Early Tertiary lavas and sills on Traill Ø and Geographical Society Ø, northern East Greenland: petrography and geochemistry

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The Early Tertiary extrusion of flood basalts in East Greenland was accompanied by intrusion of numerous sills in the Upper Palaeozoic and Mesozoic sediments of the N–S trending East Greenland rift zone. With a few exceptions the lavas and sills have low contents of Ti and other incompatible elements, indicating a genetic relationship with the lavas and sills north of Kejser Franz Joseph Fjord rather than with the lavas in the Scoresby Sund area. Two sills are described in greater detail. The first, from Geographical Society Ø, is 60 m thick and homogeneous throughout. The second, from southern Traill Ø, is more than 150 m thick and atypical as it ranges in composition from low-Ti tholeiite to diorite.

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The Early Tertiary opening of the NE Atlantic was accompanied by intense magmatic activity along 1000 km of the East Greenland coast (Fig. 1). Basaltic lavas with an estimated maximum stratigraphic thickness of 7 km were erupted between Kangerlussuaq and Scoresby Sund (Brooks & Nielsen, 1982; Watt *et al.*, 1986; Larsen *et al.*, 1989), whereas the remnants of a much thinner (less than 1.5 km) northern lava plateau are found between Kejser Franz Joseph Fjord and Shannon (Noe-Nygaard, 1976, Upton *et al.*, 1980; Upton, 1988). Apart from a few nunatak exposures (Anwar, 1955; Fawcett *et al.*, 1982) the plateau south of Scoresby Sund consists entirely of tholeiitic flows (Brooks *et al.*, 1976; Nielsen *et al.*, 1981; Larsen & Watt, 1985; Larsen *et al.*, 1989). These are apparently all reversely magnetised, and were most likely formed during chron C24R (Tarling *et al.*, 1988). Only the lavas of the Igtertivâ Formation exposed at Kap Dalton may have formed during the subsequent period of normal polarity (C24N)(Larsen *et al.*, 1989). In the plateau north of Kejser Franz Joseph Fjord most of the flows are also tholeiitic, while mainly transitional to mildly alkaline basalts enriched in incompatible elements form the upper part of the lava sequence on Gauss Halvø, Hold with Hope and Bontekoe Ø (Hald, 1976; Noe-Nygaard & Pedersen, 1983; Upton *et al.*, 1984a). The change in chemical composition almost coincides with a change in the magnetic polarity from reverse to normal, possibly C24R and C24N (cf. Eldholm *et al.*, 1989).

The lavas of the northern plateau spilled across a thick succession of Upper Palaeozoic and Mesozoic sediments which were deposited in a rift system with an overall N–S trend and bounded to the west by the Post-Devonian Main Fault of Vischer (1943). These sediments are intruded by numerous dolerite sills. Nearly all are tholeiites and compositionally related to the overlying tholeiitic lavas (Hald, 1976; Upton *et al.*, 1984a). While the Tertiary lavas are only found in a single small outcrop south of Kejser Franz Joseph Fjord (Donovan, 1955) the sills are widely distributed from Shannon in the north to Jameson Land in the south, and thus they bridge the gap between the lavas south of Scoresby Sund and those north of Kejser Franz Joseph Fjord (Fig. 1).

The main object of this paper is to give a petrographical and chemical description of the lavas in the outcrop and of the central part of the sill complex. Published analyses of lavas from the Scoresby Sund region and northwards from Kejser Franz Joseph Fjord display some regional variation (Upton *et al.*, 1984a; Larsen *et al.*, 1989); a purpose of the investigations is, therefore, to place the basalts and dolerites from the intervening area in this context. The paper also describes some scattered dykes, some of which are observed to cut the sills. No attention is paid to the major intrusive complexes, Kap Parry and Kap Simpson, which form the two eastern promontories of Traill Ø. Dominated by quartz syenites and quartz diorites (Rheinhard *in* Schaub, 1942; Engell,

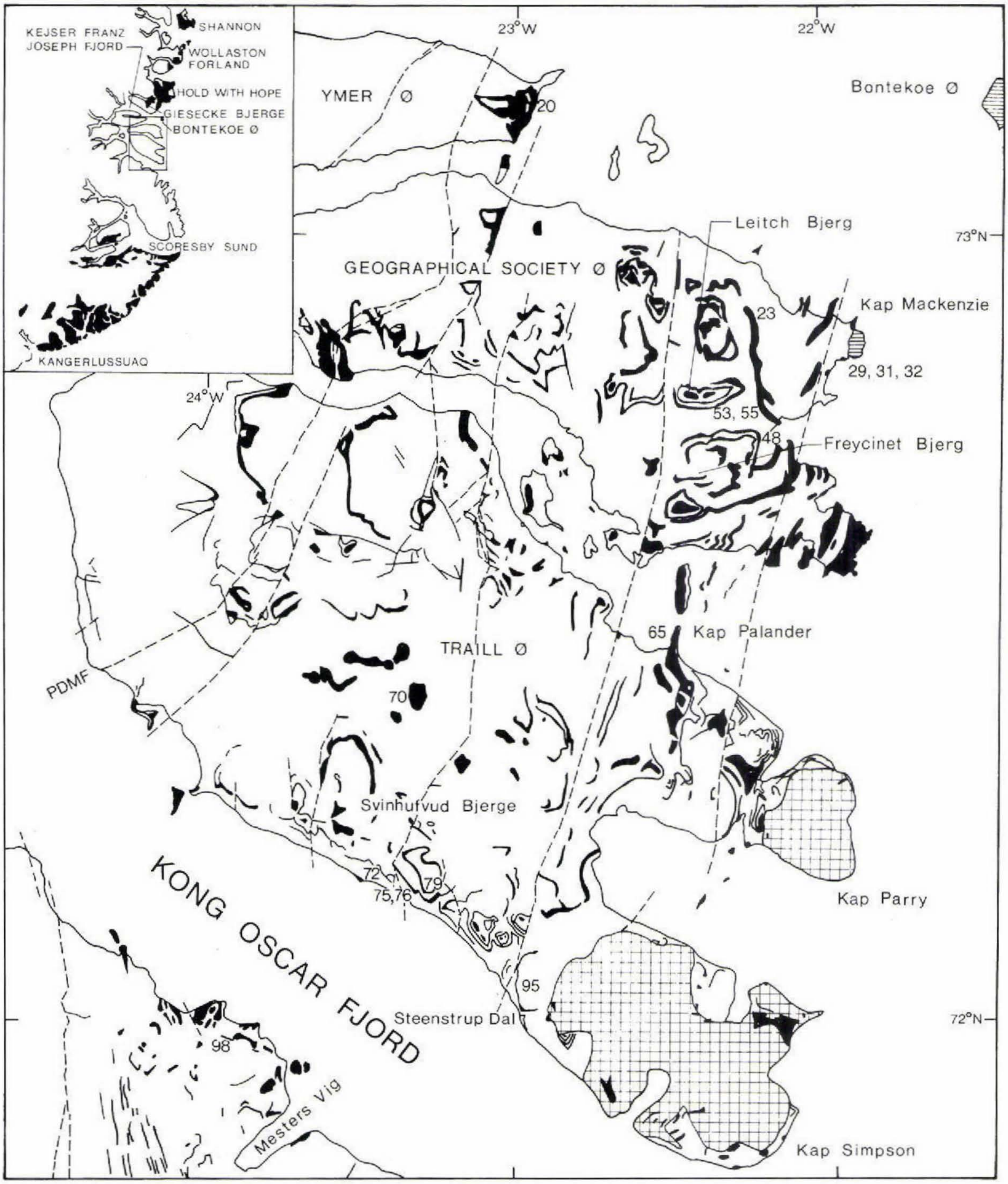

Fig. 1. Tertiary volcanic and intrusive rocks in central East Greenland. Redrawn from Koch & Haller (1971). Horizontal lines: lavas, black: sills and dykes, cross-hatched: larger intrusions. PDMF = Post-Devonian Main Fault (Vischer, 1943). Two-digit numbers refer to analysed samples in Table 1 and have the prefix GGU 2395xx.

