Petrology of the Plutonic Rocks

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Introduction

The Oslo rift is a so-called 'mixed province' of alkaline rocks (MacDonald 1975) where alkaline silica-saturated rocks and peralkaline silicic rocks are found in close association with subalkaline granites and undersaturated alkaline and peralkaline rocks. Unlike younger rift provinces, in the Oslo rift most of these rock-types are found as plutonic series. The associated volcanic rocks are described elsewhere (Ramberg & Larsen, this volume).

The plutonic rocks may be divided into two groups; 1) a series of mafic volcanic necks, and 2) a number of large batholiths of plutonic rocks ranging in composition from monzodiorite to granite, including plagifoyaite and nepheline syenite. The small amounts of more mafic material found in the batholiths (olivine gabbro = sørkedalite) are cumulates (suggested by Sæther (1962) and Bose (1969) on the basis of field observations and major element data, and confirmed by trace element data (E.-R. Neumann, unpublished data)).

The plutonic rocks in group 2 occupy about 60% of the graben surface (Ramberg 1976), and are concentrated in three sub-regions. The southern part of the rift is dominated by monzonitic rocks (kjelsåsite/larvikites) found mainly in the Larvik and Skrim massifs (Plate 1); the Larvik massif is a composite ringcomplex (Petersen 1977). The central part of the rift is occupied primarily by the Drammen and Finnemarka complexes of biotite granite. The Hurdalen area is dominated by rocks of syenitic to alkali granitic compositions.

The volcanic necks are believed to belong to the earliest period of magmatic activity in the Oslo rift (Barth 1945a). The necks occur in two sublinear rows, and are probably aligned along early major fissures. The emplacemen of the more evolved rocks found in the batholiths, on the other hand, seems to have taken place during the later stages of the main period of magmatic and tectonic activity (Ramberg & Larsen, this volume). There is ample field evidence that the evolved rocks were emplaced by stoping (Holtedahl 1935, Oftedahl 1959, Sæther 1962, Nystuen 1975b).

The intrusive activity seems to have progressed with time from the south towards the north (Sundvoll, personal comm. 1977).

Petrography

The plutonic rocks have been described by a number of authors including Barth (1945a), Sæther (1962), Dietrich et al. (1965), El-Bouseily (1971), Raade

(1973), Gaut (1975), Sørensen (1975), Nystuen (1975b) and Neumann (1976). A brief summary of the main rock-types is presented below. Although many of these rocks show a variety of interesting textures, detailed descriptions of such features are considered to lie outside the scope of this paper.

Oslo-essexite. The 'Oslo essexites' occur in more than ten volcanic necks. The main rock-type is gabbro with alkaline to quartz tholeiitic affinity, but pyroxenite, anorthosite and diorite are also common. The single necks are petrographically complex. Twin bodies may often be distinguished, one with alkaline and the other with tholeiitic affinity (Ramberg 1970).

The textures vary from fine-grained to coarse-grained and porphyritic. Major minerals (also occurring as phenocrysts) are ± olivine + titaniferous augite (often zoned) ± titaniferous amphibole ± zoned plagioclase. Accessory minerals are ± quartz + biotite ± alkali feldspar + apatite + ilmenite + magnetite ± sphene + zircon. Nepheline has also been reported (Dons 1952).

Kjelsåsite/larvikite. Kjelsåsite and larvikites were originally distinguished on the bases of the An-content of their feldspars ($An > 30$ in kjelsåsites, $An < 30$ in larvikites), the kjelsåsites thus being the more mafic variety of the two. For practical purposes the two rock-types are now treated as one group.

The kjelsåsites/larvikites are medium- to coarse-grained, sometimes with mafic and accessory minerals in interstices between feldspar laths of 1 cm or more in size. The mineral assemblage is dominated by ternary feldspar ($An_7Ab_{61}Or_{32}$ – $An_{15}Ab_{76}Or_8$) sometimes with a core of partly resorbed calcic plagioclase ($\sim An_{35}Ab_{60}Or_5$) (Neumann, unpublished data). The feldspar is unmixed to a variety of perthite. The Schiller effect characteristic of larvikite feldspars is the result of unmixing to cryptoperthite parallel to $(\bar{8}01)$ (Rosenqvist 1965). Other examples of unmixing found in connection with the feldspars are seen in the form of swapped rims, and myrmekitic intergrowth between nepheline and alkali feldspar (Widenfalk 1972). The kjelsåsite/larvikites also contain small quantities of quartz or nepheline ± olivine (or olivine pseudomorphs) + Ti-poor augite ± kaersutitic hornblende + ilmenite + magnetite + apatite + zircon ± biotite. Orthopyroxene is found in kjelsåsite/larvikite from Sande. Baddeleyite has also been reported (Widenfalk & Gorbatschev 1971).

