Porphyritic syenite at Lake Mykle, the Oslo Rift – a possible derivative of larvikite

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New Rb-Sr and Sm-Nd isotope data on porphyritic syenite from lake Mykle in the southern part of the Oslo Rift confirm a close compositional and genetic relationship between this rock and the associated larvikite. The porphyritic syentite has initial $^{87}Sr/^{86}Sr$ at 280 Ma between 0.7044 and 0.7048, and ε_{Nd} between + 1.56 and + 2.52. This pattern of variation is compatible with contamination of a mantle-derived parent magma with small amounts of Precambrian calc-alkaline gneisses in the deep crust.

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Introduction

An occurrence of porphyritic syenite located at the south end of lake Mykle, on the 1:50 000 geological map-sheet 1713 I Siljan in the southwestern part of the Oslo Rift, was described in some detail by Petersen & Sørensen (1997). This syenite contains phenocrysts of plagioclase almost identical to the feldspar of the surrounding larvikite, which is a monzonitic plutonic rock. The matrix of the syenite is very close in composition to nordmarkitic syenite which intrudes the porphyritic syenite. Based on petrography and major and trace element data, Petersen & Sørensen (1997) proposed that the porphyritic syenite was derived from a larvikitic melt by fractionation processes involving plagioclase, clinopyroxene, Fe-Ti oxides and possibly apatite.

