Petrochemistry of Jurassic and Cretaceous tholeiites from Kong Karls Land, Svalbard, and their relation to Mesozoic magmatism in the Arctic

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A study of the whole-rock geochemistry and mineral chemistry of high-TiO_2 Upper Jurassic and medium-TiO_2 Lower Cretaceous basalts from Kong Karls Land, Svalbard, is presented. Geochemical criteria indicate that the basalts are initial rifting tholeiites with weak signs of crustal contamination. The Upper Jurassic basalts appear to be associated with the Olga Rift, part of a trans-Barents rift system which failed to link the proto-Atlantic and proto-Arctic basins. The Lower Cretaceous basalts may be more closely related to initial rifting tholeiites on Franz Josef Land and Spitsbergen generated during the rifting stage of opening of the Canada Basin. During break-up of the Barents Shelf, the sequence of magma types corresponds to the pre-, syn- and post-rifting stages established in other areas of continental break-up. Evidence for a possible hot-spot or plume trail, extending from Siberia to the Yermak Plateau over 250 Ma, is assembled.

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Introduction

Kong Karls Land is a group of islands on the eastern edge of the Svalbard Archipelago (Fig. 1) and consists of Mesozoic sediments with Upper Jurassic and Lower Cretaceous basalts. The aim of this paper is to present a modern petrological description of these basalts and tectonically integrate them into the break-up of the Barents Shelf and the previously adjacent areas of North Greenland and Canada.

Geological setting

The Svalbard–Barents Sea region

The Barents Sea covers the northwestern corner of the Eurasian continental shelf (Fig. 1). Geophysical work indicates a generally stable shelf intersected by Paleozoic, Mesozoic and Cenozoic zones of rifting and uplift (Gramberg & Pogrebitsky 1984; Bogolepov et al. 1987; Malovitskiy et al. 1987; Verba et al. 1992) (Fig. 2). These structures and their sediments can be integrated to some extent with subaerial exposures on Svalbard, Franz Josef Land and northern Scandinavia and Russia.

Attention is directed to a trans-Barents structure extending from the Eastern Medvezhinskiy (Bjørnøya) Rift in the southwest to the Franz-Victoria Basin in the northeast (Fig. 2). This Olga–Bjørnøya rift system is over 600 km long and up to 60–80 km wide; much of it seems to have been initiated in Permo-Carboniferous time, but rifting and enhanced sedimentation have continued within parts of this structure up to the present day, and the Franz-Victoria Basin is an active earthquake zone (Baturin 1988). During the Mesozoic, the Barents Shelf was cut by the Olga–Bjørnøya and other rift systems; these can be seen as failed attempts to link the proto-Atlantic and Arctic basins along a northeasterly trend (Larsen 1987).

Within the Olga–Bjørnøya rift system the Olga Rift itself measures around 200 by 30–60 km and runs parallel to the NE-trending ridge which is capped by Kong Karls Land (Fig. 2). The Olga Rift has been divided into a central, fault-bounded part (Kong Karls Land High) which separates the Western and Eastern Olga Basins (Bogolepov et al. 1987). The Mesozoic terrigenous sediments and the Permo–Carboniferous carbonates in these basins are reduced in thickness over the Kong Karls Land High and the older (?) post-Silurian carbonates are absent. The long-lived presence of the Kong Karls Land High probably explains the

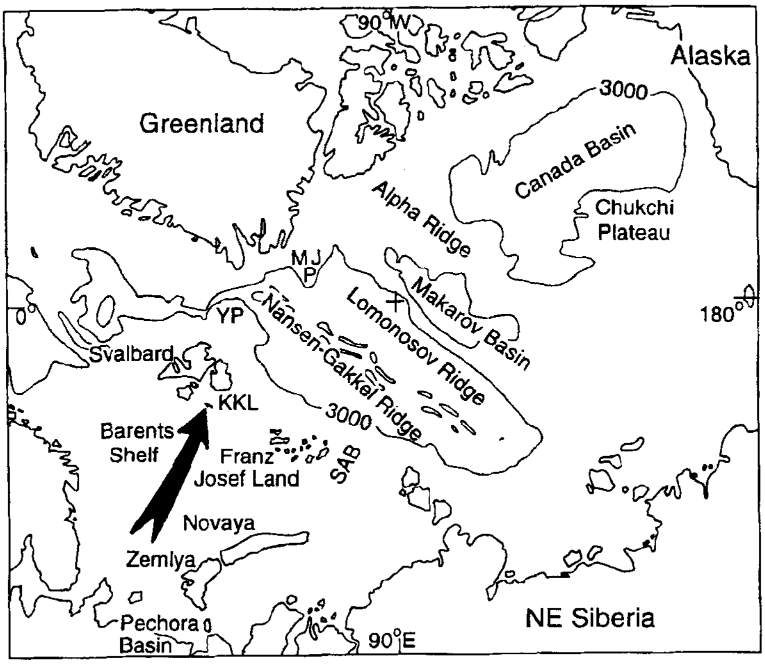

Fig. 1. Location map for Kong Karls Land (KKL) showing main geographic and bathymetric features of the Arctic Ocean basin. MJP Morris Jessup Plateau, SAB St. Anne's Basin, YP Yermak Plateau.

differences in Paleozoic–Mesozoic seismic stratigraphy observed for the Western and Eastern Olga Basins. The basement of the Kong Karls Land High consists of "granitic-metamorphic" rocks overlying "basic-granulitic" material. The junction between the Western Olga Basin and the Kong Karls Land High appears to be highly disturbed with large cross-cutting features, possibly basic intrusives or salt diapirs. After faulting ceased in Cretaceous time, the thickest Cretaceous–Cenozoic sequences of the Olga Rift occurred in the previously positive area of the Kong Karls Land High.

On Svalbard, the Mesozoic successions also point to a generally stable platform regime, though in Spitsbergen during the late Jurassic and early Cretaceous there was considerable magmatic activity accompanied by vertical movements along major lineaments (Worsley 1986; Kelly 1988).

The late Triassic and early Jurassic sedimentation in Svalbard (Kapp Toscana Group) indicates that deltaic sedimentation was preceded and followed by deposition of black, organic-rich shales. The deltas were derived from a source east of Kong Karls Land and may reflect uplift related to a rifting event in basins of the eastern Barents Shelf. Uplift was followed by stabilisation and then regional subsidence.

Subsequent uplift in the late Jurassic to early Cretaceous in Kong Karls Land and elsewhere in Svalbard (Adventdalen Group) can be related to a major regional uplift to the north, probably linked to the opening of the Canada Basin (Worsley 1986). This interpretation agrees with the presence in Franz Josef Land of Lower Cretaceous tholeiites which have been interpreted as initial rifting tholeiites, characteristic precursors to ocean-floor spreading (Bailey & Brooks 1988).

The Mesozoic magmatism known from on-land exposures of the Barents Shelf may also be extensive in submarine areas. Dredging has revealed that the Triassic and Mesozoic sedimentary-volcanic rocks characterising the ENE-trending islands of Kong Karls Land are merely the visible part of an ENE-trending belt some 200 × 60 km in size running along the north flank of the Olga rift (Dibner 1978; Elverhøi & Lauritzen 1984; Kristoffersen et al. 1984). Similar materials were dredged from a N-S fault-bounded area, 150 × 50 km in extent, stretching south of Spitsbergen and forming part of the Western Medvezhinsky (Bjørnøya) basin. Fragments of (?)Jurassic–Cretaceous hypabyssal intrusions

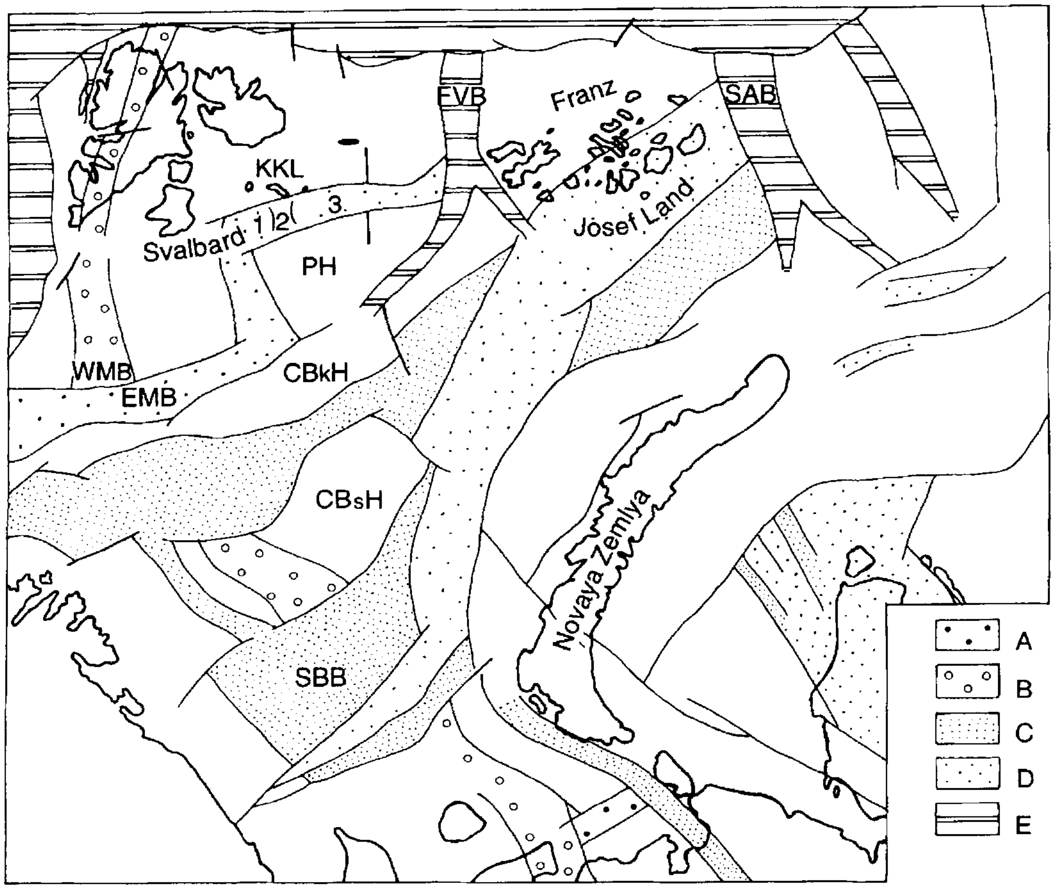

Fig. 2. Rift structures of the Barents-Kara Shelf (after Bogolepov et al. 1987 and Verba et al. 1992).

were also dredged in agreement with geophysical evidence pointing to isolated intrusive bodies in the Paleozoic–Mesozoic section of this basin (Verba et al. 1992).

Kong Karls Land

Kong Karls Land covers an area of about 330 km^2 and consists of three main islands, Kongsøya, Svenskøya and Abeløya, and a number of smaller islands. The islands lie on an ENE-trending ridge, about 200 × 60 km in size, that is defined by the 100 m isobath (Kristofferson et al. 1984). Seismic records indicate that the rocks on the islands form a broad syncline within a larger anticlinal or dome-like structure whose southern edge appears to be more structurally disturbed. This southern edge is the fault-bounded margin to the Olga Rift mentioned above.

