The Gardar period in southern Greenland

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Fig. 143. Aerial view of rhythmically-repeated layering in the syenites of the Klokken complex.

Introduction

Between Narssaq and the Inland Ice in southern Greenland, faulted outliers of sandstone and volcanic rocks lie unconformably upon a pre-1600 m.y. 'basement' of metamorphic rocks, migmatites and granites. Both 'basement' and the supracrustal rock outliers are intruded by a variety of dykes and central complexes. The region, which is the most populated in Greenland, has received a steady flow of visitors from Europe since the beginning of the 19th century. One of the first notable geologists to visit the area was Giesecke whose record of several years of travel and investigation still finds a useful place in the geological literature (Giesecke, 1910). He was followed later in the 19th century by Steenstrup, Flink, Ussing and others, all of whom paid particular attention to these younger igneous rocks, especially to the nepheline syenites of Ilímaussaq and the Igaliko region, on account of their exotic rock types and their content of hitherto unknown minerals; this was also true of the Ivigtut cryolite deposit which was mined from 1855 until recently.

Although among the early accounts those by Steenstrup (1881), Flink (1898) and Ussing (1912) are outstanding, it is to a later investigator, C. E. Wegmann, that we owe the first comprehensive account of the region (Wegmann, 1938). Wegmann distinguished several geological episodes and established the basis of the modern chronology; in particular he singled out the younger sediments, volcanics and unmetamorphosed intrusives as belonging to a single tectono-volcanic episode and he termed them the Gardar rocks, after the ancient Norse Bishopric of Garður where the present day village of Igaliko now stands.

Since the second world war, and particularly since 1954, the region has been extensively mapped by the Geological Survey of Greenland and many accounts have appeared including summaries of the general geology (Berthelsen & Noe-Nygaard, 1965), reviews of the Gardar igneous rocks (Sørensen, 1969a; Upton, 1974) and maps (Nunarssuit, sheet 60 V.1 Nord; Ivigtut, sheet 61 V.1 Syd; Narssarssuaq, sheet 61 V.3 Syd; Julianehåb, sheet 60 V.2 Nord) of the 1:100 000 series published by the Survey.

Age and divisions of the Gardar

Radiometric age determinations (Moorbath *et al.*, 1960; Bridgwater, 1965) on minerals from the younger intrusives showed them to be Precambrian. However, some of the youngest dykes, forming a swarm roughly paralleling the coastline, are now known to date from a Mesozoic event (O. Larsen, 1966; Walton, 1966); they also differ significantly in their direction of remanent magnetism from the Gardar intrusives (Tarling, 1966). Recent whole rock Rb-Sr isochron data (Table 5) indicate age limits of 1330–1150 m.y. for the Gardar. Apart from some minor volcanism and possible tilting during the Mesozoic, and the Quaternary and Recent glaciation, the region appears to have been geologically inactive for the last 1150 m.y.

Table 5. Rb-Sr isochron age determinations on Gardar rocks

Locality	Age (m.y.)	Reference
Kûngnât	1245±17	6
Ivigtut	1248±25	2
Grønnedal-Íka	1327±17	3
Nunarssuit		
Alángorssuaq gabbro	1143±48	3
Biotite granite	1162±21	3
Syenite	1154±14	3
Helene granite	1149±31	3
Tugtutôq		
Hviddal dyke	1175± 9	1
Central complex	1168±37	1
Ilímaussaq	1168±21	4
Igaliko complexes		
Motzfeldt	1310±31	3
North Qôroq	1295±61	3
South Qôroq	1185± 8	3
Igdlerfigssalik (late)	1167±15	3
Klokken	1159±11	5

All quoted ages conform to a decay constant for ^{87}Rb = $1.39 \times 10^{-11} y^{-1}$

1. Van Breemen & Upton, 1972 (values reduced by 1% from original published values for intra-laboratory consistency)
2. Blaxland (in press)
3. Blaxland *et al.* (in prep.)
4. Blaxland *et al.* (1976)
5. Blaxland & Parsons (1975).
6. Blaxland & Upton (unpublished data)

It has been difficult to establish detailed chronological correlations within the Gardar rocks throughout south Greenland, although excellent exposure makes determination of local sequences a relatively simple matter. It is convenient to subdivide the Gardar rocks into three geographic areas: (1) a western area around Ivigtut, (2) a central area in the vicinity of Nunarssuit and the region to the north-east, and (3) an eastern area including Tugtutôq, the Ilímaussaq peninsula and the intrusive complexes north-east of Igaliko (fig. 170). In each of these areas the sequences are well established; difficulties arise however in attempting to correlate the principal events across the three areas. At present, this has to be attempted (a) on the basis of similarities in the general sequence of events and (b) on the direct links between the three areas provided by the faults and dyke swarms, but the correlations can only be very tentative.

The Eriksfjord Formation

A series of clastic sediments, lavas and subordinate pyroclastic rocks, unconformably overlying the 'basement' rocks, crops out: (1) on the Ilímaussaq peninsula, (fig. 144), (2) on Nunasarnaussaq between Tunugdliarfik and Kangerdluarssuk, (3) in the vicinity of Narssarssuaq, (4) in the Qagssiarssuk region, (5) around Igaliko and on the western margin of Igdlerfigssalik, and (6) as small outliers adjacent to the Motzfeldt nepheline syenites (fig. 170). The name Eriksfjord Formation was proposed by Poulsen (1964) for these Gardar sediments and volcanics after the old Norse name for Tunugdliarfik.

Sediments also occur outside the areas mentioned above. Sandstone infills fissures in the basement north of Bredefjord (Scharbert, 1963) and inclusions of quartzitic sediments and basic rocks resembling lavas occur in the central Tugtutôq and Nunarssuit complexes (Upton, 1962; Harry & Pulvertaft, 1963), and in small diatremes on Tugtutôq and Narssaq (Upton, 1962) and Johan Dahl Land (Walton, 1965). Sandstones similar to those of the Ilímaussaq–Igaliko region occur in moraines on the edge of the

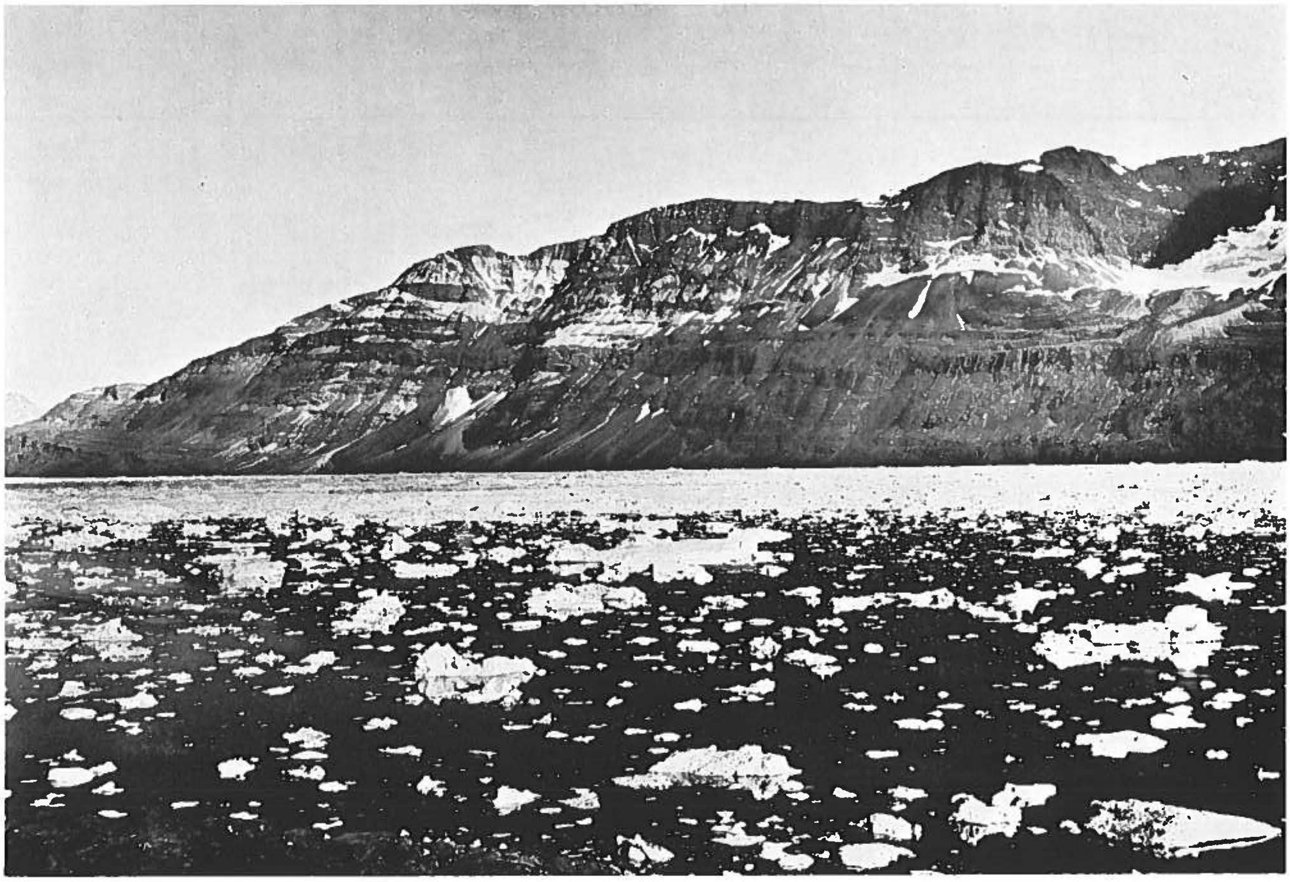


Fig. 144. Gently dipping lavas and sandstones of the Eriksfjord Formation on the north side of the Ilímaussaq intrusion. Diagonal (bottom-left to top-right) structures mark dykes belonging to the regional swarm. Height of cliff section: about 1400 m.

Inland Ice as far north as the fjord Neria in the Frederikshåb district (Watt, personal communication) and in moraines in south-east Greenland (Bridgwater, personal communication).

Thus, although the Eriksfjord Formation is now largely confined to fault-bounded outliers around and to the east of Narssaq, there can be little doubt that they once covered a much more extensive area. The principal accounts of the lavas and sediments are those of Stewart (1964) and Poulsen (1964). The thickest preserved succession (on the Ilímaussaq peninsula) comprises some 3000 m of sandstones and lavas (in approximately equal amounts). Pyroclastic rocks are generally scarce but are locally, as at Qagssiarssuk, of considerable importance (Stewart, 1970). Several of the principal measured sections are shown in figure 145.

Sediments

The sedimentary succession consists mainly of medium to fine-grained sandstones. Over much of the area these are white or grey quartzites although red quartzites and arkoses also occur. Occasionally, conglomeratic facies are present; near Tasiussaq close to the northern edge of the main outcrop, conglomerates contain granite boulders up to 3 m in diameter. Some of these boulder beds probably formed as fanglomerates adjacent to fault scarps bounding the sedimentary basins.

The sediments are apparently unfossiliferous. Cross-bedding and ripple-marks are commonly encountered and sun-cracks and rain-pits are preserved in some of the finer grained rocks. Quartz pseudomorphs after gypsum have been found in sandstones on the north shore of Tunugdliarfik. Wind-blown sand occurs as infillings of irregularities on the surface of lava flows, and sand dunes have also been described from the sequences.

The sediments are thoroughly continental in type and are regarded as fluviatile, lacustrine or aeolian, deposited under intermittently arid conditions, within fault-bounded troughs. They consist almost entirely of quartz, feldspar and granitic fragments; fragments of the contemporaneous lavas are extremely rare except where pyroclastic deposits have locally

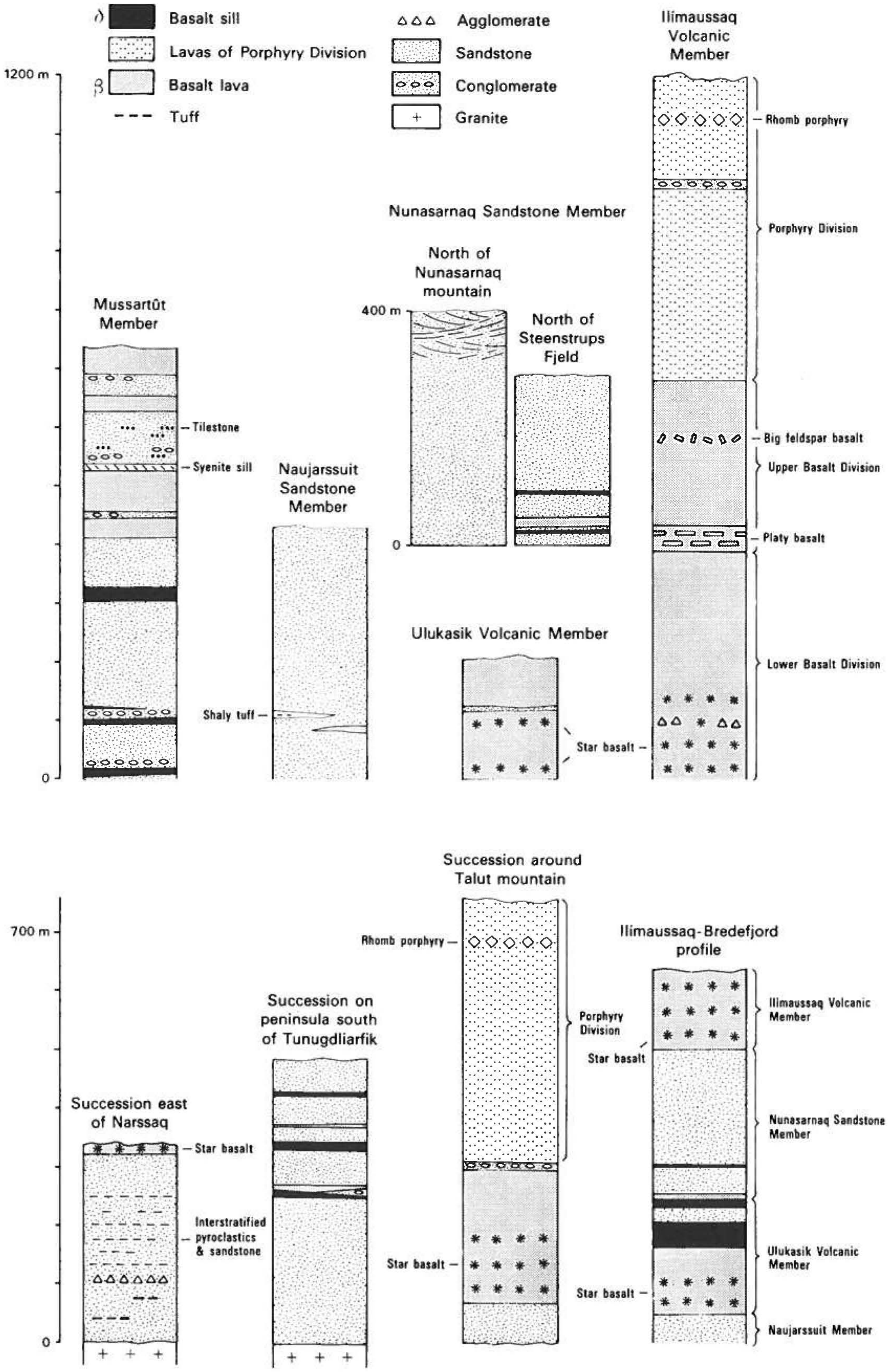


Fig. 145. Measured sections through the Eriksfjord Formation. (After Poulsen, 1964).

been reworked. The inference is that the source areas were granitic highlands surrounding the depositional basins and that volcanism was essentially confined to the basin floors. The lack of intraformational unconformities within the succession, coupled with the persistence of typically fine-grained sandstones throughout, may imply a slow and steady tectonic subsidence of these Gardar graben.

