Development of Nepheline Syenites in Rift Zones – Information from three Rift Complexes

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ABSTRACT: Occurrences of nepheline syenite in the Gardar and Oslo rift systems in South Greenland and Southeast Norway, respectively, are compared with occurrences of phonolite in the Mont-Dore volcano, the French Massif Central. Intermediate igneous rocks predominate in the two last-named provinces, where nepheline syenite and phonolite are of subordinate importance. Mont-Dore may illustrate surface conditions at the time of formation of the Oslo province. The Gardar province shows a predominance of basaltic lavas and felsic intrusions including large complexes of nepheline syenite. The Gardar and Oslo nepheline syenites are spatially associated with augite syenite (larvikite), the Mont-Dore phonolites with corresponding trachyandesite/trachyte. These rocks appear to have developed from mantle-derived basic magmas in deep magma chambers with little crustal contamination. The early stages in the evolution from augite syenite to nepheline syenite and from trachyandesite to phonolite are characterized by decreasing contents of REE and weak or positive Eu anomalies, the more evolved stages by increasing contents of REE and by distinct negative Eu anomalies.

KEY WORDS: Gardar province, Mont-Dore volcano, Oslo province, augite syenite, nepheline syenite, phonolite, rift systems.

Introduction

It is well-known that there is a marked variation between rift systems with regard to types and mutual proportions of the igneous rocks associated with rifting. Alkaline rocks are, however, commonly present and nepheline syenites and phonolites are prominent members of the petrological associations at the plutonic and surface levels, respectively, of rift systems. I have, in recent years, studied occurrences of nepheline syenites and phonolites from three rift systems, the Gardar province in South Greenland, the Oslo igneous province in Southeast Norway and the Mont-Dore section of the rift system of the Massif Central, France.

The age of the Gardar province is 1300–1100 Ma and exposures represent a depth of erosion of 3–5 km. The ages of the Oslo province and the Mont-Dore volcanism are 300–240 Ma and 5–0.7 Ma, respectively. The Oslo rift represents depths of 1–3 km and Mont-Dore a subvolcanic level.

All three rift systems are located in the foreland of major orogenic belts. The Gardar rift lies in the boundary zone between an Archean craton and the Proterozoic Ketilidian mobile belt (about 1800 Ma). A reconstruction of the paleogeography indicates that the prolongation of the Grenville front from the North American continent is located immediately south of Greenland. The Grenville orogeny is penecontemporaneous with the Gardar activity (Bridgwater 1967). The Oslo province lies in the foreland of the Caledonian front and Mont-Dore in the foreland of the Alpine orogen.

The igneous activity in the Gardar and Mont-Dore regions produced isolated intrusive complexes and volcanoes interspaced with country rocks. In the Oslo region, the whole area of the rift zone is occupied by vast lava plateaux and small and large intrusive bodies. Here and there, remnants of earlier intrusions are found in the form of screens and xenoliths enclosed in intrusions of especially syenite and granite, some xenoliths contain even enclaves of still older intrusions. This is an indication of very intensive igneous activity.

Alkaline rocks *sensu stricto* play an important role in the Gardar province in the form of alkali syenites and granites and nepheline syenites, in part of agpaitic type. In the Oslo province, some syenites and granites contain sodic pyroxenes and amphiboles, and nepheline syenites of miaskitic type are present. At Mont-Dore, only the phonolites are alkaline in the strict sense and have miaskitic mineralogy. Agpaitic phonolites occur in the Cantal volcano to the south of Mont-Dore (Varet 1969).

It is the purpose of the present paper to make a comparative study of the occurrences of nepheline syenites and phonolites in these three provinces in order to find common features and differences which can further our understanding of the formation of nepheline-bearing felsic igneous rocks.