Lardalite. The lardalites are fine- to coarse-grained. They consist of antiperthite ($An_{2-10}Ab_{55-85}Or_{15-40}$) + nepheline ± sodalite ± olivine (or olivine pseudomorphs) + Ti-poor augite + biotite + ilmenite + magnetite + apatite + zircon. Traces of kaersutitic hornblende have been found.

Foyaite/hedrumite. The foyaite/hedrumites range from nepheline-free to very nepheline-rich varieties. Major minerals are platy mesoperthites ($An < 1$) ± nepheline + augite, aegirine-augite or aegirine (often zoned with calcic cores and sodic rims). Accessory minerals are sphene + ilmenite + magnetite + apatite

+zircon. Traces of sodic amphibole intergrown with pyroxene have occasionally been found. Swapped rims (between feldspars) are common.

Nordmarkite-Grefsen syenite. Barth (1945a) divided the nordmarkites into two types. *Type 1* is alkaline and contains zoned plagioclase rimmed by mesoperthite+Na-rich alkali feldspar+common hornblende+biotite+Ti-poor augite±small amounts of quartz. *Type 2* is peralkaline with patch to braid mesoperthite (swapped rims are common)±quartz+aegirine-augite (often zoned)+riebeckitic amphibole (often zoned). Accessory minerals in both types are sphene, ilmenite, magnetite, apatite and zircon. Miarolitic cavities containing rare minerals are common (Raade 1972).

Oftedahl (1948) and Sæther (1962) proposed that the name nordmarkite should be reserved for the peralkaline variety (type 2), and called the alkaline type (1) Grefsen syenite.

Ekerite. The ekerites are peralkaline rocks consisting of coarse patch and braid mesoperthite (±antiperthite) + quartz + aegirine or calcic aegirine + riebeckite–arfvedsonite ± biotite + apatite + ilmenite ± magnetite ± sphene ±rutile+zircon. Miarolitic cavities containing rare minerals are common (Dietrich et al. 1965, Raade 1972).

Biotite granite. Gaut (1975) has divided the biotite granites in the Oslo rift into two groups. The *biotite granites I*, which constitute the majority of the large biotite granite bodies including the Drammen granite are medium- to coarse-grained with a variable plagioclase to alkali feldspar ratio. They also contain quartz + biotite + sphene + magnetite + apatite + zircon ± rutile. Common hornblende is occasionally found.

Biotite granites II are found as small bodies in close association with syenites and ekerites (Gaut 1975). They are fine- to medium-grained alkali granites grading chemically into granites and ekerites.

Chemistry

Representative major element analyses of the main plutonic rock-types are listed in Table 1. For some rock-types more than one analysis is presented in order to give an indication of the compositional variations.

A number of the available analyses of Oslo rift rocks (Brøgger 1933a, R. Wilson & M. P. Annis unpublished data, El-Bouseily 1971, Neumann 1976) have been plotted in a $NaAlSiO_4$–$KAlSiO_4$–SiO_2 diagram (Fig. 1). The kjelsåsite/larvikites and the alkaline nordmarkites plot close to the minimum on the alkali feldspar thermal divide, whereas the undersaturated lardalites and foyaite/hedrumites plot close to the thermal valley in the undersaturated part of the diagram; the other rock-types plot along the thermal valley in the over-saturated part of the diagram (at $P_{H_2O} = 1$ kb).

Mineral analyses are available (Oftedahl 1948, Muir & Smith 1956, Widenfalk 1972, Neumann 1974, 1976), but will not be discussed in this paper.