Lavas

Volcanic rocks appear within the succession a few tens of metres above the basal unconformities at Narssaq and Qagssiarssuk. Only in the Nunasarnaussaq and Igaliko district does volcanism not appear to have commenced until a considerably greater thickness of quartzites had accumulated. In a few instances, as at Narssarssuaq, the position of the lavas within the sequence is obscured by faulting.

Most of the lavas are basaltic although a few monchiquitic and carbonatitic flows have been described by Stewart (1970), principally from the Qagssiarssuk area, and some of the highest flows in the Ilímaussaq succession are trachytic (Stewart, 1964). A sequence of rhyolitic rocks in the vicinity of Narssaq has not been studied in detail but appears to be largely ignimbritic. The basic lavas are usually 1–15 m thick and are generally of pahoehoe type although aa flows characterise the successions at Narssaq and Narssarsuaq. Corded or gently undulatory surfaces are preserved on some of the exposed pahoehoe surfaces (cf. Wegmann, 1938, fig. 36). The great majority of flows are amygdaloidal, commonly commencing with pipe-amygdaloidal bases. The amygdales contain epidote, calcite and quartz; zeolites have not been recorded. Columnar jointing is prominent in some of the lower flows of the Ilímaussaq peninsula but is otherwise poorly developed.

The majority of the lavas appear to have been quietly erupted onto a lowland terrain under subaerial conditions, although rare pillow lavas low in the succession suggest very occasional sub-aqueous eruptions. Olivine basalt dominates the succession (although olivine is invariably replaced by iddingsite). Plagioclase phenocrysts occur in most lavas, and the thick Ipiutaq, Ulukasik and Ilímaussaq volcanic units of the Ilímaussaq peninsula succession (fig. 145) are notably feldsparphyric. The matrix of the lavas consists of iddingsitised olivine, sericitised plagioclase, pink augite and opaque oxides. Available analyses indicate that mildly alkaline olivine basalts and hawaiites predominate (Watt, 1966; J. G. Larsen, 1973). Except at Qagssiarssuk where the unusual alkaline ultrabasic extrusives can be correlated with local intrusives and diatremes (Stewart, 1970, fig. 5), no feeders have been definitely identified for the flows.

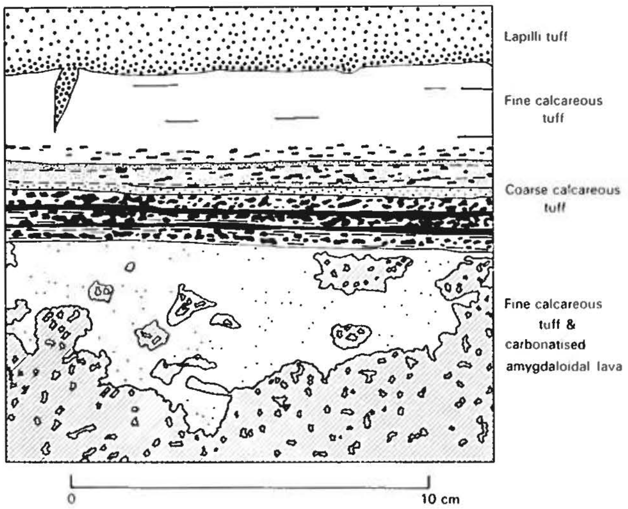


Fig. 146. Relationship of carbonated tuffs to underlying amygdaloidal lava flows near Qagssiarssuk. (After Stewart, 1970, fig. 3).

Pyroclastic rocks

Bedded ashes and agglomerates are well known from the Narssaq and Narssarssuaq volcanic successions, the outliers bordering the Motzfeldt nepheline syenites and parts of the succession east of the Ilímaussaq complex. However, the most striking development is in the Qagssiarssuk area (Stewart, 1970) where much of the explosive activity was related to carbonate-rich magmas. In a volcanic unit approximately 370 m thick, thin layers of carbonated vesicular lava are overlain by bedded tuffs and agglomerates (fig. 146). This volcanic unit is cut by tuff and agglomerate-filled vents containing blocks of sövite, orthoclasite and blocks of country rocks in various stages of alteration. Alnöitic tuffs are also found with blocks of altered alnöite in a carbonate-rich matrix. The associated intrusive rocks are heavily carbonated and include varieties rich in carbonate pseudomorphs after melilite. The relationships at Qagssiarssuk are shown schematically in figure 147.

Small diatremes, probably associated with explosive surface activity, are fairly common in the Tugtutôq–Narssarssuaq zone and have been described by Upton (1962), Walton (1965) and Stewart (1970). The diatremes are generally found penetrating basement but an example was found cutting nepheline syenite in the North Qôroq centre (Emeleus & Harry, 1970). In each, activity was probably related to ascent of carbonatite or CO_2-rich ultrabasic magmas. Analogous diatremes or tuff-pipes are rare in the

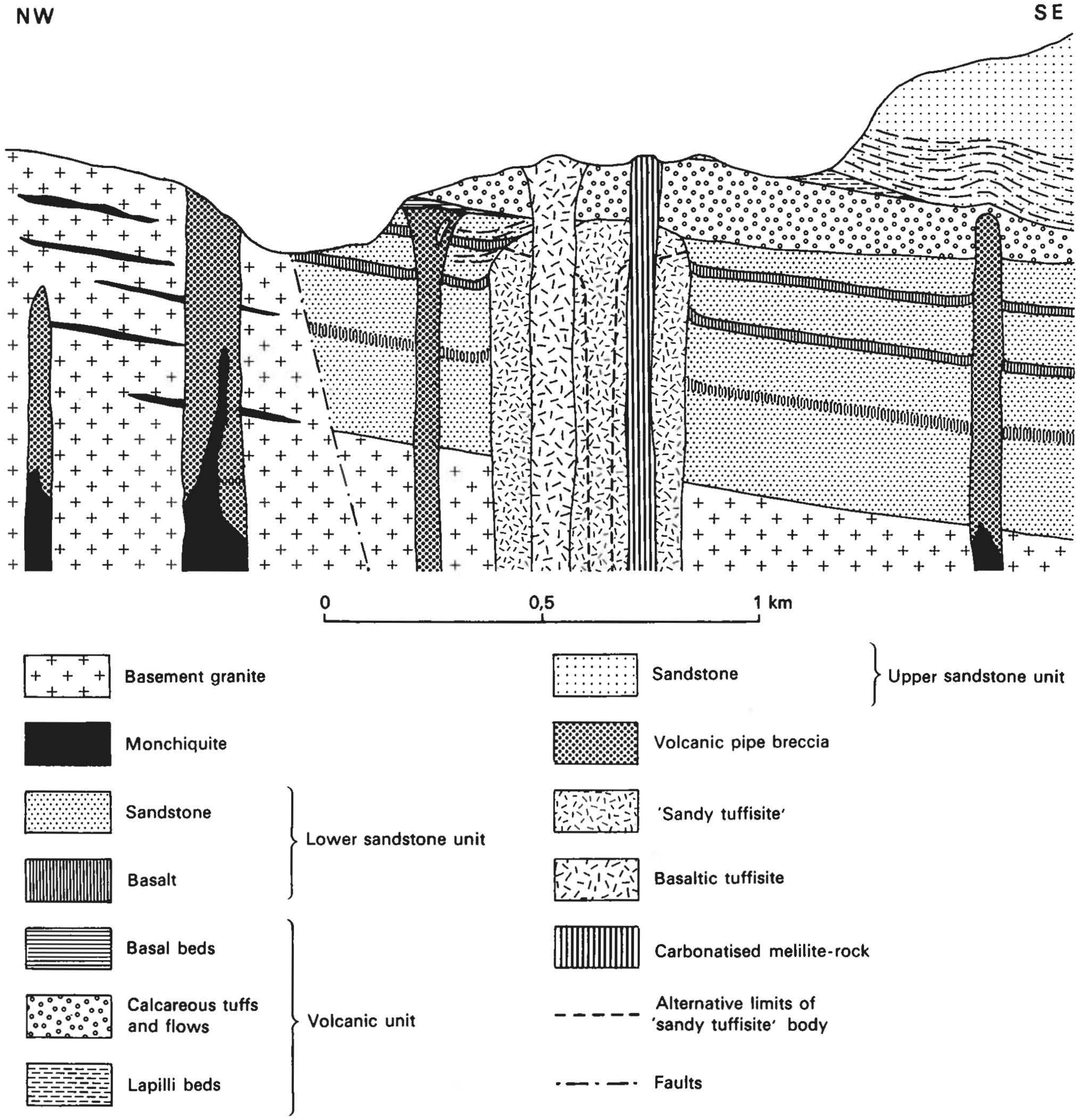


Fig. 147. Schematic cross-section through the Qagssiarssuk area. Vertical component exaggerated about 2½ times. (After Stewart, 1970, Plate 6).

Ivigtut and Nunarssuit regions, although small, enigmatic tuff-pipes surrounded by gabbro north of Ikerasagssuaq in the Nunarssuit region may be associated with ascending trachytic or syenitic magma. Trachytic tuff-dykes have also been observed adjacent to Kûngnât and cutting the Grønnedal–Íka syenites.

Absolute age of the Eriksfjord Formation

The lavas and sediments overlie deeply-eroded granites dated at 1780 ± 20 m.y. with final cooling about 1600 m.y. (van Breemen *et al.*, 1974). The formation is cut by the Ilímaussaq intrusion (1168 ± 21 m.y.) and is found as inclusions in the central Tugtutôq complex (1168 ± 37 m.y., van Breemen & Upton, 1972). Furthermore, lavas and sandstones correlated with the Eriksfjord Formation by Emeleus &

Harry (1970) are cut by the Motzfeldt complex for which Rb-Sr dating suggests an age of 1310±31 m.y. (Table 5). The Eriksfjord Formation thus accumulated within the time bracket 1600 m.y. to 1310 m.y.

Dyke swarm

Basic dykes with textures ranging from basaltic to gabbroic occur over a wide area from north of Ivigtut to south of Julianehåb and similar dykes have been recorded from South-East Greenland (Bridgwater & Gormsen, 1969). In some areas, particularly around Grønnedal–Ika and a zone extending from Tugtutôq east-north-east to the Inland Ice, felsic dykes (phonolites, trachytes and comendites) occur in dense swarms. All of these essentially unmetamorphosed dykes are regarded as belonging to the Gardar activity with the exception of the Mesozoic dykes referred to earlier.

Basic dykes

Wegmann (1938) referred to the typical olivine dolerite dykes as 'brown-dykes', alluding to the characteristic brown sandy rubble that results from their rapid weathering. The term has been retained in abbreviated form ('BD') by the Geological Survey of Greenland with numerical suffixes indicating relative ages of the dyke swarms. The oldest of these dykes are thus referred to as BD_0 (Berthelsen, 1962); these constitute a sparse swarm that has been recognised between Ivigtut and Julianehåb trending between east–west and WNW–ESE (e.g. Watt, 1968). The BD_0 dykes occur up to 150 m wide, with large-scale cross-jointing (fig. 148), and they often show signs of shearing along their length. They are typically coarsely ophitic with pegmatoid developments. Whereas the younger Gardar basic dykes commonly show layering features when over 100 m wide, layering is absent even in the broadest of the BD_0s. Some at least, carry small amounts of modal quartz and it is possible that the BD_0 dykes as a group are quartz tholeiites. Wall-rock melting up to a metre from the contact has been observed in these dykes.

Although some dykes trend approximately north–south, the great majority of the younger Gardar dyke swarms trend between NE and ENE. In the Ivigtut area there is a systematic change in dyke direction with age: the earliest (BD_0) group trending approximately east–west, later BD_1 dykes trending approximately 060° and the still younger BD_2 dykes trending approximately 020°. In the Nunarssuit–Isortoq area early ESE dykes are succeeded by (1) N–S dykes, (2) ENE dykes, (3) NE dykes and (4) ENE dykes. This region displays the most complex sequence of dyke intrusions and many of its dolerite dykes have effected considerable wall-rock melting suggesting that they acted as feeders through which large volumes of magma were conveyed to the surface. Hence, the basaltic inclusions in the Nunarssuit complex (Harry & Pulvertaft, 1963) may be the only remnants of a once substantial lava field for which these dykes were the main conduits.

Fig. 148. Gardar and (sparse) Mesozoic dolerite dykes cutting pre-Gardar rocks on the north side of Sánerut. Highest point: *c.* 940 m.

In the Tugtutôq area, BD_0 dykes are cut by a large gabbroic dyke (locally composite with syenitic and syenogabbroic components) whose age can be bracketed between 1175±9 and 1168±37 m.y., these being the dates obtained for the earlier (Hviddal) composite dyke and the younger intrusives of the central Tugtutôq complex. The eruption of basaltic magma in this area appears to have been effectively terminated at a relatively early stage with the intrusion of the gabbroic dykes and, although the Tugtutôq – Ilímaussaq area was to be extensively intruded subsequently, the later intrusives are almost invariably of trachydolerite or of still more felsic compositions. Consequently, the events in this zone are very different from those of the Nunarssuit – Isortoq area where intrusion of basic dykes appears to have been repetitive over a long time interval, and ended only with the intrusion of the Nunarssuit syenite-granite complex at about 1154 m.y.

Dykes belonging to the BD_0 generation can be traced intermittently from the Sánerut peninsula to Julianehåb. Similarly some of the BD_1 generation crop out more or less continuously for distances of

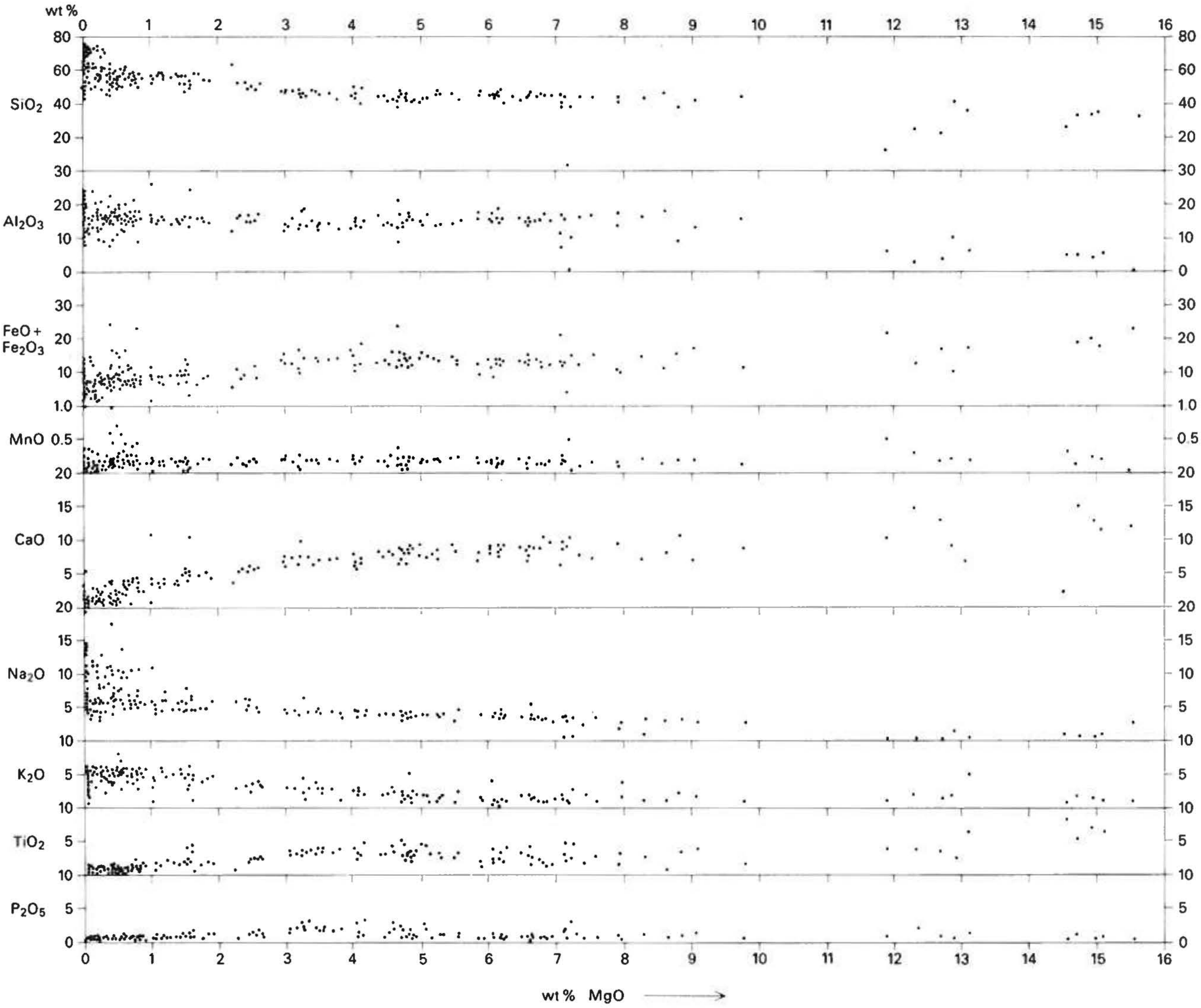


Fig. 149. Oxide variation in Gardar igneous rocks plotted against wt % MgO.

up to 60 km from the coast near Ivigtut east-north-east to the Inland Ice. In the Tugtutôq – Ilímaussaq – Narssarssuaq zone some of the ENE–trending dolerite-gabbro dykes can be traced, albeit in faulted sections, some 120 km from the Davis Strait to the Inland Ice. Dyke widths vary from under 1 m to 800 m; those with widths of 150 m or more have been referred to as 'giant dykes' and, on the grounds that they display special features not seen in the smaller dykes the 'giant-dykes' are discussed separately below.

