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Petrogenetic processes associated with intermediate and silicic magmatism in the Oslo rift, south-east Norway

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Abstract

The Permian magmatic province of the Oslo rift, south-east Norway, includes large volumes of felsic and silicic rocks. Based on their geochemical character, these rocks may be divided into two main groups. The Larvik larvikites (monzonites) are highly enriched in large ion lithophile elements (LILE) (e.g. 10–32 ppm Th. 8–15 ppm Ta), and have an initial $^{87}Sr/^{86}Sr$ of 0.70391 ± 5. The syenites and granites have moderate to high concentrations of LILE (e.g. 7–88 ppm Th, 4–25 ppm Ta), and initial $^{87}Sr/^{86}Sr$ ratios between 0.705 and 0.707. The Larvik larvikites and extrusive equivalents (rhomb porphyry lavas) have similar initial Sr isotope ratios to uncontaminated basalts and gabbros in the rift, and are believed to have a mantle origin. The higher initial $^{87}Sr/^{86}Sr$ ratios in the silicic than in the felsic rocks reflect a crustal component representing the intermediate or low crust. After intrusion into the upper crust, the major and trace-element concentrations of the silicic magmas were modified through fractional crystallization dominated by removal of alkali feldspar, and transport of elements with a fluid phase. The silicic magmas appear not to have interacted significantly with the side rock at this stage.

Keywords: larvikite, syenite, granite, magmatism, Oslo rift, Norway.

Introduction

Magmatic activity during the Permo-Carboniferous rifting event which formed the Oslo rift in south-east Norway, includes emplacement of a variety of monzonitic to granitic rocks. Such rocks cover an area of about 6200 km^2 (Fig. 1), that is about 96% of the total area covered by Oslo rift magmatic rocks (Barth, 1945; Ramberg, 1976). The present erosion surface is 1 to 3 km below the Permian one (McCulloh, 1952).

There has been considerable speculation concerning the origin of these rocks. An early model based on inferred volumetric relationships and geochemistry, proposed that the gabbros have a different origin from the monzonitic to granitic rocks, the latter being formed by *in situ* anatexis of the Precambrian country rocks with addition of alkalis (Barth, 1945, 1954; Oftedahl, 1967). A more recent model is based mainly on K–Th–U relations and preliminary Rb/Sr and Rb/Sr–Sm/Nd data. According to this model, only basaltic and monzonitic rocks are related directly to possible mantle sources, whereas the melts which gave rise to the syenites, granites and their extrusive equivalents have a large crustal component (Raade, 1973, 1978; Sundvoll, 1978*a*, *b*; Jacobsen and Wasserburg, 1978).

A series of recent investigations of felsic to silicic rock bodies in different parts of the rift has added

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considerably to our knowledge about these rocks, including major and trace-element variations within different felsic complexes (Khalil *et al.*, 1978*a*, *b*; Neff and Khalil, 1980; Neumann, 1980; Andersen, 1981, 1984*a*, *b*; Fjerdingstad, 1983; Rasmussen, 1983). It is the aim of this paper to use this information to throw further light on the petrogenetic processes associated with felsic to silicic magmatism in the Oslo rift. Some additional data, mainly on Sr isotopes and trace elements, are presented.

Geology and petrography of the Oslo Region felsic rocks

The intrusive rocks discussed in this paper range in composition from monzodiorite and monzonite via syenite and alkali syenite to granite and alkali granite. The rock classification used is a simplified version of the nomenclature for Oslo Region intrusive rocks developed by Brøgger (e.g. 1890, 1933). For a more thorough review of their petrography, the reader is referred to Barth (1945), Ramberg (1976) and Gaut (1981). The geographic distribution and intrusive relations are discussed by McCulloh (1952), Oftedahl (1953, 1960), Sæther (1962), Petersen (1977), Andersen (1981, 1984*a*, *b*), Rasmussen (1983, and in prep.).

The discussion in this paper is based on data on relatively large felsic rock complexes in different parts of the rift, presenting a representative selection of rock types as well as geographic locations: the Larvik plutonic complex, the Ramnes and Sande cauldron central plutons, the Eikeren alkali granite complex, the Nittedal cauldron, the Holterkollen biotite granite and the Øyangen area in Hurdal (Fig. 1). A brief description of the rock types discussed in the text is given in the Appendix.

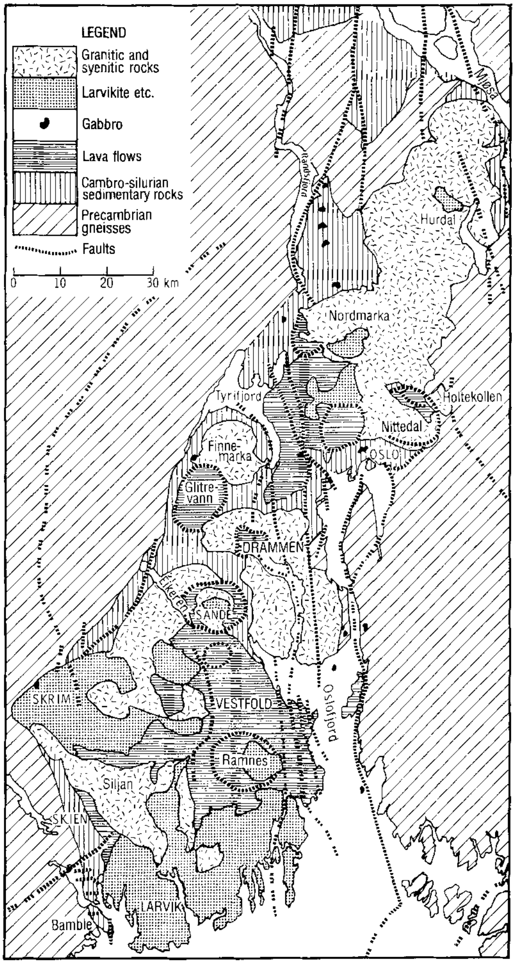

FIG. 1. Generalized map of the Oslo Region, south-east Norway, based on maps by Oftedahl (1960) and Ramberg and Larsen (1978).

Rb–Sr isotope data

In this paper we report whole-rock Rb–Sr isotope data on monzonitic to granitic rocks from the Ramnes, Larvik, Sande, Eikeren, Nittedal, Holterkollen and Hurdal areas (Fig. 1). Strontium isotopic determinations were made by solid source mass-spectrometry using the method described by Jacobsen and Heier (1978). The data are presented graphically in Fig. 2. A data listing may be obtained on request from E.-R. Neumann.

The larvikite samples from the Larvik ring-complex define a whole-rock Rb/Sr isochron of 277 ± 3 Ma and an initial $^{87}Sr/^{86}Sr$ ratio (*I* value) of 0.70391 ± 5 (Fig. 2*a*). This age is in agreement with Rb/Sr-mineral ages on recognized individual intrusive units (Sundvoll, unpublished data). Syenites and granites in the Ramnes central pluton give an age of 269 ± 5 Ma and an *I* value of 0.7048 ± 7 (Fig. 2*b*). The composite ekerite intrusion around the lake Eikeren yields a whole-rock isochron of 271 ± 2 Ma with an *I* value of 0.7053 ± 6 (Fig. 2*c*).