The following description of the successions in Kong Karls Land (Fig. 3) is largely based on the work of Smith et al. (1976) supplemented by

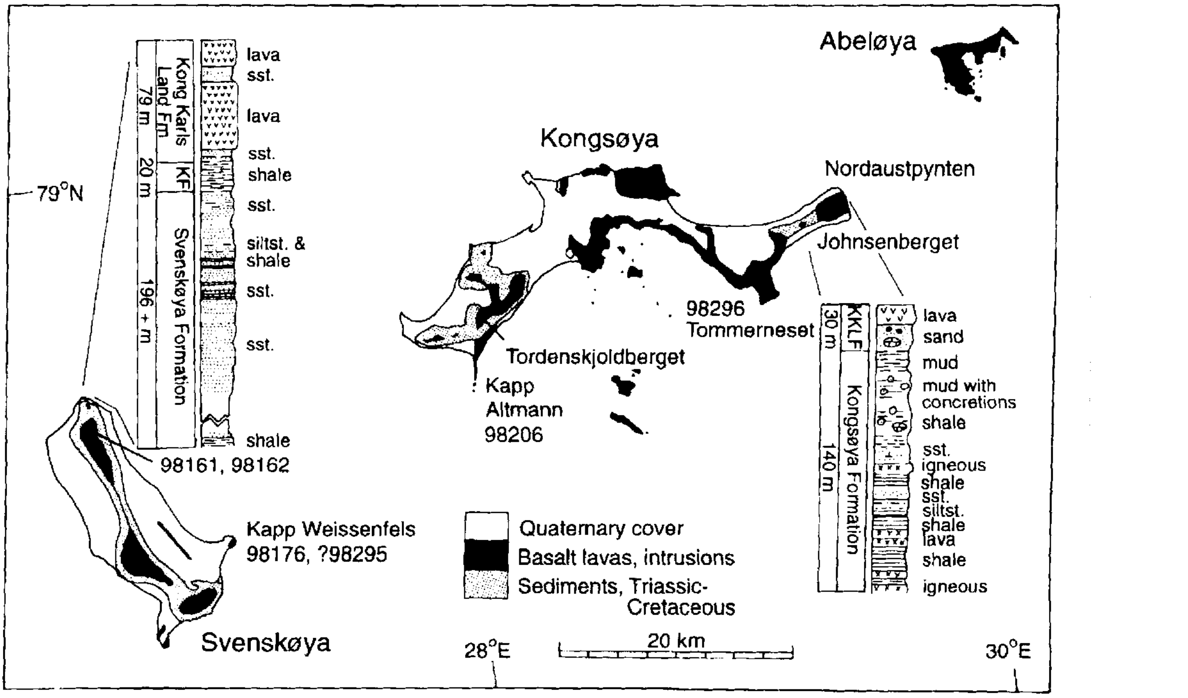

Fig. 3. Geological map of Kong Karls Land, Svalbard, after Smith et al. (1976) and Lauritzen & Ohta (1984). Sample localities are indicated.

Nathorst (1901), Worsley & Heintz (1977), Edwards et al. (1979), Pickton et al. (1979), Lauritzen & Ohta (1984), Worsley (1986), Doyle & Kelly (1988) and Larssen (1992).

The oldest sediments on the islands belong to the Wilhelmøya (Svenskøya) Formation and have been dated as Upper Triassic to Lower Jurassic (Rhaetian to Hettangian–Sinemurian). They are at least 220 m thick and evolve from shales with marine vertebrates to an overlying estuarine complex, with shallow marine sands and coastal swamps.

The overlying Janusfjellet (Kongsøya) Formation is mainly composed of argillaceous rocks deposited in a marine shelf environment; they total 170 m in thickness and range in age from mid Lower Jurassic to mid Lower Cretaceous (?Sinemurian to Hauterivian). In E Kongsøya, the oldest exposed section of the Kongsøya Formation occurs in the lower slopes of Johnsenberget and has been described from Nordaustpynten. Ammonites and bivalves suggest the age of these rocks to be mid Upper Jurassic (early Kimmeridgian). They probably include two lava flows, one 2 m thick with columnar jointing and a deeper one >3 m thick. The overlying shales include a 5 m thick scoriaceous lava of uncertain age. Nathorst (1901) would place it within the Upper Jurassic sequence but Smith et al. (1976) seem to place it in the lowermost Cretaceous (Berriasian). Above lie shales, sandstones and limestones extending into Lower Cretaceous (Volgian to Valanginian) which are cut by several sills (some apparently composite, 5–20 m thick). In western Kongsøya, at Tordenskjoldberget, a local 1 m thick lava flow of brown-red pumice appears within limestone and is thought to be Lower Cretaceous (Valanginian) in age. At the same locality, there are two (?)sills, each about 5 m thick and 30 m apart. The upper one is a vesicular basalt and the lower one a massive dolerite which is continuous with a large dyke at Kapp Altmann. On Svenskøya, the Kongsøya Formation is cut by a 5 m thick basalt sill which emerges at the surface to join the capping basalt of the overlying formation.

The uppermost, Helvetiafjellet (Kong Karls Land) Formation unconformably overlies the older beds. It has an overall maximum thickness of 65 m, dates from the mid Lower Cretaceous (Barremian) and consists of interbedded continental sandstones, coal beds and two lava flows. In northern Svenskøya, the two flows are locally separated by a brown sandstone; the lower flow is 15–43 m thick while the upper one is 5–17 m thick its top being nowhere exposed. In southwestern Svenskøya, a single flow is present but to the east the lower part becomes detached and forms a 10 m thick sill. In western Kongsøya, the same two basalt flows are locally separated by up to 10 m of shales. Here the lower flow is 5–12 m thick while the upper, incomplete flow is 5–20 m thick. The presence of loose amygdales of agate and quartz crystals on weathered surfaces of the plateaus and silicified fragments of wood probably contemporaneous with the basalts (Gothan 1911) suggest that volcanism was associated with siliceous hydrothermal solutions. The dolerite dyke of Kapp Altmann, which follows a preexisting NNE-trending fault, and a thinner basaltic sill cut the underlying strata in western Kongsøya. Much of Kongsøya is covered by basic igneous rocks probably belonging to the Helvetiafjellet Formation. Johnsenberget is capped by perhaps 20 m of basalt overlying 30 m of sandstone with Barremian plant remains.

Smith et al. (1976) were able to establish at least six volcanic events ranging from Upper Jurassic (early Kimmeridgian) to Lower Cretaceous (Barremian) in age, but the uncertainties of exposure and correlation suggest that more could be present. Sills were also recognised and, at least on southwestern Svenskøya where they emerge as lava flows, can be dated to the Lower Cretaceous.

The late Jurassic to early Cretaceous volcanism seems to have been accompanied by uplift and minor erosional periods in pre-Callovian, pre-Barriasian and, more importantly, in post-Valanginian time which took place in western Kongsøya possibly along a N–S axis. There are also gentle undulations with N–S (Smith et al. 1976) or NE–SW (Larssen 1992) axial trends.

Previous petrological work

The Swedish Arctic Expedition of 1898 was the impetus for the further field and laboratory studies made by Nathorst (1899, 1901, 1910), Hamberg (1899) and Backlund (1907) on the basalts of Kong Karls Land. Hamberg (1899) described basalts with plagioclase, clinopyroxene, olivine and hornblende phenocrysts and a basaltic andesite with bronzite phenocrysts. Backlund (1907) distinguished three varieties of plagioclase-phyric basalts according to the presence of other phenocrysts—olivine, clinopyroxene or two pyroxenes (with medium and low 2V). Smith et al. (1976) surprisingly found no phenocrysts in their collection of basalts.

Samples

Six samples, all around 200 grams in weight, were supplied to us by the Naturhistoriska Riksmuseet in Stockholm. Field notes of the Swedish Arctic Expedition of 1898 and geochemical parameters suggest that two groups of basalts are present. The Upper Jurassic (early Kimmeridgian, c. 154 my BP according to Harland et al. (1990)) basalts are characterised by their high TiO_2 contents. The Lower Cretaceous (Barremian, 124.5–132.0 my BP) basalts are united by medium TiO_2 contents and other geochemical and petrological features.

Sample 98296 is from Tømmerneset, at coastal level in E Kongsøya (Fig. 3). Well-developed jointing surfaces suggest it belongs to the 2 m flow from Nordaustpynten, dated by Smith et al. (1976) to early Kimmeridgian. Sample 98176 is from an isolated outcrop in southeastern Svenskøya which lies c. 200 m below the Barremian flows capping the island. It may thus be from an older flow which is consistent with its geochemical similarity to sample 98296. Sample 98295, from the beach on Svenskøya, is geochemically related to sample 98176 and may belong to the older group of basalts.

Sample 98161 from the highest part of the Svenskøya plateau must be from the higher of the two Barremian lava flows which cap Svenskøya. Sample 98162 is a basalt dyke from the top of the plateau on Svenskøya; its mineralogy and chemistry suggest it was a feeder dyke for sample 98161. Sample 98206 is from the prominent dyke at Kapp Altmann on Kongsøya. Geochemically, it is similar to the Lower Cretaceous basalts capping Svenskøya.

Petrography

Sample 98296 (mg. no. 0.373) is a basalt containing c. 3 vol. % plagioclase and 2% augite microphenocrysts, up to 1.5 mm in size, but also forming mono- or bimineralic clots up to 2.5 mm across. The groundmass shows a subdoleritic texture and variable grain size from 0.05–0.3 mm. Groundmass ore is less skeletal than in the other samples and is not so markedly associated with the interstitial material; it probably crystallised earlier. Interstitial material amounts to c. 10%, occurring as yellow glass or as microcrystalline material.

Sample 98176 (mg. no. 0.370) contains 5–10% microphenocrysts of zoned and resorbed plagioclase and augite, both up to 1 mm in size and often collected in clots. The groundmass shows doleritic intergrowths of plagioclase, clinopyroxene and a brown alteration material set in a fine-grained sub-doleritic matrix of the same three phases plus pigeonite, ilmenite, magnetite and brownish interstitial material.

Sample 98295 (mg. no. 0.222) is a ferrobasalt with c. 12% phenocrysts, often in irregular clots, of plagioclase, clinopyroxene, ilmenite and magnetite, individual crystals reaching 9 mm in size. These are set in a variolitic matrix. Many phenocrysts show skeletal outlines, especially the swallow-tailed plagioclase and thin platy ilmenite. Pyroxene phenocrysts are strained and recrystallised into sub-grains; zoning is confined to the outermost rim and is associated with feathery outgrowths. The groundmass has spindly, acicular and feathery crystallites of plagioclase, clinopyroxene and magnetite indicating rapid chilling, presumably by extrusion into water.

Sample 98161, like all the Lower Cretaceous basalts, has a higher mg. no. (0.450) than the Upper Jurassic flows and contains microphenocrystic and groundmass olivine. It has <1% microphenocrysts of plagioclase and rarer olivine, set in a subdoleritic groundmass. The larger groundmass grains consist of plagioclase, clinopyroxene, altered olivine and magnetite and grade into the finest groundmass of 0.05 mm grain size. However, in the finest groundmass, ore grains range from skeletal magnetite to morphologically better defined ilmenite needles and magnetite octahedra. Dusty interstitial material is patchily distributed through c. 10% of the sample.

Sample 98162 (mg. no. 0.432) is similar to sample 98161, containing <1% microphenocrysts of gently zoned plagioclase with cores rich in fluid inclusions but clear rims. The subdoleritic groundmass is composed of equal amounts of plagioclase and clinopyroxene (partly altered to nontronite), c. 10% of ilmenite and magnetite, and c. 10% of dusty interstitial material.

Dyke rock sample 98206 (mg. no. 0.426) has c. 3% microphenocrysts of plagioclase, augite, and altered and resorbed olivine. The groundmass shows the usual subdoleritic texture and consists of altered olivine, plagioclase, clinopyroxene, ilmenite, magnetite and interstitial microcrystalline material.

Mineral chemistry

Olivine microphenocrysts from two Lower Cretaceous basalts have relatively evolved compositions with Fo_{63-64} and 0.08–0.09% NiO (Table 1). Groundmass olivine in sample 98206 has a similar chemistry.