While data on the mineralogy and chemistry of the basic dyke swarms are still inadequate, it is clear that the great majority have the compositions of olivine basalts with low silica values (<50 %) and relatively high alkalies and titanium. These features can be seen in figure 149 in which weight per cent oxides of the Gardar igneous rocks are plotted against MgO %. The majority of compositions with MgO values between 4 and 10 % are from analysed dyke rocks.

Plagioclase phenocrysts are ubiquitous in the Gardar dolerite and basaltic dykes and in the chilled margins of the larger gabbroic dykes. Although many are so sparsely porphyritic as to be virtually aphyric, many are strikingly feldsparphyric. Pyroxene phenocrysts are notably rare. The groundmass of these dykes consists of plagioclase, olivine (or its alteration products), augite, opaque oxides, apatite and biotite. Quartz or analcime are rare modal constituents and pigeonite and orthopyroxene are almost unknown. In general the basic dykes crystallised to yield holocrystalline ophitic or subophitic textures.

Ultrabasic dykes and other hypabysal intrusives

Ultrabasic mica-rich (lamprophyric) dykes are locally important members of the ENE dyke swarm. This is true for the Ivigtut, Kûngnât, Grønnedal–Íka and other areas in the west (e. g. Ayrton, 1963) and for the Narssarssuaq area in the east (Walton, 1965). The dykes are dense, typically flow-banded and often sulphide-rich. Those of the Kûngnât area consist of serpentinised olivine, augite, brown hornblende, opaque oxides and carbonate. Small sheets and bosses of monchiquite and mica peridotite known from the Narssaq, east Tugtutôq and Qagssiarssuk districts may be petrogenetically related to the lamprophyric dykes (Stewart, 1970).

Dykes with anorthositic inclusions

A most striking feature of many of the Gardar dykes is the size and abundance of anorthosite and anorthositic gabbro inclusions, and plagioclase megacrysts believed to have been derived from the disaggregation of similar materials. Although seen throughout the entire Gardar province, such occurrences are particularly concentrated in the central and eastern regions. Detailed accounts of the inclusions, and their relationships to host-rocks are given by Bridgwater & Harry (1968) and Bridgwater (1967).

Although anorthositic inclusions do occur in some units of the larger alkaline complexes, the highest concentrations are seen in the ENE-trending 'big feldspar dykes', where they and associated plagioclase megacrysts comprise up to 80 % of the dykes (fig. 150). The largest known inclusions have outcrop areas of over 1000 m². The inclusions are typically coarse grained with textures varying from xenomorphic granular to those of layered plagioclase cumulates. Individual megacrysts approximately 1 m long have been described from some of the dykes. The crowding of anorthositic debris in the upper parts of the giant gabbro dykes in east Tugtutôq and in roofing zones of the gabbros and dolerites between Narssaq and the Ilímaussaq intrusive complex, suggests that the material generally floated in the host magmas.

Whereas the host rocks vary in composition from gabbroic or doleritic to trachytic, the most frequent host in the 'big feldspar dykes' is trachydolerite. Such dykes frequently have more alkalic (trachytic) marginal zones, with the anorthositic inclusions concentrated in the more basic central regions.

Bridgwater & Harry noted a simple relationship between compositions of the host rocks and the included material; namely that the more basic the host, the more calcic the feldspar of the inclusions. Thus, while calcic labradorite inclusions occur in some of the gabbro-dolerite dykes, andesine characterises the inclusions in the trachydolerites. A change was also noted in the degree of recrystallisation to which the inclusions had been subject; those of the more basic hosts are little affected, but in more alkalic hosts reaction and modification producing secondary anorthosites have been reported.

Fig. 150. Feldspar xenocrysts in basic dyke ('big feldspar dyke') on the south coast of Tugtutôq. Scale: hammer shaft *c.* 50 cm.

The evidence is such as to suggest a cognate rather than an accidental relationship between inclusions and the magmas in which they became incorporated. Furthermore the frequency of anorthosite inclusions within a wide compositional range of intrusives and over the whole geographic province suggests that the Gardar province is underlain by anorthositic rocks, akin to those of eastern Labrador.

Intermediate and salic dykes

Trachydolerite, trachyte, quartz trachyte, phonolite and comendite dykes are especially abundant in the eastern part of the province between Tugtutôq and the Inland Ice, where they constitute important elements in the ENE swarm. They are scarce in the central area but are again common in the west in the vicinity of Grønnedal–Íka and on the Ivigtut peninsula (Emeleus, 1964; Gill, 1972; Henriksen, 1960).

Descriptions of such dykes in the eastern area appear in numerous publications; notably those on Tugtutôq (Upton, 1962, 1964a; Macdonald, 1969), Ilímaussaq (Scharbert, 1966; Allaart, 1969), Igaliko – Johan Dahl Land (Walton, 1965; Emeleus & Harry,

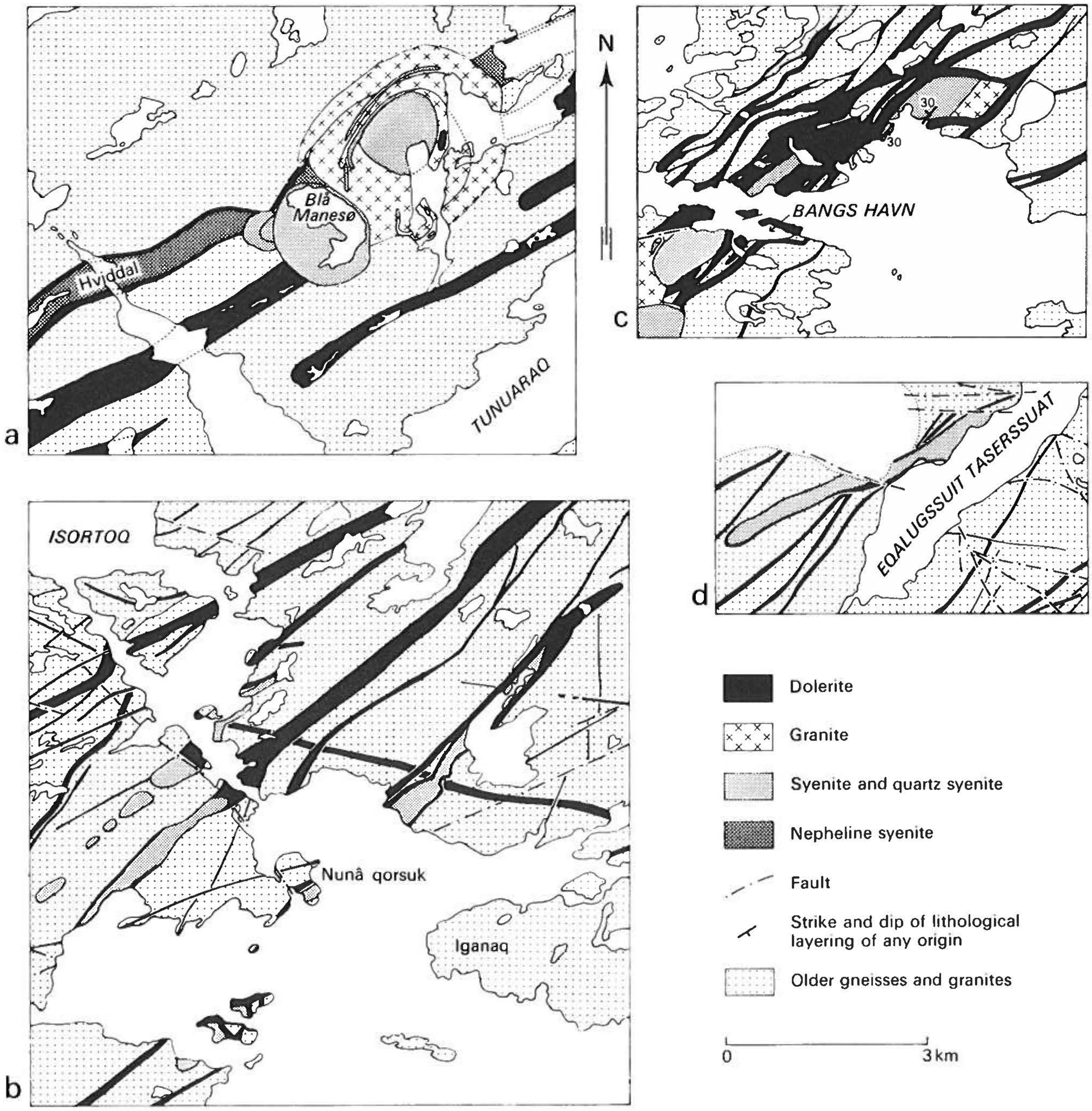


Fig. 151. Geological sketch maps of:
(a) Central complex and adjoining 'giant-dykes', Tugtutôq.
(b) 'Giant-dykes' in the Isortoq area.
(c) 'Giant-dykes' at Bangs Havn, Nunarssuit.
(d) Composite and gabbroic 'giant-dykes' at Eqalugssuit taserssuat (after Bridgwater & Harry, 1968).

1970), and Qagssiarssuk (Emeleus & Stephenson, 1970). The dykes rarely exceed 15 m in width and are younger than the four early complexes in the Igaliko group with their associated syenogabbros, augite syenites and foyaites. They also appear to post-date the syenites and granites of the Dyrnæs–Narssaq complex.

The alkalic dyke swarms are, however, generally earlier than the intrusive alkaline complexes at Ilímaussaq, central Tugtutôq and the youngest (late Igdlerfigssalik) member of the Igaliko complex. It should however be noted that a few ENE dykes transect the last two named centres. The great majority of the dykes are also earlier than the main phase of east–west left-lateral faulting that affected the whole region.

As has been mentioned, many of the 'big feldspar dykes' are trachydoleritic often with trachytic margins. More normal composite dykes, with basic margins and central units of comendite or phonolite are not uncommon in the Tugtutôq and Ilímaussaq districts but are rare elsewhere in the province.

Near Ivigtut and Grønnedal–Íka quartz trachyte, trachyte and phonolite dykes post-date the nepheline syenite and carbonatite complex as well as the principal swarms of olivine dolerite dykes. Although most of the dykes are faulted, some were intruded during and after the main faulting events (Emeleus, 1964).

Detailed studies, completed or in progress, on the dykes of the Grønnedal–Íka and Tugtutôq swarms (Gill, 1972; Macdonald, 1969) have shown them to range from mildly alkalic (or even slightly peraluminous) to strongly peralkaline. Furthermore, in the Tugtutôq swarm, there appears to be a compositional continuum from olivine dolerite through trachydolerite and trachyte to comendite, and probably also from trachyte to phonolite. Macdonald (1969) has shown that much of the variation from trachydolerite to comendite can be explained in terms of alkali feldspar fractionation and a similar feldspar control has been demonstrated for peralkaline phonolite dykes at Grønnedal–Íka (Gill, 1972).

There is some tendency for the alkaline dykes to be concentrated in the neighbourhood of some of the larger alkaline complexes, namely Grønnedal–Íka and the complexes of the eastern part of the province. Furthermore, whereas phonolites tend to be most abundant close to the larger foyaite complexes, those in the vicinity of the quartz syenite and granite complexes of central Tugtutôq and Dyrnæs–Narssaq are mainly oversaturated varieties.

'Giant-dykes'

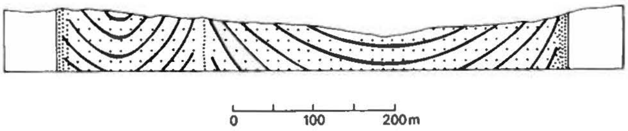
Exceptional thicknesses are locally attained by the ENE dykes in the central and eastern areas (fig. 151). These 'giant-dykes' frequently show textural and structural features more akin to those of the larger alkaline intrusions than those of the majority of the dykes. More or less detailed accounts have been given for the 'giant-dykes' at Bangs Havn (Harry & Pulvertaft, 1963), Isortoq (Bridgwater & Coe, 1970), Eqaloqarfia (Pulvertaft, 1965), Tugtutôq (Upton, 1962, 1964b) and Johan Dahl Land (Walton, 1965). A 'giant-dyke' showing comparable features to these but differing in trend (approximately east–west) crosses Qingârssûp nunâ on the north side of Bredefjord; recent mapping north-east of the Igaliko syenites and east of Qôrqup sermia verified the presence of a composite gabbro-syenite dyke and a thick dolerite-gabbro dyke, both trending about ENE (Allaart, 1971; see also Emeleus & Harry, 1970).

Fig. 152. Current-bedded structures in olivine gabbro cumulates, 'giant-dyke' at Itivdlip sarqâ, Tugtutôq.

In every case the 'giant-dykes' involve gabbroic or syenogabbroic rocks and are found in several instances to narrow or split up into smaller dolerite dykes. Hence the 'giant-dykes' represent local enlargements within the regional ENE swarms of basic dykes (cf. fig. 151c). Several of the 'giant-dykes' display layered structures (viz. rhythmic layering and feldspar lamination, alone or in combination) dipping inwards from chilled marginal zones with dips diminishing to zero along the central zone. Such synformally layered dykes are known from Isortoq (e.g. dyke No. 3, Bridgwater & Coe, 1970, fig. 1), Eqaloqarfia, Qingârssûp nunâ, Johan Dahl Land and at several localities on Tugtutôq (fig. 152). The rocks are commonly troctolitic gabbro and, where rhythmic layering is strongly developed, the differentiates include picrite and leucotroctolite. Gravity stratification, slump-structures and current bedding features occur within these (ortho-) cumulitic rocks. At several localities the 'giant-dykes' appear to have grown by successive influxes of magma to give multiple or composite dykes; thus, at Itivdlip sarqâ (Tugtutôq) two consecutive intrusions of troctolitic gabbro were involved in the development of a 500 m broad 'giant-dyke' (fig. 153).

Composite 'giant-dyke' development is seen at Bangs Havn, Isortoq (dykes 1,2,3,4 and the dyke at Eqalugssuit taserssuat; Bridgwater & Coe, 1970, fig.

Fig. 153. Diagrammatic cross-section through the gabbro 'giant-dykes' at Itivdlip sarqâ, Tugtutôq, showing two synclinal structures in the layered rocks (after Upton, 1964b).