The data on the Sande central intrusion do not fit a single isochron (Fig. 2*e*). The age of this unit may, however, be limited by the age of the ring-complex, and that of the lavas cut by the intrusion inside the cauldron. The quartz to syenite porphyry ring-dyke in the Sande cauldron defines an isochron of 268 ± 3 Ma, with $I = 0.7071 \pm 4$ (Fig. 2*d*). (The data on this unit are included only in order to be able to discuss the age of the Sande central intrusion.) The lavas inside the Sande cauldron are believed to

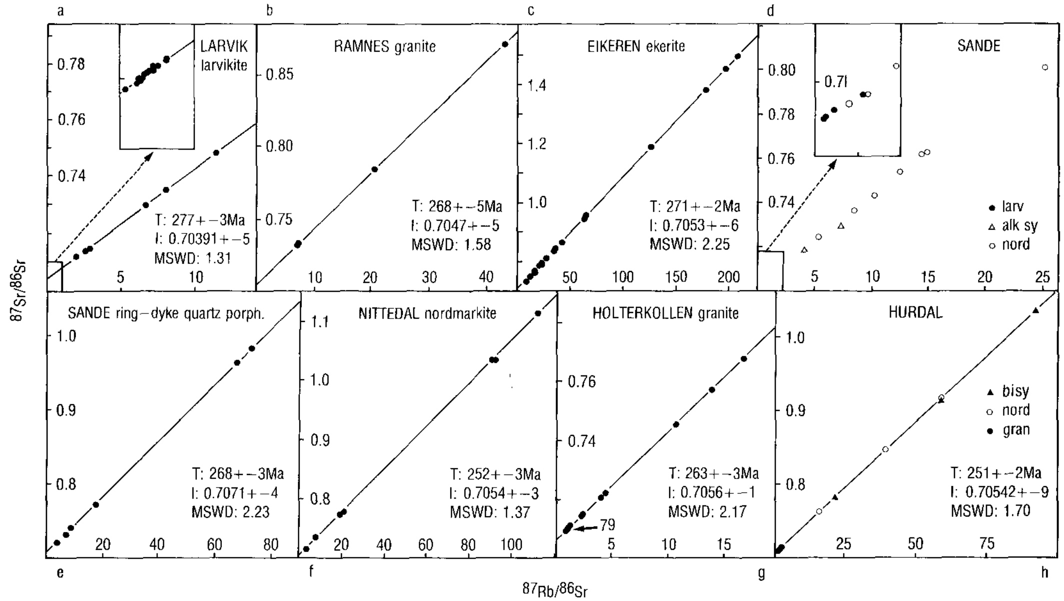

FIG. 2. Whole rock Rb–Sr isotope data for selected Oslo rift felsic intrusive complexes. The data for the Sande cauldron central intrusion do not define an isochron, but a best fit regression line gives an initial $^{87}Sr/^{86}Sr$ ratio of 0.7045.

belong to the younger part of the volcanic period which gave rise to the Vestfold lava plateau (Oftedahl, 1953; Rui, pers. comm. 1981). This effusive stage ended 270–275 Ma ago (Larsen and Sundvoll, in prep.). A mean age of 270 Ma has therefore been used to calculate $^{87}Sr/^{86}Sr$ initial ratios from the measured data (Fig. 9).

Samples from the nordmarkite intrusion in the Nittedal cauldron yield a Rb/Sr whole-rock isochron of 252 ± 3 Ma with an *I*-value of 0.7054 ± 3 (Fig. 2*f*). Nordmarkite intrusions in the Nordmarka area further west give similar ages and initial ratios (Sundvoll, unpublished data). Also akerites and granites from the Holterkollen intrusive complex define an isochron if one sample, no. 79, collected near the contact to the syenite ring-dyke of the Nittedal cauldron, is excluded (Fig. 2*g*). The age is 264 ± 3 Ma, $I = 0.7056 \pm 1$.

Nordmarkites, alkali granites and biotite syenites from the Hurdal area give a whole-rock isochron (sample B113 excluded) of 251 ± 2 Ma and an initial Sr isotope ratio of 0.70542 ± 9 (Fig. 2*h*).

Compositional trends and genetic relations among the Oslo Region intrusive rocks

All analytical data used in the discussion below were obtained at the Mineralogical-Geological Museum, Oslo. Whole-rock analyses were done by atomic absorption (Na, Mg), and X-ray fluorescence (XRF) analysis of fused pellets (other major elements). Fe^{2+} was determined by titration. Rb and Sr were analysed by XRF on pressed pellets (Table 1); other trace elements by instrumental activation analysis methods described by Gordon *et al.* (1968) and Brunfelt and Steinnes (1969); Th and U also by γ-ray spectrometry.

Larvik ring-complex. In a study of the petrogenetic relations in the Larvik intrusive complex, Neumann (1980) concluded that the larvikites formed from basaltic primary magma by a polybaric crystallization process, that is removal of $olivine_{20}clinopyroxene_{80}$ at a pressure of roughly 7–10 kbar, followed by crystallization of the assemblage $anorthoclase_{86}olivine_{8}mt(ss)_{4}ap_{2}$. Some of the rocks represent feldspar cumulates.

The highest degree of element enrichment among the Larvik larvikites is found for Rb, Hf, Ta, Th and U. These elements also show moderate to good positive correlations, and clearly behave as strongly incompatible elements (Neumann, 1980). The average Th/U ratios is 3.8 ± 0.4 (Raade, 1973, 1978), Rb/Th and Ta/Th ratios are about 6 and 0.6, respectively (Fig. 3).

The consequences of Neumann's (1980) model for *in situ* crystallization (removal of the assemblage ASII), or accumulation, are shown by dashed trends in Fig. 3. The partition coefficients used to calculate hypothetical crystallization paths in Figs. 3–8 are based on data by Arth (1976) on felsic rocks

TABLE 1 Rb-Sr isotopic data. Measured 2σ errors on ^{87}Sr/^{86}Sr data, errors on ^{87}Rb/^{86}Sr data estimated to ~0.5%.

Sample	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr 2σ
LARVIK LARVIKITE				
OB- 6	77.9	502	0.448	0.70583±08
OB- 45	203	230	2.553	0.71384±05
452	37.8	1303	0.084	0.70427±04
634	108	703	0.445	0.70567±08
508	205	221	2.690	0.71470±04
642	105	1006	0.301	0.70513±08
505	122	559	0.631	0.70629±07
479	157	714	0.636	0.70646±08
36	83.3	36.3	6.657	0.73009±07
37	66.9	360	0.538	0.70589±08
627	374	135	8.031	0.73565±05
630	120	30.6	11.370	0.74870±08
355	102	832	0.356	0.70530±09
373	108	806	0.388	0.70549±07
374	93.1	950	0.283	0.70490±07
OB- 3	76.2	941	0.234	0.70471±
472	98.1	772	0.367	0.70538±08
477	64.6	702	0.266	0.70512±08
500	88.3	992	0.257	0.70488±08
17	80.6	1189	1.968	0.71166±08
RAMNES SYENITE-GRANITE				
RA-2	377	25.6	43.323	0.87008±09
RA-4	259	102	7.367	0.73254±06
RA-5	250	103	7.076	0.73223±06
RA-13	350	49.9	20.461	0.78349±05
EIKEREN EKERITE				
E-235	236	44.6	124.290	1.19174±05
E-263	271	4.73	176.680	1.38152±05
E-269	149	34.8	11.679	0.75030±05
E-272	123	48.2	7.129	0.73249±05
E-265	187	8.0	64.288	0.95528±05
E-267	121	12.0	28.522	0.81487±05
E- 2	275	4.14	207.601	1.49710±10
E- 3	185	8.80	62.130	0.94470±10
E- 9	91.5	15.3	17.401	0.77340±10
E- 10	114	15.9	20.820	0.78520±10
E-277	124	15.7	23.015	0.79194±10
E-256	177	14.5	35.843	0.84533±10
E-268	113	19.7	16.638	0.77171±10
E-144	270	4.30	194.753	1.45628±10
E-129	273	37.4	21.302	0.78733±09
E-234	148	12.6	34.382	0.83810±10
E-255	234	16.5	41.671	0.86206±09
SANDE CAULDRON CENTRAL INTRUSION				
LARVIKITE-NORDMARKITE				
A- 20	90.0	134	1.939	0.71275±05
A- 25	78.1	559	0.405	0.70635±05
A- 28	47.7	651	0.211	0.70549±05
A- 29	56.4	848	0.191	0.70514±05
A- 93	158	44.6	10.260	0.74348±05
R-311	112	22.7	14.390	0.76294±05
A- 10	118	53	7.185	0.72991±05
A- 15	76	308	0.741	0.70710±05
R-286	117	83.9	4.041	0.71931±10
A-288	165	432	1.102	0.70839±09
A-300	168	91.4	5.346	0.72806±10
A-302	149	51.4	8.406	0.73798±09
A-308	112	25.8	12.442	0.75414±08
A-309	110	23.3	14.980	0.76278±09
A 310	200	23.3	25.048	0.80138±10
SANDE RING-DYKE QUARTZ PHORPHYRY				
R-279	150	121	3.586	0.72069±09
R-280	250	42.2	17.254	0.77279±04
R-282	191	8.4	67.619	0.96363±10
R-295	220	9.0	72.519	0.98297±10
R-298	122	51.8	6.824	0.73288±08
R-306	251	84.4	8.620	0.74091±09
NITTEDAL NORDMARKITE				
R-179	99.0	33.4	8.596	0.73552±04
R-180	81.6	2.66	91.807	1.03480±10
R-182	74.0	10.4	20.700	0.77929±09
R-183	132	134	2.864	0.71572±08
R-187	251	6.65	113.506	1.11514±10
R-188	72.6	10.9	19.337	0.77478±10
HOLTERKOLLEN COMPLEX				
BS-88	186	230	2.348	0.71426±09
BS-71	322	56.7	16.530	0.76796±09
BS-64	196	141	4.044	0.72054±08
BS-48	185	219	2.452	0.71452±08
BS-47	230	150	4.436	0.72226±08
BS1292	241	66.4	10.541	0.74546±09
BS1293	272	57.7	13.722	0.75725±09
BS- 8	129	350	1.065	0.70981±08
BS-79	126	280	1.305	0.71149±10
BS-40	111	400	0.804	0.70864±07
HURDAL AREA NORDMARKITE-GRANITES				
NO- 1	110	4.6	58.660	0.91715±05
NO- 2	147	11.1	39.379	0.84706±05
NO- 3	117	20.2	16.089	0.76296±05
GR- 1	233	11.0	58.501	0.91418±05
GR- 2	265	8.7	91.810	1.03687±05
GR- 4	168	21.7	21.532	0.78023±05
BI- 1	102	255	1.160	0.70957±02
BI- 9	120	162	2.151	0.71312±02

