Geology, age and geochemical constraints on the origin of the Late Archaean Mikkelvik alkaline stock, West Troms Basement Complex in Northern Norway

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The Late Archaean Mikkelvik alkaline stock (30x50 m) is located in the West Troms Basement Complex (WTBC), northern Norway, intruding a tonalite-trondhjemite-granodiorite (TTG) complex. U-Pb dating of titanite yielded an age of 2695±15 Ma. The stock is composed of a differentiated rock series including nepheline syenite (first and major magmatic phase), cancrinite syenite (minor dykes), and alkali (aegirine-augite) syenite (latest magmatic phase). The rocks are characterized by depletion in some HFS elements (Zr, Nb, Y), enrichment in some LIL elements (Sr, Ba) and strong REE fractionation. Geochemical data suggest that that the rocks developed from an OIB-like magma. Differentiation from alkali basalt was principally controlled by fractionation of pyroxene and amphibole. Isotopic data for Nd yield $\varepsilon_{Nd}(t) = 3.0 - 3.6$, which is characteristic of depleted mantle, but with $\varepsilon_{Sr}(t) = 5 – 19$ indicating some enrichment or crustal input. Among all known Archaean alkaline complexes, the Skjoldungen province (eastern Nain craton, Greenland) is most similar to the rocks studied here in terms of age, isotopic and geochemical signatures, indicating a similar geodynamic evolution of Greenland and WTBC in the Late Archaean.

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Introduction

Alkaline rocks and carbonatites represent less than 1% of all igneous rocks of the Earth's crust. However, the petrogenesis of these rocks is particularly interesting, in part due to their great variability and in part because they are economically important, containing most of the global reserves of, for example, the rare earth elements (REE), zirconium, niobium and phosphorus (apatite). Late Proterozoic and Phanerozoic alkaline rocks occur mainly in three geodynamic settings: (1) continental rifts, (2) oceanic islands, and (3) subduction zones. Occurrences of Archaean alkaline rocks and carbonatites are even scarcer and only a few tens of complexes in the Canadian Shield (Superior Province), Greenland (Nain craton) and Australia (Yilgarn craton) are well known to date (Libby & de Laeter 1980; Basu et al. 1984; Sutcliffe et al. 1990; Corfu et al. 1991; Blichert-Toft et al. 1995, 1996; Smithies & Champion 1999). These are composed of alkali and nepheline syenites, foidolites, carbonatites, alkali granites, lamprophyres, and potassic volcanic rocks. The oldest known alkaline rocks are about 2.70-2.65 Ga (Ben Othman et al. 1990; Cavell et al. 1992; Sutcliffe et al. 1990). Late Archaean alkaline complexes mostly belong to the potassic series. The felsic alkaline rock series show sanukitoid affinities; i.e. they share geochemical characteristics with high-Mg andesites found in modern arc settings. Most of these rocks are depleted in high field strength elements (HFSE) and enriched in some large ion lithophile (LILE) and compatible elements (Ba, Sr, Ni, Co, Cr). In general, Archaean alkaline rocks are interpreted to be related to subduction with generation in a depleted mantle source. Late Archaean subduction-related alkaline complexes presumably formed at the termination of the greenstone belt evolution (Ben Othman et al. 1990; Corfu et al. 1991). The depleted source of rocks except from sanukitoid suites is accounted for by the absence of metasomatic processes in the Archaean mantle (Blichert-Toft et al. 1996).

Two Late Archaean (ca. 2.61 Ga age) dike-like bodies of alkaline rocks and carbonatite covering an area of several square kilometers occur in the Baltic Shield (Zozulya et al. 2007). These are the Sakharjok nepheline syenite massif in the central Kola craton, NW Russia and the Siilinjärvi carbonatite massif in the western Karelia craton, Finland. Of particular interest is the 2.65-2.67 Ga Keivy alkali granite province in the central Kola craton, which is exposed over an area of ca. 2500 km^2 and formed in an anorogenic tectonic setting (Mitrofanov et al. 2000; Zozulya et al. 2005). Trace elements and Nd and Sr isotope data suggest that the Late Archaean alkaline rocks and carbonatites of the Baltic Shield were generated from a mantle source with OIB-type affinities, which is unique for the Archaean (Zozulya et al. 2007). All of the presently known occurrences of Late Archaean alkaline rocks of the Baltic Shield contain ore deposits and occurrences of rare metals (Zr, Y, REE) and apatite.

The Mikkelvik alkaline stock of Late Archaean age is a new occurrence of alkaline rocks within the West Troms Basement Complex, Northern Norway (Bøe 2000; Kullerud et al. 2006a). The purpose of this paper is to give a detailed description of these rocks, and to compare them with Late Archaean alkaline rocks from the Kola, Karelian and Nain cratons.

Geological setting

The West Troms Basement Complex

The Precambrian rocks of the West Troms Basement Complex (WTBC) occur on the islands along the west coast of the Troms region of northern Norway, from Senja in the south to Vanna in the north (Fig. 1). The northeastern part of the complex is dominated by

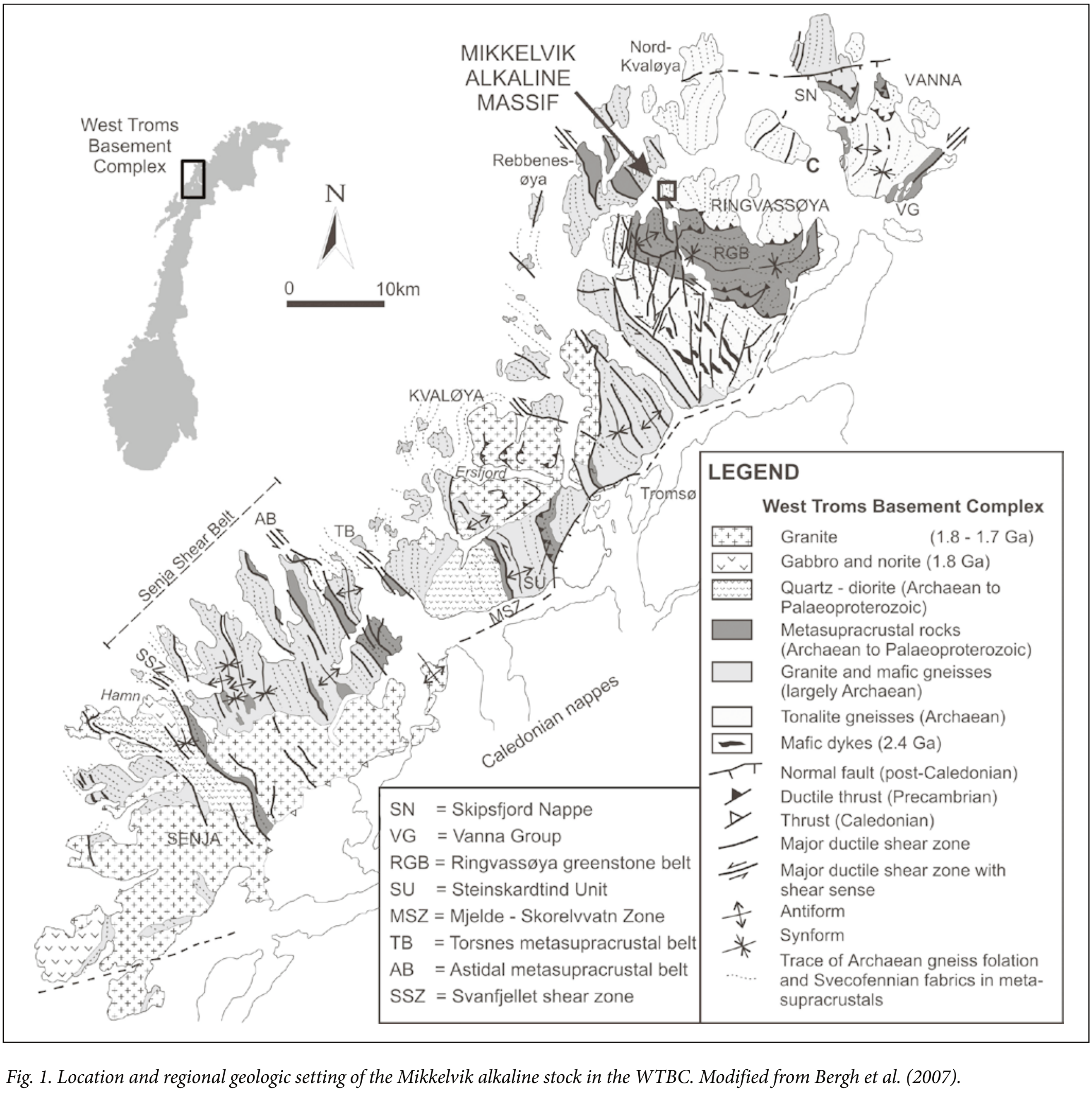

Fig. 1. Location and regional geologic setting of the Mikkelvik alkaline stock in the WTBC. Modified from Bergh et al. (2007).