1), and in two successive dykes on Tugtutôq where younger components of syenogabbro, augite syenite, foyaite, quartz syenite or alkali granite are involved (fig. 151a). Thus, at Bangs Havn (Harry & Pulvertaft, 1963) gabbro forms an envelope around a central pod of layered augite syenite gradational into quartz syenite and alkali granite (fig. 151c). In five composite 'giant-dykes' of relatively late date in the ENE swarms of Isortoq (Bridgwater & Coe, 1970), both undersaturated and oversaturated syenites occur; individual dykes are undersaturated in the east, oversaturated in the west (D. Bridgwater, personal communication). One of these dykes is represented for a part of its length by a line of small syenite bosses (fig. 151b). In eastern Tugtutôq, a large troctolitic dyke encloses two lenticular pods; one of layered syenogabbro and one (younger) of quartz syenite (Upton, 1962, 1964a,b). One of the most remarkable of the composite 'giant-dykes' is the 500 m broad Hviddal dyke on Tugtutôq which retains a more or less constant width and character for 20 km. In this, marginal sheaths of syenogabbro enclose a central 300 m unit of alkaline rock that displays a lateral variation from augite syenite in the west to peralkaline sodalite foyaite in the east (Upton, 1964a). Recent isotopic studies show that this dyke had an initial ^{87}Sr/^{86}Sr ratio of 0.7024 ± 0.0010; a Rb-Sr isochron gives an age of 1175 ± 9 m.y. (Table 5). That the 'giant-dyke' emplacement did not represent a unique intrusive event during the Gardar is obvious from the presence of intersecting (composite) 'giant-dykes' on Tugtutôq.

Anorthositic inclusions are common within the 'giant-dyke' gabbros at Bangs Havn, Assorutit (Tugtutôq) and, especially in one 'giant-dyke' development in Ilordleq.

The unusual widths attained by the 'giant-dykes', coupled with their abrupt changes in width and sometimes blunt terminations (fig. 151), raise considerable problems with regard to their mode of emplacement, as has been recognised by Bridgwater & Coe (1970). Possible mechanisms include simple dilation, stoping of wall-rock and settling or elutriation of the stoped blocks, or subsurface graben-like faulting with block-sinking as in cauldron subsidence (Walton, 1965), or initial clearance by gas fluxing prior to the ascent of magma; these processes operating alone or in combination. The case for emplacement by stoping is argued forcibly by Bridgwater & Coe (1970) on the basis of non-dilational field relations observed for the 'giant-dykes' of the Isortoq area. A difficulty with this hypothesis is that there is a marked lack of granite or gneiss xenoliths in the basic members of the 'giant-dykes'. Although Bridgwater & Coe consider that the magmas in the 'giant-dykes' were likely to be of low density, it must be remembered that evidence is clearly presented in places that anorthosite (labradoritic) floated in these same dykes. However, evidence from the larger intrusive complexes does point clearly to the reality of stoping in the more felsic magmas, and stoping may therefore be generally acceptable as a mechanism in the emplacement of the more felsic parts of these dykes. At the east end of the fjord Ikerasagssuaq to the north of Nunarssuit, some remarkable ovoid, steep-sided bodies occur in the gneisses, consisting of intrusive olivine gabbro with central zones of tuffaceous material composed of comminuted gneisses. These occurrences are aligned ENE and are roughly in line with the Isortoq 'giant-dyke'; small bodies of intrusion breccia appear also to extend the Isortoq dyke No. 4 to the west-south-west (Bridgwater & Coe, 1970, fig. 1). Although not well understood, it is possible that these occurrences may lend support to the hypothesis that gas-fluxing played some part in the 'giant-dyke' emplacement.

Remnants of what may have originally been large layered troctolitic gabbro bodies are seen at Alángorssuaq (Nunarssuit) and Narssaq. Both have been truncated by younger acid intrusives. The Narssaq troctolites almost certainly represent an easterly culmination of the younger troctolitic 'giant-dykes' on Tugtutôq.

Wall-rock melting adjacent to the 'giant-dykes' varies from very slight (affecting a few centimetres) in the Tugtutôq dykes, to melting (and hybridisation) over several metres in the case of the Isortoq dykes. Contacts between (presumed) differentiates and the enclosing gabbro or syenogabbro in the composite 'giant-dykes' are generally gradational within 3–4 cm.

Central complexes

There are approximately ten major intrusive complexes in southern Greenland, within an area of 200 km (E–W) by 70 km (N–S), to which a Gardar age is ascribed. These display a close 'family likeness' which is almost as striking as their individual distinctions. Each is predominantly composed of alkaline rocks and the ensemble constitutes one of the world's most remarkable alkaline igneous provinces.

Some, like Nunarssuit (fig. 164) are large, outcropping over areas exceeding a thousand square kilometres, while others are small (e.g. Klokken, about 2.5 km diameter, fig. 160) or diminutive like Ivigtut (fig. 162). In the east adjoining the Inland Ice, a striking cluster of foyaitic intrusions form a high mountainous area. Whether these are considered as comprising a single complex or a set of separate and overlapping complexes is a matter of semantics; certainly these Igaliko syenites (fig. 168; Ussing, 1912; Emeleus & Harry, 1970) must embrace a very considerable part of the time-span represented by the Gardar period and thus have been a very persistent site of alkaline volcanism over many millions of years.

The Gardar complexes fall naturally into two categories: those involving oversaturated rocks such as quartz syenite and granite, and those involving undersaturated foyaitic rocks. Only in the Ilímaussaq intrusion does this simple classification fail; there peralkaline granites and quartz syenites occur in the midst of peralkaline nepheline and sodalite syenites. Troctolitic gabbros, syenogabbros and augite syenites occur within both oversaturated and undersaturated complexes and hence have come to be regarded by various authors as having played some parental role in the petrogenesis of the more salic magmas.

The constituent rocks are almost invariably hypersolvus; many of the rocks are highly feldspathic with alkali feldspar and subordinate iron-rich (or Fe-Ti-rich) olivines, clinopyroxenes, amphiboles, micas and opaque oxides. The pyroxenes include relatively Ca-rich varieties ranging from titanaugite through hedenbergitic varieties to aegirine. Amphiboles are commonly hastingsitic or members of the riebeckite-arfvedsonite series. Free quartz occurs in the one association; nepheline, sodalite, analcime and natrolite in the other. Fluorite, zircon and astrophyllite are common accessories in both suites. The normative feldspar compositions of the Gardar alkaline rocks approximates to Or_{40}, close to the experimentally determined minimum Or_{35} at 1 kb in the system $Or–Ab–H_2O$ (Morse, 1969). Rare and complex silicates occur in profusion in the peralkaline pegmatites and other residua rocks of the Ilímaussaq complex and, to a lesser extent, those of the other complexes.

Differentiation sequences from olivine gabbro–ferrosyenogabbro–augite syenite–quartz syenite–alkali granite, attributed to fractional crystallisation in place or at depth, have been described from Kûngnât (Upton, 1960) and are known from Nunarssuit (P. Greenwood, personal communication). Comparable successions from augite syenite to nepheline-rich syenites are exhibited by the Ilímaussaq intrusion (Ferguson, 1964, 1970a,b) and units of the Igaliko complexes (Emeleus & Harry, 1970; Stephenson, 1972, 1974).

Fig. 154. Contact between sandstones and lavas of the Eriksfjord Formation (left) with marginal augite syenite (immediately under and to the right of the supracrustal rocks) of the Ilímaussaq intrusion. Light coloured, sandy and gravel-weathering naujaites and sodalite foyaite form the exposures on the right. View north across the head of Kangerdluarssuk; the mountain on the left (Nunasarnaussaq) rises to about 700 m. (Photo: D. Stephenson).

Intrusive forms

In general, the various units of the intrusive complexes are steep-sided and transgressive towards earlier structures (fig. 154). Outcrops are commonly arcuate in plan and permissive emplacement by stoping and engulfment of the country rocks appears to have been the rule rather than the exception. Cone sheets are wholly absent and true ring dykes are relatively rare. Ring dykes or partial ring dykes have members of the Igaliko complex (fig. 168; Emeleus 1964), central Tugtutôq (fig. 151a; Upton, 1962, 1964a), and the Igdlerfigssalik and South Qôroq members of the Igaliko complex (fig. 168; Emeleus & Harry, 1970; Stephenson, 1972, 1974); fine examples of gabbroic ring dykes occur at Kûngnât (Upton, 1960; fig. 155) and Igdlerfigssalik and Motzfeldt in the Igaliko area (Emeleus & Harry, 1970). However, more generally the annular outcrop form has resulted from younger sub-cylindrical stocks being emplaced with slight offset from earlier sub-cylindrical stocks (e. g. the western and eastern syenite stocks of Kûngnât, fig. 161b, or the relationship between the augite syenites and the agpaitic members of the Ilímaussaq intrusion, fig. 166).

Collapse or down-sagging of the country rocks close to intrusive contacts is well seen at Igdlerfigssalik, Motzfeldt and Ilímaussaq where it is demon-

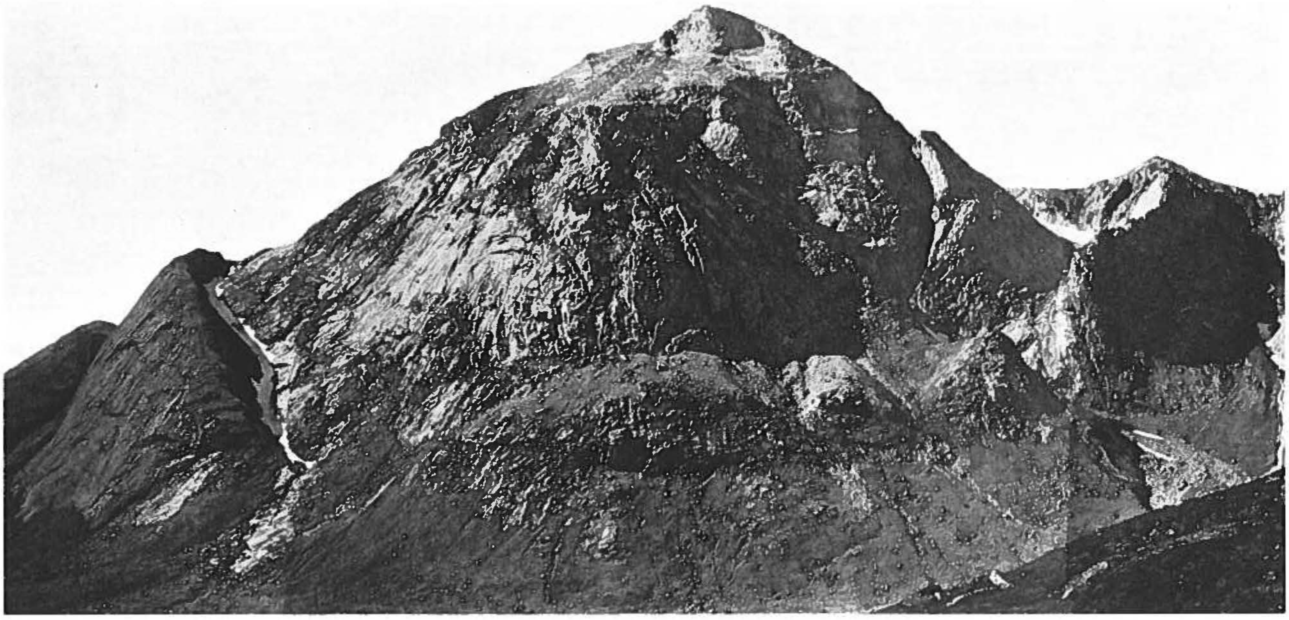


Fig. 155. Eastern side of Kûngnât (1418 m). The high central area is formed by the Eastern Layered Syenites; erosion along the gabbroic ring dyke has excavated the snow-filled gullies on the left and right of the mountain and resulted in the formation of the scree-covered shelf about one-third of the way up the central part. Eastern Border Group Syenites form the steep-sided slabs at the left-hand and right-hand extremities of the mountain.

strated by the in-dipping attitude of adjacent Gardar sandstones and lavas. The phenomenon may be more widespread but has passed unrecognised where Gardar supracrustal rocks are not present. Xenoliths and large rafts of earlier rocks are common in some intrusive units; frequently it may be shown that these have sunk, sometimes for considerable distances. Inclusions of quartzite are found within the Ilímaussaq intrusion, quartzite and metabasalt fragments occur within the Østfjordsdal satellite syenite at Igaliko, and 'Unit II' of the central Tugtutôq complex contains basalt and quartzite fragments as well as a wide range of basement granites, gabbro, trachydolerite and trachytic rocks. Altered basaltic rocks and gneisses occur in profusion in the western part of Kûngnât (fig. 156) and in the Motzfeldt centre at Igaliko, while at Nunarssuit there are rafts of basalts and quartzites (fig. 157) presumably derived from Gardar supracrustal rocks. Since in all instances the basalts or metabasalts and the quartzites are found at levels considerably below that of the basal Gardar unconformity, the inclusions must have sunk in the magmas. In the Grønnedal–Íka complex a remarkable layer of largely unbrecciated gneiss lies sandwiched between layered foyaites (fig. 163). Here, and at Kûngnât, Motzfeldt and Nunarssuit, the rafts or layers lie conformably with layered accumulitic rocks and presumably represent sheets of roofing rocks which spalled off and subsided onto the contemporary (cumulus) floor, before being covered by later crystal cumulates.

Fig. 156. Gneiss and (above) sparse basic inclusions in a flat-lying zone separating the lower and upper members of the Western Layered Syenites, Kûngnât. About 600 m vertical distance shown.

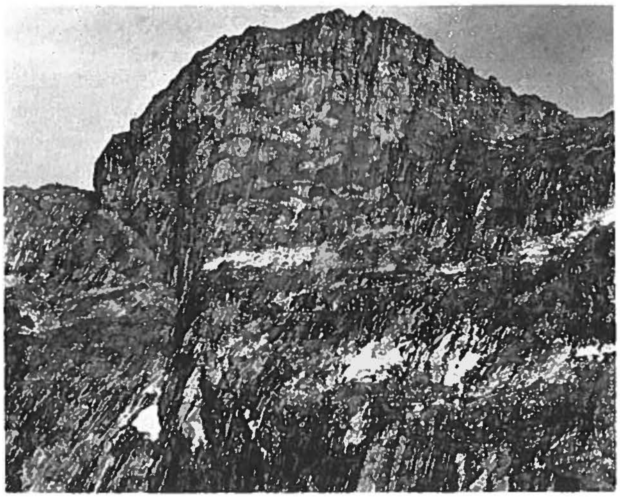
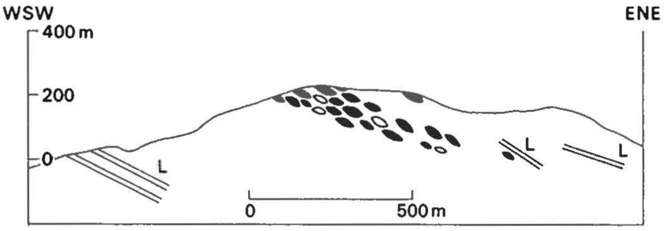


Fig. 157. Cross-section through the western part of the Nunarssuit complex showing the zone of metasedimentary and meta-igneous inclusions within the igneous rocks. L = attitude of layered structures in the syenite.



Internal structures

Layered syenites were recognised at an early stage, in the southern part of the Ilímaussaq complex by Ussing (1912), and in the last fifteen years it has become clear that virtually all of the larger intrusive units in the province (and many of the smaller ones) are layered cumulitic rocks. Layering attributable to periodic changes in conditions during crystal settling has been recognised in anorthosites, troctolitic gabbros, syenogabbros, augite syenites, nordmarkites, nepheline syenites (including the distinctive kakortokites of Ilímaussaq) and even granites. Apart from descriptions in publications discussing the individual complexes, reviews of the features of the layered rocks have been given by Upton (1961), Ferguson & Pulvertaft (1963) and Wager & Brown (1968).