1975) they are but two of several high-level intrusions formed along the East Greenland coast subsequent to the continental break-up.

Geological setting

Geographical Society Ø and Traill Ø are cut obliquely (from NNE to SSW) by the Post-Devonian Main Fault which separates Devonian sediments in the west from Carboniferous and younger sediments in the east (Fig. 1). The Devonian succession is dominated by sandstones, formed during denudation of the East Greenland Caledonides (Olsen, 1993), while the Carboniferous is dominated by interbedded sandstones and shales deposited during initial rifting in the North Atlantic (Stemmerik *et al.*, 1991, 1992). Further to the east, Mesozoic sediments formed in association with renewed tectonic activity within the rift system: generally sand and conglomerates were deposited along the shorelines and muds in the deeper parts of the basins (Surlyk *et al.*, 1981; Surlyk, 1990).

The major structural elements within the Mesozoic rift are tilted blocks bounded by faults trending NNE. Dips of the sediments are low, generally to the west (Donovan, 1953, 1955).

Lavas at Kap Mackenzie. The lavas at Kap Mackenzie were first described by Donovan (1955). They form an outcrop with an area of 2 to 3 km^2. To the west the lavas are bounded by low-lying ground with no exposures of pre-Quaternary rocks. The sequence dips 15–25° to the west, and it is cut by a few N–S trending normal faults with minor displacements. The total exposed thickness is about 150 m.

Investigations along the southern side of the outcrop (Fig. 2) show that the sequence is dominated by compound flows consisting of thin (1–5 m), vesicular feldspar-phyric or aphyric flow units, usually of the pahoehoe type. Weathered surfaces have a vivid yellowish-brown or reddish-brown colouration, while flow interiors appear to be relatively fresh. A few thin tuffaceous layers have been observed.

The original landward extent of the lavas is unknown. No intercalated sediments have been found to indicate the presence of nearby elevated ground at the time of eruption. Seawards, on the shelf, buried volcanic rocks appear to be widespread (Larsen, 1990), and through these the outlier at Kap Mackenzie is linked with the lavas north of Kejser Franz Joseph Fjord.

Sills and dykes. Large sills characterise the terrain of major parts of Geographical Society Ø and Traill Ø. They are most abundant in the eastern region where they often show strongly transgressive relationships to the sediments. Intruded in the soft Cretaceous sediments they stand out as irregular ridges or are seen to sandwich the sediments in Freycinet Bjerg and other steep-sided hills, which may also be capped by sills. Frebold & Noe-Nygaard (1938) record thicknesses of 55 m and 150 m for two sills in the Svinhufvud Bjerge on the south coast of Traill Ø, whereas three sills on Freycinet Bjerg are each around 100 m thick (Donovan, 1955). The combined thickness of 300 m at this locality appears to be the maximum value at any place for exposed sills on the two islands. No geophysical investigations exist to evalue the distribution and size of sills below the present surface.

In the pre-Cretaceous sediments sills are more wide-spaced and only a few are found west of the Main Fault (cf. Koch & Haller, 1971). The westward decrease in number may depend on the nature of the sediments, the distance to the magmatic source or the present level of erosion.

Only seven dykes were seen during the present field work despite many excellent exposures. A few other dykes are shown on the geological map of Koch & Haller (1971). The seven dykes are all less than 8 m across, and most are less than 2 m. They strike either N–NE, parallel to the major faults, or W–NW. Three are seen to cut through sills, while the opposite relationship has not been observed. A strong and pervasive hydrothermal alteration of two dykes sampled in Steenstrup Dal at the south coast of Traill Ø suggests that at least these dykes predate the Kap Simpson Complex.

Palaeomagnetism. In the field all samples were marked

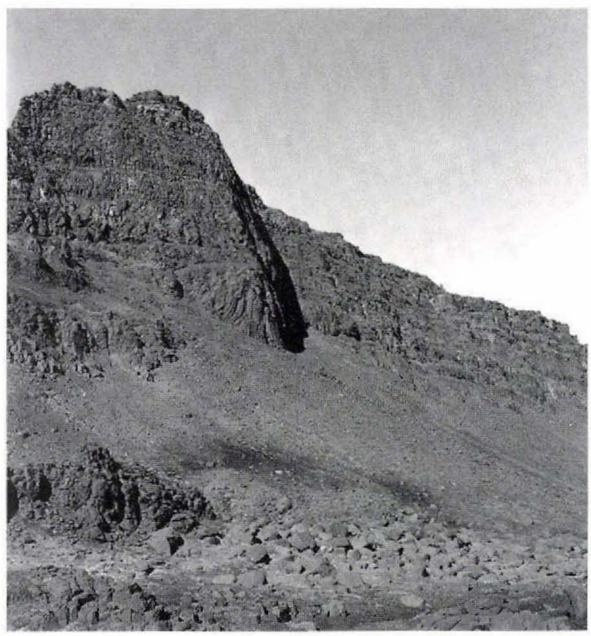

Fig. 2. The lavas along the south side of the outcrop at Kap Mackenzie, Geographical Society Ø.

'up-down'. Preliminary examination in the laboratory indicates that the lavas and the 'main type' sills (see later) are reversely magnetised, while the 'enriched' sills – except for GGU 239548 – are normally magnetised. Cores from selected specimens were demagnetised stepwise in an alternating field of up to 30 mT. Measurements on the cores support this distribution of polarities. Among the dykes both normal and reverse polarities were found during the preliminary investigations.

Petrography

Lavas. The lava flows are composed of basalt, mainly with intergranular texture, and range from almost aphyric to strongly porphyritic. Lath-shaped plagioclase phenocrysts vary in amount from < 1 to 20 %. They have maximum lengths of 1 to 6 mm and occur as single crystals or in aggregates of several grains together with a few grains of olivine ± augite. The olivines are stout and have regular subhedral to euhedral outlines. In most flows they are small (less than 0.3 mm) and rather inconspicuous as they are mostly replaced by clay minerals. A few of the flows contain equant augite phenocrysts up to 1 mm in size. The groundmasses are fine-grained with plagioclase, clinopyroxene, Fe-Ti oxides (titanomagnetite and ilmenite) and olivine pseudomorphs. Interstices are occupied mainly by green clayey material including recrystallised glass.

Microprobe analyses were carried out on the lava GGU 239529. It has phenocrysts of bytownite (An_{85-73}) and microphenocrysts of olivine (Fo_{77-71}). Groundmass plagioclases range from An_{70} to An_{60}. Augites form a well defined trend of decreasing Ca with increasing Fe/Mg ratio (Fig. 3). Pigeonite is absent.