Table 1. Streckeisen classification and representative chemical analyses of the main plutonic rock-types

Local name	Oslo-essexite				Kjelsåsite/ larvikite		Lardalite	Foyaite/ hedrumite	
Streckeisen classification	Gabbro				Monzodiorite– monzonite– syenite		Plagi- foyaite	Nepheline syenite	
Reference numb.	H–7^1	J–9^1	E–11^1	E–10^1	905^2	2^2	6^2	23^3	12^3
SiO_2	46.17	47.20	37.86	49.94	55.46	59.71	55.55	58.69	55.90
TiO_2	2.33	3.79	5.31	3.03	1.42	1.00	1.12	1.11	.61
Al_2O_3	4.09	13.88	4.40	16.01	19.63	18.59	20.38	18.04	23.18
Fe_2O_3	5.78	2.29	12.00	4.31	2.52	1.90	2.06	1.81	1.30
FeO	8.72	13.13	12.05	7.97	4.04	2.33	2.42	2.37	.67
MnO	.20	.29	.40	.39	.12	.14	.16	.23	.09
MgO	14.59	6.56	11.33	3.56	1.67	1.31	1.46	1.53	.44
CaO	17.25	8.54	15.13	5.48	6.11	3.25	2.32	1.81	1.03
Na_2O	.50	2.55	.47	4.26	4.80	6.54	8.15	6.07	10.57
K_2O	.02	.66	.10	3.45	3.21	4.11	5.04	5.64	5.70
P_2O_5					.66	.42	.64	.43	.08
H_2O						.58	.75	1.29	.58
Sum	99.70	98.89	99.05	98.40	99.64	99.88	100.05	99.02	100.15
Q					.75				
Or	.12	4.04	.63	20.92	18.95	23.92	28.82	33.35	31.65
Ab	4.58	23.75	4.49	33.06	43.08	56.31	36.46	49.32	24.85
An	9.04	25.41	10.31	14.77	22.54	9.11	4.02	5.34	
Ne			.02	3.73		.93	20.62	3.14	37.46
Wo									.45
Hy	6.94	18.52			5.94				
Di	62.63	14.84	56.19	10.51	2.76	3.26	2.46	.67	2.55
Ol	7.21	5.47	6.95	8.04		2.27	2.73	3.84	
Ac									1.53
Mt	6.16	2.48	13.46	4.62	2.63	1.96	2.08	1.89	.27
He									.29
Il	3.31	5.48	7.94	4.33	1.98	1.37	1.51	1.55	.80
Ap					1.38	.87	1.30	.90	.16

Genetic relationships between the plutonic rocks

The genetic relationships between the 'Oslo-essexites' and the other magmatic rocks in the Oslo rift are still unclear (Barth 1945a, Dons 1952, Raade 1973, Ramberg 1973, Ramberg & Larsen, this volume).

On the basis of field evidence and major element chemistry, Barth (1945a) proposed that the major plutonic rock-types in the Oslo rift are related to each other through fractional crystallization of feldspar + clinopyroxene ± amphibole to form the principal rock series kjelsåsite → larvikite → nordmarkite → ekerite, with larvikite → lardalite, and nordmarkite → granite as subordinate branches. (See Fig. 2 in the introduction, Dons, this volume). Recent work, however, has shown that several evolutionary series exist. Some of these originate from sources with significantly different compositions.

Table 1 cont.

Local name	Nordmarkite			Ekerite		Drammen granite	
Streckeisen classification	Syenite–alkali syenite			Alkali granite		Biotite granite	
Reference numb.	126^2	113^2	801^2	268^2	260^2	Av^4	Rap^4
SiO_2	60.34	62.56	69.97	73.00	75.26	77.04	72.00
TiO_2	1.41	.91	.30	.41	.31	.29	.40
Al_2O_3	16.86	16.08	14.25	13.98	11.13	11.94	14.32
Fe_2O_3	2.18	2.66	1.56	1.68	2.17	.62	1.13
FeO	2.84	.92	.48	.52	.50	.83	.92
MnO	.19	.19	.20	.14	.13	.05	.08
MgO	1.68	.68	.13	.40	.39	.06	.23
CaO	2.55	.98	.22	.33	.18	.54	.75
Na_2O	6.12	7.79	6.84	5.45	4.38	3.91	4.40
K_2O	5.11	5.49	5.12	5.04	4.59	4.98	5.09
P_2O_5	.62	.25	.00	.03	.00	.04	.09
H_2O						.59	.74
Sum	99.90	98.51	99.07	100.98	99.04	100.89	100.80
Q			14.25	19.61	30.74	31.97	23.44
Or	29.74	31.98	29.97	29.34	27.65	29.64	30.31
Ab	54.14	53.27	47.12	45.87	34.31	35.37	39.83
An	3.40					.33	3.16
Ne		.78					
Wo						.14	
Hy	1.59		.56	.74	.94		.85
Di	4.06	2.55	.87	1.14	.73	1.40	
Ol	1.61	.77					
Ac		7.31	4.31	1.88	4.63		
Mt	2.24			.35	.52	.65	1.19
He				.45	.03		
Il	1.94	1.25	.41	.56	.44	.41	.56
Ap	1.28	.52		.06		.08	.19