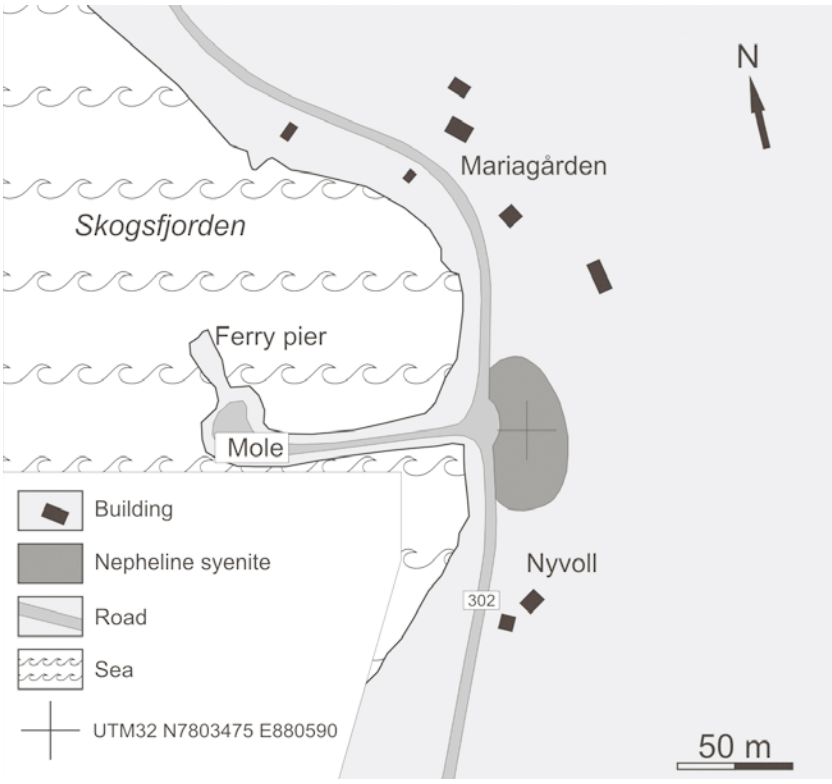

Fig. 2. Details showing the location of the Mikkelvik alkaline stock outcrop close to road 302.

Archaean tonalitic, anorthositic and gabbroic migmatitic gneisses (Zwaan & Tucker 1996; Kullerud et al. 2006a; Bergh et al. 2007). On the island of Ringvassøy, the gneisses are tectonically overlain by the Archaean Ringvassøy Greenstone Belt (Motuza et al. 2001, Kullerud et al. 2006a). Mafic dykes that cross-cut both the gneisses and the Ringvassøy Greenstone Belt were emplaced at c. 2400 Ma (Kullerud et al. 2006b). These dykes correlate broadly with a global Palaeoproterozoic magmatic event that formed extensive bimodal intrusive and extrusive suites in most Archaean cratons, including the north-eastern Fennoscandian Shield. The island of Vanna is dominated by c. 2.86 Ga tonalitic gneisses, with local cross-cutting 2.4 Ga mafic dykes (Bergh et al. 2007). Along the southern and western coast of the island, however, these rocks are unconformably overlain by the Vanna Group metasediments. The metasedimentary rocks were intruded by ca. 2.22 Ga dioritic and gabbroic sills (Bergh et al. 2007). Thus, the age of deposition of the sediments is constrained to the 2.4 – 2.22 Ga interval.

Archaean gneisses of variable composition are also present in the central and southern parts of the WTBC, an area widely overprinted by magmatism, metamorphism and deformation at 1.8 – 1.7 Ga (see references in Zwaan et al. 1998; Corfu et al. 2003).

Throughout the WTBC, large Archaean crustal segments are separated by narrow NW-trending belts of high-strain, low- to medium-grade metavolcanic and metasedimentary rocks (Armitage & Bergh 2005). Bergh et al. (in press) have suggested that these narrow belts of supracrustal rocks may represent suture zones between Archaean microcontinents that amalgamated during Svecofennian time.

The WTBC is separated from the Caledonian thrust complex in the east by a combination of a basal low-angle Caledonian thrust fault and Paleozoic-Mesozoic normal faults (e.g. Zwaan 1995; Olesen et al. 1997). It is generally believed that the WTBC represents an extension of the Fennoscandian Shield to the west of the Caledonian allochthons, but the remarkably weak Caledonian overprint of the rocks of the WTBC has led some to suggest that the complex is in a parautochthonous to allochthonous position (e.g. Brueckner 1971; Dallmeyer 1992; Motuza 1998).

The Mikkelvik alkaline stock

At Mikkelvik, on the Ringvassøy Island, a small 30x50 m stock of alkaline rocks occurs within the TTG gneisses (Fig. 2), but its contact is not exposed. The stock is composed mainly of nepheline syenite and minor cancrinite syenite dykes (Fig. 3). In addition, patches and veins of alkali syenite can be observed within the nepheline syenite.

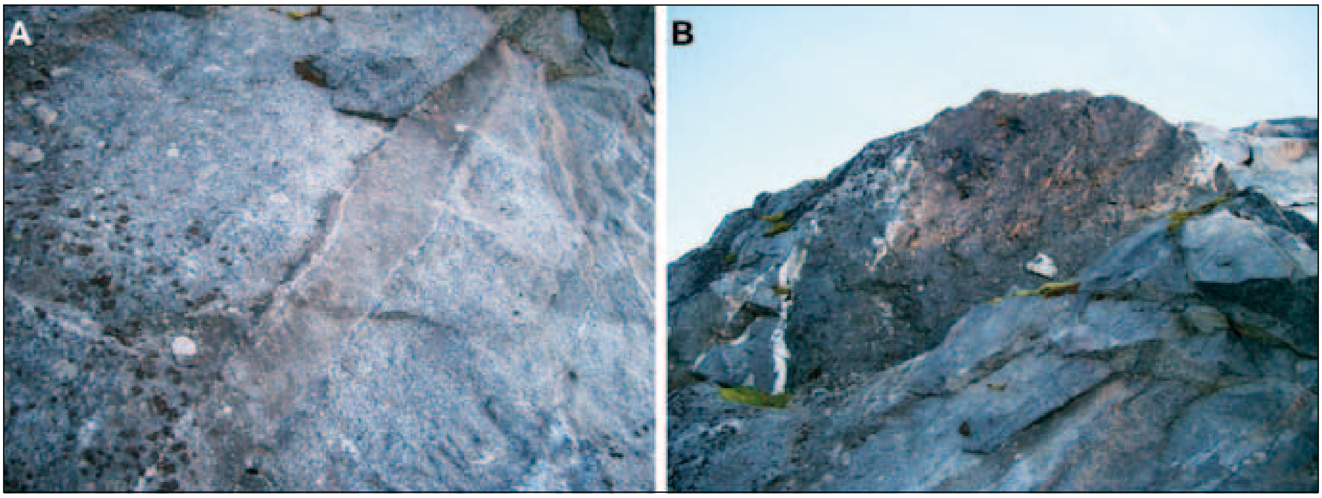

Fig. 3. Photographs of the relationship between hosted nepheline syenite and cancrinite syenite dyke 15-20 cm in thickness (A), biotitic shear zone (width of outcrop is about 3 m) and calcite veins (B).