Sills. The sills are dolerites consisting of plagioclase, olivine, clinopyroxene and Fe-Ti oxides. Quartz and alkali feldspar, often found in granophyric intergrowth, apatite and clay minerals occur interstitially. Samples GGU 239548 and 235970, which are both enriched in potassium, contain small grains of biotite.

In general, superficial deposits prevent sampling of individual sills from the lower to the upper contact. A 55 m thick sill exposed on Leitch Bjerg on eastern

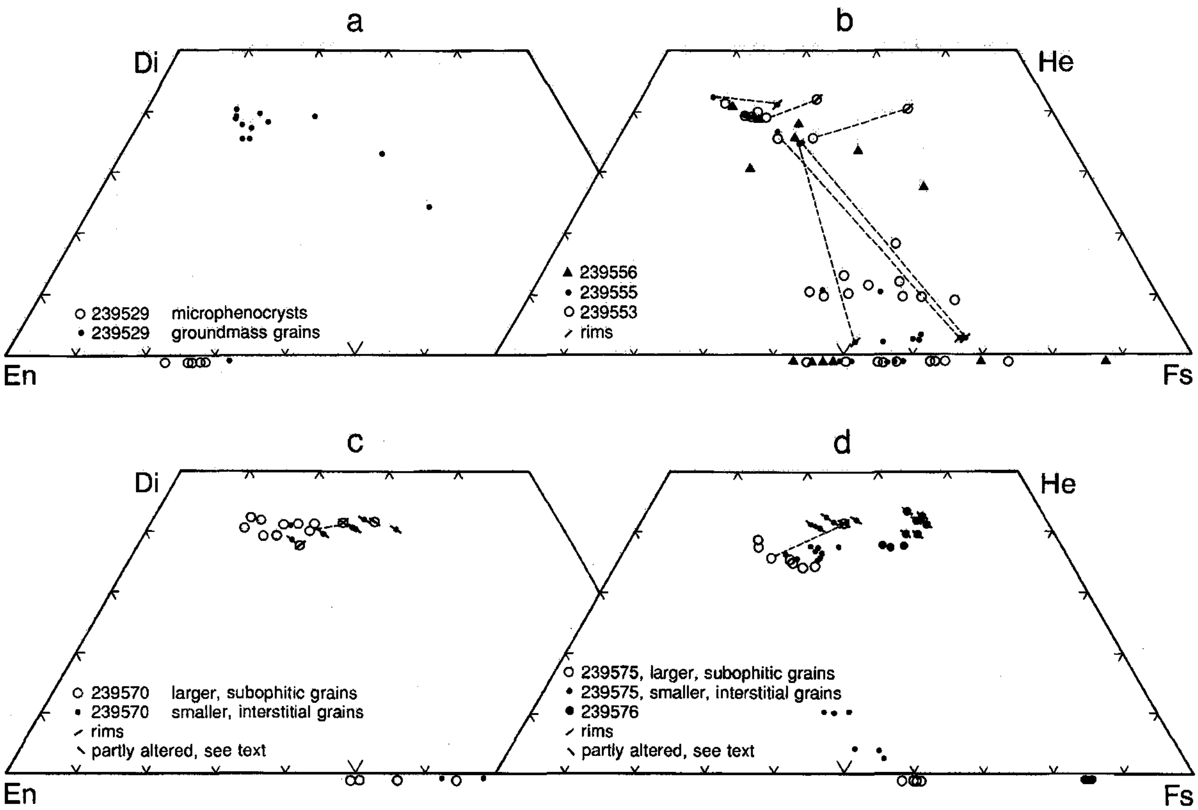

Fig. 3. Composition of pyroxenes and olivines. a. Lava from Kap Mackenzie (GGU 235529). b. Sill on Leitch Bjerg (GGU 239556, 75 cm above lower contact; GGU 239555, 3 m above lower contact, and GGU 239553, 40 m above lower contact). c. Enriched sill on southern Traill Ø (GGU 235570). d. Strongly fractionated sill on Svinhufvud Bjerge (GGU 239575, lower basaltic part, and GGU 239576, upper dioritic part).

Geographical Society Ø forms an exception to this rule, and it is therefore described in some detail.

The lower chilled margin is porphyritic with in total 1% phenocrysts of olivine (replaced by clay minerals) and clinopyroxene, both up to 0.5 mm in size, and 4% plagioclase phenocrysts. These are 0.5–1 mm in size and form clusters 5 mm across.

At 0.75 m above the lower contact the dolerite is still fine grained. Only a few plagioclase clusters are present at this level. Olivines (5%) are partly fresh. Smaller crystals have euhedral to subhedral outlines, but the larger grains may be pierced by plagioclase laths. Fe-Ti oxides mainly occur as skeletal crystals confined to interstices together with clay minerals.

The grain size gradually increases upwards. From the 3 m level the oxides form millimetre-sized irregular grains which partly enclose slender plagioclase laths. Interstitial alkali feldspar and quartz become significant constituents. At 40 m the sill reaches its coarsest grain size. Plagioclase and clinopyroxene in subophitic intergrowth, olivine partly replaced by clay minerals, and Fe-Ti oxides, all 2 to 3 mm in size, enclose fine-grained interstitial domains of strongly zoned plagioclase laths with minor pyroxenes, Fe-Ti oxides, alkali feldspar, quartz, apatite and clay minerals. Two metres below the upper contact the grain size is reduced to 1 mm.

In its upper half the sill contains scattered and discontinuous pegmatitic (gabbroic) veins. Most are only a few centimetres wide and parallel to the contacts of the sill.

The compositions of the main silicate minerals have been analysed by microprobe in samples from 75 cm, 3 m and 40 m above the lower contact (samples GGU 239556, -55 and -53). The plagioclase phenocrysts in the lowermost sample are bytownites (An_{82-72}). Major plagioclase laths in the three samples range from An_{70} to An_{50}, and the average An/Ab ratio tends to decrease upwards. Small interstitial grains in the two upper samples range from An_{50} to An_{15}. Olivine range from Fo_{55} to Fo_{35} and major grains of pyroxene (all augite) from $Ca_{42}Mg_{49}Fe_{9}$ to $Ca_{35}Mg_{35}Fe_{30}$ (Fig. 3). Ferropigeonite and ferrohypersthene are found as tiny interstitial grains in sample GGU 239555, whereas the leucocratic domains of sample GGU 239553 carry ferropigeonite and ferroaugite. In both samples the ferropigeonite shows very fine-scale exsolution structures and have apparently recrystallised to orthopyroxene and high-Ca clinopyroxene.

As detailed later the Leitch Bjerg sill only shows small chemical variations from base to top. Throughout the sill mg′ lies in the range 56.9 to 53.6. A more pronounced fractionation has occurred in the thick sill on Svinhufvud Bjerge. The lowermost sample, GGU 239575, from 125 m below the upper contact (and an estimated 50 m above the lower contact), has a basaltic composition (mg′ = 51.7) with olivine (Fo_{42-38}), plagioclase (An_{66-38}), pyroxene, Fe-Ti oxides, interstitial clay minerals and quartz feldspar micropegmatite. Larger pyroxene grains in subophitic intergrowth with the plagioclase laths are augites ($Ca_{34-39}Mg_{44-37}Fe_{18-29}$). Augite also occurs in intergranular aggregates together with pigeonite and hypersthene (Fig. 3).