Plagioclase microphenocrysts in the Upper Jurassic basalts have core-rim zoning from An_{58-55} to around An_{51}. The Lower Cretaceous basalts have slightly more basic cores (An_{69-61}) and rims (An_{53-46}) to microphenocrysts. Plagioclase crystals in ferrobasalt sample 98295 show a decrease in An contents from cores and rims of phenocrysts (An_{50-58} to An_{43-46}), to cores and rims of microphenocrysts (An_{46-48} to An_{37}). These rim values match groundmass plagioclase whether spindly, feathery or acicular (An_{33-38}).

Fe-Ti oxides are modally abundant in Kong Karls Land basalts in keeping with the elevated whole-rock contents of FeO* and TiO_2. In most basalts, TiO_2 contents of magnetites average around 20–26% but in ferrobasalt sample 98295 they increase to 29–31%. Contents of MgO, Al_2O_3, MnO, Cr_2O_3, and NiO are typical of magnetites from evolved tholeiitic basalts.

Magnetite and ilmenite coexist in phenocrysts and glomeroporphyritic clots in ferrobasalt sample 98295 (Table 1). The temperature (c. 1140°C) and oxygen fugacity (log fO_2, c. −9.7) deduced for this phenocryst stage, using the graphs of Buddington & Lindsley (1964), fall about −0.5 log units below the FMQ buffer curve. Other tholeiites where an equilibrium coexistence of magnetite and ilmenite can be reasonably inferred equilibrated at temperatures from 1020–870°C and on or −0.5 log units below FMQ, values comparable to those found in evolved tholeiitic basalts elsewhere (e.g. Frost & Lindsley 1991).

Table 1. Representative analyses of minerals and interstitial groundmass in basaltic lavas and dykes from Kong Karls Land.

	98296-67	98296-71	98295-90	98295-18	98296-96	98295-IG	98206-188	98162-10	98206-186	98206-193	98206-IG
SiO_2	53.50	55.41	59.90	0.26	0.07	59.31	36.95	50.30	0.32	0.22	66.05
TiO_2	0.10	<0.02	<0.02	28.99	51.06	1.14	<0.02	<0.02	21.01	50.00	0.76
Cr_2O_3	<0.02	<0.02	<0.02	<0.02	<0.02	0.02	<0.02	<0.02	0.04	0.04	<0.02
Al_2O_3	28.19	27.31	23.62	1.96	0.22	13.39	<0.02	30.73	2.02	0.11	11.11
FeO*	0.74	0.58	1.30	66.74	46.37	11.91	31.45	0.72	72.80	49.38	8.06
MnO	<0.02	<0.02	<0.02	0.41	0.32	0.22	0.49	<0.02	1.11	0.57	0.05
NiO	<0.02	<0.02	<0.02	0.04	<0.02	0.05	0.09	<0.02	0.05	<0.02	<0.02
MgO	0.49	0.49	0.47	1.43	1.52	0.70	31.46	0.36	0.49	0.41	1.37
CaO	11.87	10.47	7.36	<0.02	<0.02	5.27	0.26	14.36	<0.02	<0.02	1.11
Na_2O	4.72	5.33	7.04	<0.02	<0.02	4.25	<0.02	3.44	<0.02	<0.02	2.95
K_2O	0.18	0.32	0.64	<0.02	<0.02	1.03	<0.02	0.14	<0.02	<0.02	4.83
Sum	99.79	99.91	100.33	99.83	99.58	97.29	100.72	100.05	97.84	100.51	96.29

Upper Jurassic
98296-67. Plagioclase microphenocryst, core, $An_{57.5}Ab_{41.4}Or_{1.1}$.
98296-71. Same as 98296-67, rim, $An_{51.1}Ab_{47.0}Or_{1.9}$.
98295-90. Plagioclase, fine-grained groundmass, equant grain, $An_{35.3}Ab_{61.1}Or_{3.6}$.
98295-18. Titanomagnetite phenocryst, glomeroporphyritic clot, 82.0% Usp.
98295-96. Ilmenite phenocryst in glomeroporphyritic clot, 4.0% Hm.
98295-IG. Interstitial groundmass, microcrystalline.
Lower Cretaceous
98206-188. Olivine microphenocryst, Fo_{64}.
98162-10. Plagioclase microphenocryst, $An_{69.2}Ab_{30.0}Or_{0.8}$.
98206-186. Titanomagnetite, medium-grained groundmass, 60.1% Usp.
98206-193. Ilmenite, needle in interstitial groundmass, 6.2% Hm.
98206-IG. Interstitial groundmass, microcrystalline.

Clinopyroxene phenocrysts are more abundant in the Upper Jurassic basalts and also tend to be more Fe-rich with a minimum of 21% Fs versus 17% in the Lower Cretaceous basalts (Table 2, Fig. 4). This tendency is most marked in ferrobasalt sample 98295 where augite phenocrysts range from 26–52% Fs.

Augite, whether as microphenocrysts, glomeroporphyritic clots or medium-grained groundmass, tends to follow the evolution of equilibrium liquidus pyroxene in tholeiitic intrusions and fractionated lava series (Fig. 4). Further fractionation in the rims to medium- and fine-grained groundmass pyroxene, however, shows a fairly sharp decrease in Ca (Table 2, Fig. 4).

Contents of the minor elements Al_2O_3, TiO_2 and Na_2O in augite of ferrobasalt sample 98295 change abruptly from averages of 1.2, 0.85 and 0.20% at the phenocryst stage to 2.4, 1.5 and 0.25% at the groundmass stage. Plagioclase and Ti-rich oxides crystallised at both stages and cannot explain the sharp changes.

Overall, clinopyroxene in Kong Karls Land basalts is characterised by higher TiO_2 and TiO_2/Al_2O_3 values than clinopyroxene in Franz Josef Land basalts (Fig. 5), a clear reflection of the higher TiO_2 whole-rock contents of the Kong Karls Land basalts (see below). Levels of TiO_2 however, fall below those in purplish titanaugite in Mesozoic basalt sills from Spitsbergen (Weigand & Testa 1982).

Interstitial material, according to bulk analyses using a broad electron beam, ranges in composition from andesite to dacite. Alteration products include Mg-rich nontronite (after olivine and pyroxene) and calcite with up to 8.8% FeO and 4.0% MnO in amygdales of sample 98176.

Whole-rock chemistry

Major elements

The Kong Karls Land basalts are all tholeiitic (Tables 3 and 4) and, corrected for secondary oxidation, are slightly quartz normative (Fig. 6). They lie between the tholeiites from Franz Josef Land which pass over into the olivine normative field and the tholeiites from Spitsbergen which are richer in normative quartz.

Table 2. Chemistry of augite series in Upper Jurassic basalts, Kong Karls Land, arranged according to increasing FeO*.

	98176-118	98296-166	98176-1	98295-136	98295-103	98295-97	98295-93
SiO_2	49.93	50.76	50.51	48.31	46.74	47.52	45.81
TiO_2	1.18	1.34	0.78	1.08	1.52	0.86	1.21
Cr_2O_3	0.14	0.05	<0.02	0.04	<0.02	0.02	0.02
Al_2O_3	3.24	2.15	1.19	1.73	2.13	0.91	1.71
FeO*	12.74	15.45	21.81	27.64	32.02	37.59	41.29
MnO	0.29	0.22	0.46	0.41	0.72	0.68	0.90
NiO	<0.02	0.05	0.02	<0.02	<0.02	0.02	<0.02
MgO	15.16	15.54	11.63	6.98	5.05	4.71	1.08
CaO	17.12	14.97	13.27	14.36	12.01	8.05	7.84
Na_2O	0.39	0.24	0.21	0.17	0.18	0.05	0.28
K_2O	<0.02	<0.02	0.10	0.13	<0.02	<0.02	0.02
Sum	100.20	100.77	99.98	100.85	100.40	100.42	100.14
Si	1.860	1.894	1.957	1.914	1.897	1.959	1.937
Al^{IV}	0.140	0.095	0.043	0.081	0.102	0.041	0.063
Al^{VI}	0.002	0.000	0.011	0.000	0.000	0.003	0.002
Ti	0.033	0.038	0.023	0.032	0.046	0.027	0.038
Cr	0.004	0.001	0.000	0.001	0.000	0.001	0.001
Fe^{3+}	0.096	0.058	0.007	0.045	0.026	0.000	0.000
Fe^{2+}	0.301	0.425	0.700	0.871	1.061	1.296	1.460
Mn	0.009	0.007	0.015	0.014	0.025	0.024	0.032
Ni	0.000	0.002	0.001	0.000	0.000	0.001	0.000
Mg	0.842	0.865	0.672	0.412	0.306	0.289	0.068
Ca	0.683	0.599	0.551	0.610	0.522	0.356	0.355
Na	0.028	0.017	0.016	0.013	0.014	0.004	0.023
K	0.000	0.000	0.005	0.007	0.000	0.000	0.000
Z	2.000	1.989	2.000	1.995	1.999	2.000	2.000
WXY	1.998	2.012	2.000	2.005	2.000	2.001	1.999
Fe_2O_3	3.42	2.05	0.24	1.51	0.84	0.00	0.00
FeO	9.66	13.60	21.60	26.29	31.26	37.59	41.29
Sum	100.54	100.97	100.01	101.01	100.49	100.42	100.14

Formula on basis of 6O.
98176-118 microphenocryst;
98296-142 microphenocryst in glomeroporphyritic clot;
98176-1 fine-grained groundmass, core;
98295-136 spindle-shaped microlite in groundmass;
98295-103 feathery microlite in groundmass;
98295-97 acicular microlite in groundmass;
98295-93 equant grain in interstitial groundmass.

The Kong Karls Land tholeiites have relatively high FeO* (13.1–18.2%) and TiO_2 (2.7–3.5%) but low Al_2O_3 contents (10.5–13.3%). As a result, their ratio of normative pyroxene/feldspar is around 0.8–0.9 compared to 0.7–0.8 in initial-rifting tholeiites from Franz Josef Land (Bailey & Brooks 1988) and 0.4–0.5 in MORB from the Nansen-Gakkel Ridge (Mühe et al. 1993). They correspond to those MORB with high FeO* but low Na_2O found on the shallowest mid-ocean ridges (Klein & Langmuir 1987).

On the MFA triangle (Fig. 7), the location of the Kong Karls Land tholeiites again reflects their Fe-rich, Na-poor character. Na_2O values, normalised to 8.0% MgO, are low in the Mesozoic tholeiites from Kong Karls Land (1.59%), Franz Josef Land (1.70%) and Spitsbergen (1.55%) but high in modern MORB from the Knipovich (2.75%) and Nansen-Gakkel (3.39%) Ridges.

One atmosphere phase relations (Fig. 8) indicate that the Upper Jurassic tholeiites from Kong Karls Land plot close to the augite-pigeonite cotectic whereas the Lower Cretaceous theoleiites plot close to the augite-olivine cotectic. These differences in three-phase saturation agree well with petrographic distinctions. The Spitsbergen tholeiites cover the full range of the Kong Karls Land tholeiites whereas the Franz Josef Land tholeiites plot in a more magnesian position though still along the augite-olivine cotectic.

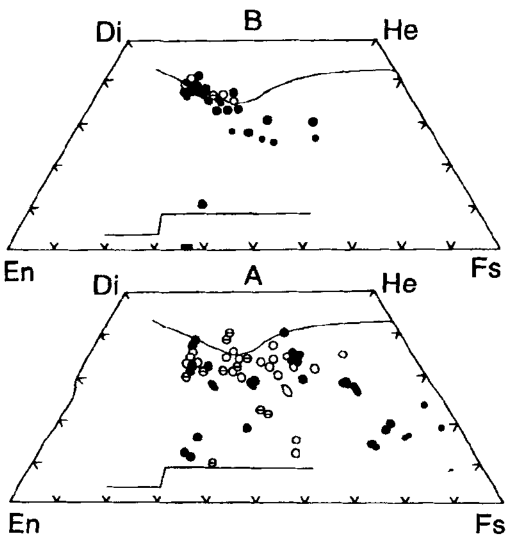

Fig. 4. Pyroxene and olivine quadrilateral for tholeiites from Kong Karls Land. Explanation: A = Upper Jurassic, B = Lower Cretaceous. o = pyroxenes from glomeroporphyritic clots; o = pyroxene microphenocrysts; ● = medium-grained groundmass pyroxenes; • = fine-grained groundmass pyroxenes; ■ = oliviness. The equilibrium crystallisation trends for high- and low-Ca pyroxenes in the Skaergaard intrusion are from Deer et al. (1978).