Petrography and mineral chemistry

Nepheline syenite

The gray to dark-gray nepheline syenite is massive and medium-grained and shows a hypidiomorphic equigranular texture. Nepheline (30-40 modal %) and plagioclase (15-20 modal %) form sub-idiomorphic crystals of 1.0-3.0 mm (Fig. 4 A and B). Mineral chemical analyses (Table 1) show that nepheline contains up to 6 wt% of K_2O and negligible FeO impurities; plagioclase is mostly pure albite without any significant potassium and calcium. Potassium feldspar (15-20 modal %) occurs as anhedral, interstitial grains less than 1.0 mm across, with a negligible sodium content, but a remarkably high content of BaO (up to 1.4 wt%). The only abundant mafic mineral is biotite (20-30 modal %), which forms laths of 1.0-3.0 mm in length and show a light-green and gray to dark-green pleochroism. Biotite shows high contents of TiO_2 (up to 1.4 wt%) and FeO (up to 22.7 wt%), and is relatively low in MgO (6 wt%). Accessory minerals are epidote, titanite, apatite, allanite, calcite and zircon. In addition, Bøe (2000) reported sodalite, analcime, muscovite and natrolite as secondary mineral phases, and fluorite, dravite, andradite and corundum as accessories.

Cancrinite syenite

The dark-grey to black cancrinite syenite dikes are massive and fine- to medium-grained with a hypidiomorphic texture (Fig. 4 E and F). Cancrinite (15-20 modal %) forms poikilitic subhedral crystals of 1.0-3.0 mm size, enclosing plagioclase, biotite and calcite. Cancrinite shows a negligible content of K_2O. The sulphur content is very low (0.24 wt%), suggesting that the composition of cancrinite is close to its carbonaceous end-member. This indicates that the mineral formed by the reaction *nepheline + calcite → cancrinite*. Nepheline (10-15 modal %) also forms poikilitic subhedral crystals of 1.0-1.5 mm in size, which enclose small flakes of biotite. Potassium feldspar (10-15 modal %) and plagioclase (15-20 modal %) are xenomorphic and up to 1.0 mm in size. Nepheline contains up to 7.4 wt% of K_2O (see Table 1) and negligible FeO; plagioclase shows compositions close to pure albite. Potassium feldspar shows compositional variations with BaO concentrations ranging from 1 to 5 wt %. Biotite (20-30 modal %) commonly occurs as small grains in the groundmass and as inclusions in other minerals, but, locally also as medium-grained laths. It is characterized by high contents of FeO (24.2 wt%), TiO_2 (1.6 wt%) and BaO (0.36 wt%). Primary calcite (2-4 modal %), which forms subhedral crystals 0.1-0.4 mm in size, is rich in SrO (up to 1.2 wt%, see Table 2). Accessory minerals are epidote, apatite, titanite, allanite, magnetite, barite and stronalsite, the latter ($Sr_{1-x}Ba_xNa_2Al_4Si_4O_{16}$) is an extremely rare mineral that has been identified in some alkaline and ultramafic alkaline rocks (Liferovich et al. 2006, and references therein). The mineral has not previously been described from Norway. It forms 200-300 µm anhedral grains commonly occurring along grain boundaries between nepheline and cancrinite (Fig. 4 G and H). Stronalsite shows variations in BaO in the range 1.0 – 3.5 wt % and SrO in the range 15 – 17 wt % (Table 2). Some chemically zoned grains have relatively strontium-poor (SrO: 15-16 wt%) and barium-rich (BaO: 2.0-3.4 wt%) cores surrounded by a relatively strontium-rich (SrO: 17 wt%) and barium-poor (BaO: 1.0 wt%) rims. Bøe (2000) reported the closely related Ba end-member banalsite as tiny grains in a matrix of natrolite from a sample from Mikkelvik. Crystallization of primary strontium and barium mineral phases in the cancrinite syenite dyke is probably a result of rapid magma crystallization, such that not all of the Sr and Ba present in the magma became incorporated in the rock-forming minerals. Apatite from the cancrinite syenite also shows compositional variations. Apatite cores are high in Y_2O_3 (0.16 wt%) and REE_2O_3 (La_2O_3: 0.27 wt%; Ce_2O_3: 0.78 wt%) and low in SrO (0.6 wt%). The rims are Y- and REE-free and have elevated SrO content (ca. 1.0 wt%).

Table 1. Chemical analyses of the rock-forming minerals from Mikkelvik alkaline rocks.

Mineral	Biotite		Nepheline		K-feldspar				Plagioclase			Cancrinite	Pyroxene
Sample	NT- 3-1	NT- 3-3	NT- 3-1	NT- 3-3	NT- 3-1	NT- 3-2	NT- 3-3	NT- 3-3	NT- 3-1	NT- 3-2	NT- 3-3	NT-3-3	NT-3-2
Rock type	ns	cs	ns	cs	ns	as	cs	cs	ns	as	cs	cs	as
SiO_2	36.36	35.45	42.88	41.85	62.74	65.15	63.57	60.81	67.44	69.06	68.81	34.51	52.55
TiO_2	1.34	1.57	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.43
$Al2O_3$	17.88	17.30	33.21	34.49	18.72	18.03	18.25	18.87	19.16	19.46	19.14	28.15	0.89
FeO	22.72	24.23	0.80	0.13	0.07	0.16	0.19	0.10	0.04	0.40	0.00	0.00	23.76
MnO	0.51	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41
MgO	6.02	5.80	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	3.95
CaO	0.00	0.07	0.27	0.28	0.05	0.00	0.38	0.00	0.15	0.00	0.42	9.06	9.05
Na_2O	0.35	0.13	15.75	14.93	0.70	0.70	0.59	0.70	11.22	11.07	10.72	13.92	8.97
K_2O	9.82	10.07	6.39	7.39	15.19	16.25	15.31	13.9	0.06	0.19	0.19	0.06	0.02
BaO	0.00	0.36	0.00	0.00	1.41	0.17	1.30	4.97	0.00	0.00	0.00	0.00	0.00
SrO	n.a.	0.00	n.a.	0.00	n.a.	n.a.	0.21	0.23	n.a.	n.a.	0.00	0.16	n.a.
SO_3	n.a.	0.00	n.a.	0.00	n.a.	n.a.	0.00	0.00	n.a.	n.a.	0.00	0.60	n.a.
Total	**95.00**	**95.49**	**99.30**	**99.07**	**98.88**	**100.46**	**99.93**	**99.58**	**98.11**	**100.18**	**99.27**	**86.46**	**100.03**
	22 ox		4 ox		8 ox				8 ox			Si + Al = 12	4 cat 6ox
Si	5.659	5.573	1.041	1.019	2.959	3.005	2.972	2.918	2.999	3.007	3.018	6.118	1.962
Al	3.280	3.205	0.95	0.990	1.041	0.980	1.005	1.067	1.004	0.999	0.989	5.882	0.039
Ti	0.157	0.186	-	-	-	-	0.005	-	-	-	-	-	0.012
Fe^{3+}	-	-	-	-	-	-	-	-	-	-	-	-	0.663
Fe^{2+}	2.957	3.185	0.016	0.003	0.003	0.006	0.007	0.004	0.001	0.015	0.000	-	0.122
Mn	0.067	0.068	-	-	-	-	-	-	-	-	-	-	0.013
Mg	1.397	1.359	-	-	-	-	-	-	0.003	-	-	-	0.220
Ca	0.000	0.012	0.007	0.007	0.003	0.000	0.019	0.000	0.007	0.000	0.020	1.721	0.362
Na	0.106	0.040	0.741	0.705	0.064	0.063	0.053	0.065	0.967	0.935	0.912	4.785	0.649
K	1.950	2.019	0.198	0.230	0.914	0.956	0.913	0.851	0.003	0.011	0.010	0.014	0.001
Ba	0.000	0.022	-	-	0.026	0.003	0.024	0.093	0.000	0.000	0.000	-	-
Sr	-	-	-	-	-	-	-	-	-	-	-	0.016	-
S	-	-	-	-	-	-	-	-	-	-	-	0.080	-

Note. Mineral analyses were made by a Cameca MS-46 electron microprobe (EMP) at the Geological Institute of the Kola Science Centre, applying an acceleration voltage of 22 kV, probe current 20 to 40 nA and beam diameter of 2 to 5 µm. n.a. – not analyzed; ns – nepheline syenite; as – alkali syenite; cs – cancrinite syenite..