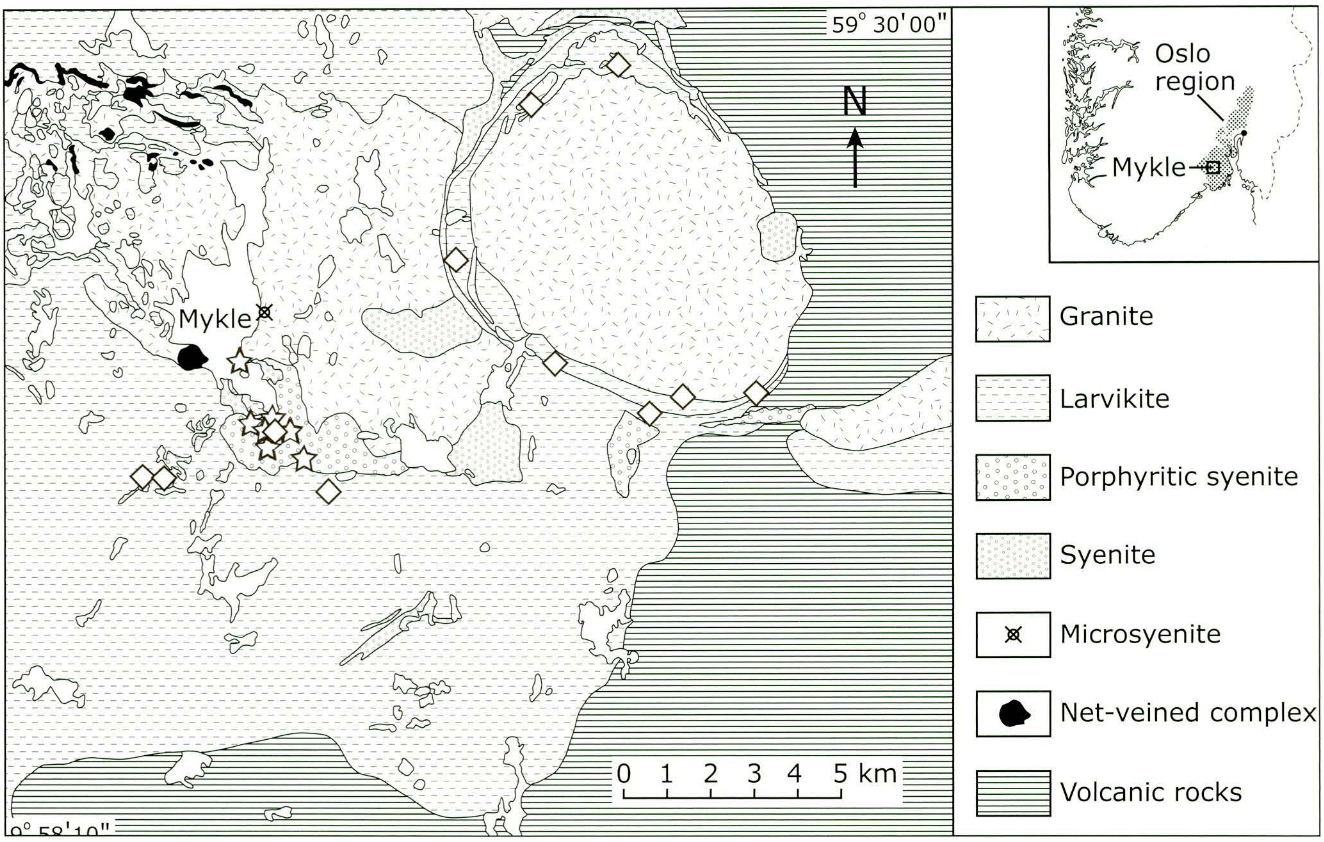

Fig. 1. Geological map of the Lake Mykle area. Sample locations: Stars: Porphyritic syenite. Diamonds: Larvikite.

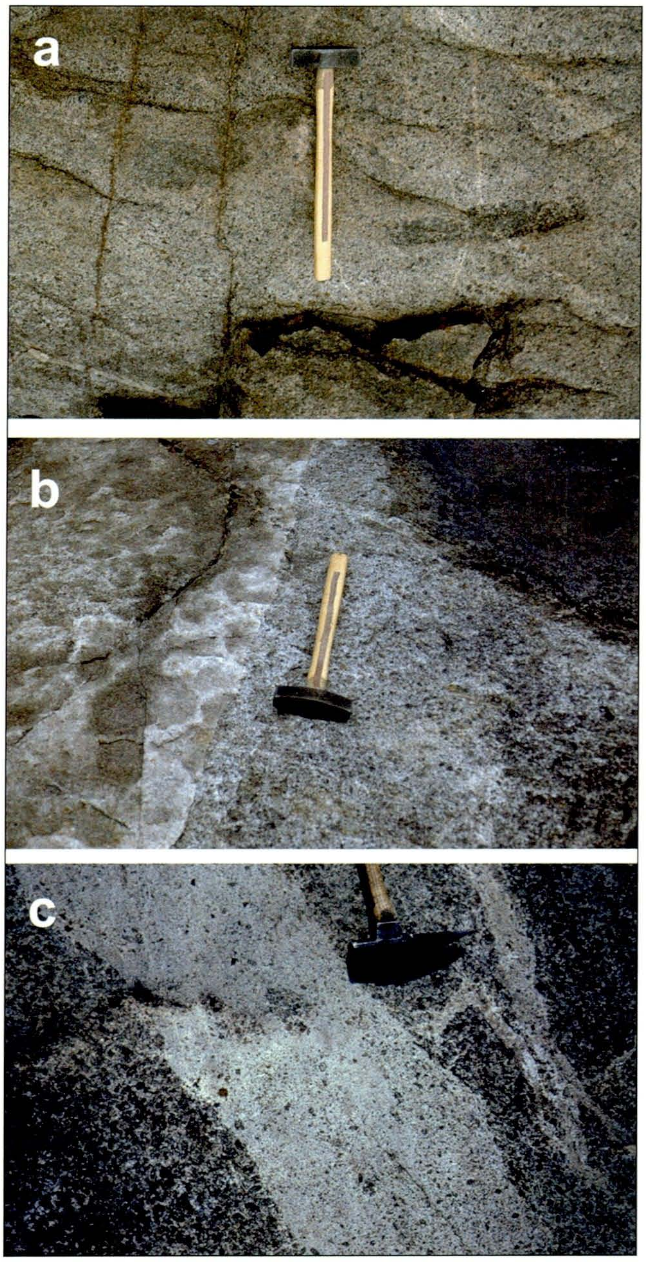

Fig. 2. (a) Two larvikite xenoliths in a state of disaggregation in porphyritic syenite. Southeast coast of Lake Mykle. (b) Porphyritic syenite (right) intruded by syenite dyke. Southwest coast of Lake Mykle. (c) Dyke of porphyritic syenite with sharp contacts against larvikite. South end of Lake Mykle.