In the upper part of the sill the composition is dioritic (Fig. 3). In sample GGU 239576 from 90 m below the upper contact (mg′ = 19.0) andesine (An_{41-35}) is intergrown with a pale brown ferroaugite ($Ca_{38}Mg_{44-37}Fe_{18-29}$). Olivine ($Fo_{20-14}$) and Fe-Ti oxides are other major constituents. Interstices are occupied by quartz-feldspar micropegmatite.

Both samples also carry colourless to pale green clinopyroxene, which is low in Ti and Al and displaced towards the He-corner (Fig. 3). This variety, which in the dolerite usually contains small patches of a sheet silicate, and in the diorite a ferroedenitic amphibole, is considered to be deuterically altered brownish augite or ferroaugite rather than a primary phase (cf. Smith, 1970, Walker *et al.*, 1973). Larger amphibole grains in optical continuity with the inclusions are often adjacent to the pale green pyroxene grains in the diorite sample.

Dykes. Among the seven sampled dykes five have basaltic composition and carry phenocrysts of olivine + plagioclase ± augite.

Two non-basaltic dykes were found on Traill Ø. One dyke strikes NNW and cuts a dolerite sill at Kap Palander. It is a fine grained basanite (as defined by Le Bas *et al.*, 1986) and consists of plagioclase, augite, brown amphibole, Fe-Ti oxides, slender needles of apatite and interstitial clay minerals and small amounts of carbonate. It contains scattered phenocrysts of augite and plagioclase up to 2 mm in size, and microphenocrysts of olivine, plagioclase and augite. The second dyke strikes NNE and cuts through Mesozoic sediments west of Steenstrup Dal. It is a hydrothermally altered plagioclase-phyric rock, apparently a basaltic trachyandesite, and may be related to the nearby Kap Simpson Complex.

Major and trace element chemistry

Fifty nine samples of lavas, sills and dykes have been analysed for major and trace elements. Selected analyses are shown in Table 1 together with analytical details. The full data set is available on request.

The lavas and sills (apart from the fractionated upper part of the Svinhufvud Bjerge sill) are marginally olivine or quartz normative tholeiites. Their tholeiitic affinity is confirmed by a plot of alkalies versus SiO_2 (not shown)

Table 1. Chemical analyses of lavas and sills in central East Greenland

GGU no.	Lavas, Kap Mackenzie 239529	239531	239532	Sills, main type and fractionated 239520	239523	239553	239555	239575	239576
SiO_2	49.34	47.57	47.58	49.26	49.08	48.55	49.07	49.83	47.57
TiO_2	1.73	3.39	2.49	2.10	1.60	1.95	1.76	2.26	3.44
Al_2O_3	14.68	15.04	13.74	13.75	14.35	14.22	14.33	13.58	10.53
Fe_2O_3	3.01	5.93	5.31	2.14	2.29	3.26	2.87	1.76	4.25
FeO	7.86	7.28	8.01	10.56	8.61	8.58	8.81	10.17	16.77
MnO	0.17	0.19	0.20	0.20	0.18	0.18	0.19	0.20	0.30
MgO	7.09	4.66	6.43	6.52	7.62	6.67	7.01	6.21	2.39
CaO	11.75	10.30	10.92	10.98	12.16	11.96	11.80	11.26	8.07
Na_2O	2.18	2.70	2.40	2.63	2.26	2.35	2.21	2.42	2.68
K_2O	0.14	0.59	0.19	0.29	0.21	0.23	0.24	0.35	0.98
P_2O_5	0.17	0.46	0.27	0.21	0.16	0.17	0.17	0.23	1.75
LOI	2.03	2.08	2.40	1.47	1.43	1.81	1.57	1.14	1.53
Total	100.14	100.19	99.94	100.11	99.94	99.93	100.02	99.40	100.25
mg′	57.6	42.8	50.4	51.4	59.1	54.0	55.4	51.7	19.0
Trace elements in ppm									
Cr	330	122	206	144	328	166	253	107	<3
Co	46	43	47	54	48	52	51	47	57
Ni	68	77	73	74	100	82	90	62	2
Cu	116	412	85	244	179	220	208	224	664
Zn	99	126	115	113	90	98	99	101	201
Rb	4.7	14	0.7	6.7	5.5	5.4	6.0	6.7	23
La	13	27	15	13	7	10	8	13	50
Ce	24	53	31	21	20	19	20	29	105
Nd	14	39	21	16	15	16	16	18	80
Sr	227	251	222	207	184	187	182	243	251
Y	25	53	37	36	29	28	29	35	111
Zr	126	277	175	146	110	114	118	143	425
Nb	10	23	15	10	6.9	7.8	7.5	10	32
Ba	38	92	62	43	83	49	58	73	247
V	300	310	364	374	319	359	346	382	67
Sc	37	32	40	40	38	38	39	39	22
$^{87}Sr/^{86}Sr$							0.70355	0.70355	0.70384

Sample locations are shown on Fig. 1. Chemical analyses by XRF. Major elements: GGU, trace elements: Geol. Inst., Univ. of Copenhagen. Sr-isotopes: Geol. Inst., Univ. of Copenhagen. For $^{87}Sr/^{86}Sr$ ratios the within run precision was better than ± 0.00001 (1 S.D.), and standard material NB 987 gave $^{87}Sr/^{86}Sr$ = 0.710268 ± 0.000009 (1 S.D., N=36) in the period of analysis. mg′ = atomic 100 Mg/(Mg+Fe^{2+}) with Fe_2O_3/FeO adjusted to 0.15.

where they all plot well below the Hawaiian dividing line of MacDonald & Katsura (1964). The mg′ ratios range from 59.1 to 42.8 which indicates that the magmas were fractionated before they were emplaced. The five basaltic dykes are also tholeiites. The alkaline affinities of the basanite and the basaltic trachyandesite are supported by low Zr/Nb ratios (4.2 and 5.4).

The tholeiitic basalts and dolerites have volatile contents between 1 and 3 wt.% and Fe_2O_3/FeO ratios between 0.14 and 0.81 (lavas: 0.33–0.81; sills: 0.14–0.43). The tholeiitic sills and dykes show good correlation between K_2O and immobile Nb (Fig. 4), indicating that remobilisation in most of the samples is of minor importance. A more severe alteration including redistribution of Ca has only been observed in dyke GGU 239589 from the vicinity of the Kap Simpson Complex.

The lavas plot slightly more scattered in the K_2O–Nb diagram and may have suffered some post-emplacement alteration.