Table 2. Partition coefficients used to calculate hypothetical crystallization paths in Figures 3-8, based on data by Arth (1976), and unpublished data on partitioning of trace elements between anorthoclase phenocrysts and groundmass in rhomb porphyry lava (B.T. Larsen, personal communication, 1980). Ol= olivine, mt= titaniferous magnetite, anor= anorthoclase, alk= alkali feldspar, ap= apatite. Eu*= interpolated Eu^{3+}.

	ol	mt	anor	alk	ap
K	0.01	0.01	0.5	1.7	
Rb	0.01	0.01	0.33		
Sr	0.01	0.01	2.3	4	5.5
Ba	0.01	0.01	0.9	4	0.07
La	0.01	0.05	0.1		26
Eu	0.01	0.05	0.07		30
Eu*	0.01	0.05	0.7		20
Th	0.01	0.01	0.01	0.01	0.01

(Table 2), and unpublished data on the partitioning of trace elements between anorthoclase phenocrysts and matrix in Oslo rift rhomb porphyry lavas (the extrusive equivalent to larvikite) (B. T. Larsen, pers. comm., 1980).

Fig. 3 shows a certain scatter of the analytical data about the hypothetical fractionation trends. Most of this scatter is caused by rocks with Eu/Eu* ratios well above 1.0 (Eu* is interpolated Eu-value, assuming all Eu to be Eu^{3+}), and relatively high, variable Sr-contents. These rocks are interpreted as feldspar cumulates.

Ramnes central pluton. The Ramnes syenitic to granitic rocks are more highly enriched in trace elements such as *REE*, Hf, Ta and Th than any other rock series of this study (e.g. Th-concentrations range from 45-88 ppm) (Fig. 4). Th and Rb/Sr increase strongly, K/Ba mildly with increasing SiO_2. Eu/Eu* ratios are low and decrease with increasing Th-content, as do Sr-concentrations. With the exception of the most Th-rich sample, these rocks also show a restricted range in Rb/Th, and Ta/Th ratios. These relations imply that the elements in question have retained a strongly incompatible behaviour to a very advanced stage of crystallization. Representative Rb/Th and Ta/Th ratios are 6 and 0.3, respectively. Also the rare earth elements, except Eu, correlate positively with Th.

The compositional relations among the Ramnes rocks, as described above, suggest that they are related through crystallization dominated by alkali feldspar. This is demonstrated in Fig. 4, where the Ramnes data are compared with a hypothetical fractionation path assuming crystallization of feldspar. Decreasing TiO_2, FeO (total), MgO and

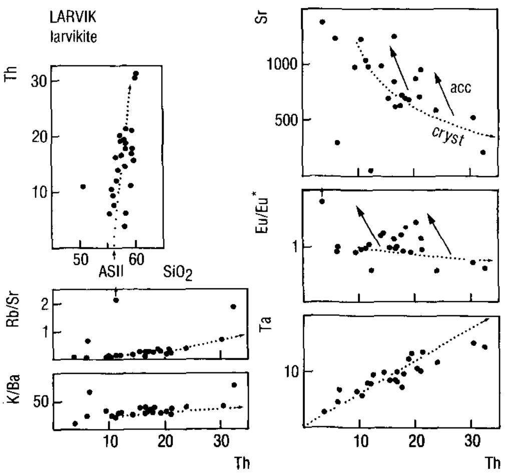

FIG. 3. Some compositional relations among rocks in the Larvik larvikite. Data from Neumann (1980). The larvikites are believed to be related through crystallization of the assemblage $anorthoclase_{80}ol_8mt_4ap_2$ (ASII) (Neumann, 1980). Dotted lines indicate crystallization paths (cryst), arrows accumulation (acc). Partition coefficients used are discussed in the text. Rocks which fall significantly above the dotted trends in the Sr-Th and Eu/Eu*-Th diagrams are believed to represent feldspar cumulates.

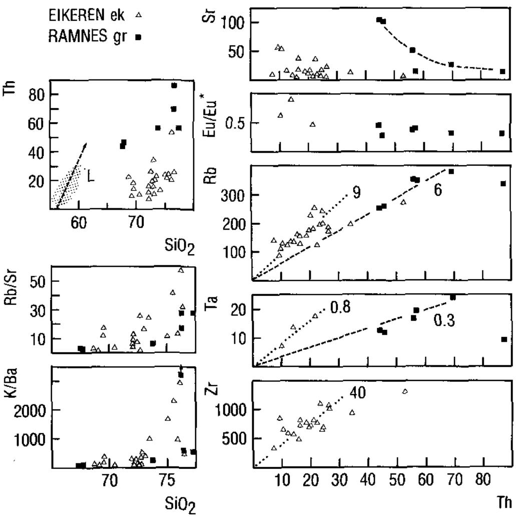

FIG. 4. Compositional variations among Ramnes syenites and granites and Eikeren ekerites. The field and crystallization trend of the Larvik larvikites is marked by L in the Th-SiO_2 plot. Possible crystallization trends are indicated by dashed and dotted lines in some of the other diagrams, with numbers showing lithophile element ratios.

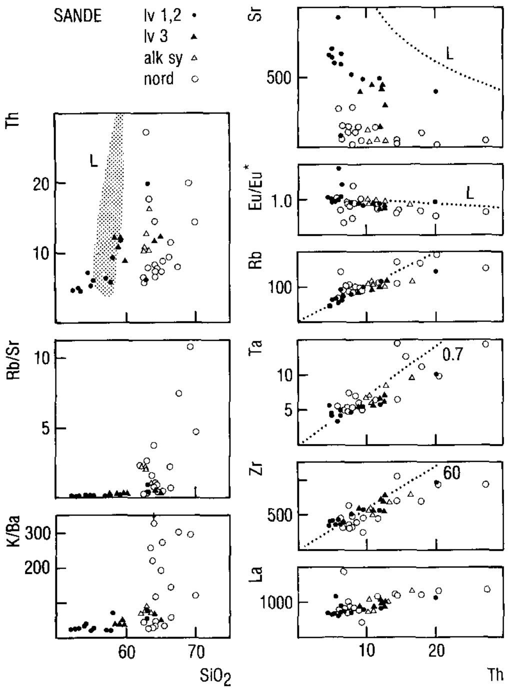

FIG. 5. Compositional variations among rocks in the Sande central pluton. The area covered by Larvik larvikites in the Th-SiO_2 plot and the Larvik crystallization trends are marked by L. Data from Andersen (1981, 1984*a*, *b*). Lv = larvikite, alk sy = alkali syenite, nord = nordmarkite.