Rb-Sr and Sm-Nd isotope data for the porphyritic syenite are presented and discussed in the present paper with the aim of constraining the mode of origin of the porphyritic syenite.

Field relationships

The porphyritic syenite forms a dome-shaped body measuring 4.5 x 2 km (Fig. 1), and the exposed vertical thickness is about 150 m. Towards the south and west, the porphyritic syenite is in contact with larvikite, which also overlies the syenite, as demonstrated by the presence of larvikite roof pendants in the porphyritic syenite. Towards the north and east it is in contact with granites (including ekerite) and minor bodies of nordmarkitic syenite. Contacts between larvikite and porphyritic syenite are generally sharp and there are no chill zones in the porphyritic syenite in contact with larvikite. Locally, however, there is a transition from larvikite into porphyritic syenite in the form of an increasing density of plagioclase phenocrysts toward the larvikite over a distance of a few cm. The porphyritic syenite contains xenoliths of larvikite which appear to disintegrate into clusters of feldspar (Fig. 2a). It also intrudes the larvikite in the form of dykes (Fig. 2c). The nordmarkitic syenite and the granites are younger than the porphyritic syenite (Fig. 2b); these younger intrusions have obliterated the original northern contact of the larvikite massif.

Petrography

The porphyritic syenite is characterised by evenly distributed phenocrysts of plagioclase (andesine-oligoclase) which measure up to about 2 cm and make up 30-70 % of the rock. They are rimmed by cryptoperthitic ternary feldspar. The fine-grained matrix consists of crypto- or microperthitic An-poor alkali feldspar, the grains of which may have cores of plagioclase, and of edenitic amphibole, augitic pyroxene, Fe-Ti-oxides, biotite and about 5 % interstitial quartz. Accessory minerals are zircon, allanite, chevkinite, apatite, fluorite and calcite (Petersen & Sørensen 1997).

The *larvikite* of the area is porphyritic and is dominated by large grains of plagioclase (50 to 20 % An), which make up about 75 % of the rock. The plagioclase is rimmed by microperthitic ternary feldspar. Augitic clinopyroxene and some orthopyroxene make up about 10 %, edenitic amphibole 5 %, Fe-Ti oxides 5 % and accessory minerals 5 % (zircon, apatite, biotite, quartz, allanite, chevkinite and fluorite). The matrix is composed of alkali feldspar and intergrowths of oligoclase and potash feldspar. Petersen (1992) distinguished two minor types of larvikite:(1) a coarse-grained type with a larger content of interstitial alkali feldspar, and (2) a fine-grained type containing subcalcic and pigeonitic clinopyroxenes and a high-temperature plagioclase. The fine-grained variety of larvikite occurs as scattered, minor bodies, and its origin remains uncertain.

The plagioclase phenocrysts of the porphyritic syenite have rims of ternary feldspar, and are almost identical to the feldspar of the host larvikite.

Major and trace element data

Major and trace element compositions of larvikite and porphyritic syenite are presented in Table 1, based on data from Petersen & Sørensen (1997), supplemented by isotope dilution trace element analyses from the present study (Table 2). The larvikite analyses are of the most abundant variety, with the exception of 81543 which represents the fine-grained type. In terms of major elements, there is a gradual transition

Table 1. Whole-rock major (wt%) and trace element (ppm) data of larvikite and porphyritic syentie from the Mykle area.