Table 1 continued

		Sills, enriched			Dykes, alkaline	
239579	239598	239548	239570	239572	239565	239595
49.22	49.25	51.08	48.77	49.03	41.21	50.12
2.20	1.98	2.48	2.86	2.64	3.06	1.89
13.29	14.05	13.87	13.52	13.06	14.17	16.28
2.63	2.97	3.56	3.28	2.93	4.12	1.84
10.41	9.32	8.54	9.56	10.18	8.17	6.68
0.20	0.20	0.18	0.20	0.20	0.19	0.15
6.45	6.63	5.55	5.57	5.90	5.69	2.66
10.82	11.25	9.38	9.90	10.30	11.88	6.43
2.43	2.47	2.71	2.84	2.52	2.28	3.75
0.32	0.28	1.10	1.06	0.76	0.77	2.53
0.21	0.19	0.32	0.37	0.31	0.65	0.64
1.47	1.46	1.37	1.54	1.61	7.13	6.67
99.66	100.03	100.14	99.47	99.46	99.32	99.65
50.5	52.8	48.9	47.4	48.2	49.2	39.2
108	164	38	105	100	21	8
58	51	45	48	50	46	21
69	78	20	67	72	31	10
204	234	18	143	171	34	8
109	106	105	111	110	89	100
7.5	6.3	32	26	18	16	128
15	13	36	31	28	39	63
26	24	56	51	43	72	119
20	17	34	30	26	41	58
228	200	345	328	337	674	589
34	34	34	39	36	27	34
145	135	230	217	195	176	315
12	8.4	31	34	27	42	58
80	51	390	374	260	425	768
355	345	324	375	360	367	165
36	40	29	27	28	23	13
	0.70395		0.70471			

Lavas. Eight lavas have been analysed. In the plot of TiO_2 versus mg′ (Fig. 5), seven of the lavas define a narrow elongated field with mg′ decreasing from 57.6 to 44.5, accompanied by an increase in TiO_2 from 1.8 to 2.6 wt.%. These 'main type' lavas also form a coherent group in most other variation diagrams: decreasing mg′ values correlate with increasing concentrations of total iron, Na_2O, K_2O, P_2O_5 and incompatible trace elements, and decreasing contents of Al_2O_3, MgO, CaO, Ni and Cr. SiO_2, Co and Sc remain constant (Table 1 and Fig. 5).

The lava GGU 239531 (mg′ = 42.8) has significantly higher concentrations of the incompatible minor and trace elements than the other lavas. The content of TiO_2 is 3.5 wt.% as compared to 2.6 wt.% TiO_2 in the most fractionated lavas of the 'main type', and the relative enrichment of Nb is even higher: 23 ppm versus 14 ppm in the 'main type' lavas. The lava contains 20 % plagioclase phenocrysts which were probably accumulated, judging from the high whole-rock concentration of Al_2O_3 (Table 1, Fig. 5).

No regular up-section variations have been found in the chemical composition of the lavas.

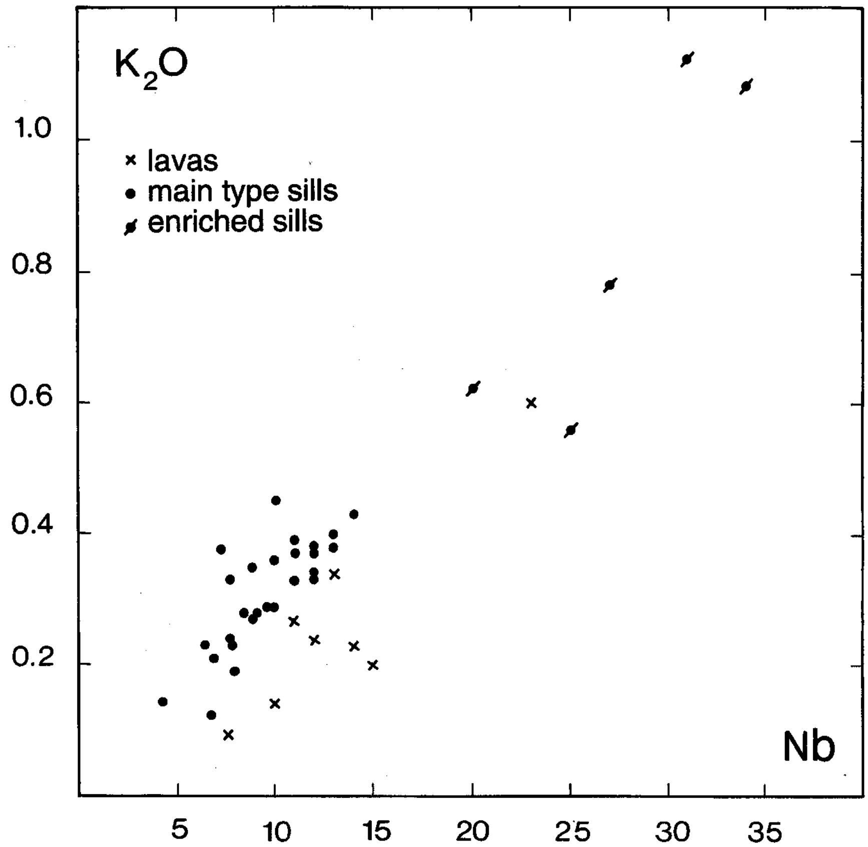

Fig. 4. Correlation between K_2O and Nb.

Sills and dykes. Sills may display systematic compositional variations from base to top due to flow differentiation or differentiation during solidification. Investigations of doleritic sills from Antarctica (Hergt *et al.*, 1989) and South Africa (Le Roex & Reid, 1978) similar in thickness to those of East Greenland suggest that the variations are mainly restricted to the middle and upper parts of the individual sills, and that samples from the lower parts in most cases provide good estimates on the average compositions. Samples of the East Greenland sills were, therefore, collected 3 to 5 m above the estimated lower contact.

The oxides and trace elements versus mg′ diagrams demonstrate that most of the sills (the 'main type' sills) and a few of the dykes fit the 'main type' lavas rather closely. The sample GGU 239521 (mg′= 52.3), which otherwise plots within the field defined by the 'main type' lavas, has a higher-than-usual content of Al_2O_3 and a low total-iron, whereas the opposite relationship is found in GGU 239543 (mg′= 57.3). The two analysed samples are high in plagioclase and clinopyroxene, respectively, and may reflect local enrichment of these two minerals.

A few sills (GGU 239544, -47, -48, -70 and -72) and the dykes GGU 239540 and -41 plot outside the field of the 'main type' lavas in most diagrams. They are all enriched in incompatible elements and especially in the strongly incompatible elements: K, Rb, Ba, Nb, La and Ce (2–3 times the concentration in the 'main type' sills), while the enrichment is less marked for P, Zr and Ti.

As also indicated by the mineralogical investigations, the chemical variations in the sill on Leitch Bjerg (Fig. 5) are subtle, mg′ ranges from 56.9 (sample collected 15 m above the base) to 54.0 (most coarse-grained sample 40 m above the base) and 53.6 (lower chilled margin).