P_2O_5 with increasing Th and SiO_2 imply that the fractionation process has also involved removal of minor amounts of pyroxene, Fe-Ti oxides and apatite.

Eikeren ekerite. In spite of their considerably higher SiO_2 contents, the Eikeren ekerites show a similar range in lithophile elements as are found in the Larvik plutonic complex (Fig. 4). The range in Rb/Th, Zr/Th and Ta/Th ratios is relatively restricted, typical values are Rb/Th = 9, Zr/Th = 40, and Ta/Th = 0.7. With one exception, Sr concentrations are below 52 ppm.

The Eikeren ekerites show a trend of strongly increasing K/Ba ratios with increasing SiO_2 (Fig. 4). In the Rb/Sr-SiO_2 plot, however, the ekerites show a considerable scatter, but a rough positive correlation between Rb/Sr and SiO_2 is suggested.

Sande central pluton. Petrogenetic studies of the central pluton in the Sande cauldron (Andersen, 1981, 1984*a*, *b*) have revealed the following evolutionary history: (1) intrusion of larvikitic magma (larvikites 1 and 2); (2) intrusion of green alkali syenite; (3) intrusion of nordmarkite in which the older larvikite now appear as partly hybridized megarafts. The hybridized larvikite found along the contacts of the megaraft is called larvikite 3. Compositional variations within the larvikite 1 is mainly attributed to crystallization of plagioclase followed by alkali feldspar, Fe-Ti oxides, and biotite at a late stage. Accumulation of feldspar has also taken place. Crystallization in the green alkali syenite was dominated by alkali feldspar, followed by sodian augite and Fe-Ti oxides. According to Andersen, the nordmarkites do not define clear crystallization trends.

The conclusions of Andersen (1981, 1984*a*, *b*) are supported by Fig. 5. The existence of unrelated rock units is indicated by the Th-SiO_2 and Sr-Th plots, where larvikites 1 and 2, and syenites define different trends or groups, with larvikite 3 trailing between these groups. Larvikite 3 furthermore shows a clear tendency for lower Rb/Th, Ta/Th, Zr/Th and La/Th ratios than have larvikites 1 and 2. The syenites show a wide scatter in lithophile element ratios. Fractional removal of feldspar from the larvikite 1 and 2 melts is suggested by trends of increasing Rb/Sr and K/Ba with increasing SiO_2, and decreasing Sr and Eu/Eu* with increasing Th. A few samples have high Eu/Eu* ratios suggesting accumulation of feldspar. The nordmarkites in contrast, show a wide scatter in the Rb/Sr-SiO_2 and K/Ba-SiO_2 and Eu/Eu*-Th plots.

Nittedal cauldron. The major and trace-element relationships among the rhomb porphyry lavas and syenitic to granitic intrusive rocks in the Nittedal cauldron have been studied by Fjerdingstad (1983). The rhomb porphyry lavas plot on, or close to, the larvikite trend in the Th-SiO_2, and Eu/Eu*-Th diagrams (Fig. 6). Rb/Sr and K/Ba ratios are rather uniform. The average Ta/Th ratio is 0.44 ± 0.06, whereas both the Rb/Th and the Zr/Th ratios cover a considerable range.

The Nittedal nordmarkites and alkali syenites show many of the same compositional characteristics as the Sande syenitic rocks. They fall to the SiO_2-rich, and Sr-poor side of the larvikite trend in the Th-SiO_2 and Sr-Th diagrams (Fig. 6), with the lowest Th-concentrations among the nordmarkites (8-13 ppm). There is no correlation between Rb/Sr or K/Ba and SiO_2. Four syenite samples which show petrographic evidence of alteration appear to have been enriched in SiO_2, but significantly depleted in K_2O, Rb, Zr and *REE* during the alteration process. Even disregarding the altered samples, the Nittedal syenitic rocks show a considerable range in Rb/Th, Zr/Th and *REE*/Th ratios (Fig. 6). With one exception, Eu/Eu* ratios are below 0.7.

Holterkollen intrusive complex. On the basis of

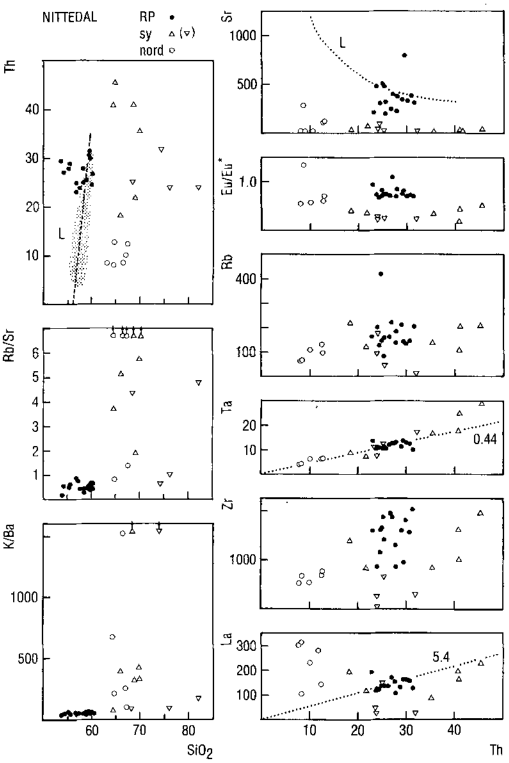

FIG. 6. Compositional variations among rocks in the Nittedal cauldron. Data from Fjerdingstad (1983). RP = rhomb porphyry lava, sy = syenite (parentheses indicate altered samples), nord = nordmarkite.

the trace-element relations among the felsic to silicate rocks in the Holterkollen plutonic complex, Khalil *et al.* (1978*a*, *b*) suggested that these rocks belong to two crystallization series, one represented by the granites, the other by akerite (quartz monzonite)-syenite-ekerite.

The Holterkollen syenites and granites have moderate to high Th-concentrations (15-45 ppm) (Fig. 7). Like the Eikeren, Sande and Nittedal syenitic to granitic rocks, they fall away from the Larvik field in the Th-SiO_2 diagram. The suggestion of crystallization trends is not supported by Khalil *et al.*'s (1978*a*, *b*) data. Rb/Th, Zr/Th and Ta/Th ratios tend to decrease with increasing Th-concentrations. The rocks also show a negative correlation between light *REE* and Th (Fig. 7) or SiO_2, whereas the concentrations of heavy *REE* remain near constant.

Decreasing concentrations of Zr with increasing Th suggests removal of zircon. However, zircon is found only in the syenites, and then only interstitially (Neff and Khalil, 1980). There is thus no petrographic evidence that zircon has acted as a fractionating phase. Furthermore, as zircon has an extreme preference for heavy relative to light *REE* [D(La) ~ 3, D(Lu) ~ 370] (Arth, 1976), removal of zircon should be accompanied by a decrease in heavy relative to light *REE*. This is not the case. The observed compositional relations must therefore be governed by other processes than fractional crystallization.