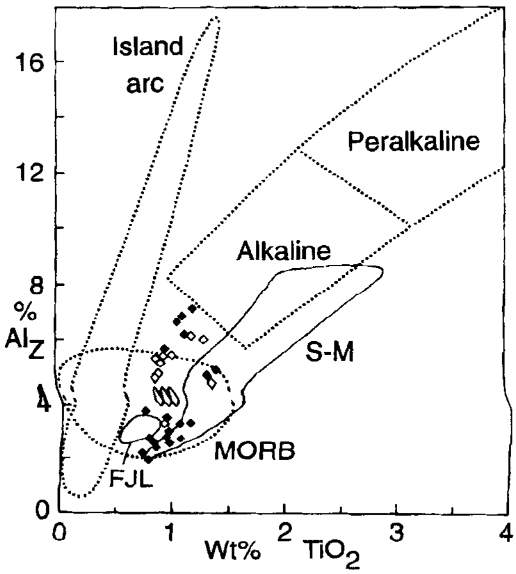

Fig. 5. Al_z (percentage of tetrahedral sites occupied by Al) versus TiO_2 wt.% in clinopyroxenes from Upper Jurassic (♦) and Lower Cretaceous (◇) basalts of Kong Karls Land. Clinopyroxene fields for various magma types are from Loucks (1990); for Franz Josef Land tholeiites (FJL) from Bailey & Brooks (1988) and for Spitsbergen Mesozoic dolerites (S-M) from Weigand & Testa (1982).

Younger basalts from the Barents Shelf and adjacent ocean ridges tend to show higher-pressure phase relations.

On the TiO_2-K_2O-P_2O_5 diagram (Fig. 9), the Kong Karls Land tholeiites, along with the other Mesozoic tholeiites from Franz Josef Land and Spitsbergen, show oceanic affinities whereas younger basalts from the Barents Shelf have continental, within-plate affinities.

Trace elements

Spidergrams for all Kong Karls Land tholeiites are in broad agreement (Fig. 10), the only discordance centring on the alkali and alkali-earth elements (Rb,K,Ba,Sr) which are commonly disturbed in slightly altered basalts. Overall, the patterns have an open inverted U shape typical of initial rifting tholeiites (Holm 1985). The positive anomaly for Nb is clear against K and U but weaker against La, differing in this respect from the initial rifting tholeiite pattern presented by Holm (1985) where an unambiguously positive anomaly occurs. The difference is likely to be explained by slight contamination by continental crust (see below).

The most meaningful differences among the Kong Karls Land tholeiites are between the three Upper Jurassic samples with high values for Zr-Sm-Ti-Y-Yb and the three Lower Cretaceous samples with contents of these elements about 30% lower. The Aptian-Albian basalts on Franz Josef Land can be considered as low-TiO_2 initial rifting tholeiites (Bailey & Brooks 1988).

The Upper Jurassic flows on Kong Karls Land have La/Yb_N around 2.3 and lack any detectable Eu anomaly (Fig. 11). There is a sharp increase in REE contents between the two basalts and the more fractionated ferrobasalt sample 98295. The Lower Cretaceous tholeiites have more fractionated patterns with La/Yb_N from 3.1–3.5. Positive Eu anomalies (Eu/Eu* 1.06–1.09) do not correlate with amounts of plagioclase microphenocrysts.

Average Sc contents fall from the high levels in the Fe-rich tholeiites from Kong Karls Land (39ppm), Franz Josef Land (39 ppm) and Spitsbergen (36 ppm) to lower values in Fe-poor MORB from the Nansen-Gakkel Ridge (30 ppm) (see Fig. 6 for references). Even lower values are

Table 3. Major element analyses and CIPW norms of basalts from Kong Karls Land, Svalbard.

	Upper Jurassic			Lower Cretaceous		
	98296	98176	98295	98161	98162	98206
SiO_2	49.62	49.58	51.13	49.32	49.10	49.16
TiO_2	3.52	3.48	3.30	2.72	2.74	2.85
Al_2O_3	11.95	11.87	10.54	13.33	13.29	12.83
Fe_2O_3	3.54	3.74	4.45	3.47	4.92	4.14
FeO	12.50	12.48	14.19	10.01	8.66	10.37
MnO	0.248	0.245	0.293	0.225	0.222	0.246
MgO	4.61	4.59	2.56	5.31	4.93	5.17
CaO	8.66	8.73	7.33	9.82	9.92	9.48
Na_2O	2.53	2.51	2.80	2.69	2.55	2.53
K_2O	0.734	0.724	0.613	0.369	0.342	0.763
P_2O_5	0.394	0.381	0.680	0.419	0.401	0.437
LOI	1.20	1.19	1.51	1.79	1.94	1.37
Sum	99.51	99.52	99.40	99.48	99.01	99.35
FeO*	15.69	15.85	18.20	13.13	13.09	14.10
Mg. no.	0.373	0.370	0.222	0.450	0.432	0.426
CIPW weight norm.[1]						
Q	4.12	4.06	8.61	2.30	3.39	1.95
OR	4.42	4.36	3.71	2.24	2.09	4.61
AB	21.81	21.64	24.26	23.34	22.30	21.90
AN	19.44	19.34	14.72	23.79	24.61	21.90
DI	18.23	18.72	15.45	19.44	19.65	19.46
HY	21.19	21.17	21.66	20.02	19.03	20.84
MT	3.06	3.09	3.57	2.58	2.59	2.76
IL	6.81	6.73	6.42	5.30	5.38	5.54
AP	0.92	0.89	1.60	0.99	0.95	1.03
PX/PL[2]	0.96	0.97	0.95	0.84	0.82	0.92

Analyst: Chemistry Laboratory GEUS.
1 calculated volatile-free and with Fe_2O_3/FeO adjusted to 0.15;
2 normative (DI + HY)/(AB + AN).

found in the Fe-poor Tertiary basalts from Spitsbergen (20 ppm) and the Pliocene basalts from the West Barents margin (25 ppm). The lowest values of all are found in the Quaternary alkali basalts of Spitsbergen (15 ppm) and are consistent with derivation from a garnet lherzolite source where Sc has been strongly retained by garnet during partial melting.

Crustal contamination

There are only weak signs of crustal contamination of the Kong Karls Land tholeiites. On key diagrams such as TiO_2-K_2O-P_2O_5 and TiO_2-Nb/3-Th (Holm 1985), the Kong Karls Land tholeiites plot with other initial rifting tholeiites rather than with the continental tholeiites.

On a Ti/Y – Ti/Nb diagram (Fig. 12), continental tholeiites such as the Siberian traps and the Tertiary Spitsbergern lavas that have low Ti/Y and Ti/Nb ratios relative to the mantle array (extending from ocean island basalts to depleted N-MORB) plot towards the composition of bulk continental crust consistent with their contamination by crustal materials.

Intra-cratonic rift zones, such as the Forties field of the North Sea basin, have marked alkalic affinities. Enriched MORB, such as the Icelandic lavas, plot on a strongly curved line reflecting mixing between depleted MORB and enriched magmas or magma sources.

Franz Josef Land tholeiites plot closer to the mantle array but the high-TiO_2 and medium-TiO_2 tholeiites from Kong Karls Land plot closer to the field of continental tholeiites and this is taken as evidence for slight crustal contamination.

Positive Eu anomalies in REE patterns of medium-TiO_2 Lower Cretaceous tholeiites may reflect contamination by plagioclase-rich melt residua with positive Eu anomalies from the lower crust (Taylor & McLennan 1985). Such material is represented by the two-pyroxene

Table 4. Trace element analyses of basalts from Kong Karls Land, Svalbard.

	Upper Jurassic			Lower Cretaceous		
	98296	98176	98295	98161	98162	98206
Cs	0.45	0.53	1.00	0.57	0.36	0.45
Rb	20.4	19.6	23.5	9.1	3.8	19.6
Ba	44	144	267	273	355	207
Pb	1.1	<0.5	4.1	<0.5	1.6	0.6
Sr	196	222	206	273	277	256
La	20.5	20.2	37.2	21.5	20.9	21.4
Ce	49.3	47.9	85.4	50.4	49.4	49.0
Nd	30.4	29.7	54.9	29.6	31.2	26.8
Sm	8.67	8.71	14.7	6.94	7.02	7.46
Eu	3.03	3.04	4.42	2.62	2.62	2.74
Tb	1.86	1.79	3.12	1.37	1.40	1.48
Yb	5.74	5.72	9.11	4.08	4.39	4.35
Lu	0.90	0.84	1.29	0.61	0.66	0.67
Y	63.6	62.9	111	49.2	48.2	47.2
La/Yb_N	2.36	2.33	2.70	3.48	3.14	3.25
Eu/Eu*	0.98	0.99	0.85	1.09	1.07	1.06
Th	2.54	2.39	4.46	2.78	2.73	2.67
U	0.63	0.63	1.14	0.64	0.61	0.63
Zr	257	254	466	188	183	193
Hf	6.77	6.58	11.6	4.84	4.60	5.03
Sn	*3.0*	*2.5*	*4.1*	*1.9*	*2.0*	*2.3*
Mo	1.3	1.4	2.5	0.8	1.3	1.3
Nb	19	19	31	19	19	19
Ta	1.33	1.37	2.01	1.41	1.40	1.53
Li	9	7	6	3	5	5
Zn	160	170	218	144	139	152
Cu	226	223	311	139	140	148
Co	42	42	35	34	34	33
Ni	46	45	8	60	61	53
Sc	48	41	35	38	39	38
V	531	508	182	401	389	412
Cr	38	41	<1	104	105	86
As	2.0	2.7	2.4	2.0	1.5	2.1
Ga	25	26	29	25	23	24
Ge	1.6	1.6	1.8	1.5	1.6	1.6
Au	0.55	0.03	<8.5	0.08	0.15	0.02
S	1220	750	920	620	488	1230
Cl	65	120	160	35	35	130

Analysts: J. C. Bailey, R. Gwozdz, H. Kunzendorf, B. Møller.

granulites which appear to dominate the lower crust in NW Spitsbergen (Amundsen et al. 1987) and often exhibit positive Eu anomalies (Amundsen, pers. comm. 1996).

Magmatism and break-up of the Barents Shelf

The setting of the Kong Karls Land basalts is best judged against the magmatic and tectonic events taking place during break-up of the Barents Shelf. Elsewhere, a three-stage evolution of magmatism has been recognised during continental break-up (Upton 1988; Pe-Piper et al. 1992; White 1992). Along the zone of future continental rupture, a lengthy stage prior to break-up is marked by formation of grabens with minor igneous activity of an alkalic character. Continental break-up itself – the second stage – begins with a period of renewed faulting and crustal thinning which leads to the emplacement of dyke swarms and, in hotter rift zones, voluminous sills and flood basalts of tholeiitic composition. The appearance of oceanic crust with its capping of MORB is followed by

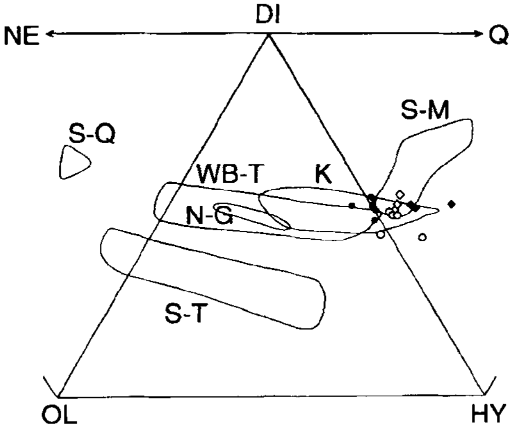

Fig. 6. Basalt saturation diagram. Explanation: ◆ = Kong Karls Land, Upper Jurassic; (◇) = Lower Cretaceous (this paper); ● = Franz Josef Land, lavas; ○ = Franz Josef Land, sills, mainly Lower Cretaceous (Bailey & Brooks 1988, Tarakhovskiy et al. 1982, 1983). S-M, S-T, S-Q = Spitsbergen, Mesozoic (Tyrrell & Sandford 1933, Burov & Livshits 1965, Weigand & Testa 1982); Spitsbergen, Tertiary (Prestvik 1978); Spitsbergen, Quaternary (Furnes et al. 1986, Skjelkvaåle et al. 1989). WB-T = West Barents Shelf margin, Pliocene (Mørk & Duncan 1993); K = Knipovich Ridge, Quaternary (Neumann & Schilling 1984); N-G = Nansen-Gakkel Ridge, Quarternary (Mühe et al. 1991, 1993).