Changes are much more pronounced in the thick Svinhufvud Bjerge sill. The lowermost sample has a basaltic composition, although slightly enriched in silica relative to the main field dolerites, while the three samples from 90 m, 85 m and 20 m below the upper contact are strongly iron-enriched, similar to the fractionated upper parts of the Skaergaard intrusion (Wager & Brown, 1968) and the Basistoppen sill (Naslund, 1989). The close chemical relations between samples from the fayalite diorite zone of the Basistoppen sill and from the upper part of the

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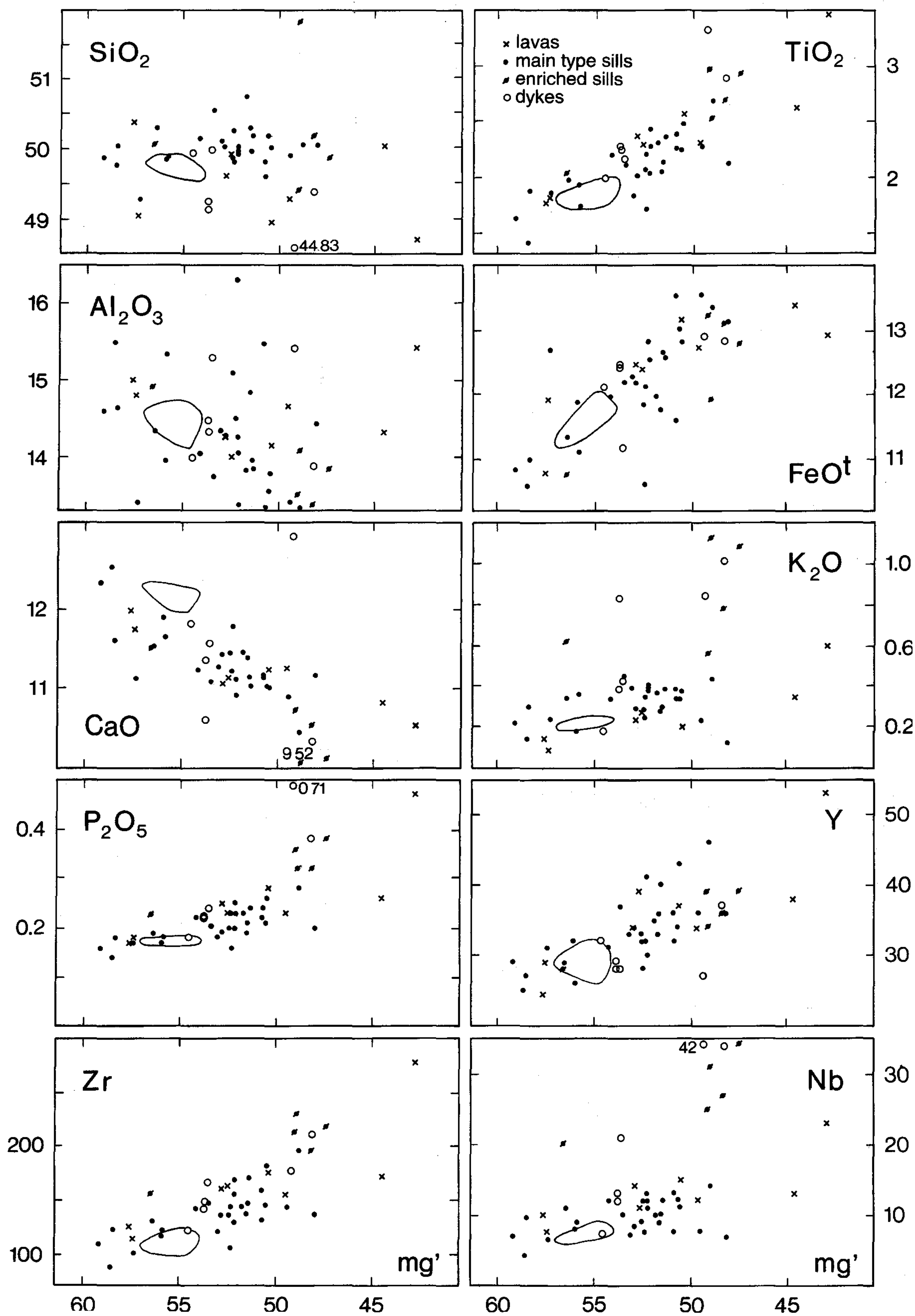
Fig. 5. Major and trace elements versus mg′. The major elements have been recalculated assuming an oxide total of 100%. Encircled areas: five analyses of a sill on Leitch Bjerg, do not include analysis of the lower chill.


SiO2
TiO2
× lavas
• main type sills
enriched sills
○ dykes
44.83
Al2O3
FeOt
CaO
K2O
9.52
P2O5
0.71
Y
Zr
Nb
42
mg'
mg'
51
50
49
3
2
16
15
14
13
12
11
12
11
1.0
0.6
0.2
0.4
0.2
50
40
30
200
100
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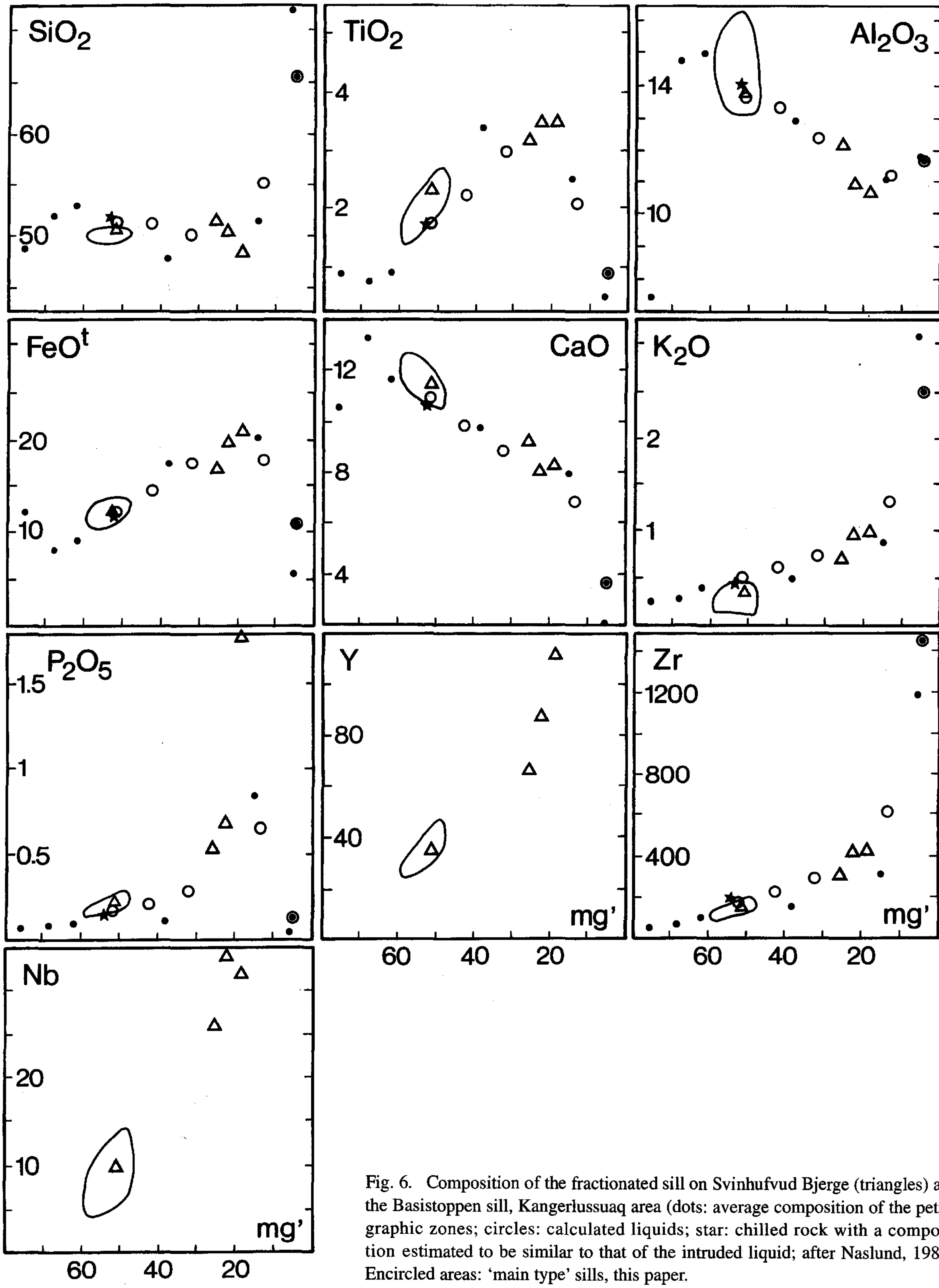


Fig. 6. Composition of the fractionated sill on Svinhufvud Bjerge (triangles) and the Basistoppen sill, Kangerlussuaq area (dots: average composition of the petrographic zones; circles: calculated liquids; star: chilled rock with a composition estimated to be similar to that of the intruded liquid; after Naslund, 1989). Encircled areas: 'main type' sills, this paper.