Hurdal area. The petrogenetic relations among the various rock types in the Øyangen area in Hurdal have been studied by Rasmussen (1983). He found that the rhomb porphyry lavas in the area may be derived from a basaltic primary magma by a crystallization sequence similar to that of the Larvik larvikites: removal of ol+cpx at depth in the crust, followed by crystallization of plag ± ol ± cpx in shallow magma chambers. Some rhomb

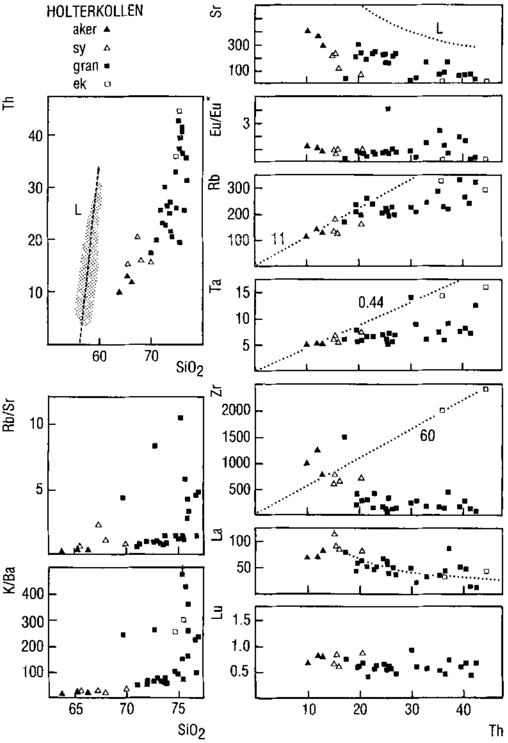

FIG. 7. Compositional variations among rocks in the Holterkollen plutonic complex. Data from Khalil *et al.* (1987*a*, *b*). The area covered by Larvik larvikites in the Th-SiO_2 plot and the Larvik crystallization trends are marked by L. Trends of constant lithophile element ratios are shown in some of the diagrams, and a hypothetical crystallization trend assuming *D*(La) = 2.1 in the La-Th plot. Ak = akerite, sy = syenite, nord = nordmarkite, gran = granite.

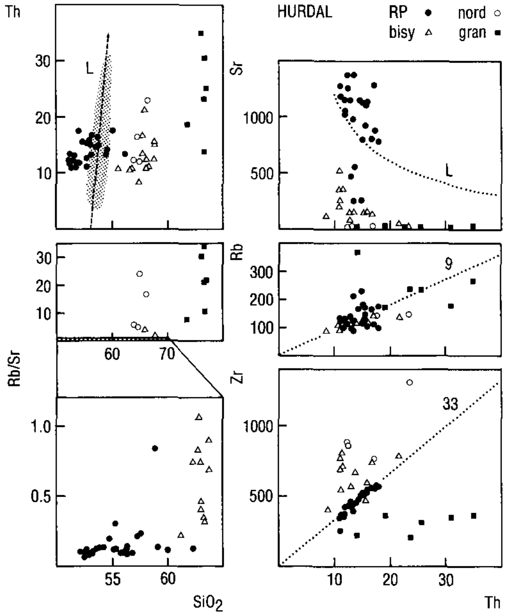

FIG. 8. Compositional variations among rocks in the Hurdal complex. Data from Rasmussen (1983). The area covered by Larvik larvikite and Larvik crystallization trend are marked by L. RP = rhomb porphyry lava, sy = syenite, nord = nordmarkite, gran = granite.

porphyry lavas have accumulated 5-10% plagioclase. Rasmussen furthermore found that the syenites and granites in the area cannot be comagmatic with the mafic and intermediate rocks, but probably result form mixing between mantle-derived melts with relatively low K/Rb and Th/U ratios, and anatectic melts from the lower crust with high K/Rb and Th/U ratios, and low concentrations of trace elements like Th, U and Rb. Some fractional crystallization primarily involving alkali feldspar ($\pm$ amph $\pm$ bi) has taken place after mixing.

Some of Rasmussen's conclusions are demonstrated in Fig. 8. The RP lavas show very constant Th/U and Zr/Th ratios of 4.0 ± 0.8 and 33 ± 3, respectively. In the Th-SiO_2 and Sr-Th plots they show a certain compositional scatter, but fall close to the larvikite trend (L in Fig. 8). The high Sr-/low Th-contents in some of the RP-samples are interpreted as the result of accumulation of feldspar, whereas some of the scatter in e.g. Rb/Th ratios may be due to secondary alteration.

Most of the syenitic rocks in the Hurdal area have Th-contents similar to those of the rhomb porphyry lavas (10-18 ppm), but considerably lower Sr-contents (Fig. 8). The syenitic and granitic rocks also differ from the RP-lavas by covering a wide range in Rb/Th and Zr/Th ratios.

Discussion

The Rb-Sr isotope data presented above (and Table 1) give slightly higher ages for felsic to silicic rocks in the southern (277-268 Ma) than in the northern (264-251 Ma) part of the Oslo rift. The data thus support earlier findings of a northward shift in the magmatic activity with time (Sundvoll, 1978*a*, *b*).

The compositional characteristics among the Oslo rift felsic and silicic rocks suggest a complex origin involving at least two sources. The main evidence is: (1) The rocks cover a range in initial Sr isotope ratios (0.7039 ± 5 to 0.7056 ± 1); (2) Similar concentrations of Rb, *REE*, Ta, Th, and other lithophile elements are found in rocks which differ considerably in SiO_2 contents; (3) Several of the silicic rock complexes show considerable variations in lithophile element ratios. Processes which may have been involved in the formation of these rocks are discussed below.

Contamination by wall-rock assimilation. The analysed rocks show a significant range in initial $^{87}Sr/^{86}Sr$ ratios (I). The monzonic Larvik larvikites have $I = 0.70391 \pm 5$. The majority of the syenitic and granitic rock complexes define isochrons with I in the range 0.7048 ± 7 (Ramnes) to 0.7056 ± 1 (Holterkollen). Rocks from the Sande cauldron central intrusion are at some variance with this pattern by not defining an isochron.

The observed range in I, with the higher values found among the silicic rock types, strongly suggests that the isotope systems of these rock groups contain a crustal component. However, the compositional relations among these rocks are not compatible with a simple mixing model. Each rock group with a given I-value covers a wide range in e.g. SiO_2 and Sr contents (Fig. 9). This implies that after the parent magmas of the various rock series had attained their Sr isotope character, they were subjected to processes which do not affect the isotope ratios, such as fractional crystallization, accumulation and/or volatile transfer. Rocks from the central intrusion in the Sande cauldron show a dispersion of data when I is plotted against SiO_2 or 1/Sr (assuming an age of 270 Ma) (Fig. 9). This suggests a combination of processes, such as assimilation and fractional crystallization which has been discussed by DePaolo (1981).

The well-defined isochrons shown by most of the silicic rock series imply, furthermore, that the magmas were isotopically homogenized after interaction with the crust. Also a number of other silicic intrusions in the Oslo rift define isochrons in the Rb-Sr system, e.g. the Nordagutu granite with age $= 284 \pm 7$ Ma, $I = 0.7044 \pm 2$ (Jacobsen and Raade, 1975), the Siljan nordmarkite with age =