[1] Ramberg 1970, [2] Neumann 1976, [3] Neumann, unpublished data, [4] El-Bouseily 1971.

In the Skrim and Larvik areas there seem to be transitions between larvikite and nordmarkite (Raade 1973), whereas in the Ramnes cauldron (Sørensen 1975), Nordmarka (Sæther 1962), the Nittedal cauldron (Naterstad 1971) and Hurdal (Nystuen 1975b) two magmatic differentiation series are suggested; kjelsåsite–larvikite, and nordmarkite – ekerite/alkali granite. The field evidence is supported by Th–U data (discussed by Sundvoll, this volume).

Major and trace element data (Neumann et al. 1977, Neumann unpublished data) show that:

1) The lardalites have rare earth element (REE) characteristics of a system in which feldspar has accumulated. It is highly unlikely that the magma involved in the formation of the lardalites is related to the ones from which the kjelsåsite/larvikites crystallized.
2) The foyaite/hedrumites are related through fractionation mainly of feldspar, and are derived from a magma with a composition that was significantly different from those which gave rise to the kjelsåsite/larvikites.

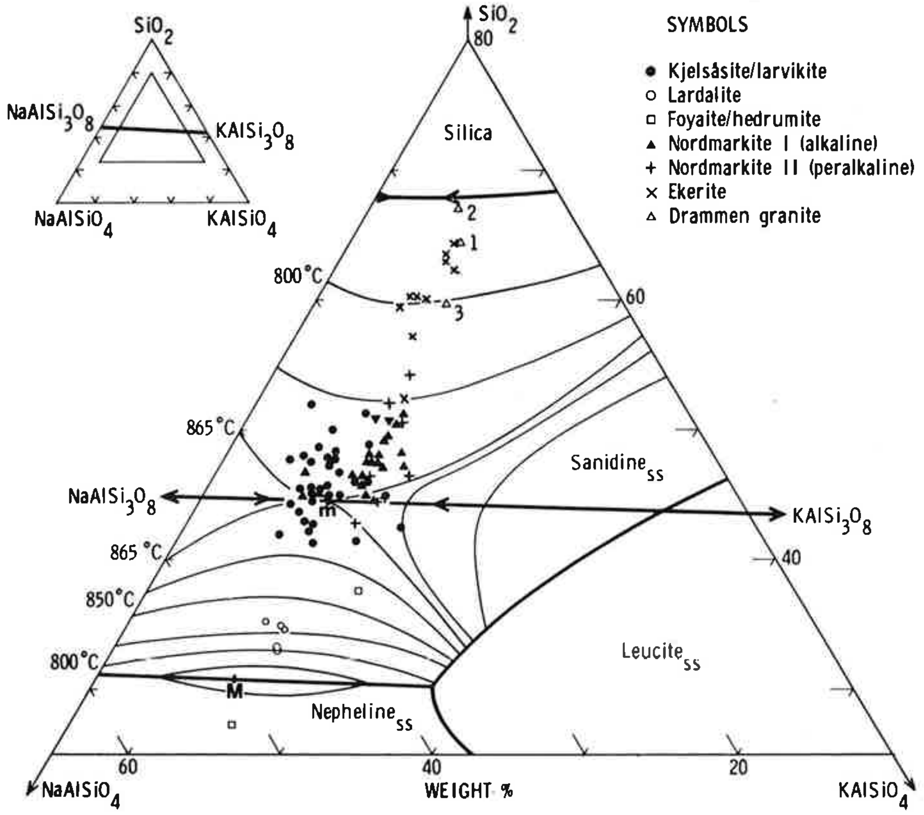

Fig. 1. Whole rock analyses projected into the SiO_2–$NaAlSiO_4$–$KAlSiO_4$ compositional plane. The isotherms ($P_{H_2O} = 1$ kb) are from Tuttle & Bowen (1958) and Hamilton & MacKenzie (1965). The analytical data are from Brøgger (1933a), El-Bouseily (1971), Neumann (1976), and unpublished data kindly made available by R. Wilson & M. P. Annis. △ 1, △ 2 and △ 3 are average analyses (used because of the homogeneity of these rocks) of the coarse- to medium-grained variety, the medium- to fine-grained variety, and the rapakivi variety of the Drammen granite, respectively (El-Bouseily 1971).

