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The Phanerozoic development of the Kangerdlugssuaq area, East Greenland

Charles Kent Brooks and Troels F. D. Nielsen

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Charles Kent Brooks and Troels F. D. Nielsen

In memory of the late Professor L. R. Wager on the occasion of the 50th anniversary of the initiation of his work in East Greenland as geologist on the British Arctic Air Route Expedition.

MEDDELELSER OM GRØNLAND, GEOSCIENCE 9 · 1982

Table of contents

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CHARLES KENT BROOKS and TROELS F. D. NIELSEN

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This paper presents an up-to-date description of the state of knowledge on the post-Precambrian geology of the Kangerdlugssuaq area, which is a key area for the early stages of continental break-up in the North Atlantic. The area is analogous to present-day Iceland but differs from Iceland in that continental crust is present and the erosional level is deeper.

The area was affected by the Caledonian orogeny as revealed by the Batbjerg intrusion, which contains screens of Palaeozoic limestones and unique potassic rocks which relate it to the Assynt Province of Scotland.

Basin formation in the early Cretaceous heralded a period of sedimentation and volcanism which formed deposits several kilometres in thickness. The basalts are believed to have been extruded just prior to anomaly 24 (i.e. 55 – 53 m.y. ago) which reaches the coast just north of this area. The basalts are overwhelmingly tholeiites of "plume" type and include picrites. They may be derived from two different mantle sources.

Layered gabbroic intrusions which are penecontemporaneous with the basalts are widespread in the area and a number of ultramafic plugs also occur. Syenites, both under- and oversaturated, are the most voluminous rock types of the area at the present erosional level and are somewhat later. The syenites show abundant signs of contamination with the country rocks.

The Gardiner complex is the eroded core of a nephelinitic volcano and contains melilite rocks and carbonatites. Related nephelinitic lavas are found in inland areas.

In the area many dike swarms are recognized which vary from tholeiitic to strongly alkaline suites emplaced between ca. 55 and 35 m.y. ago and which give good evidence of the magmatic and chronological development of the area.

Tertiary tectonism includes three main elements: the well known coastal flexure, a major dome centred on Kangerdlugssuaq and regional plateau uplift.

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In the Lower Tertiary the Kangerdlugssuaq area was one of intense igneous activity during which voluminous basaltic lavas, major gabbroic and syenitic intrusions and dense dike swarms were emplaced. This igneous activity was part of the development of the North Atlantic province, whose other manifestations are to be found in Britain, the Faeroe Islands, West Greenland and Baffin Island (Noe-Nygaard 1974). The present-day volcanic activity in Iceland and Jan Mayen is now regarded as being an extension of the earlier activity, the relationship to which, so long obscure, is readily understood in the framework of plate tectonics (Brooks 1973 a, b).

The large volume and remarkable variety of igneous rocks in the Kangerdlugssuaq area, combined with the excellent degree of exposure and relief make this a key area in our understanding of the province as a whole and particularly in elucidating the events during the early stages of continental break-up in the North Atlantic. Fig. 1 shows the position of Kangerdlugssuaq in the North Atlantic area prior to spreading and in relation to the rest of the East Greenland Tertiary province. Fig. 2 shows the geology of the Kangerdlugssuaq area and Table 1 shows the areal distribution of rock types in the area.

This paper presents a description of the present state of our knowledge of the geology of Kangerdlugssuaq. We are well aware of the fact that many areas still remain to be visited and many subjects are as yet only superficially investigated. This contribution is therefore to be regarded as a progress report only and is designed to present the regional setting for the new, comprehensive studies of the Skaergaard intrusion being conducted by a team under the leadership of Professor A. R. McBirney, University of Oregon.

Table 1. Areal distribution of rock types in the Kangerdlugssuaq area.

	area (km^2)	percent total area	percent land area
1. total area of map sheet, Fig. 2 (67°45′–68°45′N; 31°00′–33°30′W)	12000	–	–
2. area of *sea and fjord*	3000	25	–
3. area of *land*, including land with permanent snow and ice cover	9000	75	100
4. total area of *gabbro* outcrop	470	4.0	4.3
Kap Edvard Holm complex	360	–	–
Skaergaard intrusion with Vandfaldsdalen macrodike	70	–	–
others	31	–	–
5. total area of *syenite* outcrop (see footnote 1)	950	8.0	10.8
Kangerdlugssuaq intrusion and satellite intrusions	850	–	–
Kap Boswell	59	–	–
others	38	–	–
6. area of *Gardiner complex*	31	0.3	0.4
7. estimated area of *basalts and sediments* (see footnote 2)	960	8.2	11.0
8. area of *basement gneiss* outcrop	6370	54.2	72.6

Footnotes

1. Kap Deichmann and Kap Boswell have been extrapolated on the basis of exposed contacts to give circular bodies. Only the exposed part of the Kræmer Ø syenite is included in the above figures. If it also is extrapolated to include some small exposures on the N side of Amdrup Pynt, the total syenite area rises to 1000 km^2.

2. The area occupied by sediment and basalt, mainly to the E of the Frederiksborg Gletscher, requires much extrapolation due to extensive ice cover in this region and the figure given above is not regarded as being very accurate.

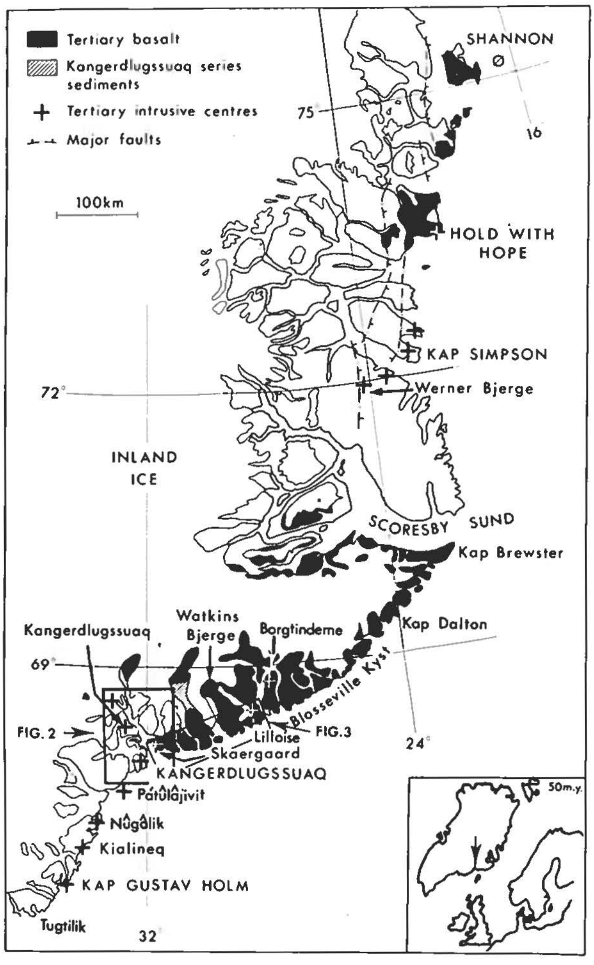

Fig. 1. The distribution of Tertiary rocks in East Greenland. Major intrusive centres are shown with crosses and named. Inset: position of East Greenland prior to the initiation of spreading after the reconstruction of Bott & Watts (1971). The approximate areas shown in Figs 2 and 3 are outlined.

Lower Palaeozoic events: the Batbjerg complex

From the immense period of time (of the order of 3×10^9 y) which elapsed between the metamorphism of the Archaean basement (Leeman et al. 1976) and the deposition of the Cretaceous-Tertiary sediments of the Kangerdlugssuaq Group (Nielsen et al. 1981), geological events are only recorded at one locality within the area. This is the Batbjerg complex (Brooks et al. 1981) which is located on the NE side of the Kangerdlugssuaq Gletscher about 80 km inland from Kap Hammer (Fig. 2). This complex consists largely of ultramafic rocks, predominantly pyroxenites and including some unique leucite-bearing types, and has, somewhat unexpectedly, given an age of 439 ± 8 m.y. (Brooks, Fawcett & Gittins 1976, Gleadow & Brooks 1979) which is similar to that of a number of Caledonian intrusions in Scotland (particularly the petrographically rather similar alkaline rocks of Assynt, Brown et al. 1968, van Breemen et al. 1979) and East Greenland (e.g. the Hurry Inlet granite and the granodiorite of Milne Land, both some 500 km to the north, Hansen & Steiger 1971, Gleadow & Brooks 1979, Hansen & Tembusch 1979).

The Batbjerg intrusion, recently described by Brooks et al. (1981), is of great petrological interest due to the unusual potassium-rich rocks which occur there. The

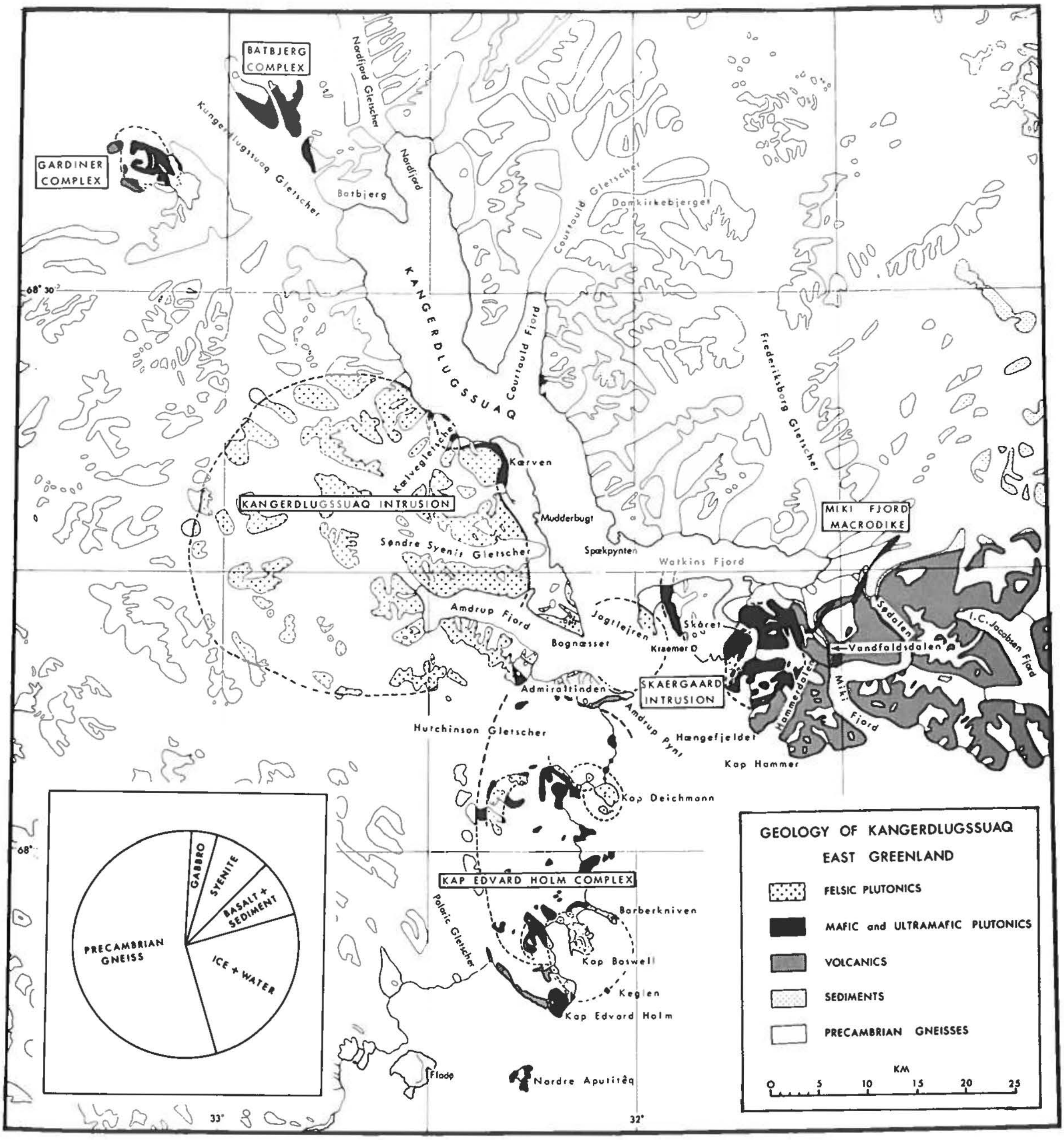

Fig. 2. Geology of the Kangerdlugssuaq area from 67°45′–68°45′ N and 31°–33°30′ W. Insert: the proportions of land covered by the principal rock types and ice and water.

bulk of the intrusion consists of ultramafic plutonic rocks: peridotites, dunites, pyroxenites and hornblendites; typical analyses of Batbjerg rocks are shown in Table 2. Some units are calc-alkaline in character while others are strongly alkaline. The calc-alkaline types are apparently related to a host of vents in the surrounding basement which are filled with hornblende-rich breccias similar to the Caledonian appinites of Scotland (Bowes & McArthur 1976). The pyroxenites sometimes contain varying amounts of feldspathoids and are related to nepheline syenitic dikes. Most interesting are intergrowths between nepheline, alkali feldspar and kalsilite which occur together with leucite. These intergrowths provide a natural example of relations predicted experimentally in the relevant synthetic system (Gittins et al. 1980) and some of the assemblages are unique.

Table 2. Selected analyses of rocks from the Batbjerg complex.

	1.	2.	3.	4.	5.
SiO_2	44.18	45.13	53.24	62.13	58.97
Al_2O_3	2.97	7.35	21.58	18.30	16.27
Fe_2O_3	11.33	8.74	1.51	0.99	3.00
FeO	6.27	5.27	0.34	1.33	3.31
MgO	13.14	9.62	0.05	1.31	2.68
CaO	18.56	14.39	1.10	2.81	4.37
Na_2O	0.60	1.46	3.80	7.78	4.77
K_2O	0.69	4.67	13.46	2.68	3.88
MnO	0.19	0.19	0.04	0.08	0.12
TiO_2	1.11	1.12	0.15	0.20	0.71
P_2O_5	0.18	0.60	0.01	0.16	0.37
volat.	0.92	0.71	2.15	0.87	0.91
	100.14	99.25	97.43	98.64	99.36
CIPW weight norm					
Q	–	–	–	–	4.52
Or	4.08	4.54	46.97	15.84	22.93
Ab	1.35	–	–	65.84	40.36
An	3.37	–	2.07	7.10	11.52
Lc	–	18.08	25.54	–	–
Ne	2.02	6.40	17.42	–	–
Ac	–	0.48	–	–	–
Di	68.29	52.78	0.27	4.68	6.23
Wo	–	–	1.24	–	–
Hy	–	–	–	1.32	6.33
Ol	1.16	0.31	–	0.81	–
Hm	–	–	0.96	–	–
Mt	16.43	12.43	0.79	1.44	4.35
Il	2.11	2.13	0.28	0.38	1.35
Ap	0.42	1.39	0.02	0.37	0.86

1. Typical alkali pyroxenite (MM30272).
2. "Malignite" with prominent white spots (MM30237).
3. Syenite from lens concordant with pyroxenite "foliation" (MM30273).
4. Discordant syenite from vein network in pyroxenite (MM30274).
5. Typical appinite forming matrix to abundant hornblende-rich xenoliths in vent just outside pyroxenites in basement (MM30224/1).

Along the contacts of the intrusion are screens of dolomitic marbles which are believed to be remnants of a former sedimentary cover, emplaced and preserved by cauldron subsidence. Radiometric dating of the intrusion indicates that these sediments must be earlier than Middle Ordovician and this, together with lithological similarities, suggests that they are to be equated with the Cambrian to Ordovician Durness limestones of Scotland. These rocks have undergone intense metamorphism and complex mineral assemblages are developed in original chert nodules (Gittins et al. 1977). In one of these, the hitherto unreported spinel end-member Mg_2TiO_4 has been recorded (Gittins et al. 1982). Many features of the Batbjerg complex suggests that it is an outlier of the Assynt alkaline suite of NW Scotland, from which it has been separated by ocean-floor spreading.