The Gardar province

A review of the geology of this province is presented by Upton (this conference, see also Upton and Emeleus 1987). Surface volcanism is mainly represented by transitional basalts and hawaiites which most probably covered a major part of the area but now are only preserved in down-faulted blocks and as xenoliths in intrusive rocks. Flows of trachybasalt, trachyandesite, trachyte and phonolite occur in the upper part of the lava succession (Larsen 1977). There are swarms of mainly doleritic dykes. Some giant dykes are up to 800 m wide (Upton 1962). Dykes of trachyte and nepheline microsyenite/phonolite occur in the vicinity of the nepheline syenite complexes (Allaart 1969, Emeleus and Harry 1970, Gill 1972) and have also been observed at Tugtutôq together with dykes of trachydolerite, microsyenite and microgranite which chemically form an almost continuous series (Upton 1962, Macdonald 1970). Many of the dykes of the province may have been feeders to surface volcanism.

The intrusive complexes have augite syenite as a prominent member, often in a marginal position. It consists of ternary alkali feldspar, minor plagioclase, augite, fayalitic olivine, biotite, pargasite/kaersutite, apatite and Fe-Ti oxides. The syenite is accompanied by granitic rocks when it is silica-oversaturated and by nepheline syenite when it is undersaturated and nepheline-bearing (Sørensen 1966). Gabbro is a minor component of a few intrusions.

Nepheline syenite is found in three large intrusive complexes, the Igaliko complex (Ussing 1912, Emeleus and Harry 1970),

	Tugtutôq older giant dyke complex		Motzfeldt Centre			Ilímaussaq alkaline complex		
	Upton et al. 1985		Jones and Larsen 1985			Bailey et al. 2001		Khomyakov et al. 2001
	augite syenite (86116)	foyaite (86035)	larvikite (AM 54)	nepheline syenite (AM 82)	lujavrite (46261)	augite syenite (154334)	foyaite (154384)	naujakasite lujavrite (bh.7, 85.1)
SiO_2	57.59	54.52	53.44	57.93	56.97	56.97	58.50	51.90
TiO_2	1.01	0.30	2.26	0.34	0.02	1.27	0.32	0.19
Al_2O_3	16.67	18.85	15.77	20.66	18.72	16.82	16.21	12.83
Fe_2O_3	7.43[1]	6.88[1]	0.00	0.48	7.42	1.47	3.03	7.01
FeO			9.46	2.91	1.39	6.68	3.80	5.64
MnO	0.16	0.17	0.25	0.14	0.17	0.22	0.19	0.91
MgO	0.72	0.17	1.73	0.30	0.03	0.76	0.11	0.01
CaO	2.78	1.44	3.26	0.92	0.75	3.47	1.76	0.38
Na_2O	6.32	9.67	9.67	8.74	10.55	5.65	7.56	10.49
K_2O	5.47	5.39	5.39	6.28	3.96	5.16	5.64	2.44
P_2O_5	0.24	0.04	1.30	0.13	0.02	0.34	0.04	0.57
LOI[2]	0.65	1.88	0.74	0.47	0.06	0.80	1.51	4.32
Total	99.04	99.31	99.79	99.30	100.06	99.61	98.67	96.69
Agpaitic index	0.98	1.15	0.8	1.02	1.16	0.88	1.14	1.55
Rb	96	241	89	201	357	68	315	703
Ba	2105	35	2685	878	40	2320	42	–
Sr	255	21	872	428	26	395	27	28
La	69	120	82	67	352	77	244	5190
Ce	148	252	181	142	667	163	512	7840
Nd	61	88	63	48	225	76	219	2220
Sm	10.5	14.1	14.2	8.4	45.1	33.9	38.2	177
Eu	3.2	1.1	6.1	2.9	2.5	4.5	3.6	175
Tb	–	–	1.7	1.0	8.2	1.9	5.8	27.1
Yb	4.5	4.6	3.4	2.6	34.6	5.3	17.9	63.2
Lu	0.7	0.8	0.6	0.4	4.7	0.8	2.4	6.6
Y	49	61	47	26	251	45	184	1060
Zr	518	897	448	707	4230	272	2070	1270
Hf	–	–	13	16	147	11.4	42.5	18.1
Nb	74	143	102	154	478	93	325	198
Ta	–	–	7.5	10	79	6	19.2	6.8
Th	4	23	5	10	5.8	7.9	28	1370
U	–	–	2	4.5	21	1.9	10	483
Ni	2	3	–	–	–	< 0.5	0.5	–
Cr	4	6	–	–	–	1.8	1.8	–
V	5	–	–	–	–	< 0.5	< 0.5	–
Sc	12	–	51(?)	2.3	0.3	18	0.5	< 0.05