Rhythmically-repeated gravity-stratified layers commencing with bases rich in olivine–pyroxene–Fe-Ti oxide grading up into feldspathic tops are most commonly encountered (fig. 158). An unusual variation is seen in the Ilímaussaq kakortokites where the mafic bases are rich in arfvedsonite rather than olivine and pyroxene. Such layers may be laterally continuous for hundreds of metres or, in extreme cases, may be highly localised in the form of trough bands (fig. 159) similar to those described from the Skaergaard intrusion (Wager & Brown, 1968). Trough-banded structures are well exhibited by the Nunarssuit and Kûngnât syenites. Current-bedding features, slump-structures and deformed or disrupted layered rocks resulting from pre-consolidational disturbances in the cooling magma bodies are found, for instance, in the Nunarssuit syenites and the troctolitic gabbros of Tugtutôq and Narssaq (fig. 152). In the superbly layered syenites of the Klokken intrusion (fig. 160; Parsons, 1972b), in the eastern part of the region, an unusual upward gradation is found from feldspathic bases to mafic (pyroxene-rich) tops, the reverse of the general case.

The rhythmic layering is commonly associated with feldspar lamination. This is developed to an excellent degree in the foyaitic complexes in which the alkali feldspar crystals are highly tabular parallel to (010). Cryptic layering has been described from the west Kûngnât stock (Upton, 1960). It is also known to occur in the early unit of the late Igdlerfigssalik centre and is probably present in some of the other layered sequences. The compositional variation in the Hviddal 'giant-dyke' syenites has been attributed by Upton (1964b) to cryptic variation in an accumulitic sequence although in this case rhythmic layering and feldspar lamination are absent.

The layered structures invariably dip inwards towards the intrusion centres, shallowing as they do so. Commonly, they commence in steeply dipping marginal zones or 'border groups' although clear and sharp distinction between 'border groups' and 'layered series', as in the classic Skaergaard example, is rarely present in the Gardar intrusives.

The fact that nepheline and alkali feldspar have undoubtedly sunk within the Gardar magmas to produce accumulitic series implies relatively low magma densities (<2.5 g/cm^3) while the sinking of feld-

Fig. 158. Gravity-stratified, rhythmically-layered syenites in the Lower Banded Group of the Lower Layered Series, Western Syenite, Kûngnât.

Fig. 159. Trough-banding in the Lower Banded Group, Lower Layered Series, Western Syenite, Kûngnât. Figure on the slabs above structure provides scale.

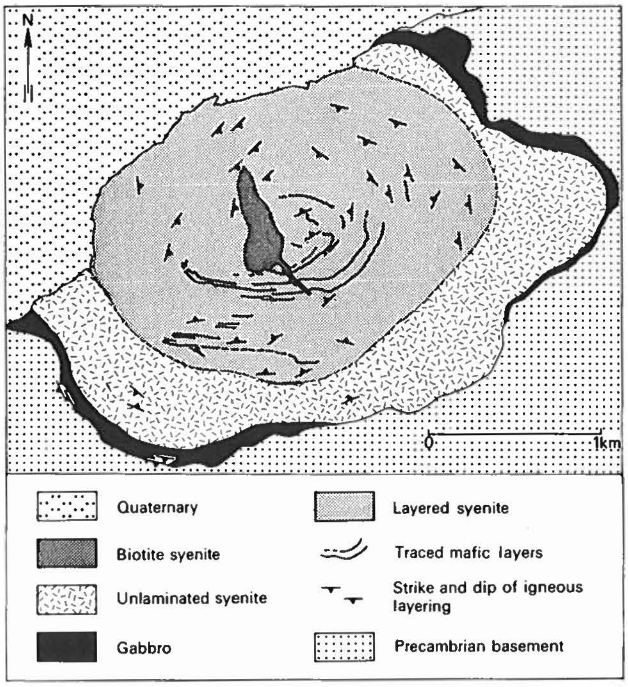


Fig. 160. Geological sketch-map of the Klokken centre. (After Blaxland & Parsons, 1975).

spar and nepheline and the flotation of sodalite in the Ilímaussaq agpaites sets limits for the magma density between 2.5 g/cm^3 and 2.2 g/cm^3 for that intrusion (Emeleus, 1964). The ubiquity of layered structures and the abundance of evidence pointing to the operation of current flow in the magmas suggests that convective circulation was normal and vigorous, and that viscosities of the magmas were unusually low. Furthermore, the widespread presence of fayalite, hedenbergitic pyroxene, poorly exsolved (cryptoperthitic) alkali feldspar and ulvöspinel suggest low f_0 (cf. Morse, 1969) and relatively dry magmas. This latter point is emphasised by the lack of well-developed metasomatic or metamorphic aureoles around the intrusions, their generally hypersolvus character and the paucity of pegmatite–aplite developments except in highly fractionated and relatively water-rich residua like the late-stage granites of Nunarssuit and the Ilímaussaq lujavrites (cf. Luth, Jahns & Tuttle, 1964).

Summaries of individual complexes

Kûngnât

The Kûngnât complex (5 × 2.5 km) in the vicinity of Ivigtut is one of the smaller Gardar intrusive centres. An age of 1240 ± 150 m.y. (Moorbath *et al.*, 1960) has recently been confirmed by Rb-Sr isochron work on whole-rock samples as 1245 ± 17 m.y. (Table 5). However, it cuts an array of ENE-trending dolerites and lamprophyres representing earlier Gardar activity and is thus relatively young in terms of Gardar activity in the western area.

Kûngnât consists of two intersecting syenite stocks and a narrow and complete ring dyke of troctolite and syenogabbro (figs 155, 161b; Upton, 1960). The western stock is stratiform and displays both rhythmic and cryptic layering. Differentiation has been attributed to gravitational settling of alkali feldspar, Fe-rich olivine and clinopyroxene and Fe-Ti oxides in the presence of convective overturn, leading to the production of peralkaline granitic residua. The (younger) eastern stock also shows some layering and gives rise to (peraluminous) granitic differentiates. Further ring faulting admitted the basic ring dyke, approximately 100 m broad, which displays internal structures comparable to those of the basic 'giant-dykes'.

Ivigtut

This celebrated locality consists of a small, peralkaline granite stock 270 m in diameter (fig. 162; Callisen, 1943; Berthelsen, 1962) surrounded by an intrusion breccia of gneiss, veined by fine-grained granite, and an adjacent body, the Bunkebreccia, that has been interpreted as a diatreme (Berthelsen, 1962). Subsequent to the emplacement of ENE-trending tinguaitic dykes, the cryolite ore body was explosively introduced into the granite, shattering the surrounding rocks. The ore body was (prior to its removal during mining operations) a zoned pegmatite with extremely complex mineralogy. The major components were fluorides, carbonates and sulphides and the major part of the body consisted of essentially siderite–cryolite rock which, according to Pauly (1960) crystallised at temperatures below 590°C.

Grønnedal–Ika

The original form of this heavily faulted centre was a simple ovoid measuring about 5.9 × 3.5 km involving nepheline syenites penetrated by a central plug of carbonatite and breccia (Callisen, 1943; Emeleus, 1964). It pre-dated the main episode of dolerite dyke intrusion (BD_0–BD_2) and faulting, and may initially have been sited at the intersection of ESE and N–S trending faults. Left-lateral movements on the former and right-lateral movements on the latter considerably deformed the complex at a later date in the Gardar (fig. 169). A Rb-Sr isochron date of 1327±17 m.y. has recently been reported (Blaxland *et al.*, in prep.). The principally foyaitic nepheline syenites comprise two layered

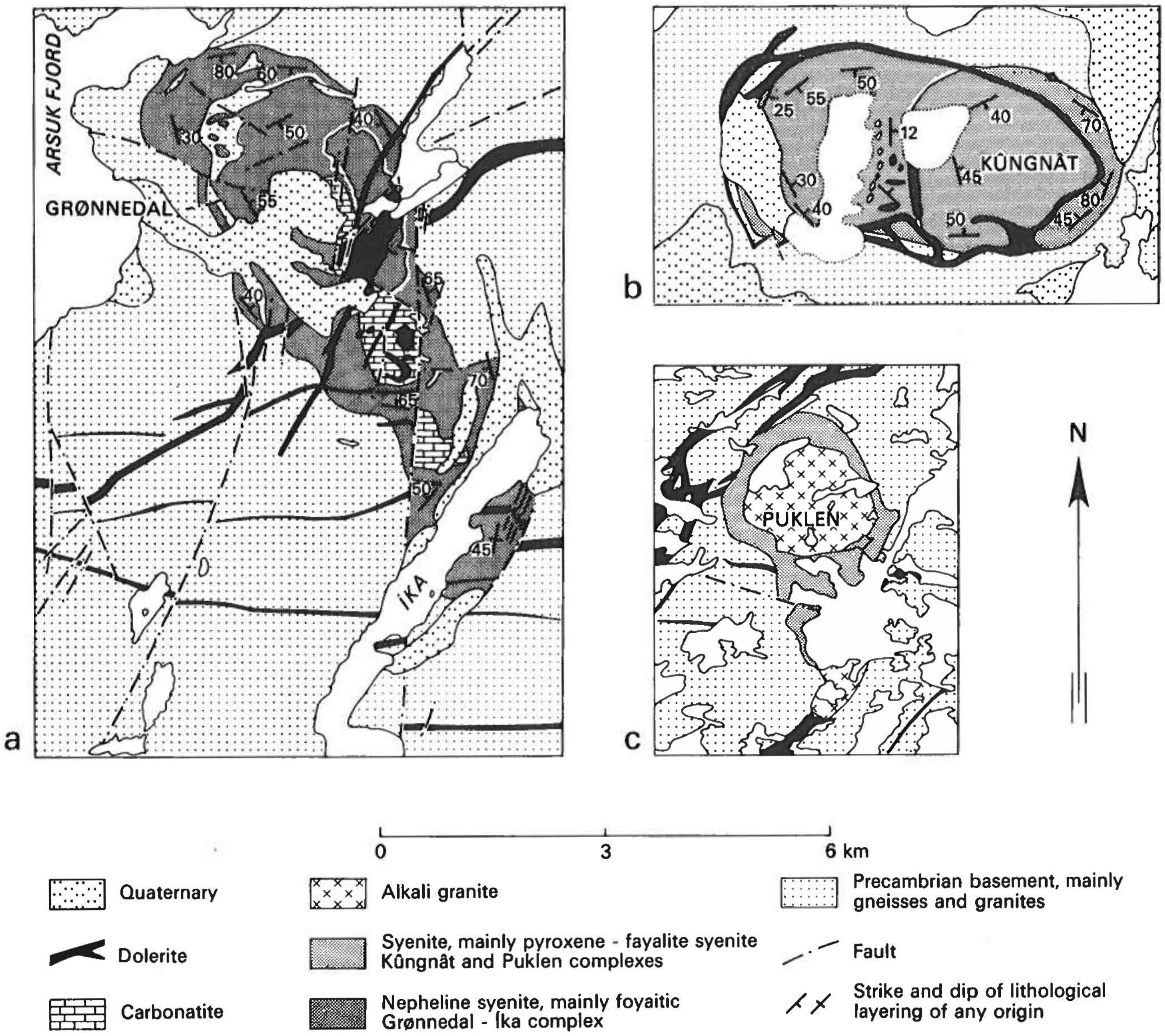


Fig. 161. Geological sketch-maps of: (a) Grønnedal–Íka, (b) Kûngnât, (c) Puklen. Scale: all *c.* 1:100 000.

series showing strong lamination, relatively steep original dips (30–70°) and occasional mineral layering. According to Emeleus, they are cumulates formed by gravity settling of alkali feldspar, nepheline, aegirine-augite and apatite on a steeply dipping floor (fig. 163). The two series are separated by a raft-like layer of gneiss, and large blocks of gneiss occur also within the lower series. Subsequently minor intrusions of microsyenite were emplaced and a stock of highly xenolithic foyaite was intruded by piecemeal stoping. Prior to the faulting, the carbonatite formed a steep sided plug. Inside a marginal zone of brecciated and altered foyaite, sövite passed inwards to a siderite-rich core containing sphalerite, apatite, pyrites, Sr-rich barytes and rare-earth minerals.

Nunarssuit

A part of this complex is covered by the Davis Strait but it is very large and measures at least 45 × 25 km. It is situated across the intersection of one of the ESE-trending left-lateral faults and a zone in which ENE and NE-trending dolerite and composite syenite-gabbro/dolerite dykes are highly concentrated (fig. 164). Although the field relationships between the 'main granites' and the Nunarssuit syenite are somewhat equivocal, the tentative succession proposed by Harry & Pulvertaft (1963) is: (a) Alángorssuaq gabbro, (b) Kitsigsut syenite, (c) main granites, (d) Nunarssuit syenite and (e) late granites.

The gabbro has already been referred to in connection with the 'giant-dykes'. The inner and outer groups of Kitsigsut skerries consist of syenites pos-

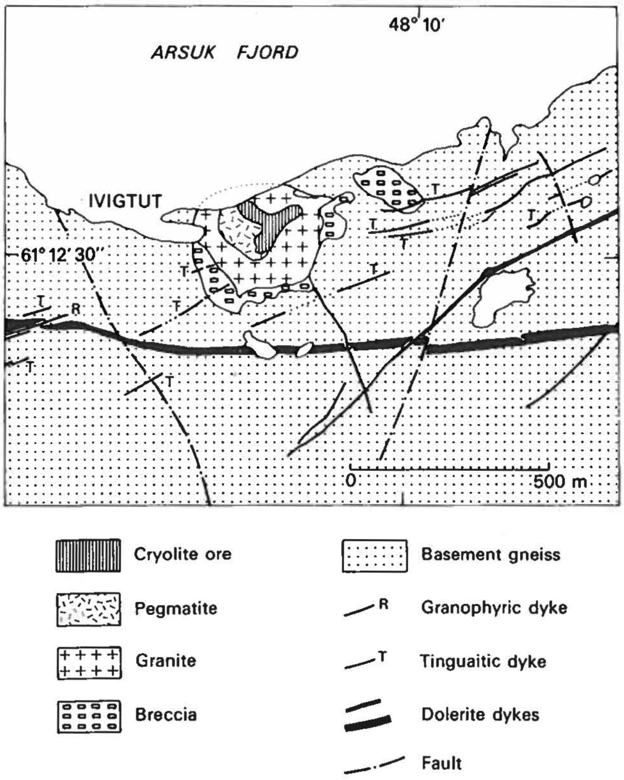
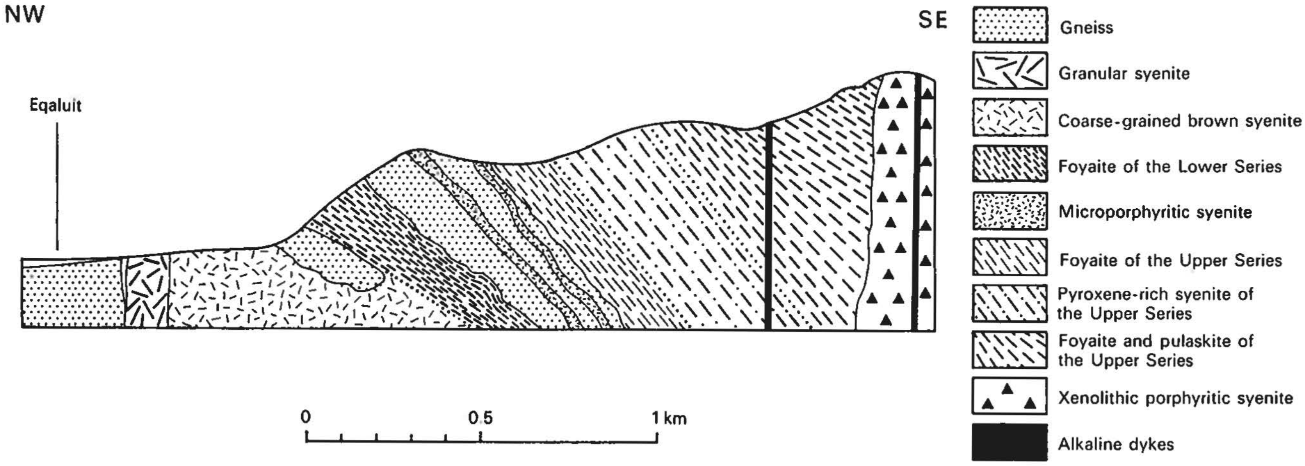


Fig. 162. Geological map of the Ivigtut intrusion. (After Berthelsen, 1962).

sibly representing a single intrusive unit. The Indre Kitsigsut skerries consist of layered larvikites carrying inclusions of layered mafic and ultramafic rocks composed of andesine and augite. Biotite-hornblende granite, one of the two facies of the main granites, cuts the Kitsigsut syenite. It is a subsolvus granite with abundant pegmatites and aplites, thereby differing from the 'drier' and hypersolvus Helene granite. This very coarse-grained fayalite-hedenbergite granite constitutes the second facies of the main granites. Its age relative to the biotite-hornblende granite is uncertain. The Helene granite is layered (Harry & Emeleus, 1960) and must be regarded, at least in part, as an accumulitic rock. It is believed that the Helene granite was in place when the Nunarssuit syenite was intruded but that locally it was still mobile or, at least, at a relatively high temperature.