	81541	81543	81456	81595	81594	81559	81561	81566	81571	81577
	LK	**LK**	**LK**	**LK**	**LK**	**PS**	**PS**	**PS**	**PS**	**PS**
					Weight percent oxides					
SiO_2	57.30	60.04	58.62	57.53	59.91	60.74	59.80	58.81	60.52	59.19
TiO_2	1.25	1.44	1.36	1.33	1.11	1.33	1.43	1.42	1.30	1.52
Al_2O_3	18.77	15.82	17.39	18.09	17.64	16.17	16.16	16.36	16.17	16.25
Fe_2O_3	1.43	1.72	1.81	1.46	1.20	1.80	2.02	2.26	1.67	2.15
FeO	3.63	4.29	3.52	4.02	3.55	3.67	3.90	3.73	3.75	3.87
MnO	0.12	0.16	0.13	0.11	0.12	0.15	0.15	0.15	0.14	0.15
MgO	1.36	1.38	1.44	1.50	1.12	1.28	1.47	1.49	1.29	1.57
CaO	5.16	3.20	4.22	5.17	3.56	3.38	3.87	3.80	3.35	4.08
Na_2O	5.54	4.90	5.48	4.89	5.87	5.08	5.01	5.37	5.13	4.96
K_2O	3.27	4.82	4.42	3.43	4.14	4.61	4.28	4.68	4.71	4.25
P_2O_5	0.60	0.54	0.55	0.60	0.45	0.47	0.56	0.54	0.45	0.62
Volatiles	0.69	0.69	0.63	1.00	0.75	0.67	0.71	0.68	0.68	0.71
Total	99.12	99.00	99.57	99.13	99.42	99.35	99.36	99.29	99.16	99.32
(Na+K)/Al	0.67	0.84	0.79	0.65	0.80	0.83	0.80	0.85	0.84	0.79
					Parts per million					
Rb	109	157	144	112	155	211	201	215	218	191
Cs	3.1	3.8	n.d.	n.d.	3.7	4.5	n.d.	2.7	n.d.	n.d.
Sr	573	*296*	*488*	*515*	*435*	*329*	*394*	*379*	*334*	*439*
Ba	728	1000	915	780	948	627	640	604	582	695
Zr	939	1180	907	750	819	1190	1010	1300	1300	1040
Hf	24.2	31.1	n.d.	n.d.	19.8	33.6	n.d.	31.1	n.d.	n.d.
Nb	119	139	137	99	117	165	151	204	133	136
Ta	7.9	9.4	n.d.	n.d.	7.8	11.1	n.d.	13.2	n.d.	n.d.
La	104	118	111	95	106	138	124	147	139	117
Ce	204	239	223	188	202	273	264	288	278	253
Nd	85	*107*	*98*	*85*	*85*	*127*	*109*	*119*	*115*	*106*
Sm	14.3	20	n.d.	16	14	19.2	20	22	21	20
Eu	4.2	4.4	n.d.	n.d.	4.4	3.7	n.d.	3.7	n.d.	n.d.
Tb	1.9	2.9	n.d.	n.d.	2	2.9	n.d.	3.1	n.d.	n.d.
Yb	5.7	8.4	n.d.	n.d.	5.7	10	n.d.	9.9	n.d.	n.d.
Lu	0.8	1.1	n.d.	n.d.	0.8	1.2	n.d.	1.3	n.d.	n.d.
Y	57	80	66	59	59	87	83	95	93	n.d.
Th	17	22	21	16	20	38	39	41	38	81
Zn	104	124	101	84	94	106	105	93	94	103
V	45	23	40	52	32	38	55	54	42	55
Sc	8	11.1	8	8	8	9.7	12	10.3	11	13

LK: Larvikite, PS: Porphyritic syenite. n.d. not determined

Major elements by XRF on fused discs prepared with sodium tetraborate flux at the Geological Survey of Denmark and Greenland; trace elements by XRF on pressed powder pellets at Geological Institute, University of Copenhagen and by Instrumental neutron activation analysis By Tracechem A/S, Copenhagen. Rb, Sr, Sm and Nd data in *italics*: Isotope dilution analyses (Table 2).

from larvikite over porphyritic syenite to nordmarkitic syenite, as shown by Harker variation diagrams (Figs. 6 and 7 in Petersen & Sørensen 1997). When compared with the larvikite, nordmarkite and porphyritic syenite are enriched in Si, K, Rb, Th, Nb, Ta, REE (with the exception of Eu), Y, Zr and Hf and relatively depleted in Al, Ca, Na, Eu, Sr and Ba, that is in the components of plagioclase . The two syenites have practically identical REE patterns; larvikite has a weak positive Eu anomaly, whereas the syenites have very weak negative anomalies (Fig. 8 in Petersen & Sørensen 1997). Nordmarkite and porphyritic syenite have almost indistinguishable lithophile element patterns, which differ only in Sr (higher in the porphyritic syenite) and Zr, Th and Hf (lower in the porphyritic syenite). These differences reflect differences in modal mineralogy; plagioclase is present in the porphyritic syenite, whereas zircon is more abundant in the nordmarkite (Fig. 9 in Petersen & Sørensen 1997).