[1] total iron, [2] Loss on ignition and H_2O. Numbers in brackets are sample numbers in original publications.

Tab. 1. Examples of chemical analyses of syenitic rocks, the Gardar igneous province, South Greenland.

Grønnedal-Ika (Emeleus 1964) and Ilímaussaq (Ussing 1912, Sørensen 2001). Additionally, foyaitic nepheline syenite forms the axial part of one of the giant gabbro dykes (Upton 1962, Upton et al. 1985).

The Igaliko complex consists of four major units and about thirty intrusive phases. The nepheline syenites are of foyaitic type. Eudialyte-bearing agpaitic nepheline syenites, partly of lujavritic type, are associated with one of the major units, the Motzfeldt centre (Jones and Larsen 1985). There is a progressive evolution from augite syenitic (larvikitic) marginal facies through foyaite to eudialyte nepheline syenite (Table 1). Lujavrites form the youngest intrusive phase of this unit (Jones and Larsen 1985) and are accompanied by a pyrochlore mineralization near the roof of the unit (Tukiainen et al. 1984)

The Grønnedal-Íka complex consists of several intrusive phases of foyaitic nepheline syenites which are intruded by a plug of carbonatite (Emeleus 1964).

The Ilímaussaq complex, the type locality for agpaitic nepheline syenites (Ussing 1912), comprises three intrusive phases (Sørensen 2001): **1**. augite syenite occurring as a partial rim along the marginal contacts and below the roof and as large xenoliths in rocks of phase 3. A former large intrusion of augite syenite has apparently been partially replaced by later intrusions. **2**. Alkali granite and quartz syenite only occurring below the roof and in the form of xenoliths in rocks of phase 3. **3**. Major part of the complex consists of three series: a roof series which crystallized downward from pulaskite through foyaite to sodalite-rich agpaitic nepheline syenites (naujaites); a floor series formed by a layered series of agpaitic nepheline syenites (kakortokites); and an intermediate series of various types of lujavrite, strongly agpaitic nepheline syenites enriched in rare elements and rare minerals (Rose-Hansen and Sørensen 2002). Table 1 presents chemical analyses of augite syenite, foyaite from the roof series and naujakasite lujavrite, the most evolved lujavrite of the complex (Khomyakov et al. 2001).

The older giant dyke at Tugtutôq is composite with a marginal zone of olivine gabbro, an intermediate zone of syenogabbro and a core of syenitic rocks which, from west to east, show an evolution from augite syenite to foyaite (Table 1). The foyaite is interpreted as the uppermost part of the syenitic core of the dyke (Upton 1962, Upton 1964, Upton et al. 1985).

Most foyaites have agpaitic indices less than 1, the agpaitic nepheline syenites have higher indices, up to 1.5 or more. The agpaitic nepheline syenites contain a wealth of minerals, 27 of which, including arfvedsonite, eudialyte and sodalite, were first described from the Ilímaussaq complex and nine minerals are unique to this intrusion (Petersen 2001).

The initial $^{87}Sr/^{86}Sr$ ratios of the syenites and foyaites fall in the range 0.7024–0.7052, whilst the agpaitic rocks of Ilímaussaq and the granites have higher initial ratios (Blaxland et al. 1978).