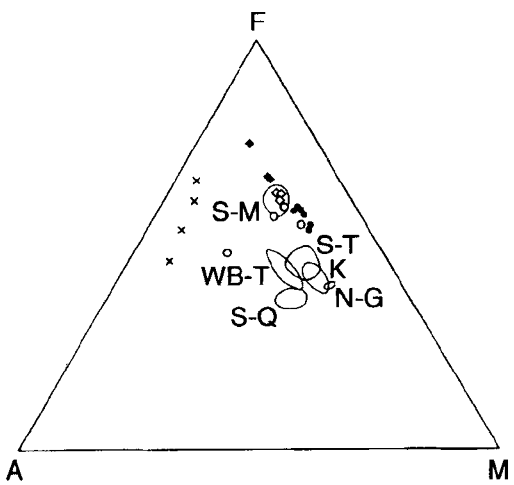

Fig. 7. MFA diagram. Symbols as in Fig. 6 plus Kong Karls Land interstitial material (X).

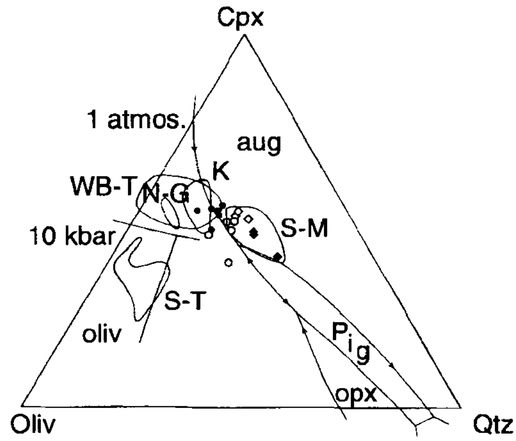

Fig. 8. Plagioclase-saturated olivine-pyroxene-quartz triangle showing anhydrous phase relations at 1 atmos. and 10 kbar pressure (Grove & Kinzler 1986). Symbols as in Fig. 6.

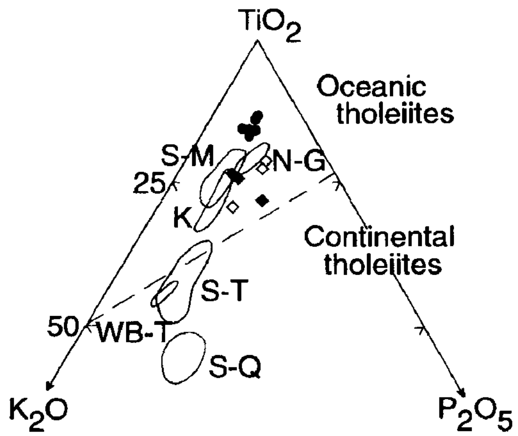

Fig. 9. The TiO_2-K_2O-P_2O_5 diagram of Pearce et al. (1975) discriminating between oceanic (including initial rifting) and continental (true within-plate) non-alkaline basalts. Symbols as in Fig. 6.

migration of the ocean rift away from the continental margin. As temperature and tensional stresses wane at these margins, increasingly alkalic magmas are emplaced as dykes and plutons in the final stage; extended fractionation and continental crustal contamination often generate salic rock types.

Against the background of this somewhat idealised evolutionary model, three stages of magmatism appear to be also recognisable during the break-up of the Barents Shelf and previously adjacent areas of N Greenland and Canada. The second stage, however, took place at different times in different places starting in Lower Cretaceous along the Arctic Ocean margin of the Barents Shelf and in Lower Tertiary along the Norwegian-Greenland Sea margin. The distribution of magmatism prior to ocean-floor spreading is given on Fig. 13. One must add that, as with many other aspects of Arctic evolution, geological controls are relatively limited.

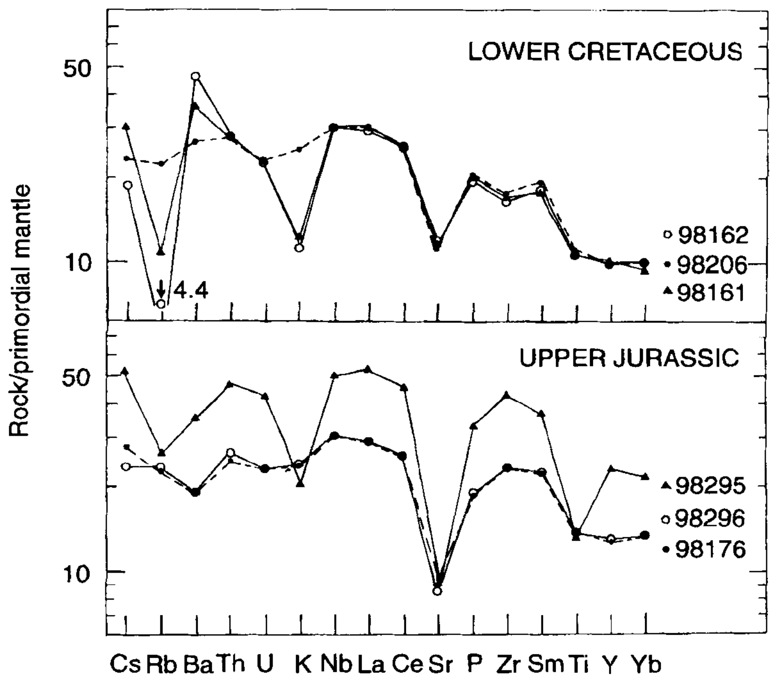

Fig. 10. Spiedergrams for Kong Karls Land tholeiites normalised to primordial mantle (Wood et al. 1979).

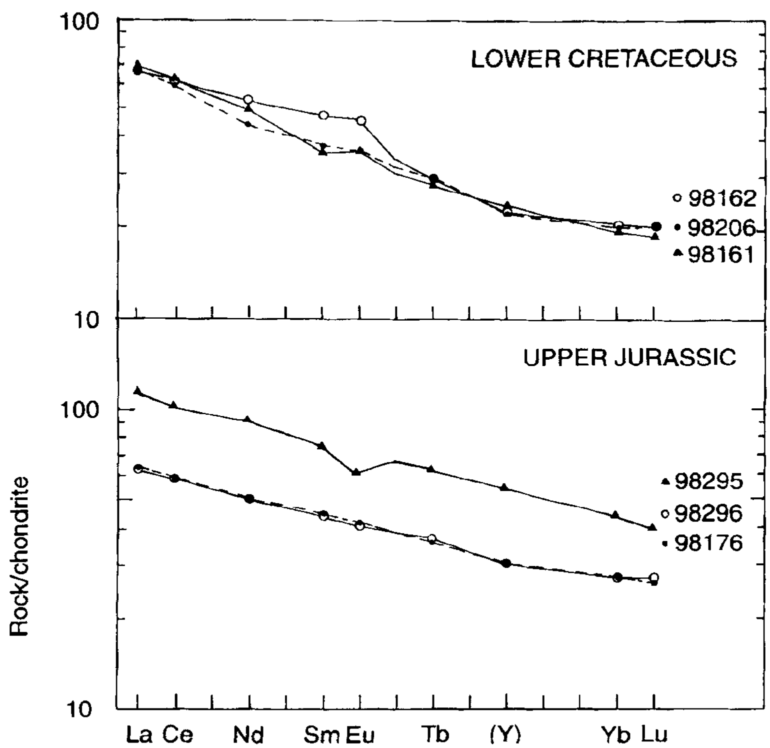

Fig. 11. Chondrite-normalised REE patterns of Kong Karls Land tholeiites. Normalising values are from Leedey chondrite data (Masuda et al. 1973) divided by 1.20.

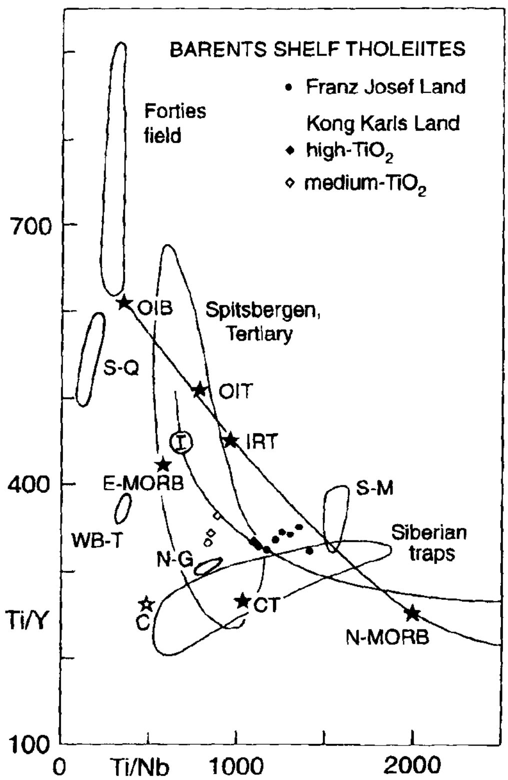

Fig. 12. Ti/Y versus Ti/Nb for Barents Shelf tholeiites with comparisons. Sources of data: Siberian traps, Mokulaevsky, Morongovsky and Nadezhdinsky suites, Lightfoot et al. (1990); Franz Josef Land, Bailey & Brooks (1988); Kong Karls Land, Spitsbergen, Mesozoic (S-M) and Quaternary (S-Q), this paper; Spitsbergen, Tertiary, Prestvik (1978) and this paper; WB-T West Barents Shelf margin, Pliocene, Mørk & Duncan (1993); N-G Nansen-Gakkel Ridge, Quaternary, Mühe et al. (1991, 1993); ocean island basalts (OIB), Fitton et al. (1991); ocean island tholeiites (OIT), initial rifting tholeiites (IRT), depleted and enriched MORB (N-MORB, E-MORB) and continental tholeiites (CT), Holm (1985); bulk continental crust (C), Taylor & McLennan (1985); Iceland and adjacent ocean floor (I), Wood et al. (1979), Devey et al. (1994); Forties field, North Sea, Latin et al. (1990).

Stage 1

Pre-break-up basins and grabens are well-established features of the Barents-Sverdrup region. Rift zones extent across the Barents Shelf, but associated magmatism has only been recognised in seismic refraction studies and a few Jurassic lavas and intrusions on Kong Karls Land and Franz Josef Land. Continental break-up failed to develop along these early rifts and they did not evolve into the marginal basins seen on the flanks of rifted oceans such as the Northeastern Atlantic.

As discussed above, the earliest lava flows on Kong Karls Land date from the Kimmeridgian (Smith et al. 1976) and are probably linked to events in the Olga Rift immediately to the south. They are here classified as high-TiO_2 initial rifting tholeiites.