Sr and Nd Isotope data

Analytical methods

Rb, Sr, Sm and Nd concentrations of four samples of porphyritic syenite and three samples of associated larvikite (Petersen & Sørensen 1997) were analysed by X-ray fluorescence and by isotope dilution thermal ionization mass spectrometry at the Geological Institute, Copenhagen University. The sample powders (200 mg) were attacked following a sequential dissolution first with 8N HBr, followed by 14N HNO_3 – 32% HF mixtures, in Teflon beakers on a hot plate (T= 150°C) for three days. A ^{149}Sm-^{150}Nd spike was added before-

Table 2. Rb-Sr and Sm-Nd data for intrusive rocks from the Mykle Area. Oslo Rift.

Sample	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	Sr_i 280 Ma	ε_{Nd} 280 Ma
Porphyric syenite												
81577	191	439	1.301	0.709559	0.000020	20	106	0.1082	0.512556	0.000021	0.70438	1.56
81566	215	379	1.682	0.711482	0.000020	22	119	0.1039	0.512591	0.000019	0.70478	2.40
81559**	221	329	1.945	0.712205								
81567**	237	328	2.093	0.712697								
81582**	206	426	1.4	0.71001								
81571	218	334	1.935	0.712187	0.000020	21	115	0.1054	0.512577	0.000012	0.70448	2.07
81561	201	394	1.492	0.710534	0.000020	20	109	0.1071	0.512603	0.000013	0.70459	2.52
Larvikite, S Lake Mykle												
81543	157	296	1.556	0.711099	0.000020	20	107	0.1068	0.512590	0.000012	0.70490	2.28
81594	155	435	1.043	0.707204	0.000020	15	85	0.1002	0.512637	0.000011	0.70305	3.43
81595	112	515	0.625	0.707015	0.000020	16	85	0.1048	0.512609	0.000011	0.70453	2.72
81456**	144	488	0.854	0.707331								
81541**	109	573	0.551	0.706017								
Larvikite, E Lake Mykle												
76461*	74	709	0.301	0.705987	0.00042	19	105	0.1119	0.512621	0.000010	0.704786	2.70
76465*	90	650	0.399	0.706144	0.00003	16	87	0.1096	0.512615	0.000010	0.704554	2.66
76468*	54	870	0.180	0.705332	0.00003	19	101	0.1136	0.512609	0.000010	0.704612	2.41
77805*	80	664	0.350	0.706097	0.00003	20	108	0.1113	0.512628	0.000010	0.704702	2.86
77814*	66	725	0.263	0.705598	0.00003	20	108	0.1145	0.512611	0.000012	0.704551	2.41
81236*	77	697	0.320	0.705833	0.00003	19	105	0.1119	0.512602	0.000010	0.704558	2.33
79389*	102	558	0.529	0.706519	0.00003	22	117	0.1133	0.512628	0.000010	0.704411	2.78
Granite												
86044*	82	24	9.820.742261548		0.000009	7.8	44.4	0.1068	0.512622	0.000010	0.70315	2.90

*: Analysed at the Laboratory of Isotope Geology, Mineralogical-Geological Museum, University of Oslo. **: Analyst: P.M. Holm, Copenhagen University. Samples 76461 to 79389 from the larvikite ring structure east of lake Mykle (Fig. 1) were provided by Uffe Larsen.

hand. Sr and REE fractions were separated over 15 ml glass stem columns charged with AG 50W cation resin. Purification of the Sr fraction was achieved by a pass over micro-columns containing SrSpec™ resin. REEs were further separated over HDEHP-coated bio beads (BioRad™) loaded in 6 ml glass stem columns. Sr and Nd isotopes were analysed in dynamic multi-collecting routines, Sm in a static mode, on a VG 54 Sector IT mass spectrometer. The mean value for our internal JM Nd standard (referenced against La Jolla) during the period of measurement was 0.511115 for $^{143}Nd/^{144}Nd$, with a 2σ external reproducibility of ± 0.000013 (five measurements). The mean $^{87}Sr/^{86}Sr$ value of the NBS 987 Sr standard was 0.710248, with a 2σ external reproducibility of 0.000011 (four measurements).