Late Mezozoic–Early Tertiary sediments and lavas

Place names referred to in this section will be found in Fig. 3.

Based on fission track results for the Batbjerg rocks, Gleadow & Brooks (1979) argued that uplift and erosion of the complex and its cover was very slow over the period of the Upper Palaeozoic but accelerated during the Mesozoic and Tertiary, presumably due to the movements associated with the break-up events in this part of the North Atlantic region.

The general uplift and peneplanation of the area before the late Mezozoic, as witnessed by the lack of sedimentary deposits and the above-mentioned fission track ages, was reversed in some areas at the beginning of the Cretaceous and a sedimentary basin began to form in a large embayment with a presumed palaeo-coastline stretching NE from Kangerdlugssuaq (Higgins & Soper, 1981) and most likely a considerable offshore extension.

The accumulated sediments of this basin are termed the Kangerdlugssuaq Group while the succeeding, predominantly volcanic sequence is the Blosseville Group (Fig. 4). These successions have been described and dated using biostratigraphic methods by Birkenmajer (1972), Soper et al. (1976a) and Soper & Costa (1976). The information below and summarized in Table 3 is condensed from Soper et al. (1976a), Nielsen et al. (1981) and Higgins & Soper (1981).

The Kangerdlugssuaq Group is divided into the Upper Albian-Cenomanian Sorgenfri Formation and the Ryberg Formation, which includes the majority of the sediments and spans the period from Senonian to at least Danian. The overlying Blosseville Group is divided into several formations which span the period from Lower Sparnacian to Ypresian. Post-basaltic sediments at Kap Brewster and Kap Dalton, to the north, have Oligocene and Miocene ages.

The Sorgenfri Formation is only known from a single inland locality (it must be stressed that large areas of the Kangerdlugssuaq and Blosseville Groups are unexplored) and consists mainly of sandy shales with calcareous nodules. An Upper Albian age is indicated by ammonite and dinoflagellate finds. The base of the formation has not been seen.

These rocks are separated from the overlying Ryberg Formation by a voluminous sill complex and the relationships are obscure. However, Turonian sediments have not been observed. The stratotype Ryberg Formation consists of 140 m of marine sandstones and siltstones with uppermost beds being rich in plant remains and recording shallowing marine conditions. The age range of this formation is from Senonian to Danian and may extend into the Paleocene, and has been established on the basis of ammonites, dinoflagellates and foraminifera.

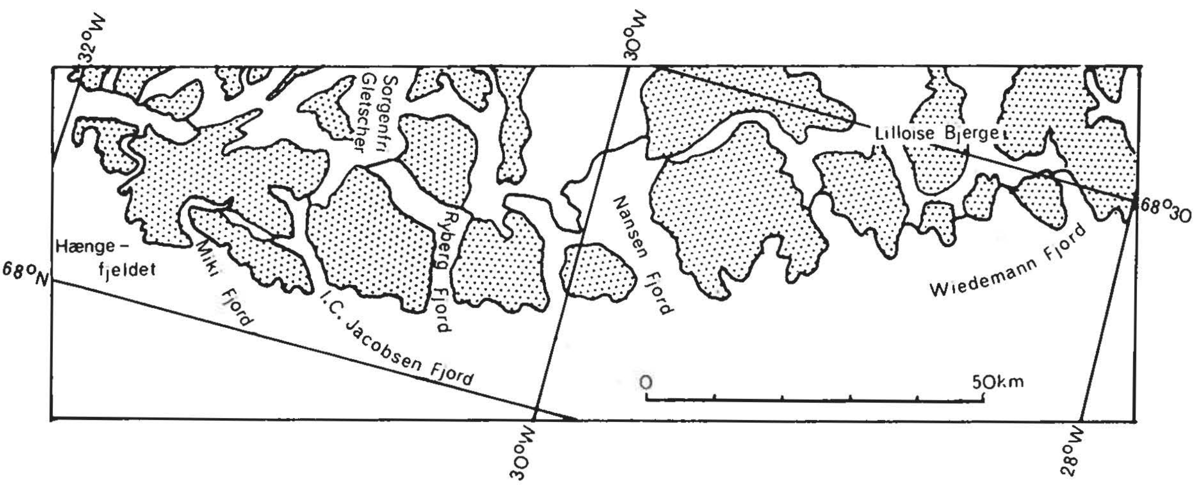

Fig. 3. Map of the southern part of the Blosseville Kyst showing place-names mentioned in the text.

The base of the overlying Blosseville Group is marked by a pebbly arkosic sandstone above which volcanogenic material appears in the eastern part of the area, indicating that volcanism had already begun in adjacent areas. The basal conglomerate is markedly unconfortable to the underlying rocks in the western part of the outcrop. The Blosseville Group is divided informally into the Vandfaldsdalen, Mikis, Hængefjeldet and Irminger Formations. However, in view of the extensive areas underlain by the Blosseville Group which are as yet unvisited, the following must be regarded as tentative.

The earliest volcanic rocks of the Vandfaldsdalen Formation are picritic to andesitic subaerial flows in the western part of the area (Vandfaldsdalen, Miki Fjord) and submarine formations to the E (I. C. Jacobsen and Ryberg Fjord). Most spectacular are massive pillow breccias (Fig. 5) with well developed foreset beds which indicate a southerly source for the lavas, but pillow lava horizons are also present. Thick horizons of polymict, matrix-supported, ungraded breccias are thought to be deposits from subaerial lahars in the W which have entered the sea and become submarine debris slides to the E. They were interpreted as subaqueous mass transport deposits by Soper et al. (1976a) but evidence for a subaqueous origin is lacking in Vandfaldsdalen where they occur among subaerial flows.

These breccias contain a variety of highly porphyritic

Table 3. Summary of the stratigraphy of the Phanerozoic supracrustal rocks of the Blosseville Kyst.

Group	Formation	Predominant character	Biostratigraphic age
Kap Brewster		talus and conglomerate overlain by sandy and silty beds at Kap Brewster.	Miocene (?)
Kap Dalton	Krabbedalen	known at Kap Brewster and Kap Dalton only – ca. 45 m coarse, basement-derived sanstones and siltstones.	Lower (?) Oligocene
	Bopladsdalen	known at Kap Brewster and Kap Dalton only – volcanogenic conglomerates and siltstones (ca. 40 m).	Middle Ypresian
Blosseville	Irminger	more than 4000 m simple lavas, individual flows several tens of metres thick, some sediments and hyaloclastite horizons towards top.	basal Ypresian (at top)
	Hængefjeldet	300–500 m marine tuffs.	?
	Mikis	200–400 m thin, compound lavas and ca. 200 m picrites in Miki Fjord, marine tuffs to E. All overlain by ca. 1000 m lavas (earlier Jacobsen Formation).	?
	Vandfaldsdalen	lowermost ca. 20 m (Schelderup Member) is conglomerate and sandstones (deeper water facies to E). In W this is overlain by ca. 500 m lavas or ca. 80 m. hyaloclastites and tuffs in the E.	Lower Sparnacean (at top)
Kangerdlugssuaq	Ryberg	100–200 m siltstones and shales.	Senonian to Danian and perhaps younger
	Sorgenfri	ca. 30 m sandy shales, base not seen.	Cenomanian to Upper Albian

Fig. 4. Sediments (predominantly arkosic sandstones and siltstones) of the Ryberg Formation (Senonian to Paleocene) underlying the lavas of the Vandfaldsdalen Formation, which are partly picritic. The high bluff to the right is composed of a thick hyaloclastite unit. Rocks in the foreground are the Miki Fjord macrodike veined by granophyres. Taken from head of Sødalen to E.

Fig. 5. Hyaloclastite breccia in Sødalen, Miki Fjord. Large pillows with chilled, originally glassy, margins are set in a matrix of glassy fragments, now highly zeolitized. No glass is preserved in these rocks.

basalt types not otherwise recognized from the area. The age of the early volcanism has been determined from a shale horizon, 60 m above the base of the pillow breccias in Ryberg Fjord, which contains dinoflagellates of Lower Sparnacian age (Soper et al. 1976a). As with the preceding sediments, it is clear the basin deepened considerably towards the SE; the Vandfaldsdalen Formation increases from 500 m to 800 m from Vandfaldsdalen to I. C. Jacobsen Fjord and thins out towards Nansen Fjord where it is mainly represented by tuffs.

The succeeding Mikis Formation also increases in thickness from W to E. The lower part is composed of vesicular pahoehoe flows (Fig. 6) and about 10 horizons of strongly olivine-phyric massive lavas (Fig. 7). The upper part, earlier designated the Jacobsen Formation, consists of more massive tholeiitic flows. According to Wager (1947), Soper et al. (1976a) and Nielsen et al. (1981), these lavas are represented in the Ryberg Fjord area by tuffs. Within the Mikis Formation in Miki Fjord occasional pillowed bases to the flows and thin sediment horizons suggest that these lavas were extruded onto coastal flats while the same material was forming tuff deposits offshore to the E and SE. A return to marine conditions is recorded in the succeeding Hængefjeldet Formation which is represented by 300–500 m of tuffs, breccias and lavas extending from Hængefjeldet at the

Fig. 6. Pahoehoe surface to flow unit, typical of the Mikis Formation compound lavas. This exposure at the foot of Vandfaldsdalen, Miki Fjord was also figured by Wager (1934), but such structures are common. Rifle for scale. Wager states that this lava was poured out under water, but such is not the case. He presumably interpreted the pahoehoe toes as pillows.

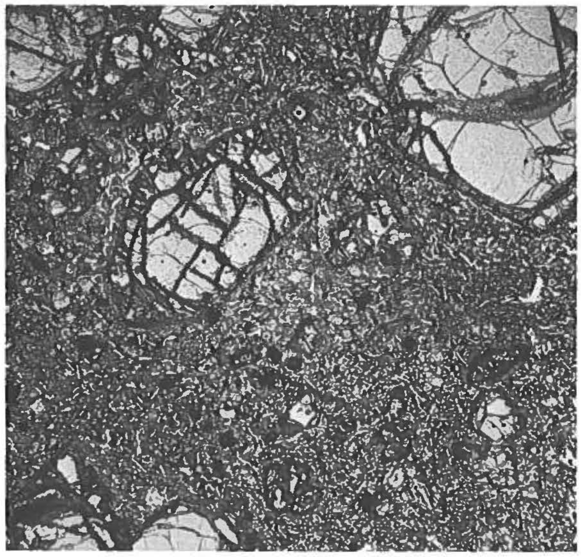

Fig. 7. Strongly olivine-phyric lava from ca. 5 m thick flow in I. C. Jacobsen Fjord. Other examples may show quench textures with hopper olivines and feathery clinopyroxenes in the groundmass. Sample CKB 71/81. The crystal towards the centre of the field is ca. 3 mm across.

mouth of Kangerdlugssuaq to a basement ridge about 60 km to the E at the head of Nansen Fjord which probably formed an island with respect to most of the marine sedimentation and volcanism. The Hængefjeldet Formation is again succeeded by subaerial flows which were called by Soper et al. (1976a) the Irminger Formation and which correspond to the Main Basalts of Wager (1947). This formation is presumed to occupy most of the ca. 250 km between Nansen Fjord and Scoresby Sund. The bulk of the lavas are massive tholeiitic flows which extend over great distances and are frequently 30–40 m thick, but occasional hyaloclastite horizons occur in the Scoresby Sund area and reddened flow tops are quite common (Fawcett et al. 1973, W. S. Watt et al. 1972). A single nephelinitic pyroclastic horizon occurs in the upper part of the succession in this area (Larsen 1982) which is the only recorded alkaline unit in the entire Blosseville Group. The uppermost part of the Irminger Formation is preserved in inland plateau areas (Fawcett et al. 1973a, Brooks 1979) and in downfaulted blocks at Kap Brewster and Kap Dalton. (Birkenmajer 1972, Wager 1935, Soper & Costa 1976), and is dated by dinoflagellates from intrabasaltic sedimentary horizons to be basal Ypresian (Soper & Costa 1976). Post-basaltic sediments at these localities include the Kap Dalton Formation, a series of conglomerates and shelly sandstones with volcanogenic detritus, which probably follows the basalt without any appreciable time lag, and the Kap Brewster Formation, which consists of sandstones free from volcanogenic components, and fault breccias (at Kap Brewster). Soper & Costa (1976) determined the Kap Dalton Formation to be Ypresian to lower Oligocene and the Kap Brewster Formation is believed to be Miocene (Hassan 1953). Wager (1935) described clasts of strongly alkaline rocks in the basal conglomerate of the Kap Dalton sequence indicating that alkaline magmatism closely followed the tholeiitic plateau lavas in this area as it did to the south. Birkenmajer (1972) drew attention to the fact that the lithology of the Kap Brewster Formation is indicative of the development of high relief in the area and suggests that the coast-parallel faulting (W. S. Watt et al. 1972, M. Watt 1975) occurred immediately prior to the deposition of these beds. This is confirmed by offshore geophysical work by Larsen & Jacobsen (1982) which shows that oceanic magnetic anomaly 24 extends into this area. The geology of these areas which lie 300–400 km N of Kangerdlugssuaq has been discussed here in some detail because of the information they give on the upper part of the Tertiary succession which is now removed by erosion in the Kangerdlugssuaq area but was probably originally present.

Isolated exposures of basalt occur elsewhere in the Kangerdlugssuaq area, notably in a down-faulted block on Amdrup Pynt, on Keglen and on Kap Edvard Holm; their relationships have not been determined with certainty but they resemble lithologically the Vandfaldsdalen Formation. Basaltic rafts and xenoliths are common in the intrusive rocks outside the area of basaltic outcrop. These are sometimes rich in clinopyroxene phenocrysts and do not appear to correspond to the lithologies of the Blosseville Group, but perhaps to the alkaline Prinsen af Wales lavas (Anwar 1955). Excellent examples of such basalts are among the very large blocks (up to 300 m across), immersed in the Kræmer Ø syenite (Fig. 14).

The work of Soper and his colleagues (Soper et al. 1976a & b, Soper & Costa 1976, Higgins & Soper 1981) has established the biostratigraphic age of the Blosseville Group with some degree of confidence. This limits the span of basaltic activity to Lower Sparnacian to early Ypresian which in terms of the presently accepted Tertiary time scale (e.g. LaBreque et al. 1977, Berggren et al. 1978) is only a few million years as pointed out by Brooks (1973a) and Soper et al. (1976a & b). A similar conclusion was arrived at by Faller (1975) and Nielsen et al. (1981) on the basis of palaeomagnetic studies, as all the basalts so far examined have reverse polarity. Several authors (Soper et al. 1976a & b, Tarling & Mitchell 1976, Brooks & Gleadow 1977, Berggren et al. 1978, Brooks 1980, Hailwood et al. 1979) have stressed that this has significant implications for the calibration of the polarity time scale in the ocean basins. The consensus of opinion is that the basalts were extruded immediately prior to anomaly 24 which is located in ocean floor close to the present coast line (Larsen & Jacobsen 1982) and that the existing radiometric age determinations of these basalts (Beckinsale et al. 1970, Fitch et al. 1978) indicate an age for this anomaly of 53–55 m.y. This problem has been discussed in some detail by Brooks (1980). The Ypresian or pre-Ypresian age of the basalts has considerable significance in the evaluation of the faunas of the North Atlantic area (see Berggren et al. 1978).

Another subject of some controversy regards the thickness of the Blosseville Group, a problem which has important bearing on volcanological questions such as the rate of lava extrusion. Wager (1947) originally estimated a maximum exposed thickness of 7½ km in I. C. Jacobsen Fjord and Soper et al. (1976a) suggested a figure of as much as 9 km. In contrast, Nielsen (1975) has shown the presence of a large number of largely concealed faults in the coastal area and has urged caution in the acceptance of these estimates. An example of such faulting on a small scale is shown in Fig. 24 and it is believed that the entire basalt column (i.e. both that exposed and that removed by erosion) may not have been more than ca. 7 km (Nielsen & Brooks 1981) which indicates a comparable rate of eruption to that of Iceland at the present time (Brooks, Nielsen & Petersen 1976) instead of the exceptional values derived by other authors (Soper et al. 1976b, Brown & Whiteley 1976).