Nepheline syenites of the Oslo igneous province

A recent review of the geology of this classical igneous province was presented by Neumann et al. (1995). Widespread plateaux of basalts and, especially, of latitic rhomb-porphyries are present; flows of rhyolite and trachyte are associated with cauldrons. Large plutons consist mainly of larvikite, syenites and granites. Larvikite is a syenitic to monzonitic rock characterized by large crystals of ternary feldspar and having the same chemical composition as the rhomb-porphyry lavas. Mineralogically and chemically it is similar to the augite syenite of the Gardar province. Small bodies of gabbro are also present.

Nepheline syenite forms comparatively small bodies. Brøgger (1890) distinguished two main types: lardalite, a coarse-grained nepheline syenite characterized by rhomb-shaped grains of alkali or ternary feldspar and large crystals of nepheline, and ditroite characterized by granular and schistose textures. Foyaites characterized by platy crystals of alkali feldspar and an intergranular (foyaitic) texture also occur. The largest area of nepheline syenite is found in the Larvik massif in the southernmost part of the province (Petersen 1977, Oftedahl and Petersen 1978). This massif is dominated by larvikite and is made up of annular structures which cut each other in a manner suggesting a shift of activity towards the west (Petersen 1977). The larvikites in the eastern part contain quartz, whereas those in the western part nepheline. Lardalite forms the central part of the massif and intrudes the larvikite. The lardalite itself is intruded by foyaite and other syenites (Petersen 1977, Oftedahl and Petersen 1978) but the isotopic ages of larvikite and nepheline syenite are practically identical (Sundvoll et al. 1990). Numerous dykes of nepheline syenite pegmatite intersect the larvikite, especially in the westernmost part of the Larvik massif, and also occur in the country rocks. Some of these pegmatites contain rare minerals. About twenty minerals were first found here including aegirine, astrophyllite and låvenite (Brøgger 1890, Neumann 1985). Nepheline-bearing microsyenite dykes have been described from various places in the rift zone (Brøgger 1898).

Nepheline syenite has also been found near the Mykle Lake 30 km north of the Larvik massif where it occurs as xenoliths in syenite and in granite located 5 km from each other (Andersen and Sørensen 1993). These scattered occurrences may represent remnants of a former larger nepheline syenite complex. Larvikite in this region is cut by dykes of nepheline syenite. This places the formation of nepheline syenite between that of larvikite and syenite (which is again older than the granite). Xenoliths in granite were first intruded by syenite and after this by granite, an example of the above mentioned succession of intrusive events.

Nepheline syenites of the Oslo rift are of miaskitic type. The agpaitic index is generally less than 1, but greater than 1 in some of the foyaites which contain sodic pyroxenes and amphiboles (Table 2). Parts of lardalite contain olivine. Lardalite has higher $MgO/(MgO + FeO + Fe_2O_3)$ than larvikite which makes the direct derivation of lardalite from larvikite unlikely (Neumann 1980). Foyaite has lower $MgO/(MgO+FeO+Fe_2O_3)$ than larvikite.

According to Oftedahl and Petersen (1978), ultramafic schlieren made up of olivine, clinopyroxene, oxides and apatite in the olivine-bearing lardalite are restites left after the formation of lardalite by partial melting of larvikite.

As with the larvikite, lardalite and the Mykle nepheline syenite have low $^{87}Sr/^{86}Sr$ initial ratios in the range 0.7038–0.7041, and foyaite has slightly higher initial ratios (Sundvoll et al. 1990, Andersen and Sørensen 1993).

The Mont-Dore phonolites

At Mont-Dore, trachybasalts and trachyandesites are the predominant lavas. Extensive deposits of rhyolitic pumice are associated with the formation of a caldera.