Additional samples of larvikite and granite were analysed at the Laboratory of Isotope Geology, Mineralogical-Geological Museum, University of Oslo, by methods described by Andersen et al. (2001).

Results

Rb-Sr and Sm-Nd isotope data for selected samples of porphyritic syenite, larvikite and granite from the Mykle area are given in Table 2. Larvikite and porphyritic syenite show marginally overlapping ranges of $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$. Neither of the two rock types define statistically valid Rb-Sr isochrons; the samples of porphyritic syenite and a majority of the larvikite samples scatter around a reference line with an age of 280 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7045 (Fig. 3). One, off-lying larvikite sample (81594) plots significantly below this line, with $^{87}Sr/^{86}Sr2_{80\ Ma}$= 0.7031.

Larvikite and porphyritic syenite show small and overlapping ranges of $^{147}Sm/_{144}Nd$ and $^{143}Nd/^{144}Nd$. At 280 Ma, all samples have positive epsilon Nd values, ranging from 1.56

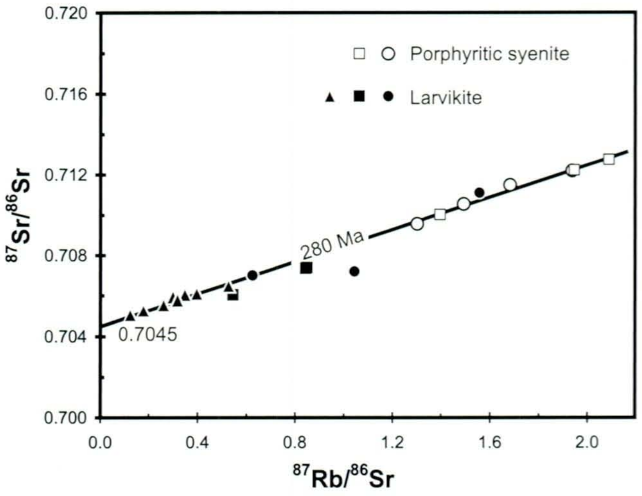

Fig. 3. Rb-Sr correlation diagram showing larvikite and porphyritic syenite, compared to a 280 Ma reference line with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7045. Circles and squares: Samples from the south end of Lake Mykle. Triangles: Samples from NE of Lake Mykle.