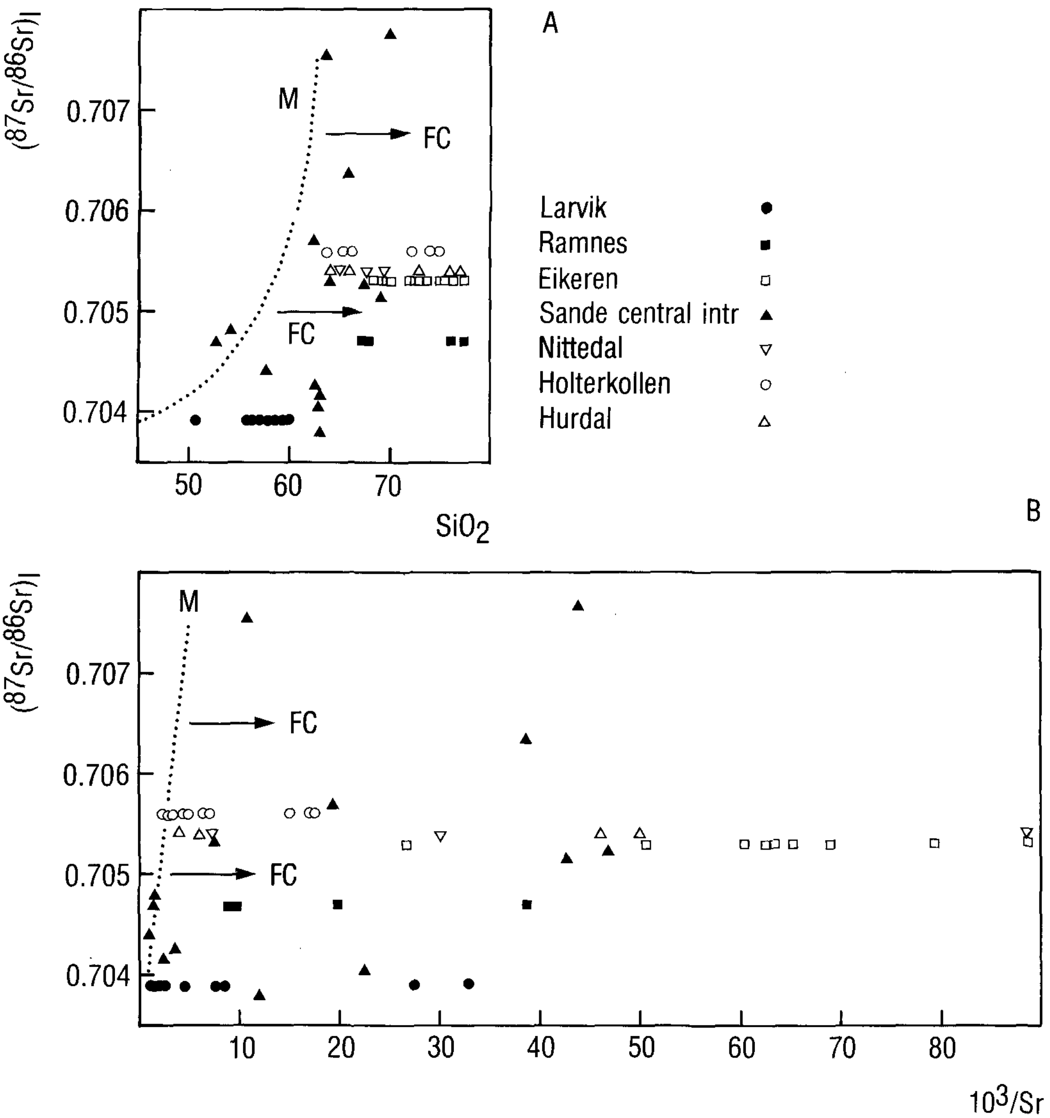

Fig. 9. $^{87}Sr/^{86}Sr$ initial ratios among the Oslo rift intrusive complexes of this study, plotted against SiO_2 (A) and $10^3/Sr$ (B). The dotted line (M) shows a hypothetical trend of mixing between a mafic ($SiO_2 = 45\%$, Sr = 100 ppm, $^{87}Sr/^{86}Sr = 0.7039$) and a silicic magma ($SiO_2 = 63\%$, Sr = 200 ppm, $^{87}Sr/^{86}Sr = 0.7075$). Arrows (FC) indicate trends of fractional crystallization.

278 ± 7 Ma, $I = 0.7042 \pm 2$, and the Drammen biotite granite, age = 284 ± 13 Ma, $I = 0.7033 \pm 11$ (Sundvoll, 1978*b*). It seems highly unlikely that homogenization can be attained as the result of interaction between a viscous silicic magma and the wall-rocks during the final stages of crystallization. *In situ* wall-rock contamination is more likely to result in the dispersion of Rb–Sr isotope data seen in the Sande central intrusion. The fact that most of the silicic rock series define isochrons in spite of a wide range in major and trace-element concentrations, strongly suggests that their parent magmas attained their isotope compositions before intrusion into the upper crust, that is in the intermediate to deep crust. Wall-rock contamination in the shallow magma chambers where these rock complexes crystallized has not been significant.

The apparent lack of *in situ* contamination most

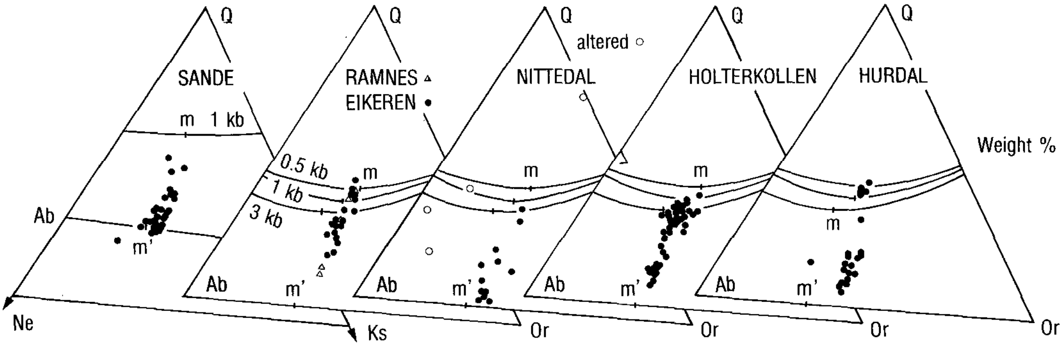

FIG. 10. Quartz–nepheline–kalsilite (Sande) and quartz–albite–orthoclase relations among the syenitic and granitic rocks of this study. The quartz-feldspar boundary with temperature minima (m) for water-saturated liquids at 0.5, 1 and 3 kbar are shown (after Tuttle and Bowen, 1958, and Hamilton and Mackenzie, 1965). The temperature minimum at 1 kbar on the albite–orthoclase join is marked by 'm'.

likely reflects a lack of capacity by the silicic magmas to melt significant masses of wall-rock. This assumption is in agreement with field observations. In his monograph on contact metamorphism in the Oslo rift, Goldschmidt (1911) emphasized that he had observed no evidence of melting caused by intrusion of the silicic magmas in the Precambrian or Cambro-Silurian wall-rocks or in wall-rock xenoliths. Mineralogical evidence of contamination in the silicic intrusions, when observed at all, was restricted to a contact zone only a few centimetres wide. Samples for the present study were therefore (with a few exceptions) collected well away from the contact zone.

Fractional crystallization. It has been shown that the compositional variations among the Larvik larvikites can be accounted for by fractional crystallization of the assemblage anorthoclase$_{86}$ olivine$_8$[mt(ss)]$_4$ ap$_2$, accumulation of feldspar has taken place in some samples (Neumann, 1980; discussion above).

The rhomb porphyry lavas show similar compositional characteristics to those of the Larvik larvikites, such as moderate to high concentrations of incompatible elements, and low K/Ba and Rb/Sr ratios (about 50 and 0.5, respectively) which show a moderate increase with increasing SiO_2 (or Th). Eu/Eu* and Sr decrease with increasing Th. These relations may be accounted for by separation of feldspar as the major phase. Evidence of accumulation of feldspar is seen in some examples of higher Eu/Eu* ratios, and high Sr concentrations. A certain scatter in Rb/Th and Rb/Sr ratios is believed to be due to secondary alteration.

Fractional crystallization may also have affected the silicic complexes. This possibility is supported by some of the data. Alkali feldspar was the first crystallizing phase (see Appendix). When projected into the Q–Ab–Or system, the syenites and granites plot in the thermal valley at low pressure (1 bar to 1 kbar) (Tuttle and Bowen, 1958; Hamilton and Mackenzie, 1965) (Fig. 10). The (Na + K)/Al ratios are about 1.0. The SiO_2–Al_2O_3–Na_2O–K_2O relations, which make up more than 90 weight percent of these rocks, thus appear to be controlled by removal of alkali feldspar at low pressure. However, with the exception of the few samples from the Ramnes central intrusion, the trace-element relations of the syenites and granites do not support the assumption of fractional removal of feldspar. Examples of this disagreement are wide variations in Rb/Sr, K/Ba, Zr/Th and Ta/Th ratios in rocks with similar SiO_2 or Th concentrations (Figs. 3–8). (Th is the element which shows the strongest degree of enrichment within each group of rocks; it also increases strongly with increasing SiO_2.) The lack of trends in the various trace-element diagrams also excludes the possible effect of removal of minor phases in addition to alkali feldspar.