3) Some nordmarkites are likely to have been derived from a larvikitic parent magma or magmas. Other nordmarkites must have been derived from other sources, or had their REE contents changed by contamination.
4) Different paths of differentiation have led to different REE characteristics among the oversaturated peralkaline nordmarkites.
5) Mineralogical data (Neumann 1976) strongly suggest that the peralkaline ekerites are derived by fractionation of feldspar (plus other phases) from an alkaline source. There is a gradual change in nordmarkite and ekerite REE patterns with increasing silica contents, supporting the hypothesis of a fractionation relationship between the ekerites and (some of) the nordmarkites.

The different paths of differentiation observed among the peralkaline nordmarkites probably reflect the marked differences in f_{O_2} and P_{H_2O} found among the syenitic and granitic rocks (Neumann 1976). Differing permeabilities of the country rock have caused the gas phase either to remain in the magma or have allowed it to escape.

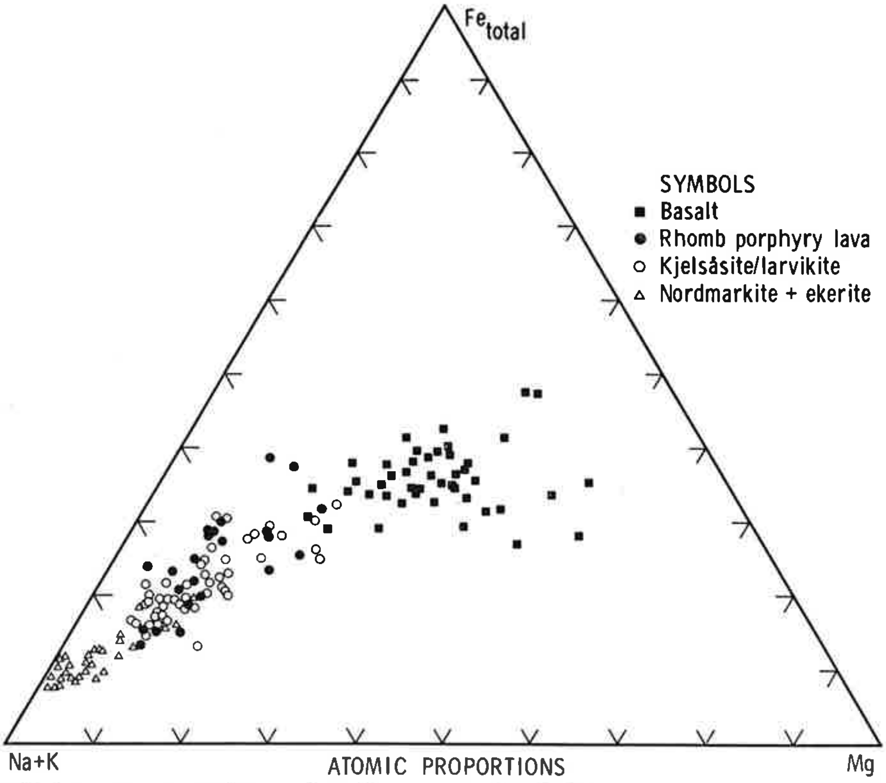

Fig. 2. Whole rock analyses projected into a (Na+K)–Fe–Mg diagram. Analytical data from Brøgger (1933a), Weigand (1975), Neumann (1976), and unpublished data kindly made available by R. Wilson & M. P. Annis.