The Nunarssuit syenite (24 × 13 km) shows variation from larvikite to nordmarkite. Recent work on the complex has shown the presence of five distinct syenite types fitting into a regular differentiation sequence, but the disposition of these distinct types does not conform to a simple concentric pattern (P. B. Greenwood, personal communication). The pattern is more nearly a series of arcuate bodies, some possibly segmented, and circular bodies which do not conform to a regular spatial sequence. Differentiation processes operating *in situ* cannot be entertained to explain the observed configuration; emplacement of contrasted syenite types in a series of magma pulses is indicated. The spectacular development of layered rocks (Harry & Pulvertaft, 1963; Ferguson & Pulvertaft, 1963) is largely confined to one major syenite unit. In the western part of the syenite conspicuous rafts of metabasalt and quartzite (fig. 157) are conformable with the layering. The syenite develops a suite of late-stage peralkaline granites, analogous to those formed on a smaller scale in west Kûngnât; these show chemical trends which are continuous with trends recognised within the syenites (P. B. Greenwood, personal communication). The Malenefjeld granite in the extreme east of the complex grades from peralkaline

Fig. 163. Cross-section through the north-west part of the Grønnedal-Íka complex, showing (a) the gneiss wedge separating the two foyaite series, and (b) the marginal ring dyke syenite. Vertical and horizontal scales are equal.



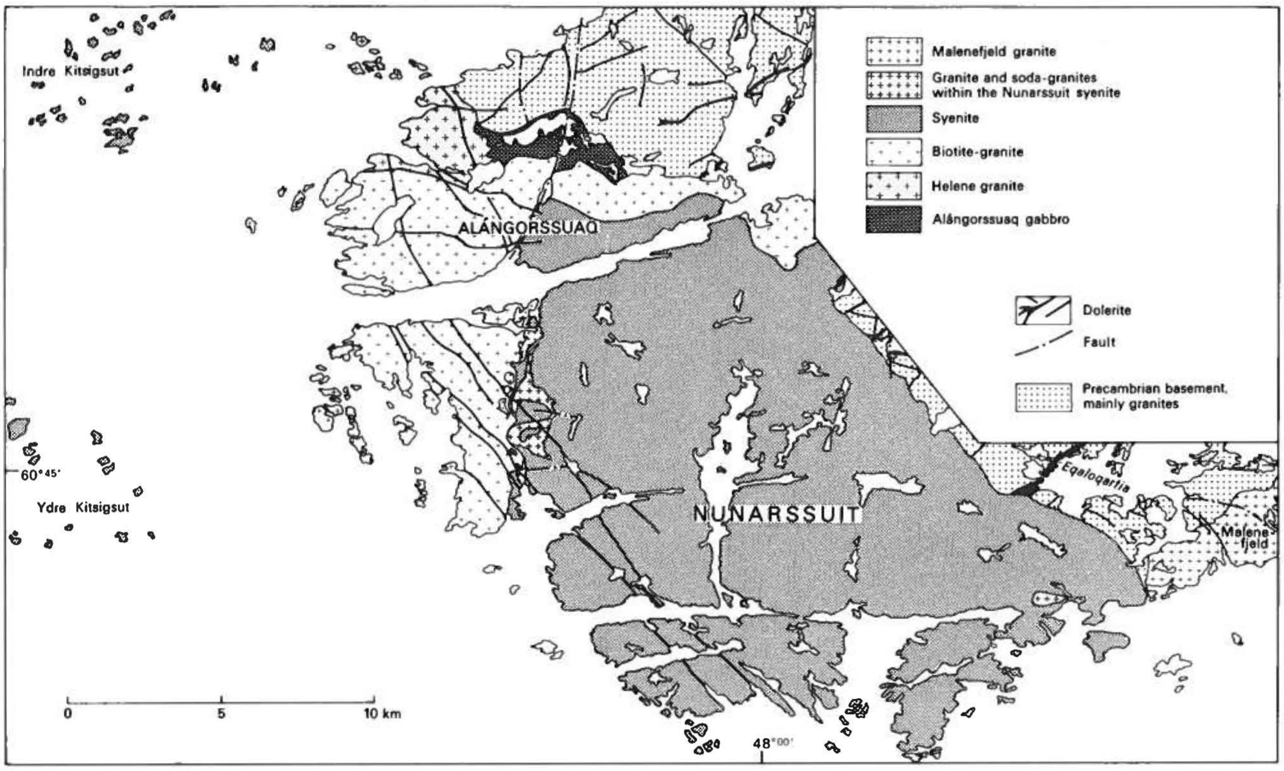


Fig. 164. Geological sketch-map of the Nunarssuit complex and surroundings (Based on Harry & Pulvertaft, 1963, Plate 3).

granite to syenite resembling the main Nunarssuit syenite and also probably belongs to the suite of 'late granite'.

Age determinations give dates of 1149 ± 31 m.y. and 1162 ± 21 m.y. (Table 5).

Puklen

This small intrusion (4 × 2 km) adjoins the Nunarssuit complex and lies across the Eqaloqarfia 'giant-dyke' (fig. 161c; Pulvertaft, 1961; Parsons, 1972a). An early slightly oversaturated augite syenite was followed by peralkaline soda granite; granophyric and spherulitic structures in the leucocratic rocks are attributed to pressure loss prior to completion of crystallisation.

Central Tugtutôq complex

This is a quartz syenite–granite intrusive centre, of similar size to Puklen, lying across the main Tugtutôq – Ilímaussaq dyke swarms which, with the exception of a few small trachytic and trachydolerite dykes, it entirely post-dates (fig. 151a; Upton, 1962, 1964a). After initial intrusion of small stocks of microsyenite, a ring complex developed by four further episodes of fracturing and roof-collapse about a single centre. The five intrusions comprising this particular ring complex grade from quartz syenite to peralkaline granite and are relatively fast-chilled, sub-porphyritic rocks in which layering is scarcely developed. A later intrusion of quartz-bearing perthosite forms a distinct stock-like body offset to the west of the earlier ring complex. Although Kûngnât is similar in size and overall composition to the central Tugtutôq complex, it is thought to have acquired its thoroughly accumulitic nature by much slower cooling. A comparative discussion of the two complexes is given by Upton *et al.* (1971). A Rb-Sr isochron age on whole rock samples from the complex has given 1168 ± 37 m.y. (Table 5).

Dyrnæs–Narssaq

This is one of the least well-understood of the Gardar centres (fig. 165; Ussing, 1912). Although the present outcrop extends over 9 km SE–NW and about 4 km SW–NE, the complex appears to have been torn in two by one of the major E–W trending left-lateral faults. The fact that no simple arcuate pattern can be discerned in the constituent units is almost certainly the result of the present level of dissection since here one is probably seeing the roof-zone of a complex, with rocks intruded as irregular sheets into supracrustal lavas and sediments of the Eriksfjord Formation. The earliest major unit is the Narssaq gabbro representing a high-level culmination

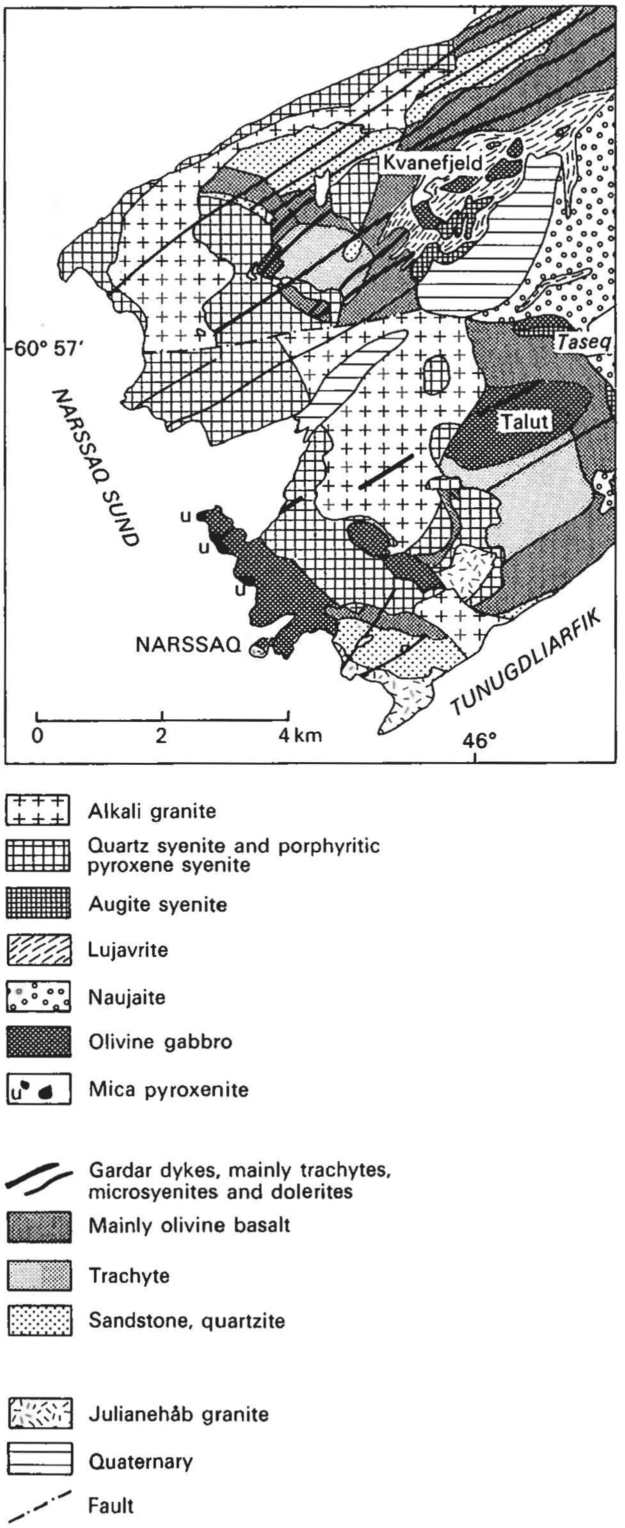


Fig. 165. Geological sketch-map of the Narssaq–Dyrnæs complex. (Based on field maps by J. W. Stewart).

of the gabbro 'giant-dykes' seen to the west on Tugtutôq. It displays layering dipping between 10–50° towards a hypothetical centre subsequently obliterated by the intrusion of syenites. It is clear that several intrusions of quartz syenite followed but the age relationships are uncertain. A large body of peralkaline granite intrudes and brecciates quartz syenite and may be younger than all the quartz syenite intrusions.

Ilímaussaq

By far the best known of the Gardar centres, the Ilímaussaq intrusion (fig. 166), is ovoid in plan, measuring 16 km on a NW–SE axis and 7 km NE–SW. In its north-west corner it cuts across the Dyrnæs – Narssaq complex and is clearly younger than this and the regional trachydolerite and trachyte dyke swarm. It also lies across the E–W left lateral fault that displaces the Dyrnæs–Narssaq complex but the fault appears to have become largely inactive by the time the Ilímaussaq intrusion was emplaced. Nonetheless, the fault probably helped to dictate the form of the intrusion and does produce a zone of slight crushing and discolouration across the Ilímaussaq intrusion.

The principal features of the complex have been described in numerous publications since N. V. Ussing's original memoir in 1912. These include reviews by Ferguson & Pulvertaft (1963), Wager & Brown (1968), Sørensen (1958, 1962, 1970) and Gerassimovsky & Kuznetsova (1967). The intrusion is faulted in such a way that successively lower erosion levels are seen towards the south-east. In the north-west, the complex is partially roofed by Gardar lavas; by contrast, in the south-east the contacts are with basement granites well below the level of the Gardar basal unconformity.

The earliest unit consists of augite syenites that form a sheath around the western and southern margins of the complex. Although these carry modal nepheline they are generally similar to the augite syenites of Nunarssuit and Kûngnât; however, they become more nepheline-rich away from the contacts (Hamilton, 1964), grading into foyaitic rocks (Ferguson, 1964). The augite syenites show rhythmic-layering dipping inwards from the contacts. In the north, a roofing zone of augite syenite is preserved beneath the volcanic cover (Hamilton, 1964) and it is likely that the augite syenites comprised a single layered intrusion, resembling those of the Igaliko centres, before being largely obliterated in a subsequent intrusive event. The latter involved a more highly differentiated magma which has produced one of the most remarkable suites of peralkaline rocks known. It includes a roofing zone of pulaskite, foyaite and sodalite foyaite, sharply underlain by a great thickness (*c.* 1 km) of sodalite-rich rocks. The latter, termed naujaite by Ussing, were interpreted by him as having formed by sodalite flotation and accu-

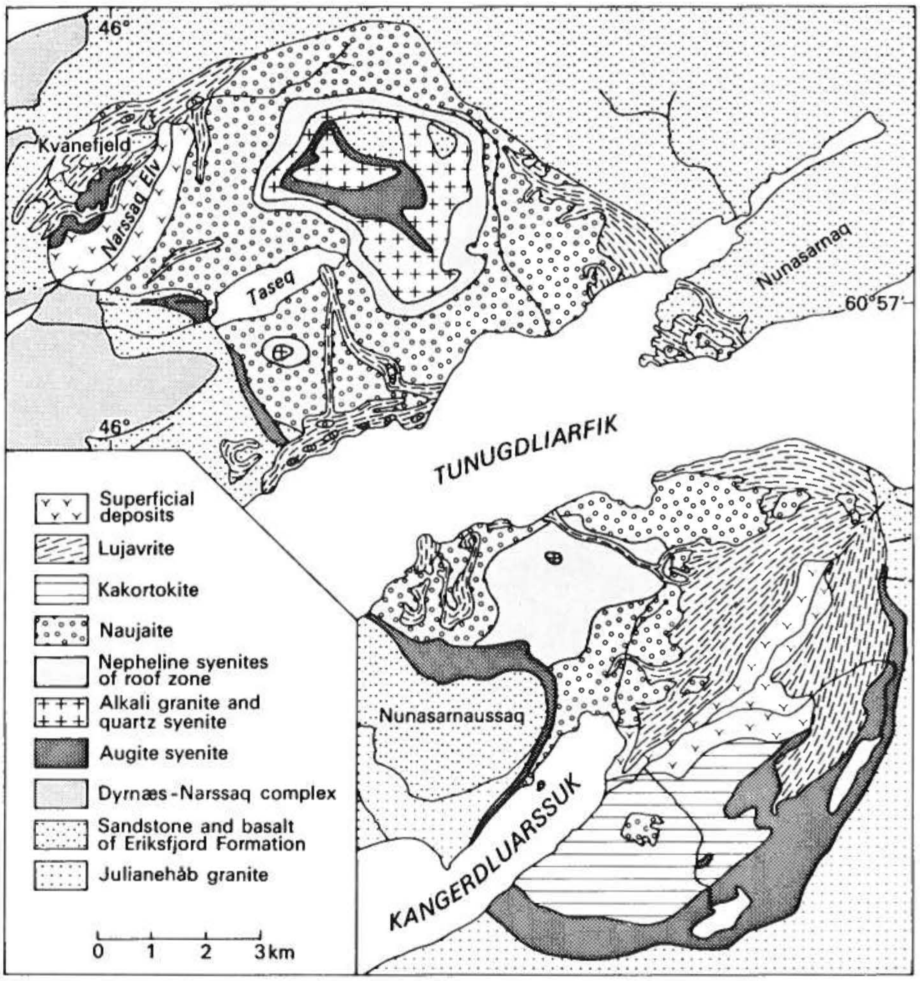


Fig. 166. Geological sketch-map of the Ilímaussaq intrusion. (After Ferguson, 1964).

mulation beneath the intrusion roof. This hypothesis has been upheld by subsequent investigators and the naujaites appear to fall into the category of cumulates referred to as flotation heteradcumulates by Wager & Brown (1968). The rocks consist mainly of sodalite crystals enclosed by very large (typically 5–10 cm, occasionally up to 1 m) poikilitic crystals of alkali feldspar, eudialyte and arfvedsonite.