It is concluded that the trace-element relations among the syenites and granites is also affected by other processes than fractional crystallization. One possibility is fluid transfer.

Transport of elements in a fluid phase. There is abundant evidence of the presence of a late magmatic fluid phase among the felsic intrusive rocks in the Oslo Region, in the form of well-developed miarolitic textures, miarolitic cavities (Raade, 1972) and fluid inclusions in interstitial quartz (Andersen, unpublished data). Fluorides occur as common minor interstitial phases (Hansteen, pers. comm., 1985), as crystals grown in miarolitic cavities (Raade, 1972; Raade and Haug, 1980), and as daughter minerals in aqueous fluid inclusions, together with more abundant chlorides (Andersen, unpublished data; Hansteen, pers. comm., 1985). Furthermore, important porphyry and stockwork metal deposits are associated with granitic intrusions in the Oslo rift (e.g. Schønwandt and Petersen, 1983; Olsen and Griffin, 1984*a*, *b*).

A number of studies have shown that the solubilities of LIL elements (e.g. *REE*, Zr, Hf, Nb) are strongly enhanced by the presence of complexing agents such as dissolved fluoride ions (and to a lesser extent also chloride ions) (e.g. Alderton *et al.*, 1980; Humphris, 1983). This may lead to strongly increased mobility of these ions during late magmatic stages when a magma body interacts with a halide-containing aqueous fluid. The effect is expected to be most severe for elements such as U, Zr and *REE*, less pronounced for an element like Th, which forms stable halide complexes less easily.

The evidence cited above [large ranges in Th/U (Raade, 1973, 1978), Zr/Th and *REE*/Th ratios] strongly suggests that a number of the felsic rocks the Oslo Region may have been affected by volatile transfer processes, as was initially suggested by Dietrich *et al.* (1965). The effect of such processes on the contents of incompatible trace elements would probably be strongest in the coarse-grained, strongly miarolitic varieties, such as the majority of nordmarkite samples from the Sande central pluton, some of the varieties of Eikeren ekerite, and syenite and granite in the Holterkollen complex. On the other hand, samples which are fine-grained and non-miarolitic would probably be less disturbed by late magmatic volatile transfer. Such samples should be expected to give better information on the trace-element concentrations in the silicate melts. It is likely that fluid transfer also affected the major elements, but not to a sufficient degree to significantly alter their position in e.g. the quartz–albite–orthoclase plots (Fig. 10).

The combination of fractional crystallization (which would strongly increase Rb/Sr and K/Ba ratios) and partitioning of LIL elements between magma and fluid, might easily result in the seemingly chaotic behaviour of the trace elements shown in Figs. 4–8. As long as no 'foreign' material was transported into the system, I values would not be affected by these processes. The problem of late-stage volatile transfer in nordmarkites and ekerites is currently being studied by the use of inclusion analysis and modelling of fluid composition and properties from mineralogical data. The results of these studies will be presented elsewhere (Hansteen in prep., Andersen in prep.).

Origin of the larvikites and rhomb porphyry lavas. It was shown above that the Larvik larvikites have the lowest I value (0.7039) among the rock series of this study. Similar I values are found for rhomb porphyry lavas (the extrusive equivalent to larvikite) at Krokskogen (0.7035 ± 14 to 0.70427 ± 9) (Sundvoll, 1978*a*; Andresen, 1985). These are therefore unaffected by, or less affected by contamination than are the silicic rocks. The basalts have I values between 0.7034 and 0.7054 (Table 2), the gabbros between 0.7038 and 0.7109 (Jacobsen and Wasserburg, 1978; Sundvoll, 1978*a*; Neumann *et al.*, 1985). Gabbros with relatively high initial values have compositions compatible with mixing between basaltic melts and Precambrian amphibolite facies country rocks. The larvikitic rocks thus have I values which fall within the range of uncontaminated mafic Oslo rift rocks (Table 1), and slightly below the estimated planetary value for Permian time (0.7042). The Larvik larvikites also fall within the range of Oslo rift basalts with respect to age-corrected Nd and Pb isotope ratios (E.-R. Neumann and G. R. Tilton, unpublished data). Earlier conclusions that larvikites have not suffered significant crustal contamination are thus supported.

Origin of the silicic rocks. It was concluded above that the silicic complexes of this study have acquired their moderately high I values (0.705–0.706), and syenitic to granitic composition before intrusion into the upper crust. Possible mechanisms are anatexis, and assimilation of crustal material in mantle-derived melts. It is not unlikely that such processes should have taken place during the Oslo rifting event. The compositional relations among the basaltic and intermediate rocks in the rift imply that extensive crystallization occurred at depth in the crust where the stability field of pyroxene is expanded relative to that of plagioclase (Neumann, 1980; Neumann *et al.*, 1985). Fluid inclusions in cumulate type xenoliths in a basaltic lava at Krokskogen (Fig. 1) give a minimum pressure of formation of 5.5 kbar (T. Andersen, unpublished data). The petrological evidence is supported by a positive gravity anomaly along the rift axis which reflects large masses of dense material in the intermediate to deep crust (Ramberg, 1976; Wessel and Husebye, 1986). There is furthermore a striking agreement between estimates of excess masses in the crust based on gravimetric and petrological data, assuming the dense material to represent cumulates and residues after partial melting (5–10×10^{10} kg/m along the graben axis) (Neumann *et al.*, 1986). If large volumes of hot mafic magma are stored in the crust over long periods of time, and additional heat is released through crystallization, melting of the side rock can hardly be avoided.

Some inferences may be made about the crustal rocks involved in the formation of the silicic magmas. If anatexis is the main process, melting must have occurred in crustal rocks which had Sr isotope ratios of 0.705–0.706 in early Permain time; that means that these crustal rocks must have a history of relatively low Rb/Sr ratios. The relatively low concentrations of lithophile elements characteristic of these rocks support the notion of a somewhat depleted source region. Also the assumption of assimilation of crustal rocks in mantle-derived magma implies a somewhat depleted crust. However, this model puts less rigid restraints on the composition of the crust. A simplified model for assimilation of crustal material by mantle-derived magmas at depth in the crust, followed by fractional crystallization in shallow magma chambers, is demonstrated in Fig. 9. It should be noticed, however, that the data are even better satisfied if we allow the silicic (crustal) mixing member to be somewhat heterogenous.

It is likely that provinces poor in lithophile elements existed in the crust during the Oslo rifting event. A survey of available Sr isotopic and trace-element data on Precambrian granites and granitic gneisses in south-east Norway (Jacobsen and Heier, 1978; Killeen and Heier, 1974, 1975*a–d*; Smalley, 1983; Sundvoll, unpublished data) shows that the older and younger Sveconorwegian granitic rocks in southern Norway were derived from compositionally different crustal sources. The high *I* values and Rb/Sr ratios (> 1) of the older granites are typical of melts formed in crustal rocks rich in lithophile elements. The relatively low Sr isotope initial ratios (0.703–0.72), but highly variable Rb/Sr ratios (0.5–14) of the younger Sveconorwegian granites suggest small degrees of melting of crustal rocks with low Rb/Sr ratios and plagioclase in the residue, and/or partial melting of younger magmatic rock (Killeen and Heier, 1975*b*; Sundvoll, unpublished data). Sources similar to those which gave rise to the younger Sveconorwegian granites may also have been subjected to melting in Permo-Carboniferous time.