Necks of trachyte and phonolite are prominent features of the landscape of the Col de Guéry region in the central part of the Mont-Dore volcanic massif. A suite of volcanic rocks is also

	The Oslo province *Neumann 1980*			*Andersen and Sørensen 1993*	**The Mont-Dore** *Bernth et al. 2002*		
	larvikite (360)	lardalite (6)	foyaite (22)	nepheline syenite (78851)	trachy-andesite (97104)	trachyte (88942)	phonolite (97106)
SiO_2	55.72	55.55	56.19	55.10	54.56	57.09	60.83
TiO_2	1.21	1.12	0.96	0.55	1.48	1.06	0.25
Al_2O_3	19.45	20.38	22.01	20.16	19.36	18.05	20.00
Fe_2O_3	2.21	2.06	0.90	2.43	4.51	2.25	1.05
FeO	2.89	2.42	1.22	1.48	1.33	2.28	0.82
MnO	0.17	0.16	0.12	0.19	0.16	0.14	0.14
MgO	1.22	1.46	0.51	0.68	1.75	1.82	0.15
CaO	3.98	2.32	0.83	3.50	5.78	3.46	1.01
Na_2O	5.48	8.15	9.06	7.35	4.31	5.38	8.64
K_2O	4.15	5.04	5.94	4.87	3.76	5.61	6.25
P_2O_5	0.66	0.64	0.14	0.17	0.38	0.22	0.03
LOI[1)]	1.46	0.75	1.83	2.62	1.82	2.05	0.89
Total	98.60	100.05	99.71	99.10	99.20	99.47	100.06
Agpaitic index	0.69	0.93	0.96	0.89	0.58	0.83	1.05
Rb	52	131	159	213	112	145	275
Ba	1390	1150	116	2440	989	886	20
Sr	1230	760	58	1670	1110	457	31
La	145	95	136	139	104	94	65
Ce	210	130	210	207	174	147	90
Nd	–	–	–	77	60	46	13
Sm	15	7.4	17.1	10	8.3	5.5	1.5
Eu	4.6	2.7	3.0	3.3	2.5	1.6	0.2
Tb	1.8	1.0	1.9	1.2	1.1	0.8	0.2
Yb	2	3	5	2.8	2.8	2.3	1.1
Lu	0.7	0.6	0.2	0.5	0.4	0.3	0.3
Y	–	-	-	39	32	24	10
Zr	–	-	-	561	534	560	952
Hf	5.1	21	14	9	9.5	9.7	14.7
Nb	–	-	-	198	144	158	96
Ta	5.8	14	29	10	7.3	9.1	2
Th	10.4	23	27	25	16	20	26
U	2.4	5.6	7.2	9	4	n.d.	n.d.
Ni	–	–	–	4	4	24	3
Cr	–	–	–	3	2	51	1
V	–	–	–	28	104	98	25
Sc	6	4	1	3	3	4	0.4

1) Loss on ignition and H_2O. Numbers in brackets are sample numbers in original publications.

Tab. 2. Examples of chemical analyses of syenites and phonolites from the Oslo igneous province and from Mont-Dore.

present in this region, comprising basanite, hawaiite, trachybasalt, trachyandesite (latite) and trachyte (Brousse et al. 1989, Briot et al. 1991, Sørensen et al. 1999, Bernth et al. 2002).

Some of the trachytes and the phonolites are closely related and appear to grade into each other. In the TAS diagram, they plot on both sides of the boundary line between the trachyte and phonolite fields, whereas other trachytes plot away from this boundary.

The phonolites are of miaskitic type with an agpaitic index almost invariably less than 1, exceptionally just greater than 1

(Table 2). Feldspar, clinopyroxene and amphibole often show zoning, embayments and overgrowths. Some alkali feldspar crystals have cores of bytownite; xenocrysts of forsteritic olivine and Al–Ti-rich diopside–hedenbergite are also present (Bernth et al. 2002).

The trachytes and phonolites contain enclaves of tephritic rocks which are porphyritic, vesicular and with an aphanitic matrix. They contain the same minerals and xenocrysts as the host rocks and generally have up to 50 % or more of kaersutitic amphibole.