Petrological and petrochemical information on the lavas is far from complete but some information has been published by Fawcett et al. (1973), Brooks, Nielsen & Petersen (1976), Brown & Whitley (1976)

Table 4. Selected analyses of basalts from the Blosseville Group.

	1	2	3	4	5	6	7	8
SiO_2	45.10	50.90	43.84	47.06	48.86	47.72	47.37	47.33
Al_2O_3	7.80	12.69	6.51	10.72	12.43	13.33	13.19	13.38
Fe_2O_3	3.16	4.29	2.81	7.59	4.29	5.53	4.82	4.89
FeO	8.95	7.73	8.98	5.64	7.08	8.18	8.54	8.62
MgO	20.32	4.45	23.52	11.80	8.45	6.31	6.55	6.31
CaO	7.44	9.16	5.99	9.94	10.70	10.74	11.40	10.79
Na_2O	1.02	2.16	0.81	2.00	1.97	2.03	2.48	2.35
K_2O	0.18	1.12	0.12	0.38	0.54	0.25	0.26	0.26
MnO	0.18	0.17	0.20	0.16	0.17	0.20	0.21	0.18
TiO_2	1.83	3.39	1.68	2.12	2.36	2.38	2.48	2.64
P_2O_5	0.16	0.33	0.14	0.31	0.17	0.26	0.25	0.30
volat.	3.27	3.02	4.67	3.09	2.73	2.61	1.92	2.15
	99.41	99.41	99.27	100.31	99.75	99.54	99.47	99.20
CIPW weight norm								
Q	–	7.84	–	–	1.86	1.31	–	–
Or	1.06	6.62	0.71	1.95	2.72	1.54	1.48	1.60
Ab	8.63	18.28	6.85	4.82	16.84	17.69	21.49	20.48
An	16.17	21.62	13.77	24.49	23.93	27.37	24.70	25.97
Di	15.74	17.99	11.98	13.29	22.46	21.40	26.09	22.48
Hy	23.09	14.35	24.19	16.39	21.50	22.42	12.75	19.46
Ol	25.17	–	31.33	26.13	–	–	5.23	1.25
Mt	2.26	2.22	2.21	2.47	2.17	2.62	2.52	2.57
Il	3.48	6.44	3.02	4.14	4.92	4.65	4.82	5.17
Ap	0.37	0.76	0.32	0.37	0.49	0.65	0.58	0.72

All norms calculated on basis of $Fe_2O_3/FeO = 0.15$ (Brooks 1976).

1. Vandfaldsdalen Fm. – picrite, ca. 250 m above base, Sødalen, Miki Fjord (GM 40633).
2. Vandfaldsdalen Fm. – basaltic andesite, ca. 100 m above base, Sødalen, Miki Fjord (GM 40632).
3. Mikis Fm. – picrite flow close to base of formation, head of I. C. Jacobsen Fjord at 450 m (GM 40644).
4. Mikis Fm. – olivine tholeiite, base of formation in Sødalen, Miki Fjord (GM 20332).
5. Mikis Fm. – tholeiite, upper part, I. C. Jacobsen Fjord (GM 40640).
6. Irminger Fm. – average Nansen Fjord lava (Brooks et al. 1976).
7. Irminger Fm. – average Wiedemann Fjord lava (Brooks et al. 1976).
8. Irminger Fm. – average Scoresby Sund area lava (Brooks et al. 1976).

and Nielsen et al. (1981). These authors have shown that the Irminger Formation is characterized by Fe- and Ti-enriched tholeiites similar to those of Iceland but distinctly different from mid-ocean ridge tholeiites (Brooks & Jacobsson 1974). Rare earth element patterns (Brooks, Nielsen & Petersen 1976, Brown & Whitley 1976) confirm this conclusion and isotopic compositions (Carter et al. 1979, Evans & Brown 1981) show that most of these lavas were derived from a similar mantle which had earlier suffered depletion in the large ionic radius lithophile elements. In contrast to the later lavas of the Irminger Formation, which appear to be relatively uniform, the earlier formations are much more variable; picrite types were first recognized in the Miki Fjord by Brooks, Nielsen & Petersen (1976). The Vandfaldsdalen and Mikis Formations range from picrites and ankaramites with MgO in excess of 20% to basalts and basaltic andesites with MgO down to around 4%. A more detailed account for the chemical variation is given by Brooks & Nielsen (1982). The obtained compositions (major and trace elements including REE) show the picrites, the ankaramites and the LIL-element-enriched basaltic andesites to form a distinct trend, whereas other Ol-tholeiites and tholeiites of the Irminger Formation define a LIL-element depleted trend. The dominant group of the lavas is intermediate between these two groups. The Vandfaldsdalen Formation includes most lava types of the picrite trend and some depleted types and mixing products.

The lower part of the Mikis Formation is dominated by Ol-tholeiites, which are intermediate to the two trends, as well as picrites and ankaramites. The upper part of the formation is composed increasingly of intermediate-trend tholeiites and lavas of the depleted group. The petrogenetic model presented by Brooks & Nielsen (1982) suggests a primary deep-seated picritic liquid (> 20% MgO) rising to shallow mantle level, where it is trapped at the density barrier. The liquid fractionates by crystallization of olivine followed by clinopyroxene along the picrite trend. In doing so the liquids give heat to the surrounding mantle, which eventually melts to produce the LIL-element-depleted basalts. The different liquid types mix and fractionate to produce the observed spectrum of lava compositions. The cessation of picrite vulcanism in the Mikis Formation is explained by the trapping of these liquids at the base of the accumulating tholeiite magma-pools in the upper mantle (see Sparks et al. 1980).

The evaluation of the chemical data however is rendered difficult due to an often pervasive alteration. The lavas have in general low $^{18}O/^{16}O$ ratios, indicative of alteration by meteoric water (Taylor & Forrester 1979). Some typical analyses of the different basalt types are shown in Table 4.

Gabbroic and ultramafic intrusions

The Skaergaard intrusion is but one of a large number of gabbroic intrusions from Kap Gustav Holm in the south up to Lilloise, and to the Mesters Vig area 600 km to the north. Skaergaard is of course the best known (Wager & Deer 1938a), but is by no means the largest (see Table 1). In these intrusions, layering is well developed and is often spectacular.

Within the Kangerdlugssuaq area itself, the following gabbroic bodies occur: the Miki Fjord, Vandfaldsdalen and Kræmer Ø macrodikes (Deer 1976), the sills of Basistoppen, Hammerdalen and Hængefjeldet (Hughes 1956, Douglas 1964), the Kap Edvard Holm complex (Abbot & Deer 1972, Elsdon 1969) and the Kap Edvard Holm intrusion[1], Kærven (Ohja 1966), Nordre Aputitêq, Skaergaard and the volcanic vents at the mouth of Courtauld Fjord. In addition several ultramafic, plug-like bodies occur. Of the gabbros, only the Kap Edvard Holm complex and Skaergaard are quantitatively important, the rest making up only about 6% of the total outcrop area of gabbro together. The extent of the Nordre Aputitêq body is unknown as it is covered by sea, while only a small part of the Kærven gabbro is preserved, the rest being removed by later syenites.

Outside the immediate Kangerdlugssuaq area other major gabbroic intrusions occur at Igtutarajik/Pátûlâjivit, Nûgâlik/Agtertia (Rex, Gledhill, Bridgwater & Myers 1979) and Imilik (Brown & Farmer 1972, Myers et al. 1979). The relations between Nordre Aputitêq and the Igtutarajik/Pátûlâjivit exposures are unknown. However, a group of skerries situated about 10 km SW of Nordre Aputitêq also consist of layered gabbro suggesting that such rocks are very extensive in this area. It is to be hoped that forthcoming geophysical work (Larsen & Thorning 1979) will clarify this problem.

Recent summaries of the Kap Edvard Holm complex, Kærven, the Basistoppen sheet and the three macrodikes have been presented by Deer (1976). Nordre Aputitêq consists largely of a rather leucocratic gabbro which is well layered and has several much more mafic

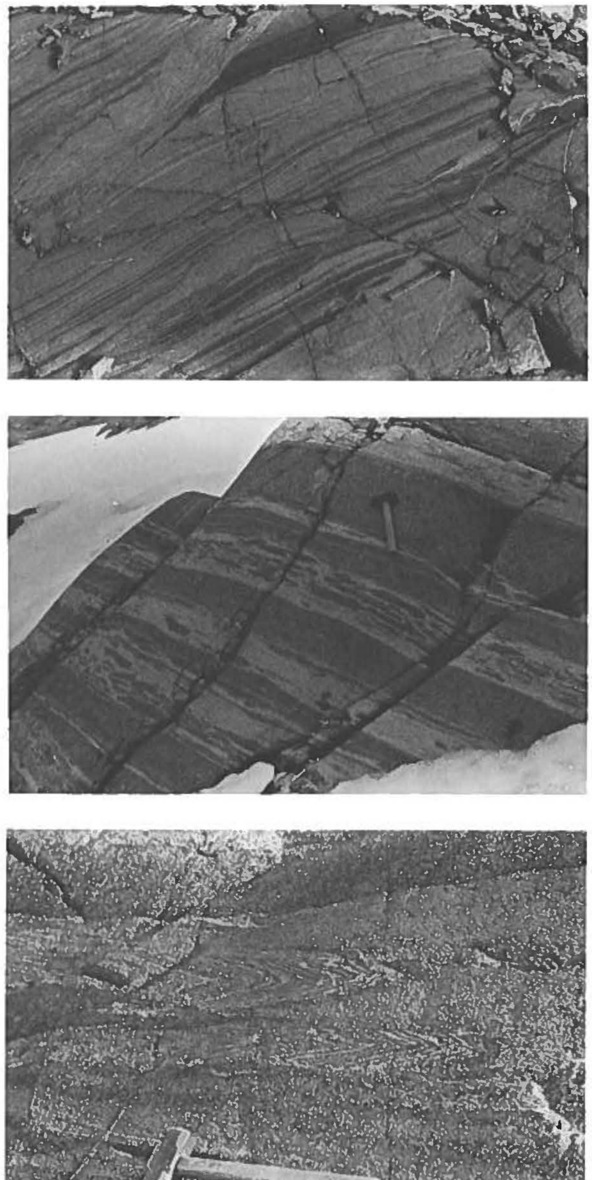

Fig. 8. Penecontemporaneous layered structures indicative of instability during the formation of the gabbros on the island of Pátûlâjivit: a) penecontemporaneous erosion surface in strongly layered gabbro, b) leucocratic horizons with numerous inclusions of the more melanocratic intervening material, and c) tightly folded layering with nearly horizontal fold axes formed by slumping of unconsolidated material.

1. Unfortunately the complex which has hitherto been called after Kap Edvard Holm is not situated on the cape of that name, which is however also occupied by a gabbroic body. This will be called the Kap Edvard Holm *intrusion* and the much larger body, which is known to be formed by multiple magma pulses, the Kap Edvard Holm *complex*.

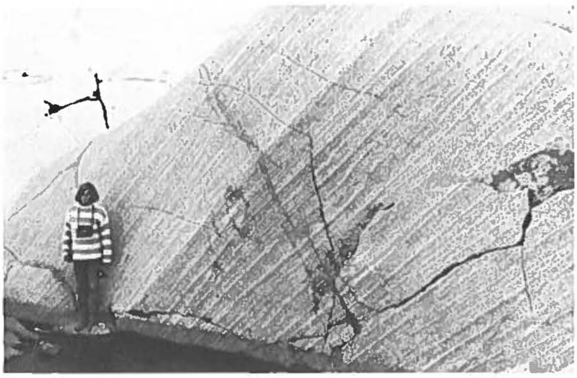

Fig. 9. Structures in the Nordre Aputitêq gabbros: a) slumping in leucocratic and more melanocratic horizons, and b) regular inch-scale layering in which a lower slightly more mafic type is separated by a slight angular unconformity (resulting from a tectonic disturbance) from an overlying type with a slightly more leucocratic bulk composition.

horizons. Spectacular slumped horizons occur (Figs 8 & 9), and abundant vuggy patches containing epidote, prehnite, amphibole, etc. are evidence of a wet magma such as is also believed to have given rise to the nearby Kap Edvard Holm Upper Layered Series (Elsdon 1971). All the Aputitêq gabbros are charcterized by very basic plagioclase, commonly anorthite. A typical analysis is shown in Table 5 which reflects these features.

Myers (1980) has drawn attention to the fact that, contrary to the conclusion of Wager & Deer (1938b), Wager (1947) and several subsequent investigators (Elsdon 1969; Abbott & Deer 1972, Wager & Brown 1968, Deer 1976, Schwartz et al. 1979), the major gabbroic plutons were emplaced largely subsequent to the coastal dike swarm. This fact was first recognized by Nielsen (1978) who noted that his oldest dike swarm is cut by Skaergaard, and it is this dike swarm which forms the coastal dike swarm proper. The presence of slumped layering, which is so widespread in the Kap Gustav Holm, Imilik, Nûgâlik, Pátûlâjivit (Fig. 8) and Nordre Aputitêq (Fig. 9) gabbros, combined with evidence for multiple intrusion, is evidence that deformation along the coastal flexure had already begun before these bodies were completely solidified.

In contrast the gabbros which lie outside the zone of flexuring (Kap Edvard Holm complex, Skaergaard, Kærven and probably also the very poorly known Agtertia intrusions inland from Nûgâlik) are tilted but otherwise undeformed with very little evidence of slumping of the cumulates. In accordance with the suggestion of Brooks & Nielsen (1978), who found evidence for the development of the Skaergaard magma in an intermediate magma chamber, Myers regarded these bodies as being formed during the early stages of flexuring by the tapping of magmas into the upper limb of the developing flexure. The Miki Fjord macrodike shows evidence of synplutonic deformation in the area to the north of Sødalen. Here it has clearly been cut by a transcurrent fault swarm before it was completely solidified. Slumping also occurs at the southern end of this macrodike and penecontemporaneous deformation has been noted in the Skaergaard intrusion (Nielsen & Brooks 1981). Evidence for the age of gabbro intrusion comes from the fact that they are earlier than the syenites, whose age is accurately known to be close to 50 m.y. (50 ± 1 m.y.: Pankhurst et al. 1976; 50.9 ± 1.5: Gleadow & Brooks 1979). The basalts which the gabbros cut are not well dated but K-Ar studies by Beckinsale et al. (1970), later refined by Fitch et al. (1978) and Berggren et al. (1978) – but see discussion of this refinement in Brooks (1980) – suggest an age of around 54 m.y. The only direct radiometric age so far reported for the gabbros is a zircon fission track age for Skaergaard which gives 54.6 ± 1.7 m.y. which is entirely consistent with this. If the slump structures in some of the gabbros indicate that these are penecontemporaneous with the coastal flexuring, this age is particularly significant as it dates this important tectonic event. There is however no certainty that all gabbros belong to a single event as hitherto assumed and further dating of the gabbros is required.

The gabbros are all of tholeiitic character. Specifically they appear to have formed from magmas similar to those encountered along spreading axes (Brooks & Nielsen 1978). These intrusions thus provide good models for the processes taking place at depth under constructive plate margins and are comparable to layered gabbros of ophiolite complexes (Coleman 1977).

Several ultramafic, plug-like bodies cut the gneisses in the Kangerdlugssuaq area. These are located in the snout of Kælvegletscher, just W of Kærven and on the S side of Watkins Fjord just N of the Skaergaard intrusion (Kays & McBirney 1982). A K-Ar age on biotite separated from marginal facies of the Kærven plug has given a value of 55 ± 2 m.y. (D. C. Rex, pers. comm.). These rocks are predominantly dunites and wehrlites (Table 5) and are characteristically cut by thin veins (up to 1 cm) of asbestos. Their affinities with the other rocks of the

Table 5. Analysis of gabbro from Nordre Aputitêq and some ultramafic rocks.