On Franz Josef Land, two tholeiitic gabbro-dolerite intrusions drilled on Alexandra Land gave K-Ar ages of 200 ± 8 myBP (Tarakhovskiy et al. 1982, 1983). They may be coeval with sills on other islands which were gently interfolded with the host Triassic-Liassic sediments prior to erosion and extrusion of Lower Cretaceous basalts (Dibner 1970: Bailey & Brooks 1988; Ntaflos et al. 1995).

The Sverdrup Basin (Fig. 13) is viewed as an incipient or failed rift zone of Carboniferous – Late Cretaceous age and, allowing for rotational and transcurrent motion, may have been subparallel, at least in Jurassic – Neocomian time, to a second failed rift zone, the Arctic Alaska Basin, which now extends offshore of north Alaska (Balkwill & Fox 1982; Embry 1990; Grantz et al. 1990a).

Magmatism in the Sverdrup Basin included a long stage prior to opening of the Arctic Basin when small amounts of magma were emplaced (Thorsteinsson 1974). The oldest, Carboniferous basalts occur on northern Axel Heiberg Island, while Permian basalts are found at one horizon around much of the basin. Basic sills are found in strata of Carboniferous to Late Cretaceous age but K-Ar dating only indicates a range from about 180–90 myBP. Basic magma activity apparently coincided with periods of accelerated basin subsidence (Balkwill 1978).

In the Hanna Trough of northern Alaska, thick mid-Permian basalts are associated with shallow-water sandstones. Widespread basalts (Esayoo Formation) of similar age occur in the north-eastern Sverdrup Basin (Embry et al., in press).

Stage 2A

Along the northern edge of the Barents-Sverdrup Shelf, we recognise three sub-stages to stage 2A, the rifting and spreading of the Arctic Ocean floor. During the first sub-stage, from 130 to 80 myBP, in the Lower Cretaceous, the Canada Basin appeared. Recent models favour the swivelling of continental blocks away from polar Canada about a pivot near the Mackenzie River delta (Harland et al. 1984; Embry 1990).

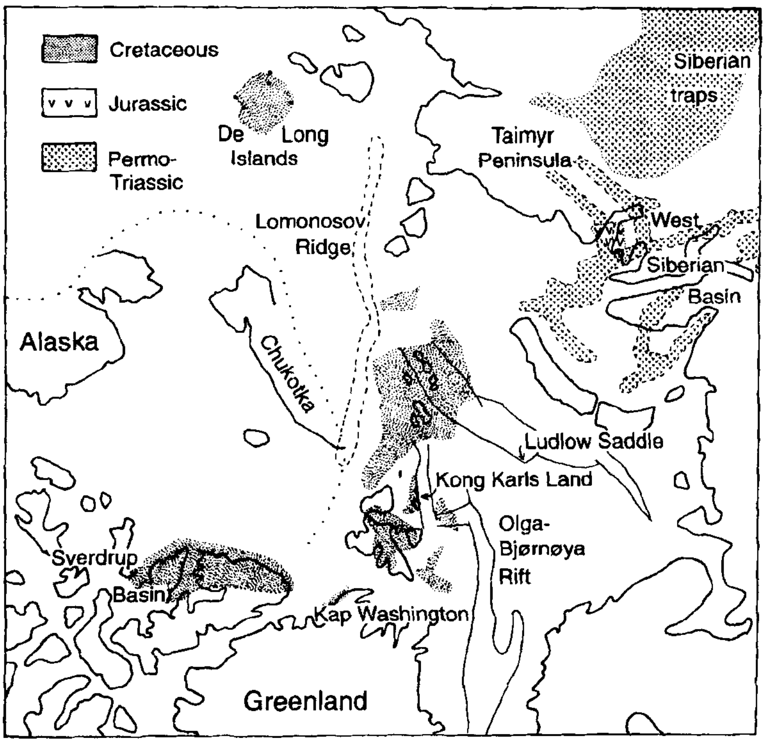

Fig. 13. Distribution of Permo-Triassic to Late Cretaceous magmatism of the Barents-Svalbard shelf areas using the Late Jurassic reconstructions of Heafford & Kelly (1988) and Grantz et al. (1990a). Mainly compiled from Dibner (1978), Larsen (1987), Embry & Osadetz (1988), Ziegler (1988), Kunin et al. (1989), Grantz et al. (1990a), Lightfoot et al. (1990), Shipilov & Mossur (1990) and Verba et al. (1992).

In the Sverdrup Basin, the earliest pulses of Cretaceous magmatism can be related to the early rifting and opening of the Canada Basin (Embry & Osadetz 1988; Osadetz & Moore 1988; Embry 1991). Rare Valanginian – early Barremian volcanic flows are found on Axel Heiberg and Bjarnason islands. Late Barremian – Aptian flows (Isaachsen Formation) are widespread from northwestern Ellesmere Island to Axel Heiberg Island and thin southwards from c. 300 m to <30 m.

Late Aptian–early Cenomanian volcanics outcrop from northern Amund Ringnes Island through Axel Heiberg Island to northeastern Ellesmere Island, and associated dykes and sills cover an even wider area of the NW Sverdrup Basin. The zenith of volcanic activity was attained during the late Albian. The more primitive basaltic magmas of the Hassel Formation (Osadetz & Moore 1988) lie in the oceanic field of the TiO_2-K_2O-P_2O_5 diagram. The stratigraphically equivalent Strand Fiord Formation, no younger than early Cenomanian (Embry & Osadetz 1988), consists of about 800 m of subaerial and marine volcanics and pyroclastics on Axel Heiberg Island (Ricketts et al. 1985). The sequence is thought to thicken northwards where, along with N-trending dykes, it breaks through the northern rim of the Sverdrup Basin suggesting a link to volcanism on the coeval Alpha Ridge. This agrees with the oceanic character of these quartz tholeiites in TiO_2-K_2O-P_2O_5 space.

Several magmatic events along the northern edge of the Barents Shelf have been related to the rift phase of the Canada Basin. On Franz Josef Land, most intrusions as well as the subaerial tholeiitic lavas which are assigned to an initial rifting type (Bailey & Brooks 1988) give K-Ar ages of 145–109 myBP with a suggestion of two groupings around 140 and 120 myBP (Campsie et al. 1988). Floral evidence indicates that the earliest basalt flows are Hauterivian, i.e. 132–135 myBP on the time-scale of Harland et al. (1990). However, the Salisbury formation consisting of about 260 m of Aptian-(?)Albian basaltic sheets and coal-bearing sediments may be significantly younger. The overall thickness of the Lower Cretaceous basalts is up to 400–500 m. Most dykes in the archipelago have a NW trend and seem related to the Lower Cretaceous volcanism.

Geophysical mapping suggests that the Franz Josef Land lava plateau continues westwards and onto the eastern side of Saint Anne's Basin (Fig. 13)(Kunin et al. 1989; Grantz et al. 1990b).

On Kong Karls Land, the youngest and thickest of the known lava flows, together with a number of sills and dykes, have been dated on fossil evidence to the Barremian (124.5 to 132.9 myBP; Smith et al. 1976) and are here considered to be initial rifting tholeiites with medium TiO_2 contents.

In the Isfjorden area of central Spitsbergen, dolerite dykes are thought to intrude Upper Jurassic sediments but are overlain uncomformably by Valanginian shales (Parker 1966). This agrees with K-Ar ages of 144–149 myBP (Gayer et al. 1966). Wider surveys of Spitsbergen intrusions yielded K-Ar ages of 198–71 myBP (Firshov & Livshits 1967; Burov et al. 1976) with maxima around 144 ± 5 myBP for E Svalbard and E Isfjorden, and 105 ± 5 myBP for slightly differentiated intrusions in central Spitsbergen. Most intrusions are sills, some extending for >60 km; thicknesses vary from 11–100 m but are most commonly 33–50 m. Many sills are linked by dykes and there is evidence for dykes acting as feeders for "cedar-tree" sill complexes. All intrusions are tholeiitic and basic (Tyrrell & Sandford 1933; Burov & Livshits 1965; Weigand & Testa 1982; this paper). TiO_2 contents group around 3.4% suggesting that a single high-TiO_2 magma type dominated the area. Geochemically, they can be classified as initial rifting tholeittes (Tables 5 and 6, Fig. 14) though negative Nb anomalies may point to crustal contamination. Syn-sedimentary faults and slides seen in Barremian delta-front sequences at Kvalvågen in south Spitsbergen are covered by marine shales enriched in volcanogenic debris (Worsley 1986).

In the De Long Archipelago, Bennett Island contains 60 m of thin basalt flows with lenses of tuff and tuff-derived mudrock whose spore-pollen complex suggests a late Early Cretaceous age (Vinogradov et al. 1976). Extensive areas of Cretaceous basalts are thought to surround the archipelago. Major-element analyses of these zeolitised basalts are disturbed (Vol'nov et al. 1970) and their petrologic character is unclear.

Other areas of Lower Cretaceous magmatism, based on dredging or geophysical work, have been compiled on Fig. 13.

The second sub-stage, the formation of the largely igneous Alpha Ridge, occurred during or shortly after opening of the Canada Basin. Alpha Ridge is formed of over-thickened oceanic-type crust, probably analogous to an Icelandic-type spreading ridge. Highly vesicular clasts of altered alkali basalt were dredged from the wall of the graben-like valley at the ridge's crest (Van Wagoner et al. 1986). The ridge was probably subaerial and forested at one stage. It may be mid-Cretaceous in age, somewhere between 120 and 80 myBP, perhaps 95 myBP (Weber 1990); this age correlates with the zenith of magmatic activity in the Sverdrup Basin.

Finally, the Hansen Point volcanics of late Cenomanian – Maastrichtian age occur on northern Ellesmere Island. They consist of basalt flows and breccias (which have an oceanic character in TiO_2-K_2O-P_2O_5 space (Trettin & Parrish 1987)) with local rhyolitic and trachytic flows and breccias. One composite sequence reaches at least 1000 m in thickness. Embry & Osadetz (1988) claim compositional similarities to the Kap Washington Group of N Greenland and thus a link to the rift phase of the Eurasian ocean basin, but more work is needed to confirm this. Gabbroic and granitic, Late Cretaceous plutons are also present on northern Ellesmere Island.

In northern Greenland, late Cretaceous transitional basalts and alkaline-peralkaline acid lavas of the Kap Washington Group, around 5 km thick, are thought to be related to nearby alkali doleritic dyke swarms of a slightly older age. They are both manifestations of continental rifting magmatism. Early work proposed a relation to late spreading on the Alpha Ridge, but this ridge appears to be older than previously supposed. Links to the (?)coeval extension in the Makarov Basin or to early rifting and spreading on the Nansen-Gakkel Ridge now seem more likely (Soper et al. 1982; Brown et al. 1987).

On the Barents Shelf, there seems to be no unequivocal evidence of magmatism related to Alpha Ridge. On Franz Josef Land, the age and petrologic character of a later generation of NE-trending dykes remains to be established. The youngest dykes of all, with a NW strike, cut Cenomanian sandstones on Hoffman Island. They are possibly matched with a leucogabbro-dolerite dated by the K-Ar technique to 94 ± 7 myBP on Alexandra Land (Tarakhovskiy et al. 1982, 1983) and/or to the final phase of magmatism from 100–90 myBP recognised by I. V. Shkola (quoted by Gramberg & Pogrebitsky 1984, p. 244).

In the final sub-stage of opening of the Arctic Basin, the Nansen-Gakkel Ridge started to spread

Table 5. Major element analyses and CIPW norms of basic rocks from Spitsbergen.