The suite from basanite grades via trachyandesite to some of the trachytes. As shown by the trace element and isotopic data, this represents a comagmatic series. The early members of the series are silica-undersaturated whilst the late members are silica-oversaturated, a trend which can be explained by amphibole fractionation (Bernth et al. 2002). Other trachytes and the phonolites differ from this suite in their trace element contents, trace element ratios and isotopic data and in all being silica-undersaturated. They are accordingly considered to have formed by fractionation processes in deep basanitic magma chambers (Briot et al. 1991, Bernth et al. 2002).

Xenocrysts and enclaves in trachytes and phonolites show that magma mixing played an important role in the formation of these rocks. The enclaves are considered to have been formed from tephritic melts injected into the trachytic/phonolitic magma chambers and modified by reaction with the enclosing melt. This complex evolution is corroborated by the $^{87}Sr/^{86}Sr – ^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb – ^{143}Nd/^{144}Nd$ diagrams according to which mixtures of melts formed in a depleted mantle (DM), a HIMU-type mantle and an enriched mantle (EM) were involved in the formation of the rocks and their enclaves. Crustal assimilation appears to have been insignificant (Bernth et al. 2002).

Some chemical relations

Some of the chemical characteristics of the augite syenites and nepheline syenites (trachytes and phonolites) of the three rift complexes are presented in Tables 1 and 2.

In common with most other associations of these rock types, an increase in Na_2O, K_2O, Rb, Zr, Th and U and a decrease in TiO_2, MgO, CaO, P_2O_5, Ba and Sr can be traced from augite syenites (and larvikite and corresponding volcanic rocks) to nepheline syenites and phonolites.

At Mont-Dore, there is a marked decrease in the contents of REE and Y from trachyandesite and trachyte into phonolite. The same relationship with regard to REE is displayed from larvikite into lardalite in the Oslo region and at the Motzfeldt centre. An increase in REE content is displayed from lardalite to foyaite and Motzfeldt nepheline syenite to lujavrite. Nb and Ta generally increase with petrological evolution except in the case of the Mont-Dore phonolites which show lower contents than trachyte and trachyandesite.

The Ilímaussaq naujakasite lujavrite shows elevated contents of Na_2O, REE, Y, Th and U but lower contents of Nb, Ta, Zr and Hf, which is explained by the exhaustion of crystallization of eudialyte, its place having been taken by steenstrupine (Khomyakov et al. 2001).

The chondrite-normalized REE diagrams of the augite syenite/larvikite, lardalite and Mont-Dore phonolite show weak or positive Eu anomalies, whereas the more evolved foyaites and agpaitic varieties have distinct negative Eu anomalies (Neumann 1980, Jones and Larsen 1985, Upton et al. 1985, Bailey et al. 2001, Bernth et al. 2002).

Discussion

The Oslo province and Mont-Dore show a parallel development with predominance of intermediate igneous rocks. The silica-undersaturated rocks of the two provinces show similar chemical and mineralogical features and appear not to have been derived directly from their predecessors, but to have had an independent origin (Neumann 1980, Bernth et al. 2002). One may speculate that Mont-Dore mimics the surface expression of the Oslo province. Magma mixing has been demonstrated for the Mont-Dore trachyte–phonolite association (Bernth at al. 2002). In the Oslo province, the ultramafic schlieren in lardalite mentioned by Oftedahl and Petersen (1978) should be re-examined in order to check if they may be related to magma mixing.

In the Oslo province as well as in the Gardar province, geophysical data show that the axial parts of the rift zones are underlain by heavy rocks, interpreted as mafic or ultramafic cumulates (Neumann et al. 1995, Upton and Emeleus 1987). This can explain the preponderance of felsic rocks at the plutonic level in the two provinces.

The Gardar Province differs from the Oslo and Mont-Dore regions in the subordinate role of intermediate rocks. There appears to be a compositional gap between the predominant basaltic surface volcanics, and the plutonic complexes dominated by felsic rocks. This gap becomes narrower if the flows of trachyandesite, trachyte and phonolite in the upper part of the lava series and the (perhaps corresponding) late dykes of trachydolerite, trachyte and phonolite are taken into consideration.