A striking layered series of eudialyte-rich nepheline syenites (kakortokites) is seen in the southeast (fig. 167; Bohse *et al.*, 1971; Engell, 1973; Ferguson, 1964, 1970b; Sørensen, 1969b). These formed as a suite of cumulates resulting from settling of alkali feldspar, nepheline, eudialyte, arfvedsonite and aegirine crystals. The kakortokites, which may have been forming more or less contemporaneously with the naujaites, comprise a sequence of at least 400 m thickness. The base is not observed. The sequence is subdivided into 29 layered units, each some 12 m thick, commencing with an arfvedsonite-rich base (black kakortokite). In an idealised layered unit, the black kakortokite grades up into red kakortokite (rich in eudialyte) and thence to a white (feldspathic) upper facies. The red kakortokite layer is, however, frequently poorly developed or absent. Small-scale rhythmic layering is also present within the major layered units. Slump-structures within the cumulates indicate that unconsolidated crystal mush was able to accumulate to thicknesses of some 20 m and was unstable on slopes steeper than *c.* 20°. The origin of the large-scale layering remains controversial. Bohse *et al.* (1971) favour crystal sorting during convective overturn of magma; Sørensen (1969b) and Engell (1973) have proposed mechanisms involving intermittent phases of crystallisation.

The kakortokites give way upwards to a succession of lujavrites. These rocks conformably overlie the kakortokites and are also regarded as being largely of cumulate origin. According to Engell (1973) the cumulus minerals include albite, microcline, nepheline, sodalite, eudialyte and aegirine, precipitated from a volatile-rich melanocratic residual magma. The lujavrites form an irregular sheet-like unit be-

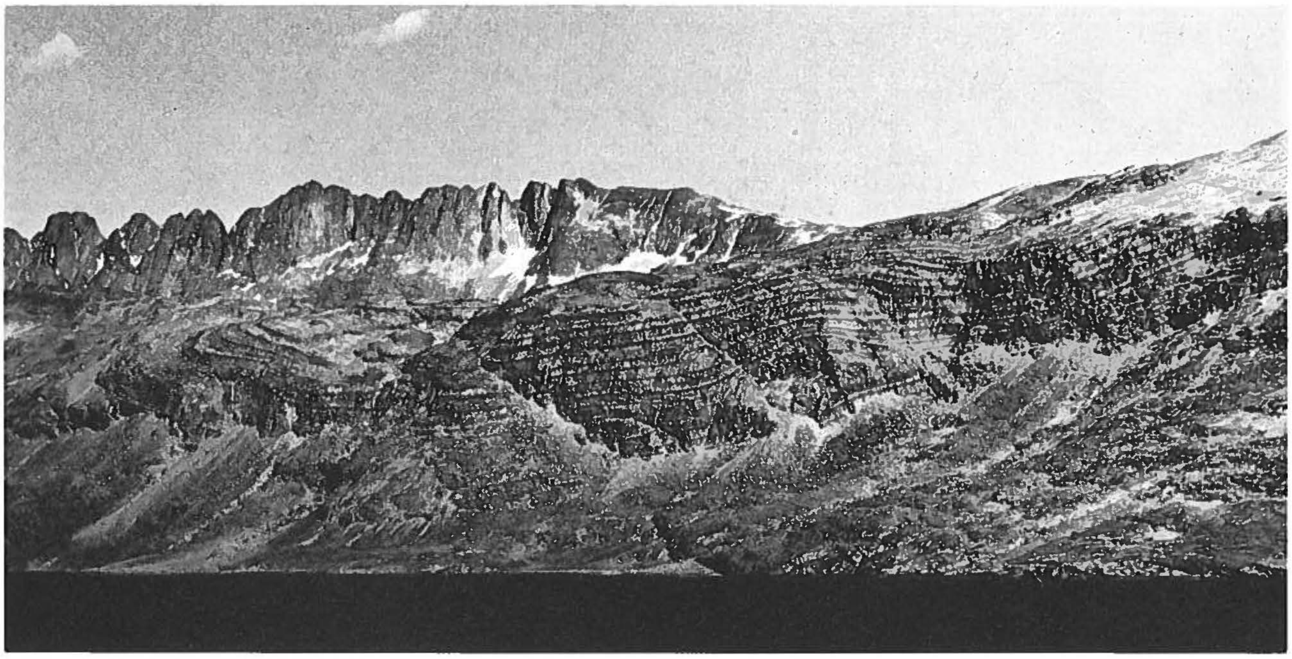


Fig. 167. Layered kakortokites south of Kangerdluarssuk, Ilímaussaq intrusion. The layers dip gently towards the fjord and are distorted over a large naujaite block (mid-centre of view). The high mountains in the background are formed of pre-Gardar Julianehåb granite at the southern edge of the complex.

tween 200–350 m thick. They are characterised by a schistose fabric and contain a variety of structures indicative of deformation during the closing stages of the evolution of the Ilímaussaq complex. Lujavritic rocks are observed to intrude and brecciate the overlying naujaites as well as the augite syenites and country rocks. Some of the lujavritic rocks in the roof zone of the complex (Kvanefjeld, NW Ilímaussaq) may possibly represent earlier basic volcanics that have undergone varying degrees of fenitisation and remobilisation by residual lujavrite magma (H. Sørensen, personal communication). Thus the lujavrites comprise a suite of rocks that are structurally, compositionally and genetically complex. On account of their high concentration of uranium, thorium, niobium, beryllium, tin etc., the lujavrites, particularly in the Kvanefjeld area in the north-west part of the complex, have been subject to intensive mineralogical, structural and geochemical investigation (Bondam & Ferguson, 1962; Oen Ing Soen & Sørensen, 1964; Sørensen, 1962; Sørensen *et al.*, 1969, and over thirty contributions to the Mineralogy of Ilímaussaq published between 1965–1975 in the Bulletins and Reports of the Geological Survey of Greenland, e. g. Sørensen, 1967).

Quartz syenite and coarse peralkaline granite form a group of rocks in the northern part of the complex which is, like the agpaites, enriched in rare elements. The position of these rocks in the intrusive sequence has been disputed. They are, however, known to postdate the augite syenites (Hamilton, 1964; Ferguson, 1970a, b).

Sass *et al.* (1972) have interpreted heat-flow data from Ilímaussaq as indicating that the alkaline rocks with high contents of heat-generating isotopes are superficial and may be underlain at shallow depths (1–2 km) by rocks deficient in K, Th and U.

Recent Rb-Sr isochron data give an age of 1168 ± 21 m.y. (Table 5). The fact that this is one of the younger dates obtained on the Gardar intrusives is compatible with the field evidence that the Ilímaussaq intrusion formed late in the period; amongst the very few proven younger intrusives are some thin lamprophyric dykes (Bohse *et al.*, 1971).

The Igaliko complexes

The Igaliko group of foyaitic nepheline syenites comprises four major intrusive complexes and several small satellitic stocks, a total of at least 28 intrusive units exclusive of alkali gabbro and syenogabbro bodies (fig. 168; Emeleus & Harry, 1970). In order of decreasing age the central complexes are: (a) Motzfeldt (20 km WNW–ESE × 15 km NNW–SSE), (b) North Qôroq (7 km E–W × 4 km N–S, originally larger and oriented with its long axis WNW–ESE), (c) South Qôroq (26 km WNW–ESE × 10 km NNE–SSW, also originally much larger), and (d) Igdlerfigssalik (16 km WNW–ESE × 11 km NNE–SSW). The relative ages of the Motzfeldt and North Qôroq centres are not directly proven. In addition

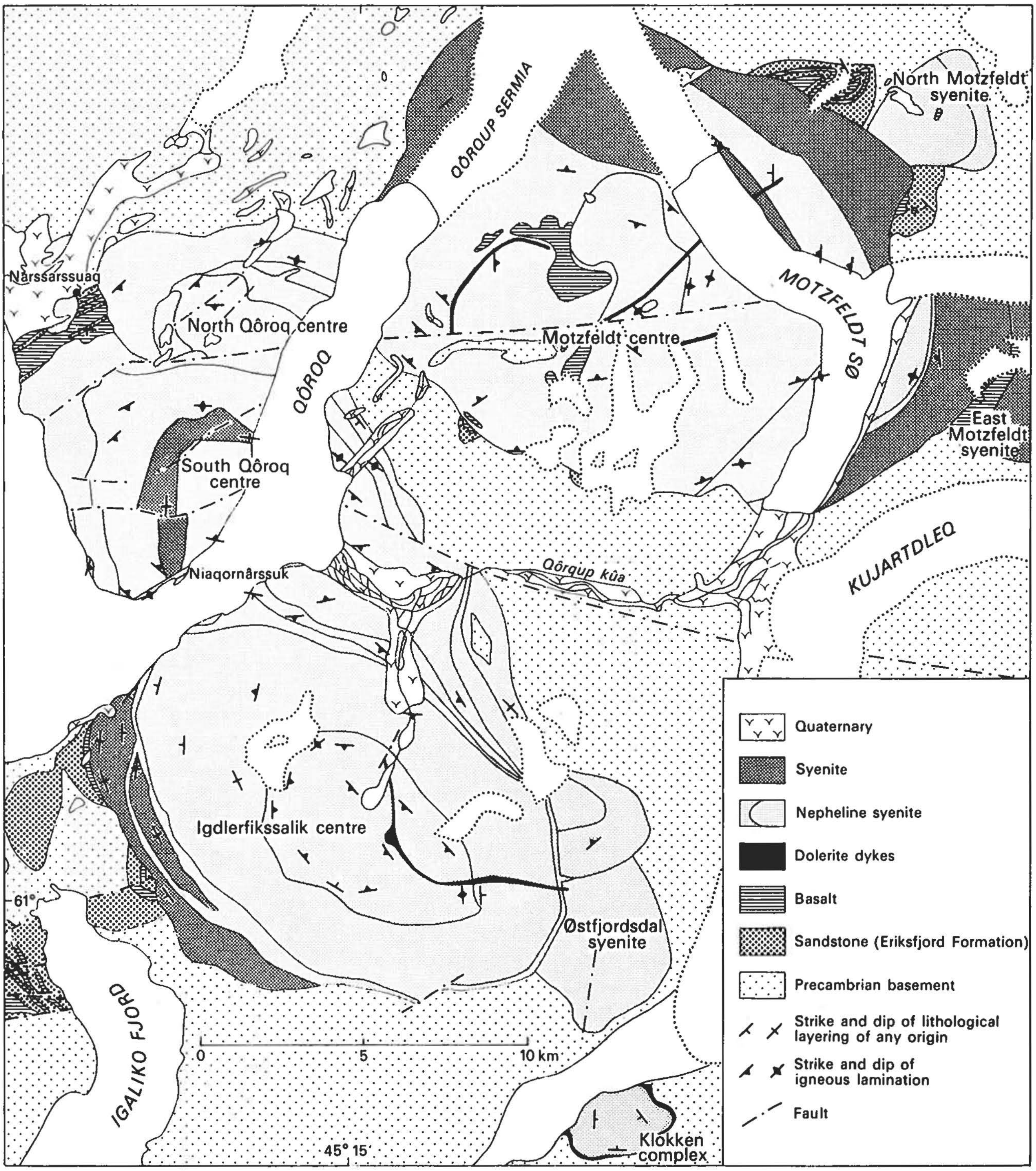


Fig. 168. Geological sketch-map of the Igaliko complexes and Klokken centre.

the Motzfeldt centre cuts an early E–W trending dolerite (= BD_0?). Trachydolerite, trachyte and 'big feldspar dyke' members of the regional swarm cut the three early centres and the three earliest members of the Igdlerfigssalik centre, but the majority of the dykes are cut and metamorphosed by the late members of that centre. The complexes range in age from 1310 ± 31 m.y. to 1167 ± 15 m.y. (Table 5).

In the *Motzfeldt centre* (1310 ± 31 m.y.) one of the syenite units forms a broad ring dyke north of Motzfeldt Sø. Between this lake and Qôroq, a later syenite contains large rafts of altered lavas and pyroclastic rocks derived from members of the (structurally higher) Eriksfjord Formation. Highly-metamorphosed gneiss rafts are also found in this unit.

The syenites are cut by several broad dolerite

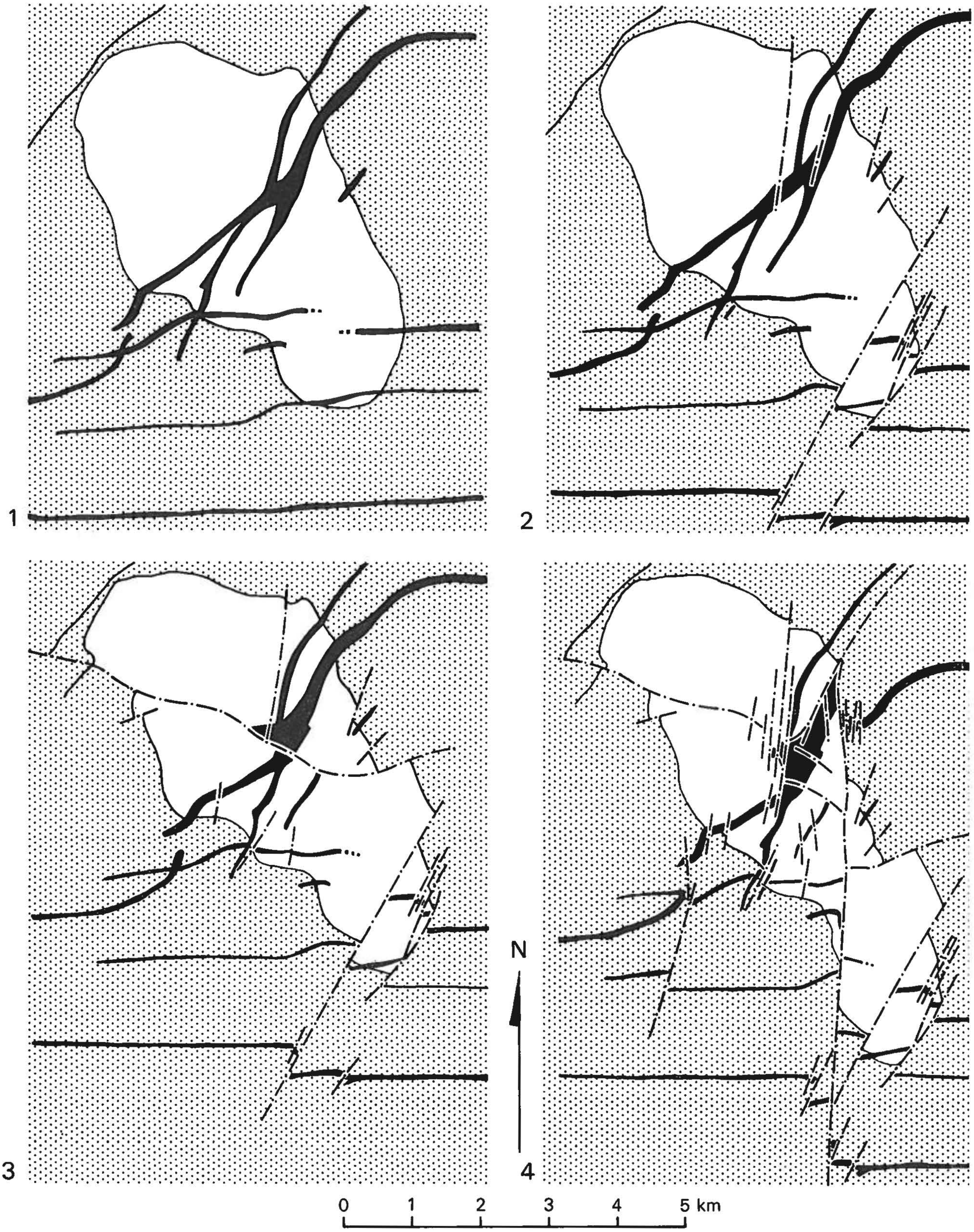


Fig. 169. Stages in the development of faulting of the early Gardar Grønnedal–Íka nepheline-syenite–carbonatite complex. (Based on Emeleus, 1964, fig. 25).