Based on the mineral content (high nepheline and mafic mineral contents), the nepheline and cancrinite syenites are transitional between nephelinitic rocks (foidolite) and foid syenite. More accurately, they correspond to juvite-malignite of the mafic alkaline rock series. However, since the rocks contain two feldspars (potassium feldspar and albite) the root name foid syenite, which is based on the classification and nomenclature recommended by the IUGS (Streckeisen 1973), is preferred.

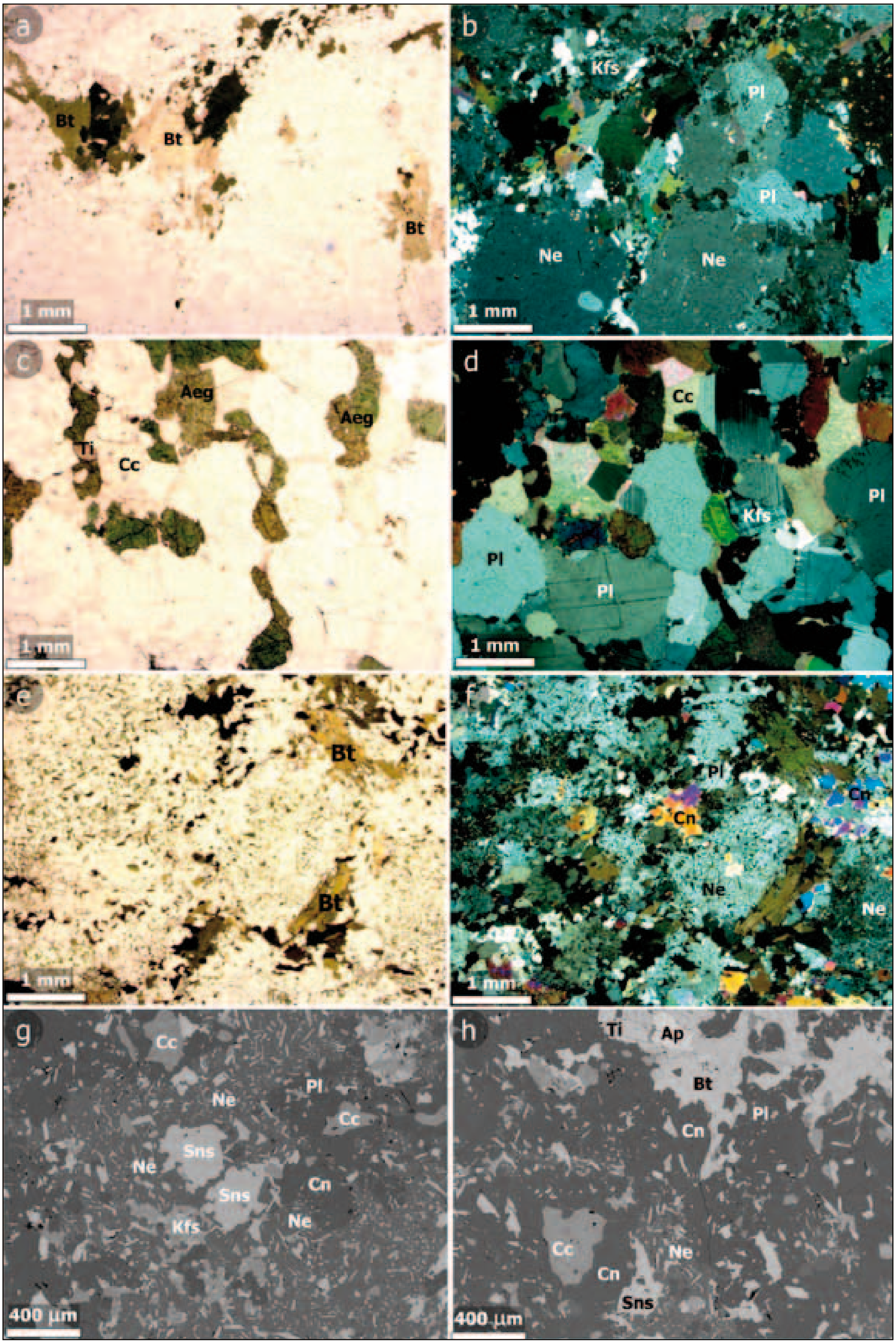

Fig. 4 A-H: Microphotographs of typical rock thin sections for Mikkelvik alkaline stock (A – nepheline syenite (polarized light); B – same as A, but with crossed polars; C – alkali syenite (polarized light); D – same as C, but with crossed polars; E – cancrinite syenite (polarized light); F – same as E, but with crossed polars; G and H – back-scattered-electron images showing textural features of accessory and rock-forming minerals from cancrinite syenite (prepared in the Geological Institute KSC using a LEO-1450 scanning electron microscope); Bt – biotite; Ne – nepheline; Kfs – potassium feldspar (microcline); Pl – plagioclase (albite); Aeg – aegirine-augite; Cn – cancrinite; Cc – calcite; Ti – titanite; Ap – apatite; Sns - stronalsite).

Table 2. Chemical analyses of some accessory minerals from the Mikkelvik cancrinite syenite sample NT-3-3.

Mineral	Apatite (c)	Apatite (r)	Calcite	Stronalsite	Stronalsite	Stronalsite (c)	Stronalsite (r)
SiO_2	0.55	0.12	0.06	38.33	38.50	38.86	38.69
Al_2O_3	0.06	0.09	n.a.	31.73	31.95	32.41	32.04
FeO	0.05	0.20	0.13	0.04	0.00	0.00	32.04
MnO	0.00	0.00	0.22	0.00	0.00	0.00	0.00
MgO	n.a.	n.a.	0.00	0.00	0.00	0.00	0.00
CaO	53.86	54.89	54.35	0.81	0.84	0.86	0.90
Na_2O	0.15	0.00	n.a.	9.60	9.61	10.22	10.10
K_2O	0.03	0.07	0.04	0.05	0.06	0.04	0.08
BaO	n.a.	n.a.	0.00	3.40	1.93	1.95	1.03
SrO	0.63	1.01	1.23	14.78	16.04	16.11	17.04
Y_2O_3	0.16	0.00	n.a.	0.00	0.00	0.00	0.00
La_2O_3	0.27	0.00	n.a.	0.00	0.00	0.00	0.00
Ce_2O_3	0.78	0.00	n.a.	0.00	0.00	0.00	0.00
P_2O_5	40.48	41.93	n.a.	n.a.	n.a.	n.a.	n.a.
Cl	0.03	0.02	n.a.	0.00	0.00	0.00	0.00
Total	97.05	98.33	56.03	98.74	98.93	100.45	99.98
	16 cat	16 cat	1 cat	16 ox	16 ox	16 ox	16 ox
Si	0.094	0.020	0.001	4.011	4.005	3.986	3.989
Al	0.012	0.018	-	3.913	3.917	3.918	3.893
Fe	0.007	0.028	0.002	0.004	0.000	0.000	0.009
Mn	-	-	0.003	-	-	-	-
Mg	-	-	0.000	-	-	-	-
Ca	9.843	9.866	0.981	0.091	0.094	0.095	0.099
Na	0.050	0.000	-	1.948	1.938	2.033	2.019
K	0.007	0.015	0.001	0.007	0.008	0.005	0.011
Ba	-	-	-	0.139	0.079	0.078	0.042
Sr	0.062	0.098	0.012	0.897	0.968	0.958	1.019
Y	0.015	-	-	-	-	-	-
La	0.017	-	-	-	-	-	-
Ce	0.049	-	-	-	-	-	-
P	5.845	5.955	-	-	-	-	-
Cl	0.009	0.006	-	-	-	-	-

Note. Mineral analyses were made by a Cameca MS-46 electron microprobe (EMP) at the Geological Institute of the Kola Science Centre, applying an acceleration voltage of 22 kV, probe current 20 to 40 nA and beam diameter of 2 to 5 µm. (c) - core; (r) - rim; n.a. – not analyzed.