	1.	2.	3.		CIPW weight norm 1.		3.
SiO_2	46.61	37.64	47.76	Q	2.36	–	–
Al_2O_3	20.32	0.66	7.19	Or	0.85	–	2.34
Fe_2O_3	3.91	2.99	3.04	Ab	6.92	–	8.53
FeO	2.10	10.77	7.50	An	52.57	–	14.28
MgO	9.20	45.57	14.07	Di	11.16	–	45.35
CaO	13.89	0.10	14.33	Hy	18.57	–	11.99
Na_2O	0.80	0.12	0.99	Ol	–	ca. 100	9.95
K_2O	0.14	0.04	0.39	Mt	5.79	–	2.00
MnO	0.08	0.25	0.15	Il	0.52	–	4.84
TiO_2	0.27	0.09	2.50	Ap	1.26	–	0.54
P_2O_5	0.53	0.01	0.23				
volat.	1.24	2.11	1.21				
	99.09	99.35	99.39				

1. Gabbro from just behind weather station, Nordre Aputitêq – typical except for being slightly less leucocratic than normal (MM27421).
2. Ultramafic body in snout of Kælvegletscher (CKB70–55).
3. Marginal inclusion-free zone of dike whose central portion is crowded with ultramafic nodules – bay on N side Amdrup Fjord (MM40554).

area is not revealed by the field evidence but it is possible that they, along with the more gabbroic plugs at the mouth of Courtauld Fjord, represent feeders to some of the lower lavas of the Blosseville Group. Tentatively ascribed to the same suite is a remarkable dike cutting the gneisses and cut by the syenites in the bay on the N side of Amdrup Fjord. This dike is about 2 m wide, and apart from its margin, is crowded with subangular dunitic fragments (Fig. 10). The margin is xenolith-free and is also ultramafic in composition (Table 5). Similar material has been found in loose blocks below Admiraltinden. Biotite from the marginal facies of the *in situ* dike has a K-Ar age of 53 ± 2 m.y. (D. C. Rex, pers. comm.), which supports the suggestion that these dikes, the plugs and the early lavas may be contemporaneous.

Syenite intrusions

Syenites cover a very large area in Kangerdlugssuaq and are volumetrically of considerable importance, even though their predominance is largely due to the large size of one intrusion (Table 1). In this respect, Kangerdlugssuaq differs from other areas of the North Atlantic province. Thus, in the Faeroes, West Greenland and Baffin Island major intrusions of any kind are absent or insignificant at the present erosional level. In the British and Icelandic areas salic intrusions are granitic. Syenitic rocks are however also prominent in other areas of East Greenland (see below).

Radiometric dating (Beckinsale et al. 1970; Pankhurst et al. 1976, Brooks & Gleadow 1977, Gleadow & Brooks 1979) has shown that these syenites were emplaced 3–5 m.y. subsequent to the gabbros, and they are not affected by the flexuring event which they therefore post-date. In neighbouring areas (Mesters Vig, Kialineq) acid rocks are significantly younger (Brown et al. 1977, Gleadow & Brooks 1979, Rex et al. 1979). In spite of the time difference with respect to the major gabbroic intrusive event, it is important to note that basic magmas were still present and form pillowed bodies within the syenites. Several basic swarms of dikes also cut the syenites (Nielsen 1978).

The bulk of syenitic rocks in the area are quartz-bearing but the 33 km diameter Kangerdlugssuaq intrusion has undersaturated syenites in its central part. However, Kempe et al. (1970) estimated these to be small in amount (5.3% pulaskite, 0.6% foyaite) relative to the oversaturated types (nordmarkite, ca.

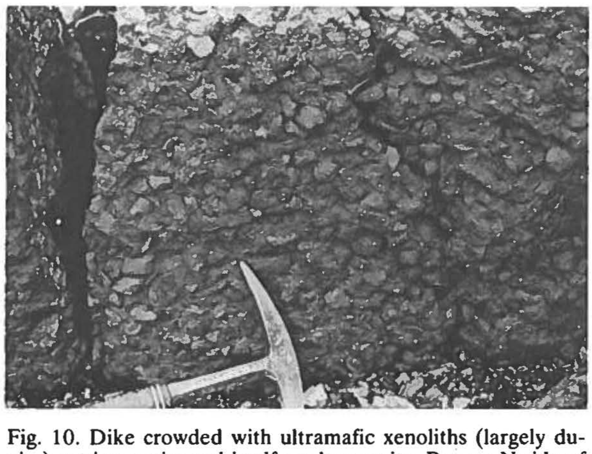

Fig. 10. Dike crowded with ultramafic xenoliths (largely dunite) cutting gneiss and itself cut by syenite. Bay on N side of Amdrup Fjord. An analysis of the xenolith-free margin is given in Table 5.

90%). A nepheline syenite pegmatite has been found cutting the basement gneisses at Bagnæsset. This pegmatite is several metres broad and may be traced for several kilometres. It does not appear to have any connection with the Kangerdlugssuaq intrusion. The nepheline syenites associated with the Gardiner complex are not considered here (see next section). Detailed descriptions of the petrology, mineralogy and petrogenesis of the Kangerdlugssuaq intrusion and its satellites have been presented by Wager (1965), Kempe et al. (1970, 1976), Kempe & Deer (1970), Deer & Kempe (1976), Pankhurst et al. (1976), Brooks & Gill (1982). Most of this work has been summarized and information given on some of the other bodies by Deer (1976).

The typical mineralogy of the oversaturated (nordmarkitic) syenites is perthite (Fig. 11), fayalite, salitic pyroxene and greenish-brown amphibole (hastingsite-katophorite) as an early paragenesis, with interstitial quartz, acmitic pyroxene and alkali amphibole appearing at lower temperatures. The trend towards alkali enrichment is exhibited to very varying degrees. Biotite is often present and minor to accessory minerals include Fe-Ti oxides, apatite, zircon, sphene, chevkinite, astrophyllite (in the more peralkaline varieties) and fluorite. The Kap Boswell syenite differs in having widespread aenigmatite, a mineral not otherwise observed. In all these rocks, the ferromagnesian minerals are typically grouped together into clusters or clots. More peralkaline varieties, usually occurring as segregation pegmatites and veins, may have major amounts of astrophyllite along with aegirine, arfvedsonite, quartz, microline and accessory pyrochlore in addition to the accessory phases mentioned above. One example at Jagtlejren in the Kræmer Ø intrusion has a central core of pegmatitic quartz with blades of astrophyllite up to 20 cm long and no other minerals. The oxide of these rocks is very Mn rich and is generally a pyrophanite. Such segregations occur in the Kangerdlugssuaq (Kempe et al. 1970), Bagnæsset and Kræmer Ø intrusions but have so far not been found at Kærven, Kap Deichmann, Kap Boswell or Barberkniven. The last two are highly peralkaline and some phases have enough quartz to be called granite. Although they are sometimes strongly miarolitic, the presence of aenigmatite as at Kap Boswell reflects not only their peralkaline character, but probably also the dryness of the magmas. Late stage phases in these syenites are limited to aplites. Tinguaites also occur at Kap Boswell. Typical analyses are presented in Table 6 and plotted in Fig. 12.

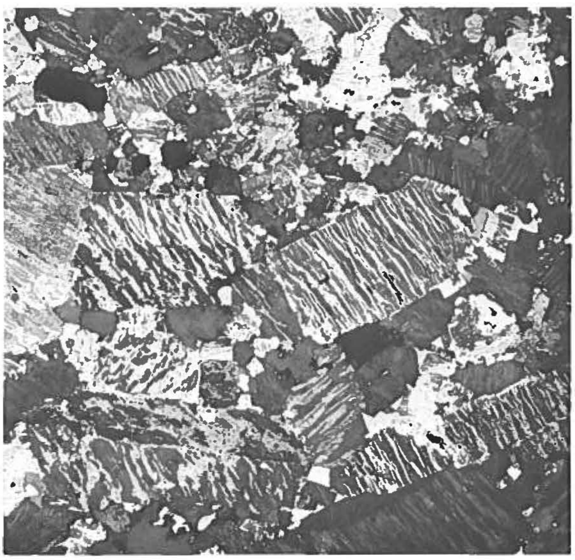

Fig. 11. Typical nordmarkitic syenite showing hypersolvus texture (CKB 70–35).

Layering has been seen on the southern tip of Kræmer Ø, where it is regular, dips 20°S (i.e. into the intrusion) and strikes approximately parallel to the contact, and on Kap Deichmann, where trough-like structures occur (Fig. 13). The layering, which is on the scale of a centimetre or so, is apparently due to a concentration of olivine and clinopyroxene, but has not been examined in any detail. Noticeable lamination is confined to the undersaturated rocks of the Kangerdlugssuaq intrusion. Xenoliths are sparse to abundant and may be gneiss, basalt, sediment or other syenitic types. Large concentrations of basalt xenoliths are to be found in the Kræmer Ø syenite, some of them being up to several hundred metres in size (Fig. 14). Gneiss xenoliths are abundant at Bagnæsset. Xenoliths are rare in the Kap Boswell, Kap Deichmann (apart from a single large raft of basalt) and Kærven intrusions. Basaltic xenoliths occur abundantly in certain horizons of the Kangerdlugssuaq intrusion where they apparently represent intermediate levels for the floor of the magma chamber (Wager 1965, Kempe et al. 1970). The latter authors provide information on the reaction which has been caused by immersion of the basalt in the alkaline magma. Both the Kræmer Ø and the Kap Boswell bodies are ringed by zones of intrusion breccia (Figs 14 & 15) consisting overwhelmingly of basaltic fragments (although other types also occur) in an acid (granitic) matrix which differs from the rocks of the main parts of the intrusions not only in being quartz-rich but also in lacking any suggestion of peralkalinity (analysis in Table 6). There is abundant field evidence at Kræmer Ø and in the bay in Amdrup Fjord that melted basement gneiss is a significant component of this acid matrix, and Pankhurst et al. (1976) have demonstrated contamination of these rocks by highly radiogenic Sr which has undoubtably been derived from the gneisses. These same authors also showed that a considerable influx of meteoric water has occurred in some of these syenites and it may be that the widespread melting of gneiss and explosive activity was caused by interaction of the magmas with ground water at the contact with the overlying porous, water-saturated lavas and pyroclas-

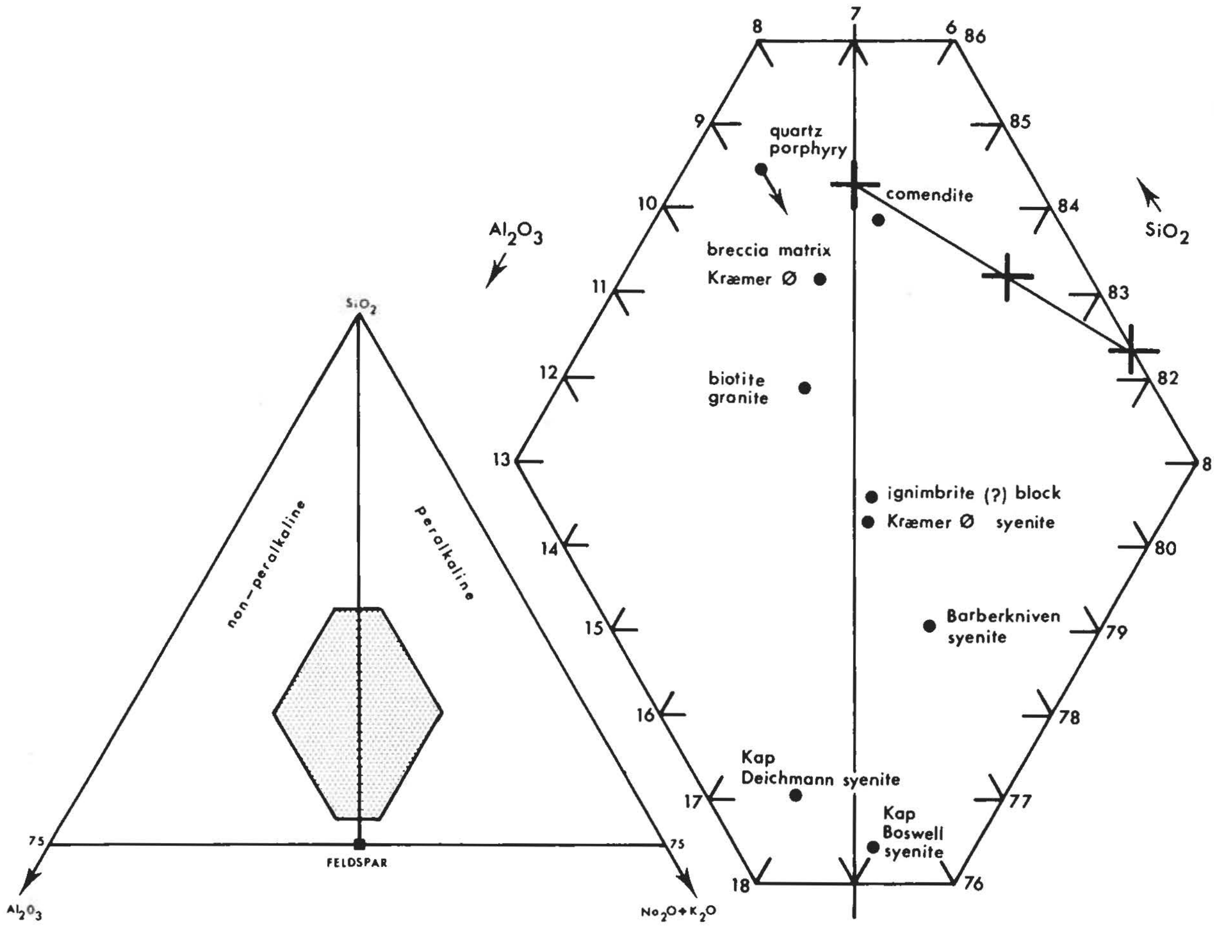

Fig. 12. The oversaturated salic rocks of Table 6 plotted in terms of $Na_2O + K_2O$–Al_2O_3–SiO_2 after Bailey & Macdonald (1969). The line extending through the crosses in the upper right shows the trend of the minimum as determined by Carmichael & MacKenzie (1963). This plot shows admirably the very wide range in silica content from syenite (nordmarkite) through quartz syenite to various types of granitic compositions as well as the wide range in peralkalinity of the Kangerdlugssuaq rocks. The arrow on the quartz porphyry point indicates that it is hydrothermally (?) altered and has probably lost alkalies. Pegmatitic segregations in the syenites probably plot near the middle cross but are difficult to analyse due to their coarse grain size and inhomogeneity.

tics. Beckinsale & Brooks (in prep.) have shown that the Sr isotope compositions of all the Kræmer Ø rocks, even the massive syenites which do not have many gneissic inclusions, are strongly contaminated with basement Sr. Brooks & Gill (1982) have presented mineralogical evidence showing widespread assimilation of country rock in the Kangerdlugssuaq intrusion.

As noted previously, basaltic magmas were also present during the emplacement of the nordmarkitic syenites, and in the bay in Amdrup Fjord melted gneiss can be seen to enclose pillows similar to those described by Brooks (1977) from the Kialineq area to the S. This exposure is also associated with a body of hybrid rocks which are believed to have arisen by mixing of these two components as recorded at Kialineq. Examples of this intimate acid – basic association are seen in Fig. 16. A large body of biotite granite on the S side of Amdrup

Fig. 13. Layering in the Kap Deichmann syenite. The trough banding structure is defined by layers enriched in fayalite and clinopyroxene. Such features seem to be confined to a narrow zone within the mainly homogeneous syenite.