The biotite granites I (the Drammen type) are among the oldest plutonic rocks exhibited in the Oslo Graben (Sundvoll, this volume). They appear to be unrelated to the main series om plutonic rocks, and may represent remobilized Precambrian crust (Barth 1945a, Raade 1973). The REE patterns of the Drammen granite are lower than those of the less evolved kjelsåsite/larvikites (Neumann et al. 1977), and rather similar to those of average Western North American granites and average European Paleozoic shales, thus supporting the above suggestion.

The biotite granites II are among the youngest plutonic rocks in the Oslo rift. They may represent an alkaline equivalent to the peralkaline ekerites (Gaut 1975).

Origin of the monzonitic rocks

In the preceeding chapter a pattern of genetic relations between the different plutonic rock-types has been outlined. The mode of formation of the least evolved of these rocks, the kjelsåsite/larvikite is, however, still not clear. The following facts are relevant to the discussion of the origin of the kjelsåsite/larvikites:

The kjelsåsite/larvikites and rhomb-porphyry lavas make up a significant

Table 2. Average compositions and standard deviations for kjelsåsite/larvikites and rhomb-porphyry lavas

Number of analyses	Kjelsåsite/larvikite 41	Rhomb-porphyry 22
SiO_2	57.27 ± 1.95	56.21 ± 2.05
TiO_2	1.44 ± 0.34	1.69 ± 0.46
Al_2O_3	17.82 ± 1.27	17.13 ± 1.64
Fe_2O_3 (tot)	6.70 ± 1.50	6.71 ± 1.45
MnO	0.15 ± 0.08	0.16 ± 0.10
MgO	1.81 ± 0.74	1.74 ± 0.56
CaO	4.65 ± 0.91	4.32 ± 0.83
Na_2O	5.37 ± 0.76	4.91 ± 0.98
K_2O	3.63 ± 0.59	4.06 ± 0.62
P_2O_5	0.63 ± 0.25	0.83 ± 0.60

proportion of the magmatic rocks in the Oslo rift (estimated to be about 40% by Ramberg & Larsen, this volume). There is no significant difference in major element compositions between the kjelsåsite/larvikites and the rhomb-porphyry lavas (Table 2). The kjelsåsite/larvikites are fairly homogeneous with respect to initial $^{87}Sr/^{86}Sr$, Th/U (Sundvoll, this volume) and REE (Neumann et al. 1977). The few Th/U ratios and REE data that exist on rhomb-porphyry lavas (Sundvoll and Ramberg & Larsen, this volume) are quite similar to those found for kjelsåsite/larvikites. Calculated temperatures and oxygen fugacities indicate that the rhomb-porphyry lavas (B. T. Larsen, pers. comm. 1975) crystallized under $T–f_{O_2}$ conditions close to those defining the QMF-buffer.

The above data strongly suggest that the compositional similarities between the kjelsåsite/larvikites and the rhomb-porphyry lavas are the result of formation under similar conditions from a fairly homogeneous source, and that these rocks have not been noticeably affected by contamination or gaseous transfer.

Barth (1945a) and Oftedahl (1967) suggested that the monzonitic rocks were formed by anatexis, partly on the basis of the preponderance of monzonitic and syenitic rocks over (exposed) mafic ones. Ramberg (1976) favoured derivation by fractionation of a basaltic parent magma. Several facts support the latter hypothesis:

1) Although only a small percentage of the exposed rocks have compositions between basaltic and trachytic, there is no compositional gap between these rocks (Fig. 2).
2) Ramberg (1976) has pointed out that if the 'pillow' of dense material found at the base of the crust along the Oslo rift is taken into consideration, 'there is no volumetric objection to the idea that the felsic rocks of the Oslo Region originated from a basaltic parent magma'.
3) The trend silica-saturated basalt-hawaiite-mugearite- (benmorite)-trachyte-peralkaline rhyolite is commonly found in rift povinces (MacDonald 1975). The kjelsåsite/larvikite-ekerite series may well represent the most evolved part of such a trend. The basaltic trends found in the Oslo rift include an alkali olivine basalt-hawaiite-mugearite suite (Sundvoll and Ramberg & Larsen, this volume).