Alkali syenite

The youngest component of the alkaline complex is represented by an alkali syenite. This forms irregular patches and veins, a few tens of centimeters thick, within the nepheline syenite. The gray alkali syenite is massive and medium-grained and shows a hypidiomorphic equigranular texture (Fig. 4 C and D). It is mainly composed of subhedral albite (50-60 modal %), 1-3 mm in size. Potassium feldspar (10-15 modal %) is anhedral and interstitial with grain sizes less than 1 mm. Pyroxene (15-20 modal %) forms elongated subhedral crystals of 1.0-1.5 mm and aggregates of 3-5 mm. Usually pyroxene grains show optical zoning with dark-green cores and light-green rims. Pyroxene is pleochroitic (gray-greenish and green) and shows the reverse absorption typical of alkaline pyroxene. Based on the chemical composition (Table 1) the pyroxene is classified as aegirine-augite. The alkali syenite contains abundant primary carbonate (6-10 modal %), occurring as small (up to 0.3 mm) subhedral inclusions in pyroxene and as interstitial grains up to 1.0 mm in size. Accessory minerals are titanite and apatite.

Post-magmatic events observed in the Mikkelvik stock are represented by 2-10 cm thick shear zones dominated by coarse-grained biotite (Fig. 3) and 1-5 cm thick veins of calcite.

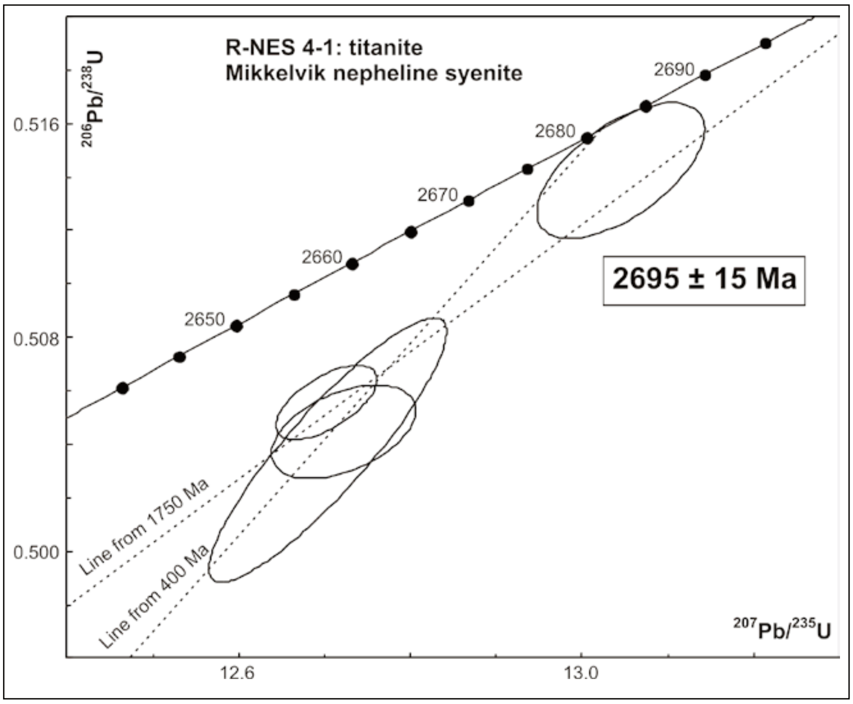

Fig. 5. U-Pb concordia diagram for titanite from the Mikkelvik alkaline rock.

Age of emplacement

Millimeter size titanite fragments were broken out of the syenite and prepared for analysis by mechanical abrasion and hand-picking. Dissolution was done in Savillex vials on a hot-plate and the chemical separation used a single stage HCl-HBr technique. Other details of the procedure are given in Corfu (2004). U-Pb data for titanite from the Mikkelvik nepheline syenite are presented in Table 3, and concordia diagram in Figure 5.

The four analyses are slightly discordant so that some Pb loss must be allowed for. The age of 2695±15 Ma incorporates the limits defined by lines projected through the data points from 1750 Ma and 400 Ma, respectively, assuming that Pb loss may have occurred during one or both of these events (Corfu et al. 2003). Nevertheless, the degree of disturbance is remarkably moderate considering that titanite in all other units studied in the WTBC was much more severely disturbed during the two subsequent orogenies (Myhre & Corfu 2008).

Geochemical constraints on the origin of the Mikkelvik alkaline rocks

Samples of about 2-4 kg of the three rock types of the Mikkelvik stock were used for geochemical studies (sample NT-3-1: nepheline syenite, sample NT-3-2: alkali syenite, sample NT-3-3: cancrinite syenite). Major elements (Table 4) were analyzed by atomic absorption spectrophotometry (Fe_2O_3 by titration) at the Geological

Table 3. U-Pb data for titanite from the Mikkelvik nepheline syenite sample R-NES 4-1.

Sample1)	Weight	U	Th/U3)	Pbc4)	$^{206}Pb/^{204}Pb$ 5)	$^{207}Pb/^{235}U$ 6)	2σ	$^{206}Pb/^{238}U$ 6)	2σ	rho	$^{207}Pb/^{206}Pb$ 6)	2σ	$^{206}Pb/^{238}U$ 6)	$^{207}Pb/^{235}U$ 6)	$^{207}Pb/^{206}Pb$ 6)	2σ	D7)
	[µg]2)	[ppm]2)		[ppm]			[abs]		[abs]			[abs]	[Ma]	[Ma]	[Ma]	[abs]	[%]
1fr y tr	209	8,5	5,28	1,2	203	13,045	0,080	0,5142	0,0021	0,61	0,18399	0,00089	2675	2683	2689,1	8,0	0,7
1fr y tr	49	10,1	5,24	1,5	199	12,722	0,069	0,5045	0,0014	0,46	0,18291	0,00088	2633	2659	2679,4	7,9	2,1
1fr y tr	62	21,2	4,76	1,8	336	12,702	0,048	0,5056	0,0011	0,62	0,18222	0,00054	2638	2658	2673,2	4,9	1,6
18 fr br-y	895	11,8	5,20	1,3	257	12,704	0,113	0,5038	0,0040	0,90	0,18289	0,00072	2630	2658	2679,3	6,5	2,0

Note. 1) fr = fragments of large crystals, abraded; y = yellow; br = brown; tr = transparent 2, 4) weight and concentrations are known to better than 10%; 3) Th/U model ratio inferred from 208/206 ratio and age of sample; 4) Pbc = initial common Pb concentration; 5) raw data corrected for fractionation and blank; 6) corrected for fractionation, spike, blank and initial common Pb; error calculated by propagating the main sources of uncertainty; 7) D = degree of discordancy.

Table 4. Major element analyses and CIPW norms of the Mikkelvik rocks.