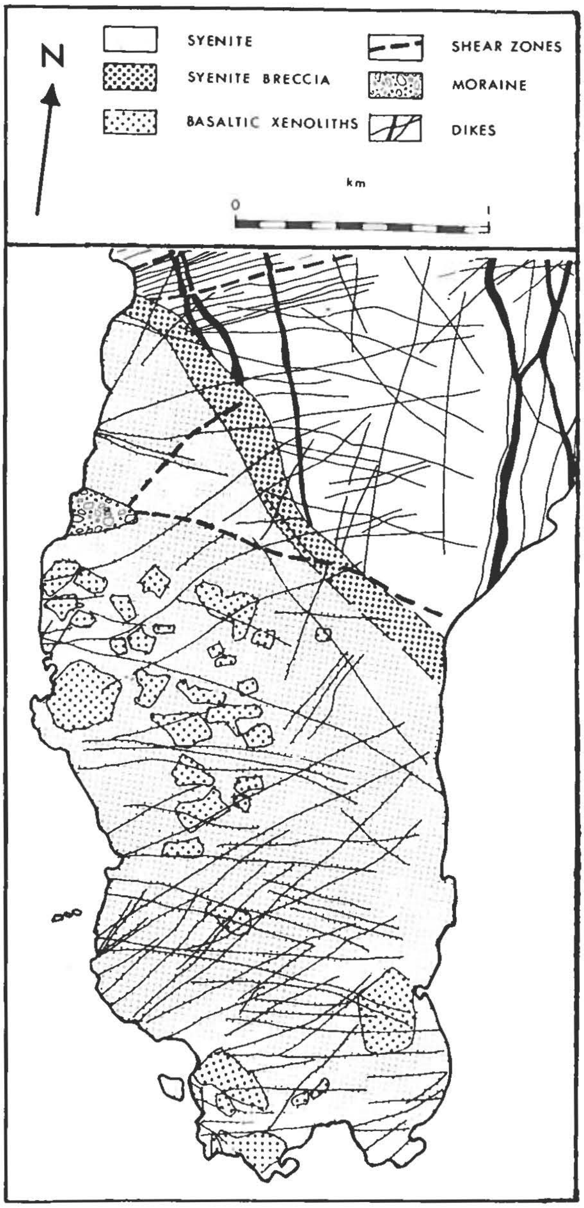

Fig. 14. Map of Kræmer Ø syenite showing marginal breccia and large basaltic inclusions.

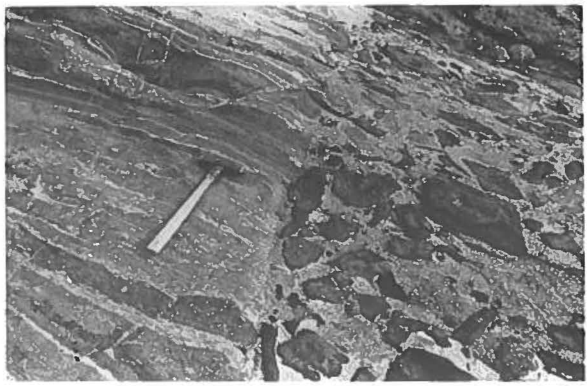

Fig. 15. Outer contact of Kræmer Ø syenite showing strongly foliated gneiss cut by an intrusion breccia consisting of abundant basaltic fragments in a granitic matrix. In some places a ghost foliation may be discerned in the matrix, which in conjunction with its high initial $^{87}Sr/^{86}Sr$ ratios (Beckinsale & Brooks, in prep.), indicates that melting of the basement has taken place.

Fjord is unique in the area. It is highly homogeneous and is not peralkaline as are many of the other salic rocks (Table 6). Pankhurst et al. (1976) showed that its Sr isotopic composition was somewhat more radiogenic than the presumed most primitive rocks of the area but its affinities are unknown. Similarly, the relations of a quartz porphyry body associated with minor intrusives which cuts the nordmarkites of the Kangerdlugssuaq intrusion on the N side of Amdrup Fjord are unknown. This body, which is in part brecciated and mineralized and is surrounded by a wide zone of hydrothermal alteration, was shown by Pankhurst et al. (1976) to be primitive with respect to its Sr and O isotopic compositions. An analysis of this rock is given in Table 6.

The nordmarkitic syenites are accompanied by several types of late stage segregation: a) the astrophyllite-bearing pegmatites mentioned above, b) comendite dikes, and c) microgranitic sheets and dikes. The comendites, described by Brooks & Rucklidge (1976), are of several types and so far have only been found near the Kræmer Ø syenite, to which they are presumed to be related. An aphyric type has a striking blue colour due to microscopic alkali amphibole, and spherulitic textures are widespread (Fig. 17). Another type has blue margins but buff-coloured recrystallized centres in which the ferromagnesian mineral is aegirine; data presented by Brooks & Rucklidge show that the change from chilled margin to centres of these dikes is one of alkali and halogen loss and oxidation. Analyses of adjacent wall rocks (gabbros) show that these have been altered by the addition of F, K and water while the Fe has been reduced. The second type of dike carries 20–30% alkali feldspar, 10–20% quartz and about 1% grass-green katophorite phenocrysts (Fig. 18). These dikes cut not only the gneisses of Kræmer Ø and Uttental Plateau but may also be found occurring in the northern part of the Skaergaard intrusion.

The acid matrix of the intrusion breccias which surround some of the nordmarkitic syenites is associated with completely different types of late-stage segregation. These take the form of sugary-textured aplites and graphic granite pegmatites, occasionally with a central zone of quartz and bright green alkali feldspar (amazonite). These segregations never contain alkali ferromagnesian minerals.

The undersaturated syenites and their segregation veins have nepheline and sodalite in place of quartz, and

Table 6. Selected analyses of salic rocks from the Kangerdlugssuaq area.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
SiO_2	67.60	60.53	64.07	67.19	74.17	72.45	69.7	72.7	75.5	54.48	57.25
Al_2O_3	13.91	16.08	16.44	13.90	11.68	12.77	14.0	14.3	13.3	24.06	21.11
Fe_2O_3	1.40	0.86	1.60	3.24	1.76	1.80	2.85	1.05	0.67	1.38	2.25
FeO	2.99	5.72	2.14	1.41	1.63	1.56	0.92	0.53	0.00	0.82	0.36
MgO	0.22	0.38	0.43	0.20	0.14	0.09	0.15	0.19	0.21	0.26	0.14
CaO	1.12	2.80	1.10	0.68	0.39	0.56	0.54	0.76	0.45	1.59	0.23
Na_2O	5.11	5.98	6.54	6.52	4.56	2.66	6.57	4.81	2.96	9.95	10.30
K_2O	5.41	4.35	5.86	5.17	4.50	7.01	3.37	4.63	4.94	6.68	6.25
MnO	0.20	0.36	0.24	0.27	0.10	0.12	0.14	0.05	0.08	0.08	0.16
TiO_2	0.58	0.61	0.43	0.28	0.31	0.40	0.44	0.26	0.18	0.38	0.13
P_2O_5	0.05	0.11	0.07	0.02	0.01	0.07	0.06	0.04	0.02	0.19	0.00
volat.	0.58	0.64	0.53	0.30	0.49	0.23	0.15	0.56	1.77	0.61	0.54
	99.17	98.42	99.45	99.18	99.74	99.72	98.89	99.88	100.08	100.48	98.72

CIPW weight norm (recalculated to 100% volatile-free)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Q	14.41	0.48	1.21	10.88	29.42	28.61	18.4	25.3	38.2	–	–
Or	32.42	26.29	35.01	30.90	26.83	41.43	19.9	27.4	29.2	39.48	37.62
Ab	42.02	51.75	52.51	43.20	35.35	22.51	53.1	40.7	25.1	16.41	25.80
An	–	4.29	–	–	–	2.20	–	3.5	2.1	1.27	–
Ne	–	–	–	–	–	–	–	–	–	36.71	26.68
Ac	1.61	–	3.03	9.48	1.24	–	2.2	–	–	–	6.63
Ns	–	–	–	0.42	0.50	–	–	–	–	–	1.43
Di	4.65	8.08	4.34	2.85	1.67	0.10	0.8	–	–	1.40	1.20
Hy	2.39	6.40	2.09	1.68	4.39	1.11	–	0.5	0.5	–	–
Mt	1.25	1.28	0.83	–	–	2.61	1.7	0.9	–	1.80	–
Il	1.11	1.19	0.83	0.54	0.59	0.76	0.8	0.5	–	0.72	0.25
Ap	0.12	0.25	0.16	0.05	0.02	0.16	0.1	0.1	0.1	0.45	–

Sporadic additional normative constituents are noted below.

Notes to Table 6
1. Typical syenite, Kræmer Ø, near Jagtlejren (MM40587).
2. Typical syenite, Kap Deichmann (MM40577).
3. Typical syenite, Kap Boswell (MM27001).
4. Quartz syenite, youngest phase, Barberkniven (MM27007).
5. Blue aphyric comendite dike, cuts gneisses at Skåret, Kræmer Ø (MM27046).
6. Acid matrix of marginal breccia, Kræmer Ø syenite (MM30006).
7. Ignimbrite (?), loose block, Nordre Aputitêq (CKB71-85/1). Norm includes 0.9% Hm and 0.5% Wo.
8. Biotite granite, S side, Amdrup Fjord (CKB70-51). Norm includes 0.4% Hm.
9. Quartz porphyry, stock intruding nordmarkites on N side Amdrup Fjord. (CKB70-59). Norm includes 2.3% C, 0.2% Ru and 0.7% Hm, probably due to pervasive hydrothermal alteration in spite of the fact that this is an unusually fresh sample.
10. Foyaite, Kangerdlugssuaq intrusion (Kempe et al. 1970: sample EG2108, Table IX. Norm includes 1.50% Wo and 0.14% Hm).
11. Undersaturated pegmatite, Bagnæsset, coarse-grained alkali feldspar – nepheline zone (MM40557). Norm includes 0.37% Ol.

All above analyses are previously unpublished except for no. 10. Samples 1–4 were collected by blasting to avoid weathering effects.

a somewhat different suite of accessory minerals (Kempe & Deer 1970) including låvenite, eudialyte, astophyllite (browner than in the oversaturated rocks), melanite, catapleiite and hjortdahlite. Feldspathoids may make up as much as 50% of the rocks. The astrophyllite-bearing pegmatite on Bagnæsset, mentioned above, consists largely of centimetre-sized nepheline and alkali feldspar but has an inner zone of widely varying breadth consisting of sugary albite which contains eudialyte, låvenite, apophyllite and narsarsukite. A thin, 10–20 cm zone of schistose, aegirine-rich rock cuts the approximate centre of the dike but is strongly discordant to the otherwise well-developed zonal structure of the dike. This schistose rock contains abundant astrophyllite and several as yet unidentified Na-Zr-Ti silicates and in texture, cross-cutting habit and richness in aegirine it resembles the lujavrites of the Ilimaussaq intrusion of south Greenland (Ferguson 1964).

It is clear from the steeply dipping contacts and the abundance of blocks from the roof that the syenites

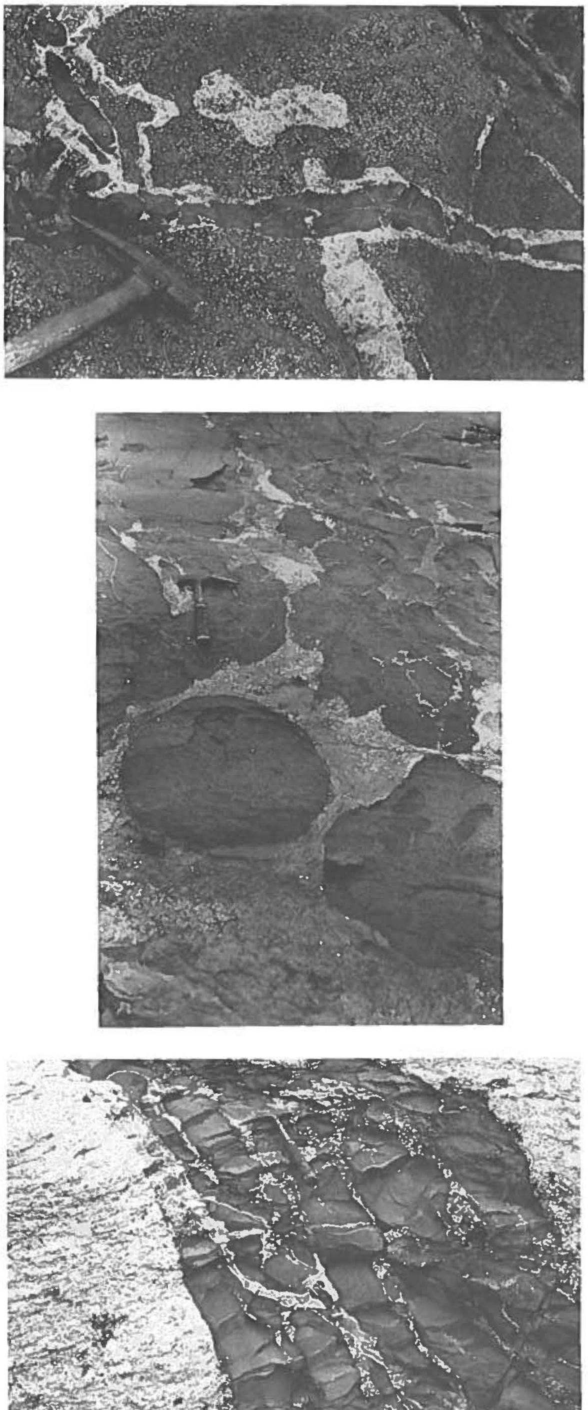

Fig. 16. Typical acid-basic associations: a) Kap Boswell contact zone – syenite veins with basaltic pillows intruding layered gabbro of the Kap Edvard Holm complex; b) basaltic pillows in an acid matrix. The matrix is clearly seen to be derived by melting of the local gneiss at this locality. Bay on N side of Amdrup Fjord; c) pillowed dike cutting syenite on Bagnæsset. The dike has clearly intruded the syenite prior to its complete solidification and is back-veined by syenitic material.

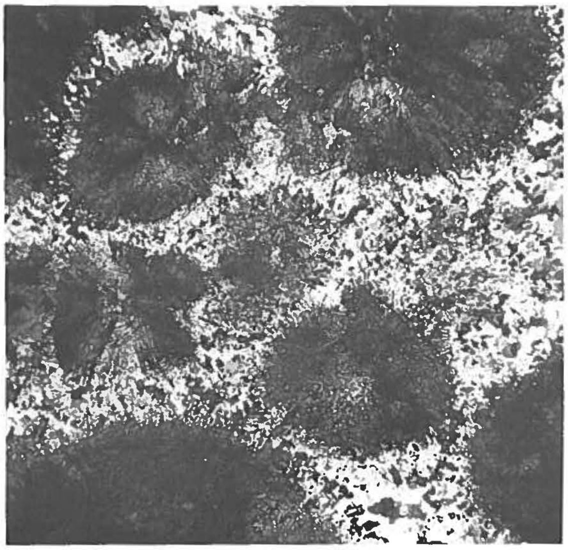

Fig. 17. Aphyric comenditic rhyolite dike rock with spherulitic texture, Skaergaard area (GM20723). Composition reported by Brooks & Rucklidge (1976).

have been emplaced by stoping. Their is no evidence to show that this stoping has taken the form of en masse cauldron subsidence except possibly at Barberkniven.

Salic extrusive rocks have only been found on Barberkniven, where they form a capping to the syenites and have apparently been preserved by down-faulting, possibly cauldron subsidence. They have not been in-

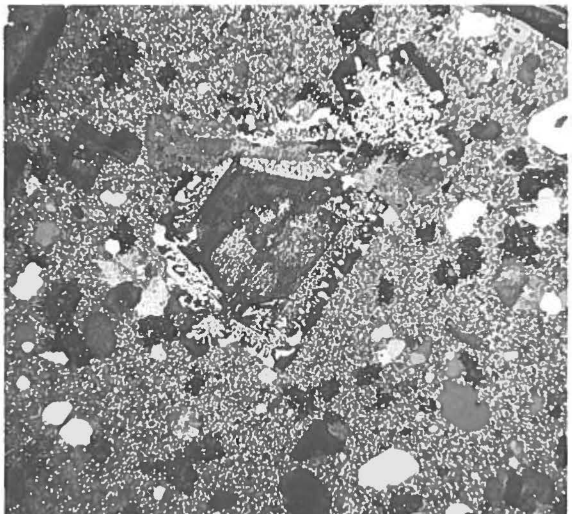

Fig. 18. Porphyritic comendite with phenocrysts of alkali feldspar, quartz and amphibole (katophorite). Sample comes from centre of a dike cutting the northern part of the Skaergaard intrusion (CKB 70–105) and was analysed by Brooks & Rucklidge (1976). The alkali feldspar phenocryst in the centre of the field is rimmed by a granophyric intergrowth and the groundmass is microcrystalline with needles of aegirine.

vestigated in any detail and are heavily altered. Many ice-transported loose blocks on Nordre Aputitêq are rhyolitic with a possible eutaxitic structure (Fig. 19) but their provenance is unknown. An analysis of one of these blocks will be found in Table 6.