Svinhufvud Bjerge sill is demonstrated in Fig. 6. More detailed sampling is needed to determine whether the evolved composition of the upper part of the Svinhufvud Bjerge sill is caused by *in situ* fractionation or reflects multiple intrusions of magmas fractionated at depth. No internal boundaries were observed during field work.

Sr isotope analyses have been carried out on five samples. Two unfractionated 'main type' sills (GGU 239555 and -98) have $^{87}Sr/^{86}Sr$ ratios of 0.70355 and 0.70395 respectively. Similar ratios are found in both the basaltic and the dioritic part of the fractionated Svinhufvud Bjerge sill (0.70355 and 0.70384). A slightly increased ratio of 0.70471 is found in the enriched sill, GGU 239570.

'Main type' and enriched compositions

To judge from the variation diagrams (Fig. 5) the 'main type' sills and lavas in the region between Kong Oscar Fjord and Kejser Franz Joseph Fjord are closely related. Decreasing contents of Al_2O_3, MgO and CaO with decreasing mg′ suggest that the chemical trends are governed by fractionation of plagioclase in combination with one or more ferromagnesian minerals.

The role of fractional crystallisation has been tested using a least squares mixing program (Table 2). The sills GGU 239523 (mg′ = 59.1) and GGU 239579 (mg′ = 50.5) have been used as end members in the calculations. Mineral compositions were obtained from the microprobe analyses of phenocrysts from 'main type' lavas and fine-grained sills. The calculations show that the transition from dolerite GGU 239523 to dolerite GGU 239579 can be reproduced by subtracting 3.1% olivine, 13.6% plagioclase and 10.7% clinopyroxene. The solution agrees in general with the slight depletion of Ni, the enrichment of elements like Ti, K, P and Zr which all have low crystal/liquid distribution coefficients, and the steady level of Sc, which is preferentially incorporated in clinopyroxene.

Table 2. Least square tests of fractionation

Parent GGU 239523, daughter GGU 239579				
	Parent observed	Parent calculated	Calculated proportions weight percent	
SiO_2	49.93	49.87	Olivine Fo_{74}	3.1%
TiO_2	1.63	1.67	Plagioclase An_{81}	13.6%
Al_2O_3	14.60	14.64	Clpx. $Ca_{43}Mg_{47}Fe_{10}$	10.7%
FeO	10.86	10.97		
MnO	0.18	0.17	$\Sigma R^2 = 0.05$	
MgO	7.75	7.74		
CaO	12.37	12.50		
Na_2O	2.30	2.17		
K_2O	0.21	0.24		
P_2O_5	0.16	0.16		

It is also clear from the variation diagrams that fractional crystallisation alone cannot account for the total spread in the content of incompatible elements. Fig. 7a and b present incompatible element diagrams ('spidergrams') for selected lavas and sills. The concentrations have been normalised to chondritic compositions after Thompson (1982). The main field sill samples all have similar patterns: relative concentrations rise from Ba to La and then fall slowly towards Y (Fig. 7b). The patterns of the enriched dolerites are different. They have steeper La to Y limbs whereas the Ba to La limbs are less steep.

The spidergrams demonstrate a close correlation between the concentrations of the non-mobile element Nb in the sills and the mobile elements Ba, Rb and K (cf. Fig. 4). This confirms that the concentration of these elements is not seriously influenced by alteration or crustal contamination. Conversely, the lower content of K and especially of Rb in the lavas (Fig. 7a) seen in connection with the scatter of the lavas in the K_2O versus Nb diagram (Fig. 4) may suggest a loss of these elements from some samples subsequent to the eruption. A similar divergence between the sills (high Rb and K) and the lower series lavas (low Rb and K) has been noticed by Upton *et al.* (1984a) on Hold with Hope.

Regional variations

Fig. 8 provides a comparison in terms of TiO_2 and mg′ between the lavas and sills from Traill Ø and Geographical Society Ø, lavas from the Scoresby Sund region and lavas and sills from the area north of Kejser Franz Joseph Fjord. Larsen *et al.* (1989) demonstrated a range of TiO_2 levels among the Scoresby Sund lavas from MORB-type basalts to the so-called Ti-tholeiites. They also noticed that the variation in terms of TiO_2 appears to be much more restricted among the lower series lavas north of Kejser Franz Joseph Fjord: with a few exceptions analysed basalt flows from this area correlate with their low-Ti type from the Scoresby Sund region.

Among the eight lavas from Kap Mackenzie the seven 'main type' lavas have compositions similar to the lower lavas and to the sills north of Kejser Franz Joseph Fjord; only sample GGU 239531 has an off-trend composition. The same pattern emerges from a comparison between the sills on Traill Ø and Geographical Society Ø and the lavas and sills from the northern area: only the five enriched sills from the two islands plot off the main trend.

The lava GGU 239531 is characterised by a steep Ba to La limb in the spidergram and by a deep Sr anomaly, similar to the Ti-tholeiites of the Scoresby Sund region. The five sills, on the other hand, with their less steep Ba