4) In the chapter on trace elements, Sundvoll presents REE evidence favouring the notion that the alkali olivine basalt suite and the rhomb-porphyries may have a common source.
5) Helz (1976) has shown that partial melting of basalts of different compositions (including nepheline-normative alkali basalt) (at $P_{H_2O} = 5$ kb) results in for formation of quartz-rich melts of calc-alkaline affinity. Although these experiments provide strong evidence against the hypothesis that the Oslo rift monzonitic rocks are formed by anatexis, this evidence is not conclusive. Experiments with ultramafic rocks (Mysen & Boettcher 1975) have shown that with an increasing P_{CO_2}/P_{H_2O} ratio, the composition of the melt will shift towards silica-saturation and under-saturation. It is, thus, at present, not clear if the compositional characteristics of the kjelsåsite/larvikites can be reproduced directly by partial melting of basaltic rocks.

Neither the alternation between basalts and rhomb-porphyry lavas typical of the Oslo rift nor the large percentage of monzonitic rocks among the exposed magmatic rocks disagrees with the hypothesis of formation of the monzonitic rocks by fractionation from basaltic parent magma(s). Gill (1973) has proposed a model whereby the continental crust acts as a density filter. This model provides a useful framework into which the known relationships between the Oslo rift magmatic rocks may be fitted. Gill (1973) assumes that in periods of crustal extension, mafic magma is admitted to the upper crust in dyke swarms and fissure eruptions may occur. In between periods of extension, the mafic magmas will be constrained at depth, typically at the base of the crust where the rising magmas encounter the mantle/crust density contrast. In these tectonically 'quiet' periods fractionation may take place in the trapped magmas and the density of the residual magma will decrease with an increasing degree of differentiation. At a certain stage of evolution of the residual magma, its buoyant force will be great enough to allow the magma to rise through the crust by a stoping mechanism.

Ramberg & Smithson (1971) have estimated the density of the rocks at the base of the crust to be about 2.94 g/cm^3, and 2.63 g/cm^3 or more at the top of the crust. The magma densities (calculated after a method by Bottinga & Weill 1970) (at 1150°C, dry) of the basalts in the Oslo rift analyzed by Weigand (1975) range from about 2.64 to 2.74 g/cm^3. The mean density of magmas of kjelsåsite/larvikite and rhomb-porphyry compositions are 2.48 ± 0.04 g/cm^3 (at 1050°C, dry). If a magma of average density is mixed with 40% crystals of the composition $An_{40}Ab_{53}Or_7$ (simulating some of the rhomb-porphyries), the total density increases to 2.55 g/cm^3 (at 1050°C, dry).

The densities of the basaltic magmas are similar to those of crustal rocks near the surface, indicating that these magmas would have easily reached the surface along fissures. The monzonitic and some of the syenitic magmas, on the other hand, have markedly lower densities and probably represent the particular stage of evolution whereby they could rise by the stoping mechanism.

The early period of extrusion of basalts, according to this model, represents the time of maximum crustal extension across the Oslo rift. This extension must already have diminished by the time when the major portion of evolved magmas were intruded (and extruded).

Summary and conclusions

It is most likely that the kjelsåsite/larvikites and rhomb-porphyry lavas are derived by fractional crystallization at the base of the crust from mantle-derived alkaline basalts. When the fractionation had reached the stage where the buoyant drive of the residual magma(s) of monzonitic compositions) was large enough to force its way towards the surface, the magma(s) extruded, or intruded the upper crust, and crystallized without being markedly affected by the country rock. The crystallization of these rocks took place under fairly dry, reducing conditions (Neumann 1976).

The relations among the syenitic and granitic rocks are more complex. Some of the ascending monzonitic magmas must have been trapped on their way towards the surface and continued to fractionate to form some of the more evolved rocks. Marked differences in f_{O_2} and P_{H_2O} have been found among these syenitic and granitic rocks (Neumann 1976). These differences probably reflect different characteristics of the country rocks, either causing the gas phase to remain in the magma, or allowing it to escape. These differences in conditions of crystallization have led to some of the different evolutionary trends observed among the syenitic and granitic rocks. Contamination from country rock seems to have occurred. It is also likely that some of the alkaline nordmarkites, at least in the northern part of the rift, have an origin similar to that of the kjelsåsite/larvikites, and are derived directly from the base of the crust from a source with somewhat different compositional characteristics than those of the source of the kjelsåsite/larvikites.

Some of the plutonic rocks appear to be unrelated to the 'main' group. The lardalites may be part of an undersaturated trend. The older biotite granites may either represent remelted crustal material, or somehow be related to the tholeiitic basalts.