Feldspathoidal syenites, which are otherwise not found in the North Atlantic province, occur also at the Lilloise and Borgtinderne intrusions which lie about 125 km to the NE. In addition, two poorly known bodies occur in a small exposure in the snout of the Sorgenfri Gletscher (Ryberg Fjord) and at an unknown location in I. C. Jacobsen Fjord where abundant loose blocks have been found. Loose blocks of a highly peralkaline nepheline syenite have also been found at Nagtivit kangertivat in the Angmagssalik district and these come from a body which according to radiometric dating was emplaced contemporaneously with the Kangerdlugssuaq syenites (Gleadow & Brooks 1979). Syenitic and granitic rocks are a prominent feature of the Kialineq and other centres to the S of Kangerdlugssuaq and in the Mesters Vig region, about 500 km to the N (Bearth 1959).

The Borgtinderne syenites show extensive contamination with the enclosing basalt (Brown et al. 1978) while the Lilloise complex is a layered gabbro cut by syenitic veins and sheets (Brown 1973). Both Lilloise and Borgtinderne are unusual among intrusions in the North Atlantic province in being free form the effects of meteoric water (Sheppard et al. 1977).

The syenites and granites of the Kialineq complex are as yet only superficially described (Wager 1934, Deer 1976, Myers et al. 1979) but their age of 35 ± 2 m.y.

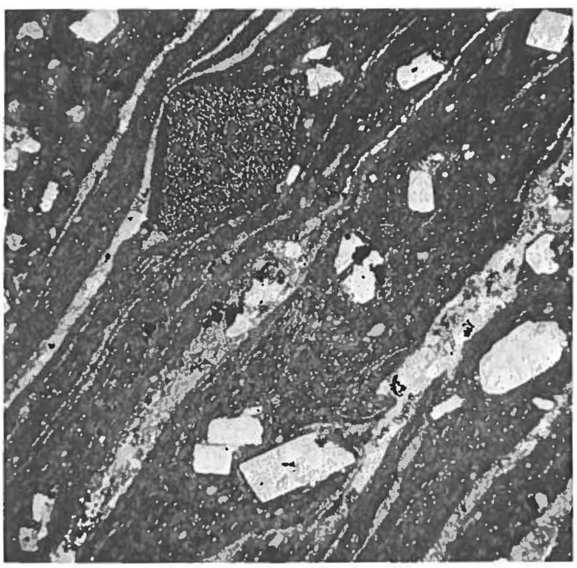

Fig. 19. Possible ignimbrite from loose block, Nordre Aputitêq. An angular lithic fragment is seen at the top left and the light streaks are believed to be deformed pumice fragments. An analysis is given in Table 6, column 7.

(Brown et al. 1977, Brooks & Gleadow 1979) is substantially younger than that of the Kangerdlugssuaq salic bodies. An interesting example of hybridization and the mechanism by which this had taken place was described by Brooks (1977) from this district, and similar processes are believed to have taken place in the Kangerdlugssuaq area.

In the Mesters Vig district, even younger activity apparently occurred. Both Rex, Gledhill, Brooks & Steenfelt (1979) and Gleadow & Brooks (1979) obtained ages of around 30 m.y. for the Werner Bjerge complex. The rocks of this area have been described by Schaub (1938, 1942), Bearth (1959), Kapp (1960), Engell (1975) and Noe-Nygaard (1976). A detailed investigation of the mineralogy of the Werner Bjerge complex, the largest of these bodies and the only one with feldspathoidal syenites, has recently been carried out by Brooks, Pedersen, Larsen & Engell (1982). It bears a strong resemblance to the Kangerdlugssuaq intrusion.

Sigurdsson & Loebner (1981) have described ash layers in the adjacent ocean basin which can be related to these episodes of acid volcanism.

The Gardiner complex and nephelinitic volcanism

This complex, which is situated beyond the head of the fjord some 85 km NW of Kap Hammer, is unique in the North Atlantic province. It is ring shaped, 6 km across, and consists largely of ultramafic rocks (dunite and pyroxenite) with ring dikes of melilitolite and a plexus of dikes, sheets and veins of pyroxenites, nepheline syenites and carbonatites. A preliminary description of the complex has been presented by Frisch & Keusen (1977) and Brooks & Nielsen (1978).

The complex is emplaced at the basement/plateau basalt boundary and intrudes the basalts. The mineral chemistry and petrography show that the ultramafic rocks are composed of discrete rings of cumulates derived from mela-nephelinitic to nepheline hawaiitic liquids (Nielsen 1981). Accordingly the ultramafic part of the complex is visualized as a series of cumulates formed in a periodically open magma chamber of a nephelinitic volcano. The melilitolites are remarkable rocks composed largely of coarse-grained melilite with perovskite, melanite, magnetite, apatite, phlogopite, diopside, nepheline (altered), calcite, etc. An investigation of the differentiation within the main melilitolite ring dike has been presented by Nielsen (1980). The carbonatitic and syenitic dikes and veins in the roof of the melilitolite ring dike were suggested to have formed from the CO_2-enriched nephelinitic differentiate by liquid immiscibility. The syenites contain Ti-rich aegirine, whose variation has been described by Nielsen (1979), while titaniferous clinohumite from veins intruding the dunite has been described by Nielsen &

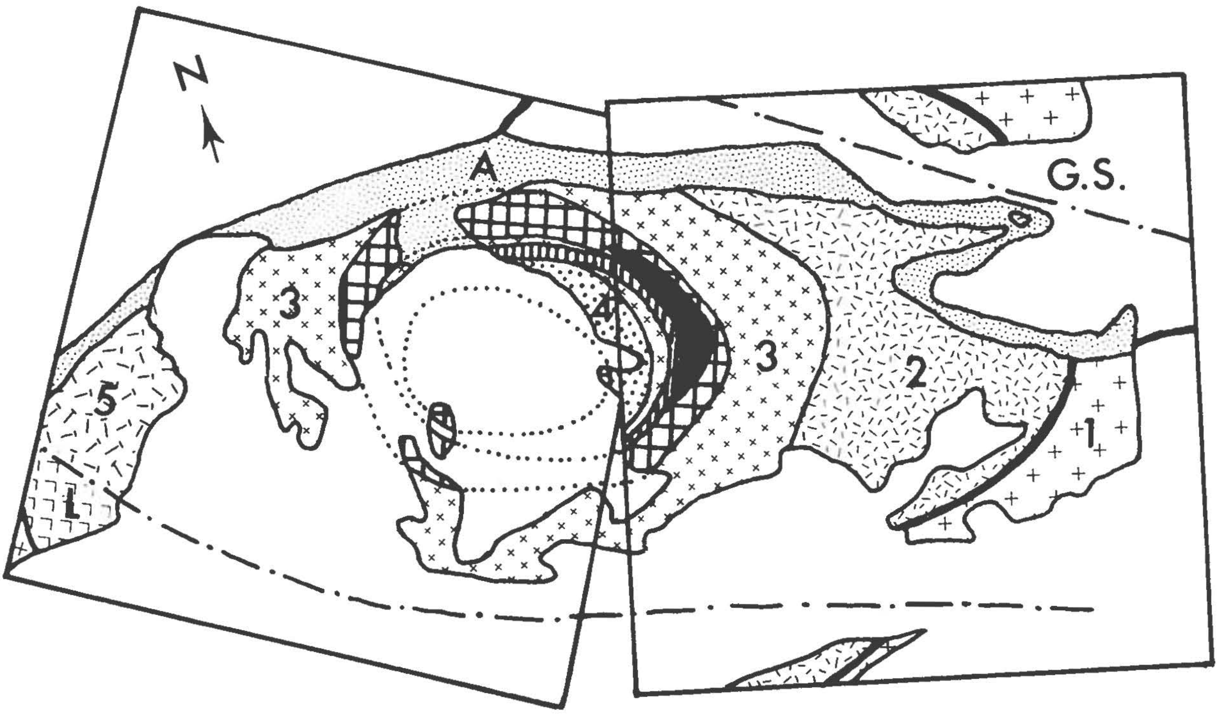

Fig. 20. Air photograph of the Gardiner intrusion. Scale app. 1:50000. The geology is indicated on the tracing. 1: basement, 2: peridotite, 3: dunite, 4: olivine pyroxenite, 5: undifferentiated olivine cumulates, L: lavas, vertical ruling: ijolite, cross-hatched: melilitolite, black: pyroxenite, blank: ice, A: alluvium, G.S.: Gardiner Sø (lake). Solid lines are contacts, broken lines inferred faults.

Table 7. Selected analyses of a nephelinite lava and some rocks from the Gardiner complex.

	1.	2.	3.	4.	5.	6.
SiO_2	38.92	38.40	34.43	36.56	44.66	1.52
Al_2O_3	4.48	1.12	5.41	3.87	13.50	0.04
Fe_2O_3	4.89	1.22	6.51	12.21	5.82	0.17
FeO	11.12	13.68	4.36	7.43	2.69	0.48
MgO	18.09	33.66	7.22	10.87	3.19	0.37
CaO	10.96	4.61	30.79	17.73	7.09	50.40
Na_2O	2.43	0.31	2.52	1.53	12.65	0.27
K_2O	1.19	0.05	0.08	0.22	0.80	0.03
MnO	0.20	0.24	0.08	0.00	0.00	0.06
TiO_2	4.10	1.77	4.98	6.74	3.84	0.10
P_2O_5	0.58	0.11	1.48	1.42	0.71	1.66
volat.	1.86	2.06	0.57	0.71	1.72	44.42
	98.82	97.23	98.43	99.30	96.67	99.52

CIPW weight norm

	1.	2.	3.	4.	5.	6.
Or	–	0.30	–	–	4.73	–
Ab	–	0.56	–	–	10.05	–
An	–	1.52	3.21	3.04	–	–
Lc	5.51	–	0.37	1.02	–	–
Ne	8.89	1.12	11.55	7.01	29.76	–
Ac	3.65	–	–	–	16.84	–
Ns	–	–	–	–	5.34	–
Di	32.33	16.45	26.96	55.68	17.14	–
Ol	29.09	69.85	3.84	0.88	–	–
Ln	3.09	–	32.53	1.28	–	–
Mt	5.26	1.77	–	4.41	–	–
Hm	–	–	6.51	9.17	–	–
Il	7.79	3.36	9.38	12.80	5.68	–
Ap	1.34	0.25	3.43	3.29	1.64	–

1. Nephelinite, loose, ice-transported block, Skaergaard area (MM20385/A); cf. Brooks & Rucklidge (1974).
2. Ultramafic rock consisting of olivine, chromite, clinopyroxene and amphibole, Gardiner complex (MM29913).
3. Afrikandite (melilite, perovskite, magnetite and apatite), Gardiner complex (MM29934). Norm includes 0.17 Pf.
4. Melteigite dike (clinopyroxene, amphibole, perovskite, apatite, magnetite), Gardiner complex (MM29965).
5. Tinguaite dike (alkali feldspar, albite, clinopyroxene, sphene, nepheline, sodalite, pyrochlore), Gardiner complex (MM29954). Norm includes: 2.33% Wo and 1.44% Pf.
6. Carbonatite dike, Gardiner complex (Frisch & Keusen 1977, Table 19, sample no. 2494). Analysis includes 0.60% Sr, norm is 92% $CaCO_3$, 2% $SrCO_3$ and 4% Ap.

Johnsen (1978). The age of the complex has been determined by fission track dating of apatite and sphene to be 50.3 ± 1.4 m.y. (Gleadow & Brooks 1979) and this agrees with a K-Ar age on phlogopite (P. E. Brown, pers. comm.) and with the fact the complex cuts the plateau basalts. It has thus been emplaced contemporaneously with the igneous activity nearer the coast in spite of its strikingly different petrological character. Frisch & Keusen (1977) suggested that the complex is cut by two fjord-parallel faults which in conjunction with the fjord-parallel dikes cutting the Kangerdlugssuaq intrusion (Wager 1947, Brooks & Platt 1975) are additional evidence for the "failed arm" nature of the fjord as proposed by Brooks (1973b) and Burke & Dewey (1973).

The Gardiner complex is an outstanding example of an ultramafic alkaline complex of the type reviewed by Upton (1967). In view of the fact that only relatively few of this type (Iron Hill, Colorado; Afrikanda, Kola Peninsula) are known, the excellent degree of exposure, and the isotopic compositions (low $^{87}Sr/^{86}Sr$ and pristine $\delta^{13}C/\delta^{18}O$, Nielsen & Buchardt (1982)), the Gardiner complex is likely to become an important locality for the understanding of similar complexes. These include some of the volcanoes of the East African rift (e.g. Napak, Uganda: King 1949, and Rangwe, Kenya: Le Bas 1977). These volcanoes have cores of plutonic rocks of the ijolite suite with melilite-rich types inside an eroded edifice of nephelinitic lavas and pyroclastics. As deduced from the petrography and mineral chemistry of the ultramafic cumulates, a similar nephelinitic volcano, which has now been completely removed by erosion, was originally situated above the Gardiner complex. In fact nephelinites are known to occur in the hinterland of Kangerdlugssuaq and have been described as loose blocks from the Skaergaard area (Brooks & Rucklidge 1974). Anwar (1955) described alkaline basic lavas from Prinsen af Wales Bjerge about 40 km NE of Gardiner where they are believed to be from central volcanoes resting on top of the plateau basalts. Similar rocks are also known to occur at Trekantnunatakker 25 km NW of Gardiner (Fawcett et al. 1982) and as sheets and dikes cutting the Batbjerg intrusion (Brooks et al. 1981). It is therefore likely that nephelinitic rocks are widespread in the Kangerdlugssuaq basin and it is interesting to note that very similar lavas have been described from the nunatak zone of northeast Greenland (a very similar tectonic setting) by Katz (1952) and Brooks et al. (1979), and from Tugtilik to the S (Rucklidge et al. 1980). Such lavas have an appropriate composition for the magmas which have given rise to the plutonic rocks of the Gardiner suite and the nephelinitic tuffs reported by Larsen (1982) from the Scoresby Sund district. Typical analyses of Gardiner rocks and one of the nephelinites are shown in Table 7.

Dike swarms and sill complex

Many generations of dikes are immediately apparent in the area to even the most casual observer and these have recently been the subject of a study by Nielsen (1978). Their emplacement spans an interval of at least 20 m.y. and 5 distinct generations have been distinguished in addition to the salic dikes which are described above and are associated with the syenitic plutons. Several mechanisms appear to have been operative in controlling their emplacement. Thus, the

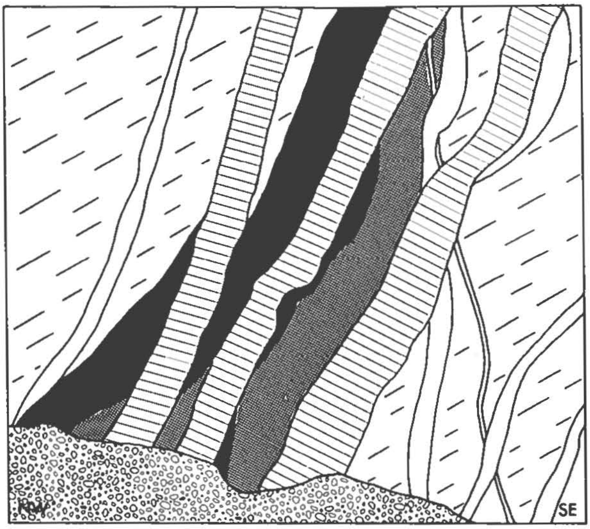

Fig. 21. Detail of the dikes at Hængefjældet as described by Nielsen (1978). This drawing is traced from a diapositive and comes from about the centre of Nielsen's profile in his fig. 2. The dip of the preflexure dikes, which prior to the intrusion of subsequent dike generations, comprised 100% of the exposure, is indicated by broken lines dipping to the left (NW). These dikes have been emplaced with very little time lag and have been split in the way found in ophiolite complexes where only single margins are traceable (Coleman 1977). The post-flexure dikes, which are petrologically more variable and steeply dipping, do not show this type of intrusion relation and have had time to solidify between intrusive events. The black dike is a rhyolitic member of the latest transitional swarm but has itself been cut by other members of the same swarm. The dike with the cross-hatched pattern is a plagioclase-phyric hawaiite of the same swarm and is the oldest post-flexure dike in this exposure. Height of profile ca. 20 m.