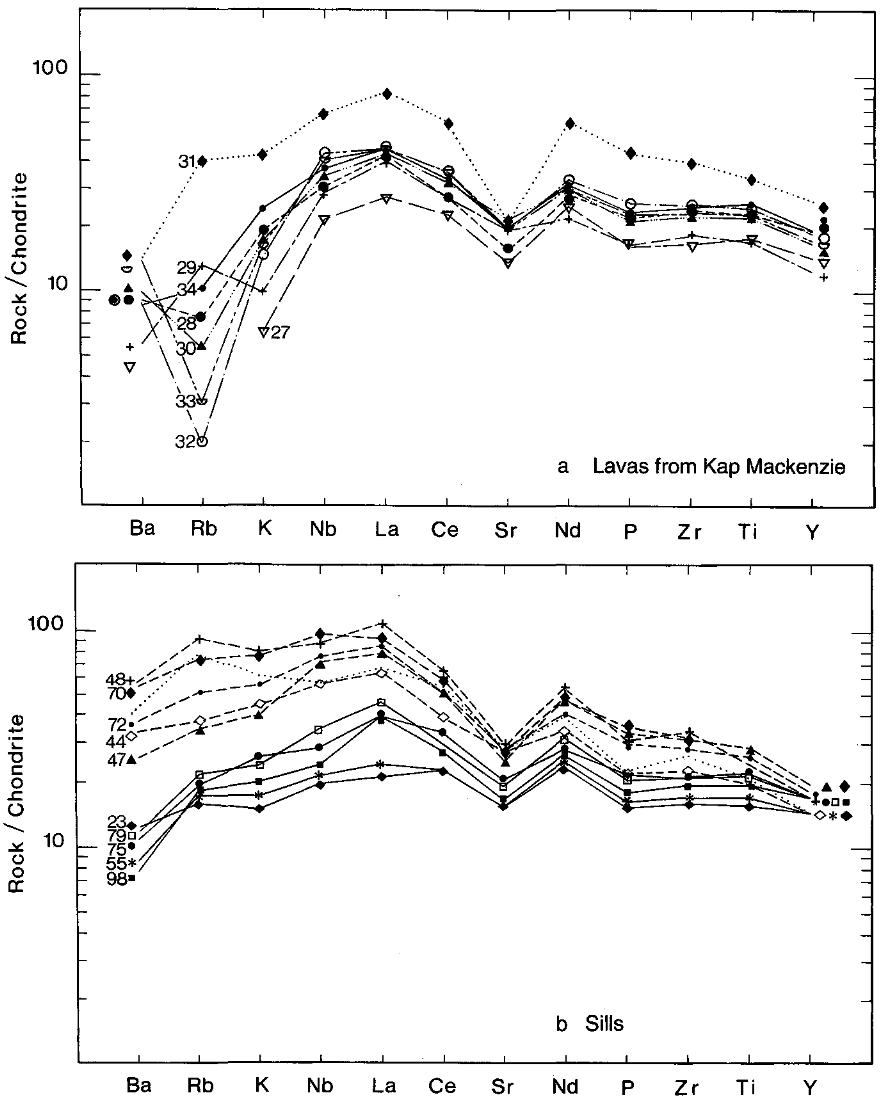


Fig. 7. Spidergrams for the incompatible elements. Normalisation factors from Thompson (1982). a. Lavas from Kap Mackenzie. b. Sills, full lines: 'main type' compositions, broken lines: enriched compositions, dotted line: average composition of normal type upper series lavas, Hold with Hope (Upton *et al.*, 1984b). GGU sample numbers are shown by their last two digits.

to La limbs, less distinct Sr anomalies and high $^{87}Sr/^{86}Sr$ ratios (sample GGU 239570) seem to be related to the hypersthene-normative lavas of the upper series of Hold with Hope and Giesecke Bjerge (Fig. 7). Independent evidence for this relationship comes from the preliminary palaeomagnetic analyses. Whereas the 'main type' sills appear to be reversely magnetised the analyses suggest that four of the five enriched sills were intruded during a period of normal polarity of the Earth's magnetic field as were the upper series lavas north of Kejser Franz Joseph Fjord.

In conclusion, the lavas and sills on Traill Ø and Geographical Society Ø are related in general to the basalts in the Scoresby Sund region and north of Kejser Franz Joseph Fjord; however, their restricted chemical variation, as shown e.g. in the TiO_2 versus mg′ diagrams, points towards a closer relationship with the sills and lower lavas in the northern part of the province (Fig. 8).

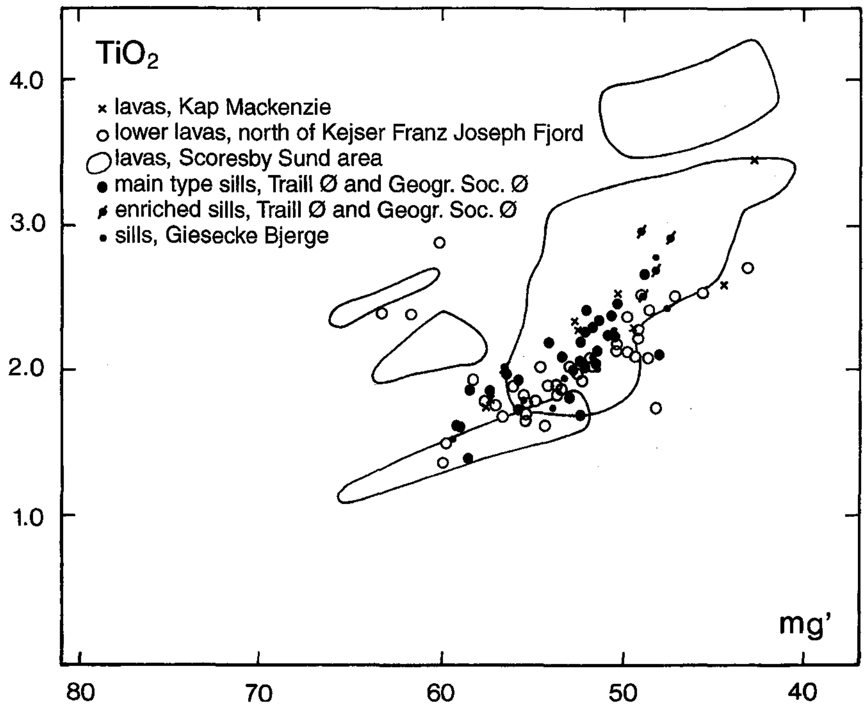
Discussion

Upton *et al.* (1984a) suggested that the source region of the lavas in the northern plateau was within a zone to the east of the present coastline where the lithosphere was greatly thinned prior to rifting. The scarcity of dykes on Traill Ø and Geographical Society Ø similarly suggests an offshore position of the feeders, also in this area.

In a detailed study of the Hold with Hope and Wollaston Forland lavas, Thirlwall *et al.* (1994) conclude that the lower lavas were probably derived from an Icelandic plume source with no component from MORB asthenosphere. They model around 20% melting, mostly in the spinel field, followed by substantial fractional crystallisation to form the lavas from the plume mantle.

The major and trace element compositions of the 'main type' lavas and sills studied here, and the few Sr isotope

Fig. 8. TiO_2 versus mg' for East Greenland lavas and sills. Data from Hald (1978) and unpublished; Larsen *et al.* (1989); Noe-Nygaard & Pedersen (1983); Thirlwall *et al.* (1994).



analyses of the sills, suggest that most of the magmas were of similar origin to those forming the lower lavas north of Kejser Franz Joseph Fjord. The composition of the few enriched sills indicates lithospheric contamination as suggested by Thirlwall *et al.* (1994) for the upper lavas.

Larsen *et al.* (1989) suggest that the magmas parental to the flood basalts in the Scoresby Sund region tended to collect near the mantle-crust boundary and that they were further fractionated in 'open' crustal magma chambers, where the Ti-enriched compositions were formed. The low-Ti basalts are found at two stratigraphic levels, and they are interpreted as being extruded during periods of increased replenishment of the upper crustal magma chambers and shortened residence time.

The apparent greater importance of mid-crustal magma chambers in the evolution of the melts in the Scoresby Sund region may reflect that the volcanic activity in this part of East Greenland took place along intra-plate fissures (Larsen & Watt, 1985) which probably reflected unsuccessful attempts to straighten the spreading axis, curving to the east between Kangerlussuaq and the initial Jan Mayen Fracture Zone (Larsen, 1988).

Candidates for mid-crustal magma chambers in the shape of thick sills intruded in a non-extensional environment have been mapped with seismic methods in the Jameson Land basin (Larsen & Marcussen, 1992). The Svinhufvud sill on nearby southern Traill Ø suggests that extensive fractionation may take place in such intrusions.

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