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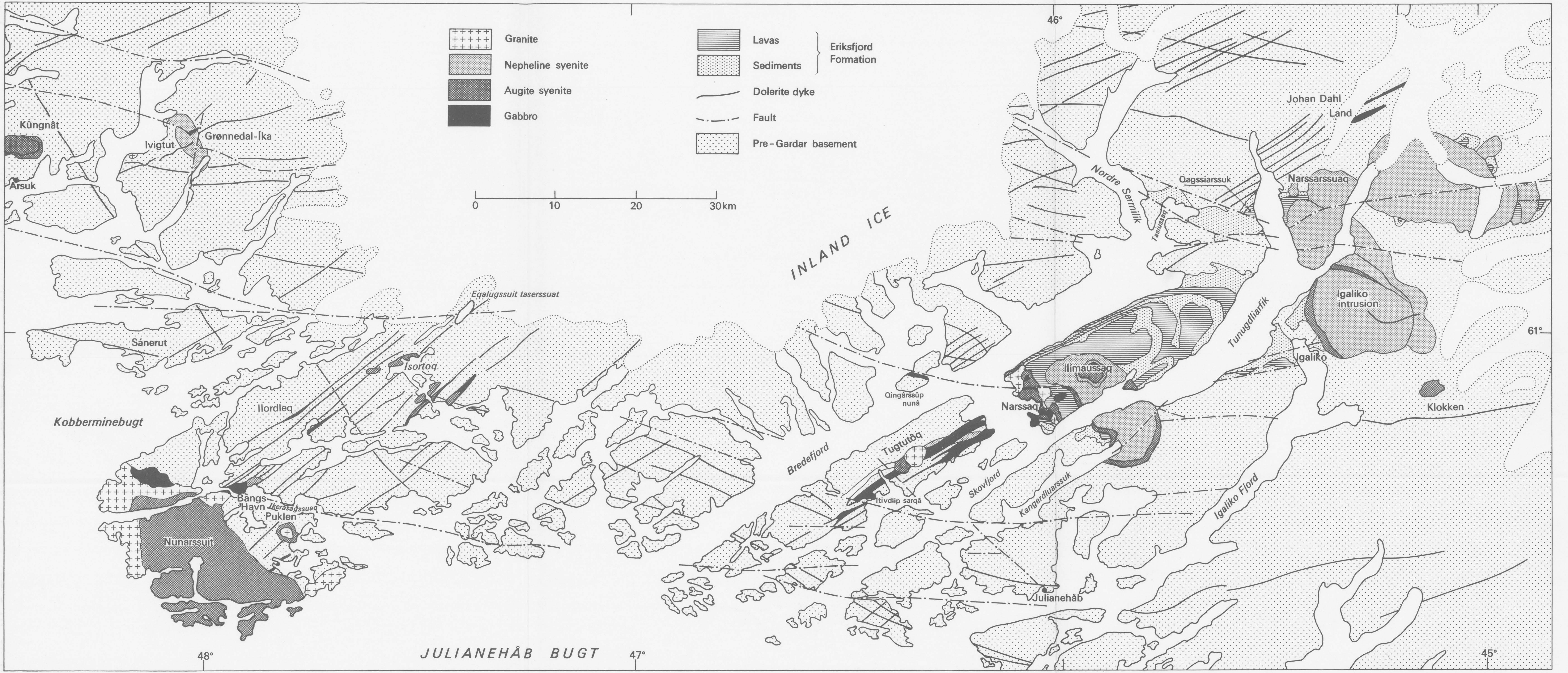
Fig. 170. Generalised geological map of the Gardar province between Ivigtut and Igaliko.



Granite
Nepheline syenite
Augite syenite
Gabbro
Lavas
Sediments
Eriksfjord Formation
Dolerite dyke
Fault
Pre-Gardar basement
0
10
20
30km
46°
INLAND ICE
Johan Dahl Land
Kûngnât
Ivigtut
Grønnedal-Íka
Arsuk
Nordre Sermilik
Qagssiarssuk
Tasiussaq
Narssarssuaq
Eqalugssuit taserssuat
Igaliko intrusion
Tunugdliarfik
61°
Sánerut
Isortoq
Igaliko
Ilímaussaq
Qingârssûp nunâ
Narssaq
Klokken
Ilordleq
Kobberminebugt
Bredefjord
Tugtutôq
Skovfjord
Kangerdluarssuk
Igaliko Fjord
Bangs Havn
Ikerasadssuaq
Puklen
Itivdlip sarqâ
Nunarssuit
Julianehåb
JULIANEHÅB BUGT
48°
47°
45°

Fig. 170

dykes and a partial ring dyke of syenogabbro; anorthositic fragments and plagioclase xenocrysts are abundant in one dolerite dyke.

The North Qôroq centre (1295 ± 61 m.y.) is much truncated by later syenites. The units are foyaitic, frequently with good feldspar lamination; one is highly xenolithic containing numerous foyaite fragments in a fine-grained, porphyritic, microsyenite matrix which resembles certain of the regional dykes. A small plug of carbonated alnöite cuts two of the units, including the youngest in the centre. The plug resembles petrographically and structurally plugs and diatremes described from Johan Dahl Land (Walton, 1965) and Qagssiarssuk (Stewart, 1970).

Recent work on the *South Qôroq centre* 1185 ± 8 m.y.) has shown that a ring dyke of layered larvikite intruded the foyaites at a late stage (Stephenson, 1972); the majority of the units are foyaites, sometimes with pronounced centrally-directed feldspar lamination and occasional concordant layering. A short length of a broad syenogabbro dyke cuts the youngest unit and is itself truncated by a later syenite belonging to the Igdlerfigssalik centre.

Electron microprobe determination on the zoned clinopyroxenes from the complex demonstrate a continuous series from titanaugite to aegirine augite with acmite in pegmatites and recrystallised rocks (Stephenson, 1972). Individual intrusive units were found to have distinctive pyroxene compositional ranges. Markedly different compositional trends occur in syenites recrystallised by the nearby Igdlerfigssalik complex. Olivines show a range from hortonolite to manganiferous fayalite and are relatively calcium rich (Stephenson, 1974).

On the basis of relationships between the dykes and the major intrusions, the *Igdlerfigssalik centre* is divided into three early (pre-regional dyke swarm) units and four late (post dyke swarm) units. In contrast to the other centres, thermal metamorphic effects are locally severe. On the north-west side of Qôroq, South Qôroq syenites are heavily altered and locally remobilised by the larvikitic 'SI.1' syenite and a similar intense metamorphism of the basement granite and quartzites and basic rocks of the supracrustal series is found south of Tunugdliarfik where a pronounced country rock sag is directed towards the larvikitic syenite 'SI.4'. This syenite is layered showing both feldspar lamination and cryptic layering. Mineral layering and lamination is often present in several units of the Igdlerfigssalik centre (and in other units of the Igaliko complex). For example, large-scale layering and extensive lamination both at low angles define a series of saucer-like structures in the latest syenite, 'SI.7'. The centre contains one complete thin syenite ring dyke 'SI.6' and a partial ring dyke of alkali gabbro which post-dates the syenites.

In the south, the satellitic *Østfjordsdal intrusion* is cut by members of the regional dyke swarm but truncates a swarm of nepheline porphyry dykes trending ENE–WSW which are texturally similar to the 'Fox Bay Porphyry' dykes (Ussing, 1912). A central microsyenite area encloses blocks of altered basalt and quartzite derived from the Eriksfjord Formation; in this area the Gardar basal unconformity must have lain well above the level at which the intrusions are exposed.

Klokken

This small complex (fig. 160; Ødum, 1927; Parsons, 1972b) consists of a marginal syenogabbro enclosing a spectacularly-layered series of larvikitic syenites and quartz syenites (fig. 143) that are cut by irregular sheets of microsyenite and quartz microsyenite. A Rb-Sr isochron age on the complex gives 1159 ± 11 m.y. (Blaxland & Parsons, 1975). It is thus one of the youngest Gardar intrusives, which is compatible with its field relations as it cuts members of the ENE-trending regional dyke swarm.

Structure

Faulting was one of the most significant processes in the Gardar events of south Greenland and it is not unreasonable to suppose that magma genesis and ascent were intimately associated with crustal dislocation.

The complexity of the faulting is well illustrated in the vicinity of the Grønnedal–Ika complex (Emeleus, 1964). At least three major phases of faulting can be recognised and the present elongate outline of the intrusion is largely attributable to faulting which was taking place at the time of dyke emplacement (fig. 169).

From west of Ivigtut to east of the Motzfeldt and Igdlerfigssalik centres the region is cut by right-lateral faults trending between 160° and 170°. These affect the dyke-swarms and the Grønnedal–Ika, Nunarssuit, Motzfeldt, South and North Qôroq and earlier Igdlerfigssalik complexes. A smaller number of faults but with individually larger displacements, trend approximately east–west and also affect the entire region. These latter are left-lateral faults and are the major structural features of south Greenland (Berthelsen, 1962; Escher, 1970). Individual faults may have displacements of several kilometres and the total left-lateral displacement of the region is at least 15 km, as indicated by aggregate displacements of basic dykes between western Tugtutôq and the Inland Ice. One left-lateral fault, the Laksenæs Fault, has been shown by Henriksen (1960) to have had a long pre-Gardar history; however, this has not been demonstrated for others and it seems probable that the entire (approximately) north–south right-lateral and east–west left-lateral fault systems were essentially a Gardar development, albeit commencing in the early part of the Gardar. Intersections of the left-lateral faults and the dyke swarms appear to have played a role in locating several of the intrusive centres.

Between Nunarssuit and Julianehåb, but to a lesser extent in the western area, the pre-Gardar basement has a pronounced WSW–ENE 'grain' imposed by foliation of the gneisses and lineaments in the migmatites and granites. The dominant dyke direction adopted in the Gardar thus appears to have been inherited from earlier structures. The 'grain' also finds contemporary topographic expression, particularly in the large ENE-trending fjords such as Bredefjord and Tunugdliarfik (fig. 170). These pronounced features may be partly due to preferential glacial erosion along Gardar dykes, but more probably to erosion along important ENE crush zones. Crush zones in this direction are abundant on Tugtutôq and the adjacent islands in Skovfjord. The crushed granites of the Bredefjord coast of Tugtutôq and the dramatic NW-facing escarpment of basalts and sandstones of the Ilímaussaq peninsula (fig. 144) are probably associated with major ENE crush zones in the fjord close to Tugtutôq and to crushing, faulting and dyke control off the Ilímaussaq shore. Many of the ENE dykes of the Tugtutôq area are not only emplaced along ENE crush zones but in some, these crush zones were operative after dyke emplacement. However, lateral displacements along these lines are uncommon and it is likely that movement was mainly vertical. Thus, the very different successions of the Eriksfjord Formation seen on opposing shores of Tunugdliarfik, south-west of Ilímaussaq, probably result from vertical movements on such an ENE fault at an early phase in the Gardar.

A NE–SW fault crossing the southern part of the Ilímaussaq intrusion, cutting the kakortokites, is probably a youthful Gardar fracture. Bohse *et al.* (1971) consider that this (Lakseelv) fault may have a downthrow of some 350 m towards the north-west. Since the fault cannot be traced north-east of the complex Bohse *et al.* conclude that the throw gradually increases towards the south-west and dies out to the north-east.

Faulting in Bredefjord must downthrow to the ESE by some 2–3 km, preserving the thick Gardar supracrustal succession of the Ilímaussaq peninsula; however, there is but little evidence for this fault at the head of Bredefjord so the throw must diminish rapidly to the ENE and possibly change in direction (cf. Fault 4, Emeleus & Stephenson, 1970).

Estimates of vertical movement on faults affecting the Gardar and earlier rocks are difficult to obtain. The majority of the structures are steep and it is only in the eastern area that the basal Gardar unconformity provides a reasonably reliable planar datum. As shown, vertical movement on the ENE shears was undoubtedly important. Vertical movements may also be demonstrated on some of the east–west left-lateral faults. Between Tasiussaq and the Tunugdliarfik coast south of Qagssiarssuk a major left-lateral fault brings sandstones down against basement to the south. A part of the 1.4 km vertical difference between lavas on Nunasarnaq and Nunasarnaussaq may be attributable to the left-lateral fault which is largely pre-Ilímaussaq complex in age. A study of the Laksenæs Fault where it cuts the Grønnedal–Ika complex showed good evidence that there had been little post-intrusion vertical movement but this may be exceptional (Emeleus, 1964).

The two sets of transcurrent faults can be regarded as a conjugate system acting on an anisotropic basement (Upton, 1974). The predominantly ENE-direction of the dyke fissuring and minor faulting is regarded as a failure of the pre-Gardar basement in response to these stresses.

The relative ages of the fault systems can to some extent be determined. Frequently, the (approximately) N–S right-lateral faults are earlier than the left-lateral set trending east–west. Exceptions are known, as at Grønnedal–Ika where the latest movements were on north–south right-lateral faults, displacing the Laksenæs Fault (fig. 169; Emeleus, 1964). Late movements appear also to have affected the left-lateral faults south-east of Narssarssuaq and on either side of Qôroq; here, the faults are deflected out of their normal (approximately east–west) trend rather than having been broken (Emeleus & Harry, 1970). Late movements also seem likely on the major ENE-trending shears since the courses of fjords such as Bredefjord – Nordre Sermilik and Tunugdliarfik are strikingly straight despite the fact that they intersect east–west left-lateral faults. A possible example of the reverse relationship may occur at Qôroq where the fjord has a fairly pronounced kink between two left-lateral faults (fig. 168).

Kumarapeli & Saull (1966) have discussed the probability of a rift system, analogous in size and scope to the East African rift system, forming a branching zig-zag pattern across the eastern part of the North American continent. This St. Lawrence rift system, which was active during the Mesozoic, is thought to have Precambrian origins and to be associated with the Lake Superior Keweenawan downwarp as well as with the 'Gardar-age' alkaline complexes of Ontario (Fairburn *et al.*, 1959; Lowdon *et al.*, 1963; Gittins *et al.*, 1967). It now seems highly probable that a branch of this Precambrian rift system extended across south Greenland and that the Gardar activity is merely a localised tectonovolcanic province within this extended system.

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