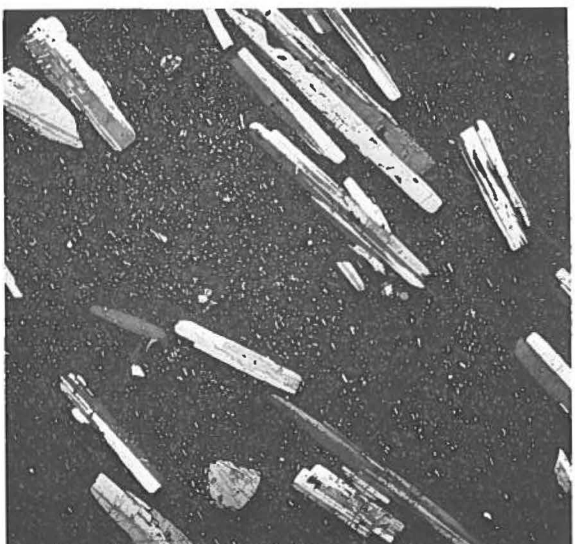

Fig. 22. Porphyritic dike from the latest coast-parallel transitional generation. Abundant flow-oriented plagioclase phenocrysts and a single clinopyroxene phenocryst (bottom left centre) may be seen (CKB 70–88).

Table 8. Selected analyses of dike rocks from the Kangerdlugssuaq area.

	1	2	3	4	5	6
SiO_2	47.66	45.11	48.21	42.91	65.80	48.12
Al_2O_3	13.30	11.88	15.23	13.92	13.41	14.38
Fe_2O_3	4.06	5.17	7.49	4.57	1.97	2.56
FeO	9.76	11.63	3.69	5.96	3.36	9.15
MgO	6.20	5.19	5.53	9.0	0.60	7.64
CaO	11.50	10.04	7.58	10.89	2.28	12.12
Na_2O	2.23	2.60	3.83	2.60	4.04	2.15
K_2O	0.20	0.73	1.50	2.16	4.00	0.26
MnO	0.20	0.26	0.19	0.18	0.16	0.22
TiO_2	2.83	5.41	2.55	2.70	0.70	1.96
P_2O_5	0.50	0.77	0.52	0.65	0.13	0.15
volat.	1.58	0.89	2.73	3.00	3.33	1.24
	100.02	99.68	99.05	98.54	99.78	99.95
CIPW weight norm						
Q	0.26	–	–	–	21.47	–
Or	1.18	4.38	8.85	13.36	24.53	1.54
Ab	18.87	22.34	32.41	4.81	35.46	18.19
An	25.69	18.88	19.94	20.87	6.86	28.82
Ne	–	–	–	9.86	–	–
Di	23.27	22.18	11.75	25.29	3.41	24.87
Hy	19.83	12.28	0.48	–	3.62	12.52
Ol	–	4.55	14.22	16.48	–	6.41
Mt	2.57	3.17	2.00	2.02	2.96	2.19
Il	5.37	10.43	4.84	5.37	1.39	3.72
Ap	1.16	1.81	1.22	1.58	0.30	0.35

All norms calculated on basis of Fe_2O_3/FeO = 0.15 (Brooks 1976).

1. Pre-flexure tholeiite (THOL-1), Hængefjeldet (Nielsen 1978, Table 1, col. 1).
2. Skaergaard-like dike (THOL-2), Kræmer Ø. This dike is the most differentiated in the collection and is equated with the liquid of the upper part of the Skaergaard LZ (Brooks & Nielsen 1978, Table 1a, col. E).
3. Hawaiite of postflexure alkaline generation (ALK-1), Hængefjeldet (Nielsen 1978, Table 3, col. 5; original analysis prior to volatile-free recalculation).
4. Late alkaline dike (ALK-2) cutting basement on W side of Kangerdlugssuaq and rich in kaersutite gabbro inclusions (Brooks & Platt, 1975, Table 1, CKB70-50). This dike is a nepheline trachybasalt of the potassic undersaturated series (lineage H)of Nielsen (1978).
5. Oversaturated alkali trachyte of the transitional postflexure suite (TRANS-1), Hængefjeldet (Nielsen 1978, Table 5, col. 3; original analysis prior to volatile-free recalculation).
6. Coast-parallel late tholeiite, I. C. Jacobsen Fjord (GM 40084, analysis previously unpublished).

coast-parallel swarms are related to the tension associated with continental rifting, while those with other orientations, including radial swarms, can most probably be ascribed to vertical movements associated with doming and plutonic activity. Table 8 shows compositions of representatives of all the more important suites.

Nielsen (1978) subdivided the dikes using a combination of field and petrological criteria, a difficult and lengthy task due to the very great intensity of dikes in the area, which in places reaches 100% (Fig. 21). In the coastal region, field relations allowed the recognition of two distinct generations: pre-flexure (very intense and with a rather low dip due to subsequent tilting) and post-flexure (more steeply dipping and not so intense). Nielsen (1978) found that the pre-flexure dikes are tholeiites of rather uniform composition (THOL-1) which could well have been feeders for some of the lavas of the overlying basalts in the Blosseville Group. He postulated that they were intruded vertically and later tilted by the flexure, in contrast to Wager & Deer (1938b) who regarded them as being a fan-shaped swarm emplaced into the convex part of the monoclinal flexure. It seems reasonable to assume that these pre-flexure dikes are the ones formed during the actual break-up event in this part of the Atlantic.

If Nielsen's interpretation of their attitude is correct, it is clear that the flexuring event occurred subsequently, a conclusion in accordance with the fact that the gabbros cut the dikes but are themselves deformed by the flexure, as discussed above. Palaeomagnetic measurements by Faller & Soper (1979) are however not in accordance with Nielsen's model.

The post-flexure dikes may be slightly tilted by continued deformation. On a petrological basis, they may be further subdivided into two groups: an earlier alkaline generation (ALK-1) and a later transitional one (TRANS-1, Fig. 22). In contrast to the pre-flexure tholeiites, these generations show considerable compositional variation presumably indicative of differentiation in subjacent magma chambers. The transitional dikes thus vary from basalts through hawaiites and mugearites to trachytes and rhyolites.

Subsequent to Nielsen's study of the dike swarms (Nielsen 1978) an additional generation of coast-parallel tholeiitic dikes has been identified in I. C. Jacobsen Fjord. These dikes are coast-parallel, nearly vertical and 5–10 m thick. They cut the sill complex mentioned below but are themselves cut by alkaline dikes and are believed to have been emplaced immediately after flexuring. These dikes carry phenocrysts of very basic plagioclase (around An_{90}) which is reminiscent of gabbros such as Nordre Aputitêq, and their often low Ti, Fe and K resemble ocean floor basalts (Brooks & Jakobsen 1974). An analysis is shown in Tabel 8.

In the inland areas of Kangerdlugssuaq, additional dike generations have been recognized, at least some of which have radial distributions about unexposed centres. The earliest of these additional swarms corresponds closely in composition to the liquids which have been deduced as having formed the major gabbros such as Skaergaard and are therefore regarded as being contemporaneous with the gabbro bodies. Like the pre-flexure coastal dikes they are tholeiites, but differ from these in some respects and are slightly later. Brooks & Nielsen (1978) have described these dikes (THOL-2) in some detail and conclude that they may represent liquids tapped from a magma body lying at depth under the entrance to the fjord.

Fig. 23. Mildly potassic basanite dike with abundant inclusions of kaersutite-bearing gabbros as described by Brooks & Platt (1975). The dike margin is on the left and the centre of the dike is under the hammer shaft.

A very extensive and intense sill complex in the sediments and basalts to the E of Kangerdlugssuaq and probably centred around the Sorgenfri Gletcher area was reported by Wager (1947) and Soper et al. (1976a). These sills are up to 500 m thick and are tholeiitic as shown by the presence of inverted pigeonite. They are cut by some coast-parallel faults and appear to have been emplaced contemporaneously with the Skaergaard intrusion. Chemically they resemble the Skaergaard-like dikes (THOL-2) described by Brooks & Nielsen (1978) in that they are enriched in Ti and Fe.

The alkaline generation of dikes recognized on the outer coast is also seen inland where it can be seen to be cut by the syenites which, because they are well dated (see Gleadow & Brooks 1979), provide a fixed point on the chronology. Subsequent to the emplacement of the syenites, a complicated group of alkaline dikes was intruded, possibly both about a centre at the mouth of Amdrup Fjord and as fjord-parallel swarms. These dikes differ petrologically, chemically, in distribution and in orientation from the earlier alkaline dikes. They include the "late dike swarm" of Wager (1947) and the "hornblende lamprophyres" of Vincent (1953), while some contain abundant inclusions of kaersutite-rich plutonic rocks (Fig. 23) which have been described by Brooks & Platt (1975). These alkaline dikes are very variable; they are often highly porphyritic, may be very undersaturated and show wide ranges of differentiation.

They were subdivided by Nielsen (1978) using chemical criteria into 4 separate suites which have equivalents in other provinces. The geological relations of these individual suites is at present not known but their intrusion extended until as late as ca. 34 m.y. (Gleadow & Brooks 1979). The transitional dikes recognized in the coastal areas cut the alkaline dikes and are therefore even younger although their precise age is not at present known. Perhaps at some future date these transitional dikes can be correlated with the latest periods of syenite emplacement at Kialineq and the Werner Bjerge areas and the acid tephra layers of Oligocene age described from the North Atlantic by Sigurdsson & Loebner (1981).

Nielsen's study of the dikes in the Kangerdlugssuaq area has not yet been extended to neighbouring areas and the placing of, for example, the nephelinitic dikes at Tugtilik (Rucklidge et al. 1980) is not known. The same is true for the lamprophyres of Wiedemann Fjord, some of which carry mantle xenoliths (Brooks & Rucklidge 1973).

Tectonic development of the area

This has been summarized in Table 9. As noted in the introduction, the Kangerdlugssuaq area provides an unusually well developed and well exposed example of igneous activity at a rifted continental margin at the site of a hot spot. It is in some respects similar to the Afar area to which it has been compared by Brooks (1973b), Nielsen (1975, 1978) and Nielsen & Brooks (1981). Perhaps the most notable feature of Table 9 is the amount of activity concentrated in and around the Paleocene-Eocene boundary. This was also appreciated by Brooks (1973a) Soper et al. (1976a & b) and Faller (1975) who all remarked on the very short time which must have elapsed during the formation of the extremely voluminous Blosseville Group.

The development of basins with clastic sediment deposition at the end of the Mesozoic can be correlated with the uplift and graben formation which occurs in the pre-drift period of the classic model of continental break-up (see e.g. Jacobs et al. 1974) and which is so well developed in NE Greenland (Surlyk 1978). This was closely followed by the uprise of tholeiitic magmas which led to the voluminous outpourings of basaltic lavas of the Blosseville Group and the intrusion of similar volumes of material in the coastal dike swarm (Larsen 1978). This phase is in many respects similar to that seen in ophiolite complexes but differs in that the magmas were emplaced into continental crust (Brooks 1973a, Brooks & Nielsen 1982) which became highly attenuated and in parts totally replaced by basaltic rocks. Towards the end of this phase, but before any marked changes in magma composition developed, magma chambers became established at high levels within the crust giving rise to numerous layered gabbro bodies and, overlapping in time, the coastal area collapsed along a flexure system which may be traced for about 800 km parallel to the present coastline. At this time ocean floor formation had apparently commenced and the earliest magnetic anomaly (anomaly 24) had formed in the adjoining ocean basins (Brooks & Gleadow 1977, Larsen 1978, Larsen & Jacobsen 1982), and indeed extended onshore in the Scoresby Sund region. The precise mechanism of flexuring is believed to be one of fault formation with a few major southwards-dipping faults separated by numerous northward-dipping ones leading to a half graben structure similar to that of Afar (Nielsen 1975, Nielsen & Brooks 1981). The numerous antithetic faults seem to

Table 9. Summary of the geological and tectonic development of the Kangerdlugssuaq area in Phanerozoic time.

35 m.y. to present	Tectonic stability with continued erosion.
Mid-Oligocene ca. 35 m.y.	Regional plateau uplift, emplacement of granites, syenites, etc. in the Kialineq area and possibly the transitional generation of dikes at Kangerdlugssuaq. Major plate reorganization in the North Atlantic area (Talwani & Eldholm 1977).
Eocene-Oligocene 50–35 m.y.	Erosion of Kangerdlugssuaq dome and unroofing of the plutons. Emplacement of the differentiated alkaline "late dikes" (ALK-2) evolved over this time period in magma chambers at various depths.
Lower Eocene ca. 50 m.y.	Emplacement of extensive syenite plutons of both undersaturated and oversaturated type. Domal uplift centred on middle part of Kangerdlugssuaq. Nephelinitic magmatism in inland region.
Upper Paleocene – Lower Eocene 55–53 m.y.	4. Intrusion of basis to intermediate, mildly alkaline dikes (ALK-1). 3. Coastal flexuring penecontemporaneous with closing stages of 2. 2. Intrusion of major layered gabbros and related minor intrusions (THOL-2). 1. Voluminous basaltic volcanism of Blosseville Group lavas fed from coast-parallel fissures of the pre-flexure tholeiites (THOL-1). Accompanying regional subsidence. Beginning of ocean floor formation in this part of the North Atlantic.
Cretaceous – Upper Palaeocene	Basin formation and deposition of the sediments of the Kangerdlugssuaq Group.
Mesozoic	Peneplaination and removal of Palaeozoic sedimentary cover. Initiation of coast-parallel fracture pattern as observed in NE Greenland and North Sea (Surlyk 1977)?
Lower Palaeozoic ca. 450 m.y.	Carbonate sedimentation, intrusion of alkaline potassic and appinitic rocks, deformation by Caledonian orogeny.

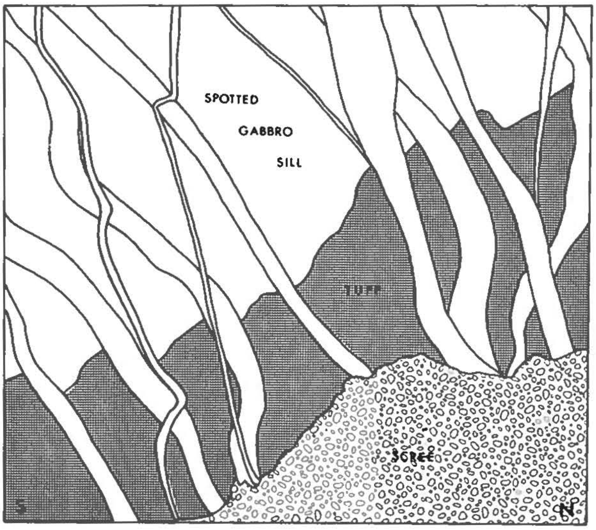

Fig. 24. Exposure near summit of Pilespidsen (just inland from Hængefjeldet) at about 700 m, taken from Hammerdalen by telephoto (traced from a diapositive). The dip of the lower contact of a spotted gabbro sill (the Hængefjeldet sill – see Hughes 1956) is offset by a number of faults, all downthrowing to the N so that the effective dip on a regional scale is much reduced. The stratigraphic thickness of the volcanic succession is therefore much lower than has hitherto been estimated (Nielsen & Brooks 1981). Note how the faults have provided channels for dike intrusion and are therefore effectively concealed in the absence of good marker horizons. The thin dike which takes a sharp bend in an earlier thicker dike follows a columnar jointing in the latter. This profile is roughly 100 m across and shows evidence of considerable crustal attenuation.

have acted as channels for dike intrusion (Fig. 24) and make the total thickness of the lavas succession in the area extremely difficult to estimate. It is clear from Fig. 24 that the regional dip is considerably less than that measured on single outcrops.