Sample	NT-3-1	NT-3-2	NT-3-3		Sample	NT-3-1	NT-3-2	NT-3-3
Rock type	**ns**	**as**	**cs**		**Rock type**	**ns**	**as**	**cscs**
SiO_2	48.67	58.41	49.45		*ap*	1.14	0.90	0.85
TiO_2	0.64	0.36	0.39		*hl*	0.11	0.03	0.04
Al_2O_3	23.43	13.91	23.19		*fr*	0.12	0.04	0.38
Fe_2O_3	1.81	4.01	1.12		*cc*	1.80	6.85	3.21
FeO	3.57	1.87	4.12		*ilm*	1.22	0.68	0.74
MnO	0.11	0.11	0.13		*mt*	2.62	0.58	1.62
MgO	1.14	1.05	1.36		*c*	0.93		2.89
CaO	2.72	5.68	2.97		*or*	21.51	12.88	23.11
Na_2O	10.18	8.44	9.27		*ab*	24.16	59.43	28.66
K_2O	3.64	2.18	3.91		*an*	5.24		2.36
H_2O	0.20	0.02	0.15		*ne*	33.29		26.85
P_2O_5	0.48	0.38	0.36		*ac*		10.44	
CO_2	0.79	3.01	1.41		*di*		2.96	
Cl	0.07	0.02	0.03		*hd*		2.67	
F	0.08	0.03	0.20		*en*		0.39	
LOI	1.84	0.22	1.50		*fs*		0.40	
Total	**99.37**	**99.70**	**99.56**		*fo*	1.99	0.60	2.37
Mg#	28.11	25.47	32.12		*fa*	3.24	0.68	4.81
K_{agp}	0.88	1.17	0.84					

Note. ns – nepheline syenite; as – alkali syenite; cs – cancrinite syenite.

Institute, Kola Science Centre, Apatity. Trace elements (Table 5) were analyzed by ICP-MS in the Institute of Geology and Geochemistry, Ural Branch of the Russian Academy of Sciences, Ekaterinburgh. Additionally the data of Bøe (2000) on major and trace element whole-rock composition of foid syenites were used for geochemical constraints. Neodymium and Sr isotopic compositions (Table 6) were measured on a Finnigan-MAT 262 (RPQ) and a MI-1201-T mass spectrometer, respectively, at the Laboratory of Geochronology and Isotope Geochemistry of the Geological Institute, Kola Science Centre, Apatity.

The silica content of the rocks of the Mikkelvik stock ranges from 48-49 wt % in the foid syenite and up to 58 wt% in alkali syenite. The low silica content of the foid syenite may be explained by the more basic character of the rock (see section "Petrography and mineral chemistry") and by the presence of biotite as the only mafic mineral. The foid syenite is characterized by relatively high contents of Al_2O_3 (ca. 23 wt%), Na_2O (9-10 wt%), and K_2O (3.6-3.9 wt%), and low MgO (1.1-1.4 wt%) and CaO (2.7-3.0 wt%). The alkali syenite is characterized by lower contents of Al_2O_3 (ca. 14 wt%), K_2O (2.2 wt%) and Na_2O (8.4 wt%), and higher contents of CaO (5.7 wt%) and $Fe_2O_3^{total}$ (6.1 vs. 5.7-5.8 in the foid syenite). The Mikkelvik foid syenite shows an agpaitic coefficient ((Na+K)/Al) in the range 0.8 - 0.9, which is characteristic of miaskitic rock types. The alkali syenite shows an agpaitic character with a coefficient of 1.2. The Na/K ratio of the rocks varies from 3.6 to 6.0, reflecting their sodic type of alkalinity. The foid syenite shows high Mg# (Mg# = 28 - 32) compared to the alkali syenite (Mg# = 25.5) indicating that the latter is more evolved. The CO_2 content of the rocks is in agreement with petrographic observations: 0.8 wt% in nepheline syenite, 1.4 wt% in cancrinite syenite and 3.0 wt% in alkali syenite, which is richest in calcite.

The alkaline character of the Mikkelvik rocks is reflected in the calculated CIPW normative values (Table 4) of feldspathoids (*ne:* 27-33 %) in the foid syenite, alkali pyroxene (*ac:* 10.4 %) in alkali syenite and alkali feldspars (*ab:* 24-59 % and *or:* 13-23 %) in both types of rocks. Silica undersaturation and the peraluminous character of the syenites are expressed by normative corundum (*c:* 0.9-2.9 %) and olivine (*fo:* 0.6-2.4 %; *fa:* 0.7-4.8 %). Normative calcite is 1.8 % in nepheline syenite, 3.2 % in cancrinite syenite, and 6.9 % in alkali syenite.

The syenites of the Mikkelvik stock are depleted in most HFSE and volatiles. The foid syenite contains 3 – 5 ppm Zr, while the alkali syenite contains 180 ppm Zr. Further, the rocks contain 13–15 ppm Nb, 0.5–1.1 ppm Ta and 8–16 ppm Y. Fluorine varies in the range 0.03-0.2 wt %. The higher contents of HFSE for the alkali syenite compared to the foid syenite indicate a more evolved character for the alkali syenite. The rocks show low and moderate contents of transitional elements (Sc 1-7 ppm, Co 8-11 ppm, Ni 2-16 ppm) for the nepheline syenite and the alkali syenite. The foid syenite shows very high concentrations of Ba (1060–1350 ppm) and Sr (2060-2370 ppm) compared to the alkali syenite (140 ppm Ba and 980 ppm

Table 5. Trace elements and REE analyses of Mikkelvik rocks (ppm).

Sample	NT-3-1	NT-3-2	NT-3-3		Sample	NT-3-1	NT-3-2	NT-3-3
Rock type	**ns**	**as**	**cs**		**Rock type**	**ns**	**as**	**cscs**
Li	39.5	3.3	36.1		Cs	0.61	0.11	1.08
Be	0.9	2.1	0.7		Ba	1345	141	1059
Sc	1.1	6.8	2.4		La	49.4	101.1	47.9
Ti	3411	1957	3681		Ce	116.4	209.3	99.6
V	22	35	23		Pr	12.8	21.1	12.1
Cr	124	87	4		Nd	44.0	69.6	42.5
Mn	835	822	786		Sm	4.99	8.18	4.93
Co	10	8	11		Eu	1.28	2.09	1.22
Ni	16	13	2		Gd	2.64	4.28	3.67
Cu	9	13	5		Tb	0.31	0.58	0.31
Zn	501	676	153		Dy	1.82	3.45	1.90
Ga	16	17	16		Ho	0.34	0.64	0.34
Ge	0.6	0.9	0.6		Er	0.85	1.69	0.86
Rb	62	15	68		Tm	0.11	0.24	0.11
Sr	2374	984	2057		Yb	0.71	1.68	0.68
Y	8	16	9		Lu	0.10	0.28	0.10
Zr	5	184	3		Hf	0.18	4.23	0.14
Nb	13	13	15		Ta	0.53	0.53	1.09
Mo	11	11	2		W	0.88	0.32	0.17
Ag	0.38	0.31	0.22		Tl	0.30	0.08	0.25
Cd	nd	nd	0.19		Pb	8.81	6.12	15.26
Sn	0.48	1.46	0.49		Bi	nd	0.01	0.03
Sb	0.16	0.12	0.19		Th	0.64	6.16	0.87
Te	0.02	nd	0.07		U	0.13	0.57	0.17

Note. ns – nepheline syenite; as – alkali syenite; cs – cancrinite syenite; nd – not detected.

Table 6. Nd and Sr isotope analyses of Mikkelvik alkaline rocks.