	Mesozoic			Tertiary		Quaternary
	SPIT 5	SPIT 4	SPIT 3	SPIT 2	SPIT 1	SPIT 7B
SiO_2	49.28	49.59	50.11	49.71	48.98	45.68
TiO_2	3.45	3.47	3.31	1.14	1.27	2.59
Al_2O_3	12.73	13.28	14.12	15.65	16.25	14.33
Fe_2O_3	3.25	2.68	4.12	1.70	6.95	1.81
FeO	10.77	11.09	8.77	8.78	4.26	7.76
MnO	0.218	0.226	0.200	0.170	0.176	0.161
MgO	5.74	4.90	4.32	9.46	7.94	9.34
CaO	9.12	8.67	9.21	8.23	8.64	8.36
Na_2O	2.44	2.85	2.73	3.49	3.27	5.01
K_2O	0.778	1.00	0.951	0.754	0.548	2.24
P_2O_5	0.358	0.361	0.350	0.157	0.139	0.818
LOI	1.80	1.48	1.30	0.42	1.06	1.75
Sum	99.93	99.62	99.47	99.66	99.48	99.86
FeO*	13.70	13.50	12.48	10.48	10.52	9.39
Mg. no.	0.458	0.423	0.412	0.650	0.605	0.667
CIPW weight norm.[1]						
Q	2.69	1.84	3.53	–	–	–
OR	4.69	6.04	5.74	4.49	3.31	13.52
AB	1.07	24.60	23.59	29.77	28.28	11.83
AN	21.93	20.90	23.96	25.01	28.66	10.19
NE	–	–	–	–	–	17.02
DI	18.15	17.16	16.97	12.31	11.64	21.50
HY	21.27	19.25	16.53	2.62	7.99	–
OL	–	–	–	21.25	15.28	17.16
MT	2.68	2.64	2.44	1.99	2.06	1.84
IL	6.69	6.73	6.41	2.19	2.46	5.02
AP	0.84	0.85	0.82	0.36	0.33	1.92
PX/PL[2]	0.92	0.80	0.70	0.27	0.34	0.98

Analyst: Chemistry Laboratory, GEUS.
[1] calculated volatile-free and with Fe_2O_3/FeO adjusted to 0.15;
normative (DI + HY)/(AB + AN).
SPIT 5 30/8-1918. Dolerite dyke, E side of hill, W from Skans Bay.
SPIT 4 3/8-1920. Dolerite, island in Storefjord.
SPIT 3 30/8-1918. Upper dolerite dyke, E side of hill, W from Skans Bay.
SPIT 2 Holtedahl 1910. Plagioclase basalt, Tavlefjellet, Wijdefjorden.
SPIT 1 Hoel 1912. Plagioclase basalt, Tavlefjellet, Wijdefjorden.
SPIT 7B. 18/8-1910. Basanite with lherzolite nodules. Dyke on N side of Sverrefjellet, 200 m a.s.l., Bockfjorden, Spitsbergen.

at anomaly 24 time (Paleocene) or somewhat earlier, and split a continental sliver – the Lomonosov Ridge – off the northern Barents Shelf. Extensive subaerial volcanism of Late Cretaceous – Oligocene age is inferred on the Morris Jessup and Yermak plateaus which straddle the western end of the Nansen-Gakkel Ridge. This volcanism may have formed in response to a plume or hot spot at a triple junction at the western end of this ridge (Feden et al. 1979), but a linkage to the intraplate volcanism of the Kap Washington group in northern Greenland or to plate realignments cannot be ruled out (Kristoffersen 1990). Activity ceased at anomaly 13 time (Oligocene), but V-shaped high-amplitude magnetic anomalies on the Nansen-Gakkel Ridge indicate renewal about anomaly 5 time.

A sample of (?)Pliocene age, dredged from the southern flank of the Nansen-Gakkel Ridge at 81°57′N, 118°47′E, proved to be a vesicular porphyritic, clinopyroxene-olivine basalt (Gramberg & Pogrebitsky 1984, p. 245). Basalts dredged at 4570 m depth from the central rift valley of the ridge have an enriched MORB character (Mühe et al. 1991, 1993).

Intraplate volcanoes in the De Long Archipelago could be related to the rifting advance of the Nansen-Gakkel Ridge towards the mouth of the Lena. K- and Na-rich basalts on Zhokov Island are

Table 6. Trace element analyses of basic rocks from Spitsbergen, Svalbard.

	Mesozoic			Tertiary		Quaternary
	SPIT 5	SPIT 4	SPIT 3	SPIT 2	SPIT 1	SPIT 7B
Cs	1.29	2.22	0.98	<0.2	<0.2	1.22
Rb	24.7	32.0	31.6	12.3	9.4	49.6
Ba	131	198	211	222	159	879
Pb	3.4	9.8	3.0	2.3	1.6	3.6
Sr	275	278	362	272	297	951
La	18.5	19.5	19.5	13.6	10.8	53.9
Ce	46.0	46.9	45.9	26.0	21.9	95.8
Nd	31.0	29.8	30.1	15.1	12.5	46.3
Sm	8.61	8.10	8.52	3.30	3.02	7.37
Eu	2.77	2.80	2.74	1.09	1.13	2.63
Tb	1.73	1.66	1.57	0.69	0.56	1.07
Yb	4.39	4.13	4.33	2.04	2.04	1.35
Lu	0.55	0.55	0.61	0.31	0.29	0.185
Y	53.3	54.3	60.4	22.5	23.0	26.2
La/Yb_N	2.78	3.12	2.73	4.40	3.50	26.4
Eu/Eu*	0.92	0.98	0.91	0.94	1.10	1.11
Th	3.18	3.05	2.91	2.22	1.23	6.91
U	0.73	0.74	0.73	0.23	0.255	1.74
Zr	238	243	236	98	85	236
Hf	6.31	6.41	6.37	2.33	2.15	5.25
Sn	2.3	3.4	2.4	1.2	1.2	3.0
Mo	0.5	1.1	1.0	0.7	0.2	4.8
Nb	13	13.5	13	9.5	7.7	76
Ta	0.95	0.95	0.97	0.59	0.46	4.26
Li	25	12	10	3	3	4
Zn	134	199	107	89	105	114
Cu	233	265	262	68	63	38
Co	45	36	32	49	46	43
Ni	95	55	41	233	158	247
Sc	37	36	35	22	25	15
V	414	417	402	161	200	156
Cr	99	67	50	323	315	291
As	1.5	1.6	1.3	<0.5	0.5	2.8
Ga	26	26	27	20	21	24
Ge	1.6	1.7	1.7	1.4	1.6	1.3
Au	0.03	<8.0	0.02	<0.01	<0.01	8.8
S	75	2120	1190	170	210	770
Cl	520	760	180	40	25	1320

Analysts: J. C. Bailey, R. Gwozdz, H. Kunzendorf, B. Møller.

dated radiometrically (K-Ar) as 3–10 myBP and include at least five fresh subaerial flows and near-vent ejecta containing spinel lherzolite inclusions (Savostin et al. 1988). Vil'kitsky Island has fresh basic rocks containing phenocrysts of nepheline, olivine and Ti-augite (Backlund 1920); other Tertiary alkalic basalts may occur on Bennett Island. A submarine eruption near Bennett Island in 1983–4 (Shabad 1984) remains to be confirmed.

The on-land extension of the Nansen-Gakkel Ridge, the Pliocene Moma rift, contains the Balagan-Tas volcano whose three flows of alkali basalt are almost certainly Quaternary and two other volcanoes with rhyolitic rocks (Fujita et al. 1990).

Stage 2B

Shearing and rifting along the western Barents Shelf margin, beginning in the Lower Tertiary, led to the opening of the Norwegian-Greenland Sea. Southwest of Bjørnøya, in the central rifted part of the margin, a marginal high is thought on geophysical grounds to be built of early Eocene subaerial extrusives cut by later intrusive volcanic centres, the whole forming the Vestbakken volcanic province (Faleide et al. 1988; Mørk &

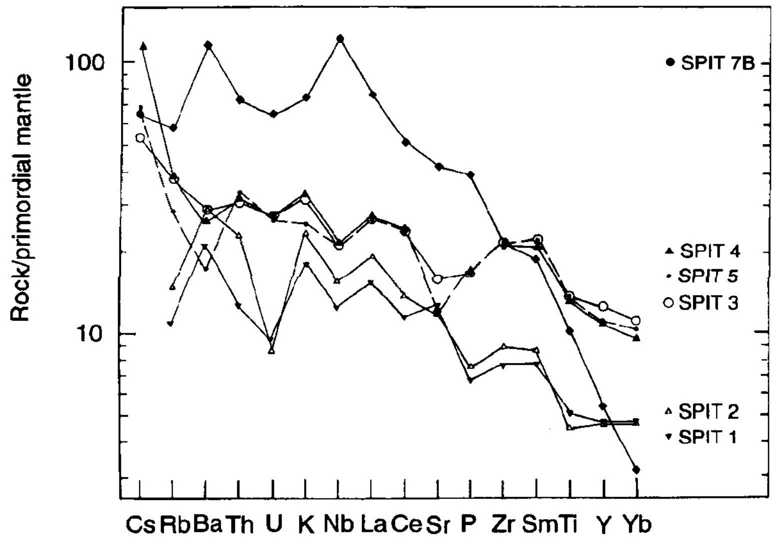

Fig. 14. Spidergrams for Spitsbergen basic rocks normalised to primordial mantle (Wood et al. 1979). Explanation: SPIT 3, 4, 5 = Mesozoic; SPIT 1, 2 = Tertiary; SPIT 7B = Quarternary. For localities, see Table 5.

Duncan 1993). Tuffaceous claystones of similar age are found in wells drilled in the SW Barents Sea (Westre 1984) and there are several ash layers in the Paleocene Firkanten Formation of Spitsbergen (Major & Nagy 1972; Dypvik & Nagy 1978).

Volcanic and intrusive activity, tentatively dated to the early Oligocene, also occurs southwest of Bjørnøya and may be linked to a major reorganisation in the motion of plates around the Norwegian-Greenland Sea at this time (Faleide et al. 1988). Recent work, however, points to a Pliocene age and non-oceanic affinities (see below).

The Knipovich Ridge, one of the modern spreading centres of the Norwegian-Greenland Sea, runs parallel to the western Barents Shelf margin. Dredged MORB are tholeiitic pillow basalts with quenched glassy rims (Neumann & Schilling 1984). Enrichment in incompatible elements such as K_2O and La is slightly higher than for the depleted MORB of the Eastern Mohns Ridge, which lies immediately to the south.

Stage 3

The post-break up stage of Barents Sea magmatism is best expressed along its western margin. In northern Spitsbergen, capping several mountains, are remnants of a roughly 300 m thick sequence of basalts, ranging from hypersthene- to nepheline-normative, and dated by the K-Ar technique to 10–12 myBP (Prestvik 1978; Skjelkvåle et al. 1989). They show continental affinities on the TiO_2-K_2O-P_2O_5 diagram (Fig. 9) and are confirmed as continental tholeiites by their spidergrams (Tables 5 and 6, Fig. 14) and low Ti/Y and Ti/Nb ratios (Fig. 12).

Basaltic volcaniclastic debris, dated to c. 2.3 myBP by the Ar-Ar technique, was recovered from shallow cores on the West Barents Shelf margin, in the same area as the older Vestbakken volcanic province (Mørk & Duncan 1993). These basalts are considered to be transitional to alkali basalts and to show signs of continental contamination; this is consistent with their location within Figs. 9 and 12 of the present paper.

Near Woodfjorden in NW Spitsbergern, three Quaternary eruptive centres consist of alkali basalt flows and ashes containing abundant xenoliths from the crust and upper mantle (Lussiaa-Berdou-Polve & Vidal 1973; Furnes et al. 1986; Amundsen et al. 1987; Skjelkvåle et al. 1989). A new analysis in Tables 5 and 6 shows the highly fractionated REE pattern and strongly positive Nb anomaly (Fig. 14) characteristic of alkali basalts.

Neogene volcanism seems related to epeirogenic uplift which is elongated along the W Barents continental margin. The uplift may be related to thinning and hot-spot warming and metasomatism of the continental lithospheric mantle (Vågnes & Amundsen 1993).