Macdonald and Upton (1993) pointed out that the Gardar Province has many features in common with the East African Rift System such as, e.g., the prominent role of, respectively, syenite and nepheline syenite and flood trachytes and phonolites. Thus, the African Rift may illustrate the surface features in Gardar times.

The composite giant dyke at Tugtutôq shows that there is a gap between the marginal gabbro and the axial syenite–foyaite. Similarly, many of the late dykes of this province are composite, some have trachytic/phonolitic margins and doleritic cores, others show the opposite relationship, a clear indication of the existence of independent but petrogenetically related trachytic/phonolitic and doleritic melts.

In the giant dykes, there is a clear evolution from augite syenite (petrographically similar to the Oslo larvikite) to foyaite (Upton et al. 1985), a feature which has been also demonstrated for some of the rocks of the Motzfeldt centre of the Igaliko complex (Jones and Larsen 1985). In Ilímaussaq, a time gap has been documented between the emplacement of augite syenite and the agpaitic nepheline syenites, but geochemical data support the idea that the melts which formed the agpaitic rocks developed in an augite syenitic, perhaps stratified magma chamber (Larsen and Sørensen 1987, Stevenson et al. 1997, Bailey et al. 2001).

Volatiles played an important role in the formation of the agpaitic rocks with high contents of Cl (in sodalite), F (in villiaumite, NaF, and other minerals) and C, mainly in the form of CH_4 and other hydrocarbons (Petersilie and Sørensen 1970).

In the Oslo and Mont-Dore provinces, the most primitive basaltic magmas are considered to have been formed by mixing of asthenospheric and lithospheric melts (Neumann et al. 1995, Bernth et al. 2002). Basaltic rocks of the Gardar province have lithospheric signatures (Upton and Emeleus 1987). Anorthosite cumulates are of widespread occurrence as xenoliths in the basalts, dolerites and augite syenites and especially the hawaiitic and mugearitic rocks of the province, an indication of the importance of fractional crystallization in the formation of the more evolved rocks which dominate the present level of exposure.

Conclusions

The syenites and nepheline syenites (phonolites) of the three rift provinces in question have clearly been formed independently from the associated basic rocks. The geochemical and isotopic data indicate that they were formed from mantle-derived melts. Crustal contamination appears to have been of minor importance, although its role in the formation of the agpaitic rocks of Ilímaussaq is not yet clear (Blaxland et al. 1976, Stevenson et al. 1997).

Augite syenitic (benmoreitic, latitic) melts evolved under favourable conditions in deep magma chambers into various types of nepheline syenite and phonolite. The examples quoted from the Motzfeldt centre and the Tugtutôq giant dyke show that this can take place in a gradual way; at Ilímaussaq, there is a time gap between the emplacement of the augite syenite and the agpaitic nepheline syenites which intrude into and engulf screens of augite syenite. In the first stages in this evolution, REE – and in the case of Mont-Dore also Nb and Ta – behaved in a compatible way and were removed by fractionating phases, first of all by amphibole and apatite (Bernth et al. 2002). In later stages, characterized by high concentrations of Na and volatiles, REE, Nb and Ta were incompatible and reached high concentrations in the most evolved foyaites and the agpaitic rocks. Differences in chemistry and mineralogy between the nepheline-bearing rocks of the three provinces may be related to differences in composition of parental basic melts and different regimes of crystallization, especially the contents of volatiles and differences in oxygen fugacity.

Magma mixing has been demonstrated to be important in the formation of the Mont-Dore phonolites, its role in the formation of the Gardar and Oslo nepheline syenites still has to be demonstrated.

The Gardar and Oslo nepheline syenite complexes do not correspond to the magma chambers from which the Mont-Dore phonolitic melts ascended but formed where magma, ascending from deep magma chambers, was trapped at the boundary between the basement and the cover of supracrustals.

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