Sample	**Rock type**	**Sm**	**Nd**	**^{147}Sm/^{144}Nd**	**^{143}Nd/^{144}Nd**	**ε_{Nd}(2695)**
		ppm				
NT-3.1	ns	5.093	43.670	0.070503	0.510569±19	3.4
NT-3.2	as	8.435	69.576	0.073285	0.510629±19	3.6
NT-3.3	cs	5.132	43.233	0.071756	0.510567±16	3.0
Sample	**Rock type**	**Rb**	**Sr**	**^{87}Rb/^{86}Sr**	**^{87}Rb/^{86}Sr**	**ε_{Sr}(2695)**
		ppm				
NT-3.1	ns	58.89	2494	0.06830	0.70468±35	11
NT-3.2	as	14.84	1131	0.03794	0.70407±49	19
NT-3.3	cs	68.11	2501	0.07878	0.70468±35	5

Note. Average values (2σ) for standards during the measurement period: La Jolla 0.511805±8 (N=13) and JNdi1 0.512066±15 (N=96); ns – nepheline syenite; as – alkali syenite; cs – cancrinite syenite.

Sr). The high contents of Rb (62-68 ppm) and Li (36-40 ppm) of the foid syenite compared to the aegirine-bearing alkali syenite (15 ppm Rb, 3.3 ppm Li) can be related to the high biotite content of the former. Of interest are the elevated values of some platinum group elements in the cancrinite syenite: Pd 0.21 ppm, Rh 0.08 ppm.

The Mikkelvik alkaline rocks are enriched in REE (rare earth elements), which comprise 220-240 ppm in the foid syenite (3-10 times chondritic values for HREE and 50-100 times chondritic values for LREE) and 420 ppm in the alkali syenite (5-10 times chondritic values for HREE and 100-300 times chondritic values for LREE).

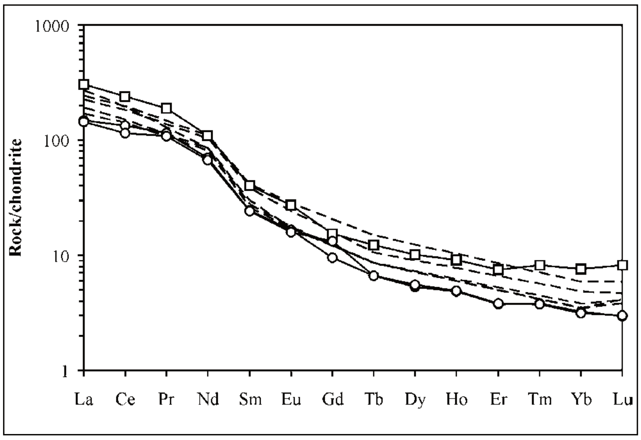

Fig. 6. REE variation diagrams for Mikkelvik alkaline rocks (this study: circles – foid syenites, square – alkali syenite; dotted line – foid syenite from Bøe (2000)). Chondrite normalizing values from Nakamura (1974).

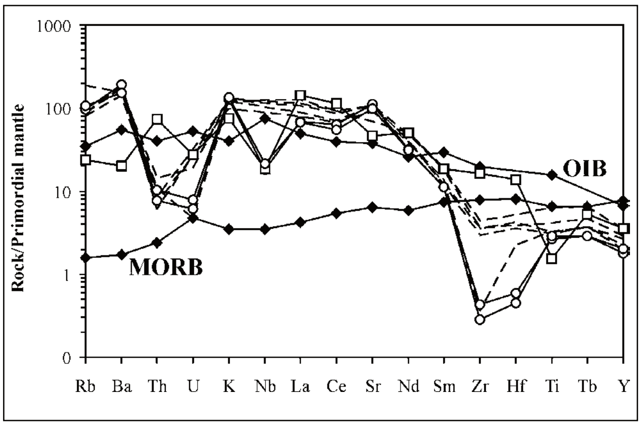

Fig. 7. Incompatible trace element variation diagrams for Mikkelvik alkaline rocks (same symbols as in Fig. 6). Primordial mantle normalizing values from McDonough et al. (1991). Average N-type MORB from Saunders & Tarney (1984) and OIB from Sun & McDonough (1989) and designated as rhombs.

The relative enrichment of REE in alkali syenite compared to the foid syenite is in accordance with the more evolved character of the former. The Mikkelvik rocks show a steep pattern in the chondrite normalized REE diagram (Fig. 6) with La/Yb$_n$ = 40–46, and have no Eu anomaly (Eu/Eu* 0.84-0.98).

In the primordial mantle-normalized diagram (Fig. 7) the incompatible trace elements show an increase from highly incompatible to more compatible elements. In general, the pattern is similar to OIB-type magmas, except for lower concentrations of the more compatible elements, especially Zr and Hf, in the Mikkelvik rocks. The most incompatible elements show distributions that are similar to OIB-type magmas, except for Th and U and Zr and Hf. It is likely that the depletion in Th, U, Zr and Hf is a specific feature of the parental magma for the Mikkelvik rocks. Similar geochemical signatures are reported for alkaline rocks from the Skjoldungen province (Blichert-Toft et al. 1995). Enrichment of these elements to concentrations similar to OIB values, as for the alkali syenite in Mikkelvik, can only occur during subsequent fractionation of a foid syenitic magma.

As the absolute values of trace elements cannot give an unambiguous characterization of the primary magma type, a petrogenetic elemental ratio analysis has been carried out. Eby (1990) showed that Y/Nb and Yb/Ta ratios can be used for identification of tectonic setting during magma formation. These ratios remain relatively constant during the evolution of a particular magmatic suite. On the Y/Nb - Yb/Ta diagram (Fig. 8) the Mikkelvik foid syenite plots in or close to the OIB field. The alkali syenite, however, plots outside the OIB field, because of its higher Yb/Ta ratio. A possible reason for the high Yb/Ta ratio of the alkali syenite is that the magma was enriched in REE during fractionation from foid syenite. All of the Mikkelvik rock types fall within the field of the Sakharjok nepheline syenite (NE Baltic shield), which originated from an enriched plume-related mantle source (Zozulya et al. 2007). Unfortunately, Yb/Ta ratios from the nephelinitic rocks of the Skjoldungen alkaline province (eastern Nain craton, Greenland) are not available. However, their Y/Nb ratios (Blichert-Toft et al. 1995) vary from 0.4 to 2.3 (average value 1.4), which is close to the ratios for the Mikkelvik rocks. The high (Ce/Yb)$_n$ ratio (37-42 in foid syenites, 32 in alkali syenite) not correlated to REE content also indicates an enriched OIB-like source, rather than IAB- or MORB sources for the Mikkelvik syenites.

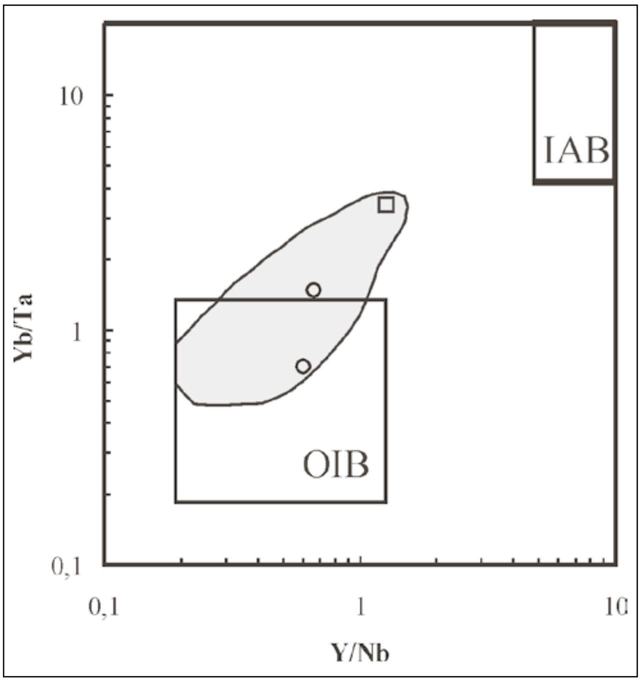

Fig. 8. Y/Nb versus Yb/Ta discriminant diagrams for Mikkelvik alkaline rocks (same symbols as in Fig. 6). OIB and IAB fields are from (Eby, 1990); shaded area – nepheline syenites of the Late Archaean Sakharjok massif, NE Baltic Shield (Zozulya et al., 2008).