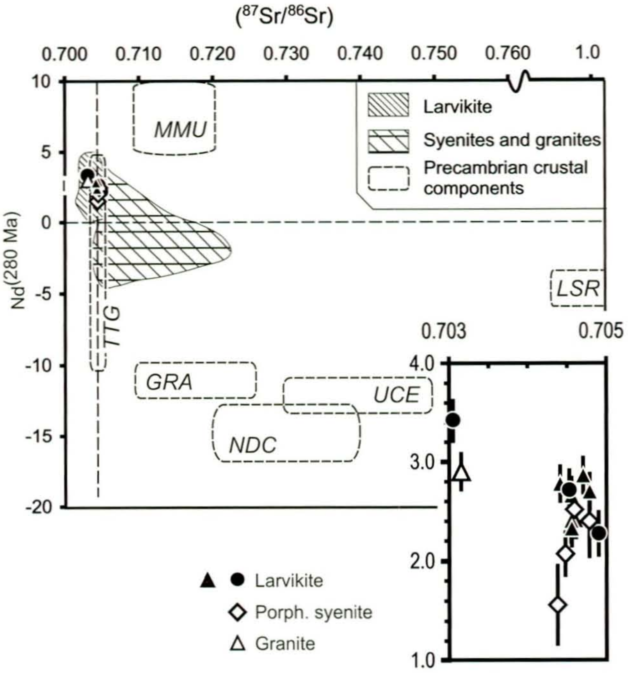

Fig. 4. Sr and Nd isotopic composition of porphyritic syenite and associated rocks from the Mykle area. Black triangles represent larvikites from NE of Lake Mykle. Ruled/cross-hatched areas represent ranges of regional variation of larvikite and syenite and granite in the Oslo Rift (data from Neumann et al. 1988). Ranges of Precambrian crustal components are taken from Andersen & Knudsen (2000): MMU: 1.15-1.50 Ga Mafic underplate, GRA: c. 0.93 Ga granites, NDC: 'Normal deep crust', i.e., moderately LILE-enriched rocks in the deep crust, UCE: Upper crustal rocks east of the rift, LSR: Upper crustal rocks of the Telemark area, showing elevated Rb/Sr ratios at normal Rb concentrations. TTG: Precambrian (1.6-1.2 Ga) calc-alkaline meta-igneous rocks, including tonalite, trondhjemite, granodiorite and their extrusive equivalents (Knudsen & Andersen 1999, Andersen & Knudsen 2000 and references therein).
The inset is an expansion of the rocks from the Mykle area, showing data points with 2s error bars.

to 2.54 for the porphyritic syenite, and from 2.28 to 3.43 for the larvikite (Table 2). Regardless of composition, the majority of samples form a cluster in a ε_{Nd} vs. $^{87}Sr/^{86}Sr_{280Ma}$ diagram (Fig. 4). Variations in initial Sr and Nd composition within this cluster are small, but exceed analytical error, and are uncorrelated (Fig. 4, inset). One sample of larvikite (81594), and one granite show significantly lower time-corrected $^{87}Sr/^{86}Sr$ than the other samples. This is probably due to loss of radiogenic strontium during late (postglacial ?) weathering. The granite sample has a high Rb/Sr ratio compared to the other samples, and only moderate loss of radiogenic Sr from this sample could increase the Rb/Sr ratio enough to cause significant overcorrection for radiogenic growth when recalculated to 280 Ma.

The total ranges of Sr and Nd isotopic variation at 280 Ma reported in Table 2 fall within the overall range of variation of larvikitic rocks from the Oslo Rift (Fig. 4, data from Neumann et al. 1988). However, in most other felsic rocks in the rift, a reduction in initial $^{143}Nd/^{144}Nd$ is commonly coupled to a pronounced increase in initial $^{87}Sr/^{86}Sr$; see cross-hatched area in Fig. 3 (Andersen & Knudsen 2000). This is not observed in the porphyritic syenite from the Mykle area.

Discussion

Larvikite magma in the Oslo igneous province is considered to have been derived by fractional crystallization of basaltic melts formed by partial melting of a mildly depleted somewhat heterogeneous mantle source (Neumann 1980, Neumann et al. 1988, Rasmussen et al. 1988). The same authors proposed that crustal contamination was involved in the formation of the syenitic and granitic rocks of the region, which is also supported by published radiogenic isotope data (Andersen & Knudsen 2000).

Based on major and trace-element data, Petersen & Sørensen (1997) pointed out that larvikite, porphyritic syenite and nordmarkitic syenite may have been formed from successive pulses of magma from a common source, and that feldspar fractionation played an important role in this process. The Harker variation diagrams of Petersen & Sørensen (1997) indicate that fractionation of clinopyroxene, Fe-Ti oxides, and perhaps, apatite, was also involved. The nordmarkitic syenite and the microsyenite at Lake Mykle described by Andersen & Sørensen (2003) mark a more evolved stage than the porphyritic syenite.

The overall outcrop pattern (Fig. 2), and the presence of roof pendants of larvikite in the porphyritic syenite, indicate that the porphyritic syenite is located inside the larvikite massif, but close to its contacts to (younger) granites and nordmarkitic syenite.

The contact relationships and the presence of disaggregated xenoliths of larvikite in the porphyritic syenite may be taken as evidence that the plagioclase phenocrysts of the porphyritic syenite originated by disintegration of larvikite. Such an origin for the porphyritic syenite is, however, hard to reconcile with the even distribution of phenocrysts over the entire volume of the porphyritic syenite, including dykes which intersect the larvikite with sharp intrusive contacts (Fig. 2c).