Conclusions

The felsic and silicic rocks in the Oslo rift may be divided into two main groups on the basis of their Sr isotope and trace-element characteristics. The Larvik larvikites define an isochron with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70391 ± 5, and are relatively rich in lithophile elements. The rhomb porphyry lavas have a similar chemical character.

The initial Sr isotope ratio of the monzonitic rock is similar to those of uncontaminated basalts and gabbros in the rift. The monzonitic rocks are therefore believed to originate from mantle-derived primary melts. The compositional variations among the larvikites are compatible with fractional removal of an assemblage dominated by anorthoclase. Some rocks are feldspar cumulates.

With the exception of the Sande central intrusion, also the syenitic and granitic intrusive complexes define isochrons, the initial Sr isotope ratios are between 0.7048 and 0.7056. The higher initial ratios among the silicic than among the felsic rocks are believed to reflect a crustal component.

The silicic rocks furthermore show a wide range in trace-element concentrations. In spite of their higher SiO_2 contents (64–77% SiO_2), a large proportion of these rocks have lithophile element contents which fall within the range of the felsic rocks (50–60% SiO_2). Most of the syenites and granites are thus depleted in lithophile elements relative to the larvikites and rhomb porphyry lavas, and this is particularly true for the nordmarkites. An exception is the rock series in the Ramnes cauldron.

The range in major and trace-element concentrations with constant initial Sr isotope ratio shown by each silicic rock complex, indicates that after intrusion into the upper crust their parent melts were subjected to magmatic processes which did not affect their Sr isotope systematics. It is therefore most likely that these melts had acquired their Sr isotope character before emplacement into the upper crust. The crustal component in the silicic rocks must consequently represent the intermediate or lower crust. Possible processes which led to the formation of the silicic melts are anatexis, and assimilation of crustal rocks in mantle-derived melts.

The major element relations within each silicic rock complex appear to be controlled by removal of alkali feldspar (at pressures below 1 kbar). However, fractional crystallization cannot explain the unsystematic scatter observed among some of the trace elements (e.g. Zr–Th, Rb/Sr-SiO_2, K/Ba-SiO_2. Abundant evidence in the silicic rocks of the presence of a late magmatic fluid phase strongly suggests that the chemistry of these rocks are also influenced by partitioning of elements between magma and fluid. The seemingly chaotic behaviour of elements like *REE* and Zr might easily be the result of a combination of fractional crystallization and fluid transfer.

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Appendix: Description of rock types

Larvikite is a monzodioritic to monzonitic rock-type, consisting mainly of 'ternary' anorthoclase, sometimes containing resorbed cores of plagioclase. Quartz, when present, is found as an interstitial phase. Nepheline occurs in silica undersaturated varieties, both as separate grains and as exsolution lamellae in feldspar (Widenfalk, 1972). Augite, amphibole (ranging from kaersutite to richterite), olivine and Fe–Ti oxides are interstitial phases. The most abundant accessories are apatite, zircon and titanite. Allanite, baddelyite and chevkinite have also been reported (Raade, 1973; Widenfalk and Gorbatschev, 1971; Andersen, 1981).

Two major occurrences of larvikite have been studied: The Larvik plutonic complex and the Sande central pluton. The Larvik pluton (Fig. 1) is a composite ring complex (Brøgger, 1898; Neumann, 1976; Petersen, 1977, 1978).

The larvikite of the Sande central pluton occurs in megarafts included in younger nordmarkite. Andersen (1981, 1984*a*) recognized three different petrographic varieties: Larvikite 1 is distinguished by the presence of two primary feldspar phases (plagioclase An_{35} and alkali feldspar); some samples of the unit also contain coexisting augite and hypersthene. Larvikite 2 is closely similar to quartz- and nepheline-free larvikites from the Larvik pluton. Both of these units, however, differ from the Larvik larvikites in the presence of biotite, formed by late-magmatic reaction between magnetite and alkali feldspar (Andersen, 1984*a*). Larvikite 3 is formed by the action of nordmarkite magma on solidified larvikite similar to larvikite 1 (Andersen, 1984*b*).

Akerite is a coarse-grained to porphyritic quartz monzonite. The main constituents are plagioclase (An_{5-20}) and perthite. Quartz, hornblende, biotite and magnetite each account for up to 10% of the rock. Traces of augite, zircon, rutile, titanite and apatite occur as interstitial phases. The rock is believed to have a hybrid origin (Sæther, 1962; Neff and Khalil, 1980).

Minor amounts of akerite are found in different parts of the composite plutonic complexes north of Oslo (Fig. 1), including the Holterkollen complex.

Nordmarkite is a medium to coarse-grained alkali or alkali quartz syenite, commonly with miarolitic mesocumulate texture. The predominant feldspar is a sericitized mesoperthite, but unexolved grains of microcline and/or resorbed plagioclase crystals are occasionally found. Quartz, aegirine-augite, richteritic to arfvedsonitic amphibole, titanomagnetite and manganiferous ilmenite occur as interstitial phases. Zircon, titanite and apatite are the most common accessory minerals. Biotite has formed by reaction between titanomagnetite and feldspar.

Nordmarkite is a common rock type in the intrusive complexes of the Oslo rift. In the Sande central pluton (Andersen, 1984*a*) nordmarkite is the most important unit in terms of volume.

Syenite is a medium-grained rock which may have a porphyritic microstructure, with plagioclase phenocrysts mantled by alkali feldspar. The groundmass consists of perthitic alkali feldspar, quartz, biotite, minor amounts of hornblende, apatite, titanomagnetite and ilmenite. Miarolitic cavities are common.

Syenite occurs within the Øyangen area in Hurdal, where it belongs to the older intrusives (Rasmussen, 1983). It is also found in the area immediately north of Oslo (McCulloh, 1952; Naterstad, 1971; Fjerdingstad, 1983).

Ekerite is an alkali granite, containing at least 20% quartz by mode. The ekerite varies from fine-grained quartz porphyry to coarse-grained, miarolitic granite. The miarolitic ekerite is similar to nordmarkite in terms of texture and mineralogy, distinguished from it by a higher modal quartz content. The modal content of mafic phases in ekerite is low. In addition to clinopyroxene and amphibole, astrophyllite occurs as a characteristic minor phase in some of the miarolitic varieties.

The major occurrence of ekerite is in the composite Eikeren pluton, which consists of different varieties of ekerite, probably representing different intrusive pulses (T. Hansteen, pers. comm., 1985). The most abundant varieties are coarse-grained miarolitic granite and porphyritic varieties; ekerite aplite is of minor abundance, but occurs both as inclusions in coarse-grained rocks and as dykes cutting these (T. Hansteen, pers. comm., 1985).

Lesser volumes of ekerite are found in association with nordmarkite, e.g. in the Nordmarka, Nittedal and Hurdal areas. Ekerite typically grades into quartz-poorer nordmarkite in these occurrences. It should be noticed that a number of rocks called ekerite by Barth (1945) and Oftedahl (1953) only contain 10 to 15 percent quartz by mode, and are thus not alkali granites in the sense of Streckeisen (1967, 1976). These rocks have therefore been reclassified as nordmarkite.

Biotite granite is a coarse-grained, hypidiomorphic-granular rock type which grades into fine-grained, porphyritic varieties with phenocrysts of rectangular alkali feldspar, sometimes of quartz and/or plagioclase. Both normal and reversed zoning of feldspar is observed. Biotite and/or hornblende are the only common primary mafic silicate minerals. Magnetite, titanite, zircon and apatite are the most common accessory phases (Raade, 1973; Gaut, 1981).

Rhomb porphyry lava is a mildly silica oversaturated to mildly undersaturated trachytic rock type regarded as the extrusive equivalent to larvikite. It has rhomb- to boat-shaped phenocrysts of ternary anorthoclase in a fine-grained to aphanitic groundmass of alkali feldspar, augite and Fe–Ti oxides. Pseudomorphs after olivine are found in some flows. Apatite and titanite are the most common accessory minerals.

Rhomb-porphyry lavas are preserved in various parts of the Oslo Region, including the Nittedal cauldron and the Hurdal area (Fig. 1).

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