In conclusion, the sequence of lengthy and minor pre-break-up magmatism (Stage 1) followed by more voluminous tholeiitic magmatism associated with continental break-up and the opening of ocean basins along two sides of the Barents Shelf (Stages 2A and 2B) and then post-break-up, within-plate magmatism of an alkalic character (Stage 3) can be reasonably fitted to the idealised model presented above. To date, however, no examples of alkalic magmatism have been recognised in the pre-break-up stage of the Barents-Sverdrup region.

A hot-spot or plume trail?

Although hot-spots or plumes may not provide the ultimate driving force for continental break-up, their gravitational and thermal effects can influence the location and timing of break-up and lead to voluminous volcanism (White & Mackenzie 1989; Hill 1991; White 1992). It has been proposed that the Icelandic plume can be traced back to a location in NW Greenland at about 90 myBP and back to Alpha Ridge at about 100 or 130 myBP (Morgan 1983; Forsyth et al. 1986; Lawver & Müller 1994). Here we examine the evidence for its prolongation to the Permo-Triassic Siberian traps (Fig. 13).

In the Siberian platform, the most voluminous igneous activity took place at the Permo-Triassic boundary (Kuznetsov & Naumov 1975; Zolotukhin & Al'mukhamedov 1988). Flood basalts ("traps") together with intrusive and pyroclastic facies cover an area of 1.5×10^6 km^2. The traps are concentrated in marginal basins around the central uplift of the platform, notably in the NW near Noril'sk. Here, traps of the Tunguska basin ("syneclise") reach a thickness of >3.5 km; Ar-Ar dating indicates that the greatest volumes were erupted in a short time interval around 248 myBP, a feature consistent with a mantle plume origin for the province (Renne & Basu 1991). However, local dates of 230–238 myBP have also been reported (Baksi & Farrar 1991). The traps are dominated by tholeiitic basalts showing indications of crustal contamination but alkali basalts are not uncommon (Lightfoot et al. 1990, 1993; Sharma et al. 1991, 1992; Wooden et al. 1993).

To the north, basic lava flows and sills of the Taimyr Peninsula are thought to be contemporary with the Siberian traps (Nalivkin 1973; Mitchell et al. 1995). A complex of basic lavas and tuffs which have beds of clastic sediments containing fresh-water faunas and plant remains varies in thickness from 100–1000 m. A K-rich, biotite-bearing glassy basalt dyke from this peninsula has been dated by K-Ar methods to 256 myBP (Campsie et al. 1988). An augite feldsparphyric glass-rich tholeiitic basalt flow has been reported from the River Adzva (Backlund 1920).

Kimberlite pipes and dykes occupy the core of the Siberian platform and date from 450–146 myBP (Davis et al. 1980) or even c. 100 myBP (Pogrebitsky et al. 1984) and show a tendency towards northerly migration.

An extensive NW–SE rift terrain flooded with Permo-Triassic basalts occupies the area of the later West Siberian Basin and extends into the southern Kara Sea. It may be the expression of back-arc extension attendant on the late-to-post orogenic collapse of the Urals subduction zone (Surkov 1986; Ziegler 1988). Volcanism continued from Late Permian to Late Triassic with a peak during Early Triassic; the final volcanism took place towards the northwest end of the rift zones and persisted through most of the Jurassic. Geophysical modelling points to basaltic materials filling the rift graben to 8–10 km depth. The >1300 m of drilled rocks consist of lavas, lava breccias, tuffs and plate-like intrusives. The lavas, 5–50 m thick, are dominantly composed of amygdaloidal dolerites and basalts with phenocrysts of plagioclase, pyroxene and occasional olivine; andesites are rare. The intrusives, 30–50 m thick, are composed of dolerites and olivine basalts. Hydrothermal alteration pervades all these materials. Sediments are often interbedded with the lavas and consist of terrigeneous to clayey materials rich in floral detritus and coal. Extension of this rift zone to St. Anne's Basin, east of Franz Josef Land (Rudkevich 1987), has not been confirmed by recent geophysical work (Malovitskiy et al. 1987; Verba et al. 1992).

Permo-Triassic igneous units up to 300 km in extent are inferred in seismic records from the South Barents Basin. Sub-horizontal but discordant, anomalous reflectors accompanied by enhanced magnetic and gravity anomalies are thought to occur at several levels from 3–6.5 km depth in the Permo-Triassic strata (Shipilov & Mossur 1990). Younger igneous activity shifted to the north: reflectors are located in Jurassic strata along NW–SE fracture zones up to 20 km long near the Ludlow saddle (Komarnitsky & Shipilov 1994) and, as bowl-shaped bodies up to 7×12 km in size, in Lower Cretaceous rocks of the North Barents Basin.

The subsequent trail of the proposed Siberian hot-spot appears to impinge on the rifting and opening events of the Arctic basin but remains tenuous.

Judging from the voluminous Lower Cretaceous magmatic activity along the northern edge of the Barents Shelf, particularly on Franz Josef Land, and along the northern edge of the Sverdrup Basin, particularly on Ellesmere Island, plume activity may have shifted to these sites though they were probably around 1000 km apart during the Lower Cretaceous. The Icelandic-type crust of the Alpha Ridge is a potential plume trail and may be related to the climax of volcanism during Aptian-Cenomanian in northern Ellesmere Island. Based on plate motions it has been suggested that the plume then followed a track beneath Greenland being responsible for volcanism in the West and East Greenland late Cretaceous–early Tertiary provinces (Forsyth et al. 1986; Lawver & Müller 1994). It is also conceivable that part of the plume was split off and became entrained in the lithosphere of the northwest margin of the Eurasian plate as it followed an easterly track due to dextral wrench movements between the Barents Shelf and northern Greenland. This would be consistent with the shift of volcanism from the northern Sverdrup Basin eastwards towards the northern Greenland margin. Here, there is an ENE shift from late Cretaceous dyke swarms and bimodal volcanism towards lower Tertiary volcanism of the Morris Jessup and Yermak plateaus. After a mid-Tertiary pause, possible V-shaped plume trails started to develop along the Nansen-Gakkel Ridge. A plume origin for the Quarternary lavas of NW Spitsbergen, however, seems unlikely since studies on their mantle nodules only point to a temperature 50°C above that of normal asthenosphere, rather than an anomaly of c. 200–300°C reported from hot spots (Vågnes & Amundsen 1993).

Although we have outlined a possible trail of the Siberian hotspot, extending from Noril'sk to Iceland (with a derivative branch to the Yermak Plateau) over a period of c. 250 million years, much work is needed to elucidate its evolution. One major consideration is that the early trans-Arctic trajectory from Noril'sk to northern Ellesmere Island and the subsequent easterly trajectory of the derivative branch towards the Yermak Plateau are in reasonable agreement with plate motions. The available evidence points to a (so-far) unexplained waxing and waning of plume intensity, a phenomenon already recognised during the history of the eastern East Greenland–Icelandic plume. Applications of submarine geophysical methods and drilling, of reliable dating techniques such as the Ar-Ar method and of trace element and isotopic fingerprinting of plume magmas, are likely to provide critical tests for this plume trail.

Discussion

Field and petrologic data have allowed us to divide the Kong Karls Land basalts into Upper Jurassic high-TiO_2 tholeiites and Lower Cretaceous medium-TiO_2 tholeiites. The earlier tholeiites are richer in Fe and this led to crystallisation of the Fe-Ti ores at an earlier stage, a feature best expressed in the large phenocrysts of ilmenite and titanomagnetite in ferrobasalt sample 98295. The younger tholeiites are characterised by lower percentages of microphenocrysts and more magnesian bulk compositions reflected in the occasional presence of olivine.

The absence among the Kong Karls Land tholeiites of pyroxene trends with high Fe/Ca ratios (to hedenbergite) and low Fe/Ca ratios (to ferropigeonite), as found in Franz Josef Land tholeiites (Bailey & Brooks 1988), probably reflects different cooling histories in the two localities. The sills from Franz Josef Land apparently cooled slowly, reaching a stage when isolated interstitial drops of melt about 0.1 mm across were trapped in Fe/Ca-poor (plagioclase-rich) or Fe/Ca-rich (pyroxene-rich) microenvironments which controlled the chemical evolution of subsequent pyroxene. Sills and lavas on Kong Karls Land may have cooled more rapidly, especially the quenched ferrobasalt sample 98295 where pyroxene shows extreme Fe enrichment. Crystallisation within this "forbidden region" of the pyroxene quadrilateral has been recorded in lunar basalts and attributed to rapid, metastable crystallisation (Papike et al. 1976). Rapid crystallisation of sample 98295 is in agreement with enhanced partitioning of Al_2O_3, TiO_2 and Na_2O into groundmass crystallites (cf. Grove & Bence 1977). The presence of acicular and spindly-skeletal clinopyroxenes points to cooling rates around 3°C/h (Corrigan 1982).

Rhyolitic interstitial material, as found in Franz Josef Land tholeiites (Bailey & Brooks 1988), appears to be absent in the Kong Karls Land tholeiites. This suggests that fractionation of trapped interstitial liquids was arrested at an earlier stage which, in turn, points to higher rates of cooling as inferred above.

According to Klein & Langmuir (1987), the Fe-rich, Na-poor character of Mesozoic tholeiites from the Barents Shelf would imply that they formed by higher degrees of melting at greater pressures of melt segregation, say 20% melting at 16 kbars, i.e. from a relatively hot mantle region. Enhanced melting of a spinel lherzolite source dilutes contents of the largely incompatible Na_2O, leads to extensive melting of the clinopyroxene phase and thereby generates the Fe-rich basalts with high normative pyroxene/plagioclase ratios. Enhanced melting of clinopyroxene, the main Sc carrier of spinel lherzolite (Klein & Langmuir 1987), would also generate the high Sc contents found in the Mesozoic tholeiites.

A sequence of initial rifting tholeiites from high- and medium-TiO_2 types on Kong Karls Land to a low-TiO_2 type on Franz Josef Land (Bailey & Brooks 1988) can be tentatively recognised. It recalls similar sequences along the E Greenland rift margin. In the Scoresby Sund area, the "main basalts" – 96% by volume – show a systematic decrease of TiO_2 and other incompatible elements with height which Larsen et al. (1989) attributed to increasing degrees of partial melting in the underlying mantle. Upton et al. (1984) found that initial rifting tholeiites with low contents of incompatible elements were the final basalts before the onset of ocean-floor spreading and eruption of MORB.

Unlike the trend from high- to low-TiO_2 tholeiites in E Greenland, there is no systematic decrease in all incompatible elements on passing from high- to medium- TiO_2 tholeiites in Kong Karls Land. However, the change to low-TiO_2 tholeiites in Franz Josef Land is accompanied by a decrease in all incompatible elements, the overall pattern showing lower values for the most incompatible elements, suggesting derivation from a moderately depleted mantle source (Bailey & Brooks 1988).

Conclusions

Based on field and geochemical evidence, it is shown that six basalts from Kong Karls Land, Svalbard, fall into a high-TiO_2 Upper Jurassic group and a medium-TiO_2 Lower Cretaceous group. Both groups are classified as initial rifting tholeiites.

The Upper Jurassic tholeiites may be related to the Olga Rift which lies immediately to the southeast and which may represent a failed attempt to link the proto-Atlantic and proto-Arctic basins. The Lower Cretaceous tholeiites seem more closely related to initial rifting tholeiites on Franz Josef Land and Spitsbergen whose age suggests a relation to the rifting stage of opening of the Canada Basin.

The pre-, syn- and post-rifting stages of break-up of the Barents Shelf area were accompanied by magmatism whose evolution generally follows that established for other areas of continental break-up such as the North Atlantic borderlands.

Based on a literature survey, a possible hot-spot or plume trail, extending from the Permo-Triassic traps of Siberia to the Yermak Plateau, West of Spitsbergen, has been assembled.

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