The similarity in structure and composition of the plagioclase of larvikite and porphyritic syenite, including their rims of ternary feldspar, led Petersen & Sørensen (1997) to propose that the porphyritic syenite may have been formed by extended crystallization of larvikitic melts caused by an increase in H_2O, other volatiles and incompatible elements in response to the fractionation of anhydrous minerals such as feldspar, clinopyroxene, Fe-Ti oxides and possibly apatite. Such evolved melts may have collected in cupola in the upper part of the still hot, solidifying larvikite. This can explain the generally sharp, non-chilled contacts and local transitional phenomena. The even distribution of plagioclase phenocrysts in the porphyritic syenite may then be explained by assuming that the magma, which formed the porphyritc syenite, was at its liquidus at the time of emplacement, and that early nucleation of plagioclase took place in a supercooled melt which solidified rapidly to form the fine-grained, quartz-bearing, syenitic matrix (Petersen & Sørensen 1997).

Similarities with both larvikitic rocks of the Oslo Rift in general, and with larvikites and granitic rocks of the Mykle area in particular, are also highlighted by the Sr and Nd isotope data (Fig. 4).

Felsic intrusive rocks in the Oslo Region show an overall tendency towards initial $^{87}Sr/^{86}Sr$ ratios of 0.710 or higher, and near-zero or weakly negative epsilon-Nd values (cross-hatched field in Fig. 4). Based on a compilation of geochemical data on Precambrian rocks from South Norway, Andersen & Knudsen (2000) defined six compositionally and geographically constrained crustal end members, which may have acted as crustal contaminants in the magmatic system of the Oslo Rift. The regional variation in the felsic intrusive rocks can be accounted for by contamination with moderately LILE-enriched, Precambrian rocks in the deep crust, represented by the 'Normal Deep Crust' (*NDC*) and 'Precambrian granite' (*GRA*) components in Fig. 4 (Andersen & Knudsen 2000). Some granitic rocks show evidence of contamination by strongly evolved crustal rocks with low Sr concentrations and correspondingly high Rb/Sr ratios (*LSR* component in Fig. 4). In the Mykle larvikite and porphyritic syenite, a minor shift towards lower epsilon-Nd is not coupled to an increase in initial $^{87}Sr/^{86}Sr$, which suggests that neither of these crustal components can have had any significant influence on the intermediate and felsic magmas of the Mykle area. However, the samples analysed in this study overlap in Sr and Nd composition with the high epsilon-Nd range of 1.6-1.2 Ga calc-alkaline gneisses at 280 Ma. Such rocks are widespread in the Østfold-Akershus, Kongsberg and Bamble sectors in the Precambrian of South Norway (Andersen & Griffin 2002), i.e., adjacent to the southern part of the Oslo Rift. These potential contaminants are represented by the *TTG* component in Fig. 4, which is constrained by data from a range of subduction-related, meta-igneous Precambrian rocks (Andersen & Knudsen 2000 and references therein). From their geographical distribution, TTG contaminants are most likely to have influenced magmas in the southern part of the rift, and the present data are compatible with moderate amounts of such contamination in the magmas of the Mykle area. However, the calc-alkaline meta-igneous Precambrian rocks are in general metaluminous to peraluminous, and major contamination with such material is not likely in rocks trending towards increasing (Na+K)/Al (Table 1).

Conclusions

Sr and Nd isotope data on porphyritic syenite and associated larvikite in the Mykle area of the Oslo Rift confirm the close genetic relationship between the two rock types indicated by petrography and major and trace element geochemistry (Petersen & Sørensen 1997). A limited variation in initial Nd isotopic composition (from epsilon-Nd = + 3.4 to + 1.6 at 280 Ma), without corresponding variation in intitial $^{87}Sr/^{86}Sr$ suggests that the larvikite and porphyritic syenite magmas were contaminated by minor amounts of Precambrian calc-alkaline rocks, similar to subduction-related meta-igneous rocks found at both sides of the southern onshore segment of the Oslo Rift.

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