.

Finally it should be recalled that Wegmann (1938) suggested that the Ilímaussaq and Nunarssuit plutonic bodies were formed, at least partly, by metasomatic processes. This view has been disproved by later investigations (see Harry and Pulvertaft, 1963, and the recent papers on the Ilímaussaq intrusion). However, strong metasomatic alteration of the rocks forming the roof of the northern part of the Ilímaussaq intrusion and of inclusions of these rocks in the lujavrites has taken place (Sørensen, unpublished observations). It should also be pointed out that the syenite centres of the composite giant dykes might be explained as the result of metasomatic processes caused by the diffusion of alkaline solutions through fractures in the partly consolidated gabbros of the dykes in accordance with the theories of Korzhinsky (1960). However, the existence of large masses of similar syenites displaying clear intrusive relations to the country rocks elsewhere in the region supports the magmatic interpretation of the development of the composite dykes.

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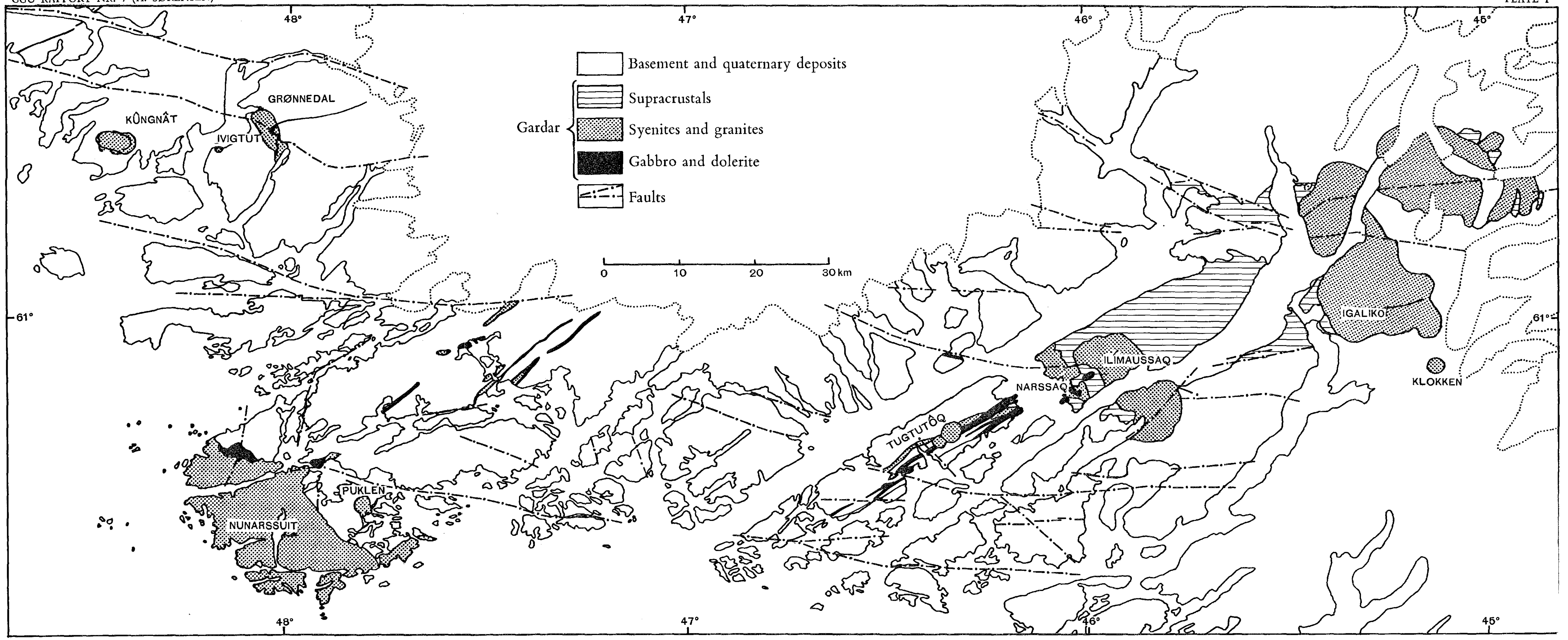
Plate 1. Map of a part of South Greenland showing the location of the Gardar supracrustals, plutonic bodies, a few larger dykes and the most prominent faults.

GGU RAPPORT NR. 7 (H. SØRENSEN) PLATE 1



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