The ratio Ce/Nb can be used in order to identify the differentiation mode. The foid syenite shows relatively constant Y/Nb ratios (0.61-0.62) but a strong variation in Ce/Nb (6.5-8.9). For this particular set of ratios, only clinopyroxene and amphibole may have been significant phases during fractional crystallization, removing Mg, Ca, Fe and Ti from the parental basaltic melt, leading to an enrichment of Al, Na and K in the residual melt. The absence of Eu anomalies for the Mikkelvik rocks suggests that plagioclase fractionation did not occur.

Since alkaline rocks and carbonatites characteristically show high concentrations of Sr and REE, contamination by these elements during intrusion and later alteration processes is negligible and the Nd and Sr initial ratios of such rocks are therefore generally regarded as true characteristics of their mantle source. Previous Nd and Sr isotopic studies of Archaean alkaline and carbonatitic complexes are limited and mostly from the Superior province. Values of 1.0 to 3.0 for ε_{Nd}(t) are reported for alkaline volcanic and intrusive rocks in the Abitibi subprovince (Barrie & Shirey 1989; Basu et al. 1984; Ben Othman et al. 1990) and ε_{Nd}(t) values of 1.0 to 1.5 for felsic-intermediate alkaline intrusive rocks in the Wabigoon subprovince (Shirey & Hanson 1986). From a nepheline syenite of the Poohbah Lake in a nearby subprovince apatite analyses yielded $\varepsilon_{Nd}(t) = 1.3 - 1.5$ and $\varepsilon_{Sr}(t) = -0.4 - -1.1$, while whole rock analyses for syenite yielded $\varepsilon_{Nd}(t) = -0.3$ and $\varepsilon_{Sr}(t) = -0.5$ (Bell & Blenkinsop 1987). Thus Sr and Nd isotopic compositions of Archaean alkaline rocks from the Superior Province indicate that the parent magma of the rocks originated from a depleted mantle source similar to that of contemporaneous tholeiitic basalts.

ε_{Nd}(t) values of -1.1 to 0.6 and ε_{Sr}(t) values of -1.7 to 20 obtained for carbonatite, nephelinitic and mafic rocks of the 2.70–2.66 Ga Skjoldungen alkaline province of eastern Nain Craton, Greenland (Blichert-Toft et al. 1995), indicate involvement of an enriched component.

Archaean alkaline rocks and carbonatites from the Baltic Shield show different Sr and Nd isotopic compositions (Zozulya et al. 2007). Carbonatites and glimmerites of the Siilinjärvi massif are characterized by ε_{Nd}(t) values ranging from −0.4 to −1.2 (Fig. 9). The variations of ε_{Sr}(t) are larger (from −2.7 to 50.5) and are probably related to Rb enrichment during the magma differentiation within the chamber or to the crustal contamination. Thus, the isotopic data indicate a moderately enriched mantle source for the Siilinjärvi rocks. Sm–Nd isotopic data from alkaline rocks in the Sakharjok massif show larger variations with $\varepsilon_{Nd}(t) = 0.4$ to −3.0 and $\varepsilon_{Sr}(t) = 100$ to 5800. The variations are consistent with the high grade of metamorphism of most of the rock varieties (Zozulya et al. 2005; 2007). However, it should be noted that data from the least metamorphosed and evolved varieties of the rocks (alkaline gabbro) plot within the field of EM-2 reservoir in the $\varepsilon_{Sr}(t)–\varepsilon_{Nd}(T)$ diagram (Fig. 9).

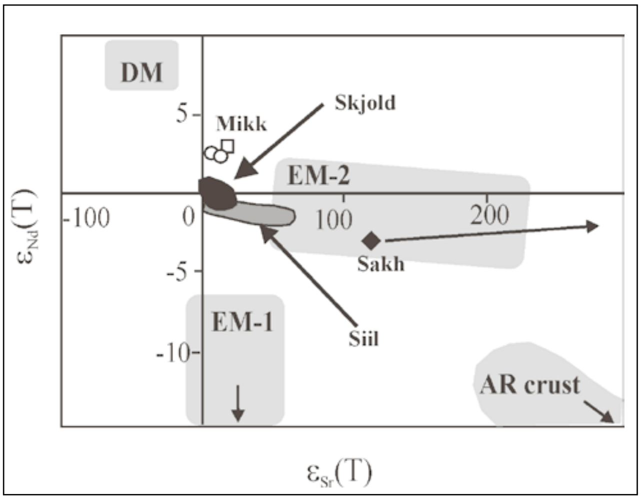

Fig. 9. $\varepsilon_{Sr}(t)–\varepsilon_{Nd}(t)$ *diagram for Archaean alkaline rocks of the Baltic and Greenland shields, and of Mikkelvik alkaline stock (WTBC). (Sakh) – Trend for alkaline rocks of the Sakharijok massif (alkaline gabbro is designated by a rhomb); (Siil) – Siilinjärvi carbonatite complex; (Skjold) – Skjoldungen alkaline province; (Mikk) Mikkelvik alkaline stock (same symbols as in Fig. 6). EM-1 and EM-2 refer to enriched mantle 1 and 2, respectively.*

The Mikkelvik alkaline rocks have high Sr and Nd contents (1100-2500 ppm and 43-70 ppm, respectively), strongly indicating that crustal contamination is negligible. Positive ε_{Nd}(t) values (3.0 - 3.6) typify rocks derived from highly depleted mantle at that time, whereas the ε_{Sr}(t) values (5 – 19) suggest some enrichment. Among the Archaean alkaline complexes that are known so far, the Skjoldungen province is the one that is closest to the Mikkelvik rocks in terms of isotopic and geochemical compositions. The overall geochemical features of the Skjoldungen rocks, combined with Nd isotopic initial ratios, provide evidence for an origin in a subduction zone environment by melting of an OIB lithospheric mantle wedge (Blichert-Toft et al. 1995). It is not, however, impossible that the Skjoldungen and Mikkelvik rocks may have originated from a plume tectonic environment. Recycling of subducted crust and sediments could have caused enrichment of Rb, Na, K, Sr, Ba in the mantle reservoir, leading to radiogenic Sr incorporation to the mantle.

The data that so far exist from the Archaean alkaline rocks of the Baltic (Kola and Karelian cratons) and Greenland (Nain craton) shields, and of West Troms Basement Complex (Northern Norway) indicate that the rocks have a common genetic and geodynamic history. This reflects the development of a Late Archaean mantle plume with incorporation of enriched mantle sources (2.70–2.66 Ga: the initial stage of the plume evolution, near-chondritic and slightly enriched mantle source of the parental magma; 2.65–2.61 Ga: the final stage, enriched source of the parental magma).

Conclusions

The Late Archaean (2695 Ma) Mikkelvik alkaline stock is composed of a differentiated rock series and may be subdivided into three stages including (1) nepheline syenite (first and major magmatic phase), (2) cancrinite syenite (minor dykes) and (3) alkali (aegirine-augite) syenite (latest magmatic phase). The foid syenite is composed of nepheline, K-feldspar, albite, cancrinite and biotite; the accessory minerals are epidote, apatite, titanite, allanite, magnetite, barite and also stronalsite (which is the first reported occurrence of this mineral in Norway). Geochemical data (REE and incompatible element distributions, low Y/Nb and Yb/Ta) suggest that the rocks developed from OIB-like magma. Differentiation of the magma from alkali basalt was principally controlled by fractionation of pyroxene and amphibole. Sr and Nd isotope data indicate a near-chondritic and slightly enriched mantle source for the parental magma. Among all known Archaean alkaline complexes, the Skjoldungen province (eastern Nain craton, Greenland) most closely resembles the studied rocks in terms of age, isotopic and geochemical signatures, suggesting a common geodynamic evolution for Greenland and the WTBC in the Late Archaean.

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