Subsequent to flexuring, a major domal uplift of the Kangerdlugssuaq area occurred, possibly due to the establishment of large magma bodies at depth and probably also to the intrusion of the sill complex described above (Figs 25 & 26 and Brooks 1979). This event marked the transition from the dominantly tholeiitic magmatism to dominantly alkaline actvity, beginning with the intrusion of a swarm of basic to intermediate mildly alkaline dikes (ALK-1 of Nielsen 1978) and subsequently the emplacement of major syenitic bodies by a mechanism of stoping. These syenites are sometimes associated with pillowed net-veined complexes and it is possible that their rise was triggered by the heating effect of associated basic magmas as postulated by Sparks & Sigurdsson (1977). It is clear that at least in some cases melted basement gneiss has been included in these bodies and this has also been facilitated by the associated basic magmas. Pankhurst et al. (1976) suggested that important petrogenetic effects in these syenites could also be traced to interaction with meteoric water and it is clear that considerably more work needs to be done to establish the origin of the syenite magmas and the importance of reactions with crustal and surface materials. These syenites are not associated with any significant amounts of rocks intermediate to basalts (apart from a few intermediate dikes of quantitative insignificance and easily demonstrable hybrids such as those described by Brooks (1977)) and their immediate derivation from basaltic magmas does not seem very likely.

In the inland regions far removed from the zone of active spreading and at a location where the lithosphere was presumably much thicker than nearer the coast (Nielsen & Brooks 1981), strongly nephelinitic, basic magmas rose to the surface, possibly along zones of weakness controlled by the existence of an oblique, non-spreading rift structure or "failed arm" (Brooks 1973a, b, Burke & Dewey 1973). Such nephelinitic magmas are also found in the inland regions of NE Greenland (Brooks et al. 1979) and as discussed by Brooks & Rucklidge (1974) are characteristic of the more tectonically stable parts of the East African rift.

The subsequent magmatic development of the area is represented by the "late dikes" of Nielsen's ALK-2 generation. The great variety of magmatic lineages developed within this group of dikes was interpreted as the result of differentiation of magma batches in separate chambers at different depths. Occasionally mixing took

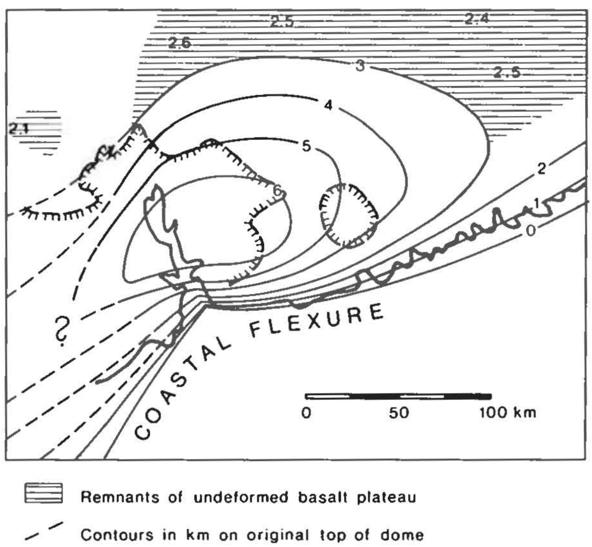

Fig. 25. Reconstruction of the lava surface prior to erosion showing the domal uplift with a major axial diameter of ca. 200 km centred on the middle part of Kangerdlugssuaq. Its nature S of Kangerdlugssuaq is almost unknown. Although the dome is now largely destroyed, remnants of the Tertiary lava plateau now at a height of about $2^1/_2$ km can be seen in perpheral areas. The present coastline is largely determined by the coastal flexure. For the method of construction and a discussion of the origin of the various features see Brooks (1979).

Fig. 26. Air view from an altitude of about 3000 m from above the Kangerdlugssuaq Gletscher looking SE. To the left is an exhumed pre-Tertiary peneplain in the gneisses now at an altitude of just over 2 km. Towards the coast this rises and becomes increasingly more dissected until a culmination is reached in the alpine peaks around Domkirkebjerget (2.6 km) in the centre before falling again towards the coast. The faint high mountains in the distance are the Watkins Bjerge (ca. 4 km high). Domkirkebjerget is approximately at the centre of the domal uplift. The dark rocks along the glacier in the right centre are pyroxenites of the Caledonian Batbjerg complex.

place between these separate magma batches as seen in sample CKB70-21 of Brooks & Platt (1975) and as described by Brooks & Printzlau (1978, fig. 2, p. 236). Radiometric dating (Gleadow & Brooks 1979) has shown that the development of this group of dikes took place over a protracted period (ca. 10 m.y.) as might be expected during the waning stages of activity.

At the time of anomaly 13 in the ocean basins (ca. 36 m.y.), a major change in spreading pattern became established in the North Atlantic (Phillips et al. 1976, Talwani & Eldholm 1977) concomittant with the cessation of spreading in the Labrador Sea. In East Greenland this event approximately coincides with the regional plateau uplift described by Brooks (1979) and possibly with the rejuventation of magmatism represented by the transitional dike swarm, for which no radiometric ages are as yet available, and the formation of the granites and syenites of the adjacent Kialineq area (Brown et al. 1977, Gleadow & Brooks 1979) and associated explosive volcanism (Sigurdsson & Loebner 1981).

The subsequent history of the area has been one of relative stability accompanied by deep erosion in fluvial regimes modified extensively in the Pleistocene by glacial activity (Brooks 1979). During the period 50–35 m.y. B. P. rivers were established on the flanks of the Kangerdlugssuaq dome, traces of which are still apparent in the drainage pattern. At the end of this period the dome had become largely removed with the deposition of about 5×10^4 km^3 of clastic material in offshore regions. At this time plateau uplift took place and a new drainage regime became established perpendicular to the present coastline, and river valleys, now occupied by glaciers, began to dissect the basaltic plateau although extensive unmodified plateau areas still exist in inland regions. The general trend of the coastline had been determined by the original locus of continental rifting and remained essentially unmodified (Brooks 1973a, b).

In contrast to typical oceanic spreading axes (e.g. Sclater et al. 1971), but in common with most rifted continental margins of the northern Atlantic (Vogt 1974), the Kangerdlugssuaq area shows no sign of subsidence which can be related to the decay of a sublithospheric thermal anomaly. Indeed, the area has suffered subsequent plateau uplift, a very poorly understood phenomenon for which at least 14 different mechanisms are currently suggested (McGetchin et al. 1979). We therefore reserve a discussion of this problem to a subsequent occasion.

Conclusions

The now classical work of Wager (1934, 1947) on the general geology and tectonics of the Kangerdlugssuaq area and that of Wager & Deer (1938b) on the coastal dike swarm, combined with an abundance of recent work described in this paper goes a long way towards cataloguing the distribution, chronology, petrological features and interrelationships of the Tertiary rocks of the area. It is now clear that magmatism in the Lower Tertiary extended over a fairly protracted period and led to an unusually wide variety of rock types. Recent work has greatly illuminated the relationship between this magmatism and plate tectonic motions, both on a broad scale (Brooks 1973, Soper et al. 1976b, Larsen 1978, Larsen & Jacobsen 1982) and as regards local and regional epeirogenic effects (Brooks 1979, 1980, Gleadow & Brooks 1979).

Nevertheless, it is only fair to point out that many gaps exist in our knowledge, some of which have more than local significance. Most prominently, the origin of the quartz syenites, the most voluminous rock type of the area, is poorly understood. However, both field work and recent isotopic measurements show that extensive melting of and contamination by crustal rocks is certainly involved (Pankhurst et al. 1976, Brooks & Beckinsale, in prep.). Likewise, the relationships between the various basaltic magmas is unclear and the light they might throw on the source regions of these voluminous magmas generated in a continental break-up event has not yet been considered in any detail. We plan in our forthcoming research to address ourselves more closely to these problems largely by trace element and isotopic studies.

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1980

3. John C. Rucklidge, Charles Kent Brooks and Troels F. D. Nielsen: »Petrology of the coastal dykes at Tugtilik, southern East Greenland«. 17 pp.

Dolerite and lamprophyre dikes from Tugtilik in the southern part of the onshore exposure of the East Greenland coastal dike swarm are described. The dolerites, which are earlier, are similar to other tholeiites from the dike swarm and the plateau basalts and also to many Icelandic tholeiites. Transitional varieties have been identified from the Angmagssalik district. The lamprophyres have a nephelinitic composition and are rich in phenocrysts and xenocrysts. In one case, abundant low pressure inclusions occur. Rocks identical to these lamprophyres have not previously been described from Greenland but are well known, for instance, in the African Rift.

1981

4. Barbara H. Scott: »Kimberlite and lamproite dykes from Holsteinsborg, West Greenland«. 24 pp.

Numerous kimberlite and lamproite dykes occur to the south and east of Holsteinsborg in Central West Greenland. This paper gives details of the petrography, mineral chemistry, age relations and geochemistry of the dykes.

The kimberlites are composed of macrocysts of olivine, phlogopite, rare ilmenite and garnet in a matrix of olivine, phlogopite, diopside perovskite, spinel, serpentine, carbonate and apatite. They can mostly be classified as clinopyroxene-phlogopite hypabyssal kimberlites. Mantle-derived inclusions are found in some of the dykes and include lherzolites, wehrlites, harzburgites and, most commonly, dunites. Both coarse and porphyroclastic inclusions occur. Garnet-granulites and eclogites, although rare, are present.

The lamproites have variable mineral assemblages and textures but the main constituents are phenocrysts of pseudoleucite, olivine, phlogopite and clinopyroxene set in a groundmass of phlogopite, potassic richterite, diopside, pseudoleucite and potassium feldspar. The mineralogy of these dykes is a reflection of unusual ultrapotassic, magnesian whole-rock compositions.

1981

5. Svante Björck and Thomas Persson: »Late Weichselian and Flandrian biostratigraphy and chronology from Hochstetter Forland, Northeast Greenland«. 19 pp.

Two lakes on Hochstetter Forland have been analysed with respect to lithostratigraphy and pollen and algae stratigraphy. The sediments have been radiocarbon dated and these dates show that Hochstetter Forland was not covered by the Inland Ice during the Late Weichselian. The early Flandrian stratigraphic sequences of the two lakes are interrupted by barren interzones, dated at 10 100 – 8100 B. P. and 10 100 – 9200 B. P., which are partly correlated to an ice-advance. No evidence for an earlier ice-advance during the Late Weichselian has been found. Apart from the abundance of pollen grains indicating pioneer vegetation, *Artemisia* pollen grains are found in high quantities in the Late Weichselian, although it is today not found within the area. The Flandrian pollen stratigraphy indicates a development similar to that which has been found in the Scoresby Sund area. However, *Cassiope tetragona* and *Salix arctica* immigrate much earlier than further south. The Flandrian climatic optimum in the Hochstetter Forland area seems to have been reached between 6000 and 5000 B. P. The Flandrian shore-line displacement is roughly estimated.

1981

6. T. F. D. Nielsen, N. J. Soper, C. K. Brooks, A. M. Faller, A. C. Higgins and D. W. Matthews:
»The pre-basaltic sediments and the Lower Basalts at Kangerdlugssuaq, East Greenland: their stratigraphy, lithology, palaeomagnetism and petrology«. 25 pp.

This paper presents a new 1:40 000 topographic and geological map of the area around Miki Fjord and I. C. Jacobsen Fjord, East Greenland. The post-Precambrian sedimentary succession, the Kangerdlugssuaq Group, begins with the Ryberg Formation (Campanian to Danian (?)) and continues into the Vandfaldsdalen Formation of Late Paleocene age. These sediments were laid down in a basin which subsequently became filled and covered by basaltic rocks of the Blosseville Group, including lavas, hyaloclastites, tuffs and breccias. Considerable facies variations are apparent in both the sediments and volcanics indicating that the basin deepened in an easterly direction. Palaeomagnetic measurements confirm previous results for the Blosseville Group on the Lower Basalts but do not yet entirely eliminate the possibility that some of the succession has normal polarity. Petrographically the volcanics include picrites (oceanites and ankaramites), olivine tholeiites, tholeiites and tholeiitic andesites. They have almost all suffered alteration up to greenschist facies and some show evidence of sedimentary contamination. They are all of tholeiitic affinity and are Fe and Ti enriched when compared to normal ocean ridge basalts. They are however much more variable in composition than the overlying Plateau Basalts and have not been produced in such large volumes. It is suggested that a primary picritic magma gave rise to the oceanites and ankaramites by olivine and clinopyroxene fractionation and accumulation. The olivine tholeiites, which appear to be separated from the picrites by a compositional gap, may be derived from a different parental magma. Petrological parallels are drawn with other provinces.

1981

7. C. Kent Brooks, John Engell, Lotte Melchior Larsen and Asger Ken Pedersen:
»Mineralogy of the Werner Bjerge alkaline complex, East Greenland«. 35 pp.

The Tertiary Werner Bjerge complex is divided into a basic complex, a northern complex and a nepheline syenite complex. The basic complex consists of cumulate rocks (ranging from ultramafic to gabbros) containing plagioclase, clinopyroxene, olivine and titanomagnetite with intercumulus kaersutite or biotite and subsolidus amphiboles and sheet silicates. Similar cumulates but containing cumulus kaersutite occur as inclusions in dykes associated with the nearby Theresabjerg intrusion and have been included in the study. The northern complex includes a wide range of felsic rock types of which two granites have been examined. In the nepheline syenite complex the rock types investigated include foyaites, a tinguaite, and quartz-bearing pegmatite. The main minerals in these rocks are alkali feldspar, nepheline, sodalite, alkali pyroxene, alkali amphibole and biotite together with a wide range of minor and accessory phases.

Clinopyroxenes vary from diopsides and salites in the basic rocks to aegirine-augites and acmites in the more evolved types, which are unusually MnO-rich. Ti-tan-aegirines occur in the pegmatite.

The amphibole in the basic rocks is kaersutite; in the granite it is manganoan richterite, and in the nepheline syenite complex the amphiboles vary from hastingsitic hornblende through katophorite to manganoan arfvedsonite. The pegmatite contains unique Li-arfvedsonites. Minor late-stage calcic amphiboles occur in the basic rocks.

Sheet silicates include micas and secondary mixed layer types, chlorite and talc. Primary micas of the basic complex are titaniferous biotites and in the nepheline syenites are Mn-rich biotites, while the pegmatite contains the rare Li-mica, taeniolite.

Feldspars range from bytownite in the basic rocks to mainly alkali feldspar in the nepheline syenites which is often optically homogeneous and strongly potassic. Analyses of feldspathoids and zeolites are also presented.

The oxides of the evolved rocks are also MnO-rich and pyrophanite has been encountered in both the granite and the nepheline syenites. Other Mn-rich phases are also present, such as Mn-pectolite and kupletskite (the Mn analogue of astrophyllite). Data have also been acquired for a wide range of accessory phases including (additionally) sulphides (pyrrhotite, pyrite and sphalerite), apatite, sphene, titanian garnets, narsarsukite, pyrochlore, calcite, chevkinite and several unidentified zirconosilicates from the nepheline syenites.

It is concluded that the geochemical coherence between the various rock units of the intrusion suggests a comagmatic origin for these, while the close similarities between the mineralogies of the Kangerdlugssuaq and Werner Bjerge alkaline complexes suggest a similar origin.

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