Petrogenetic processes in the ultramafic, alkaline and carbonatitic magmatism in the Kola Alkaline Province: a review

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[Revised version accepted for publication in Lithos – June 2004]

Abstract

Igneous rocks of the Devonian Kola Alkaline Carbonatite Province (KACP) in NW Russia and eastern Finland can be classified into four groups: (a) primitive mantle-derived silica-undersaturated silicate magmas; (b) evolved alkaline and nepheline syenites; (c) cumulate rocks; (d) carbonatites and phoscorites, some of which may also be cumulates. There is no obvious age difference between these various groups, so all of the magma-types were formed at the same time in a relatively restricted area and must therefore be petrogenetically related. Both sodic and potassic varieties of primitive silicate magmas are present. On major element variation diagrams, the cumulate rocks plot as simple mixtures of their constituent minerals (olivine, clinopyroxene, calcite etc). There are complete compositional trends between carbonatites, phoscorites and silicate cumulates, which suggests that many carbonatites and phoscorites are also cumulates. CaO/Al_2O_3 ratios for ultramafic and mafic silicate rocks in dykes and pipes range up to 5, indicating a very small degree of melting of a carbonated mantle at depth. Damkjernites appear to be transitional to carbonatites. Trace element modelling indicates that all the mafic silicate magmas are related to small degrees of melting of a metasomatised garnet peridotite source. Similarities of the REE patterns and initial Sr and Nd isotope compositions for ultramafic alkaline silicate rocks and carbonatites indicate that there is a strong relationship between the two magma-types. There is also a strong petrogenetic link between carbonatites, kimberlites and alkaline ultramafic lamprophyres. Fractional crystallisation of olivine, diopside, melilite and nepheline gave rise to the evolved nepheline syenites, and formed the ultramafic cumulates. All magmas in the KACP appear to have originated in a single event, possibly triggered by the arrival of hot material (mantle plume?) beneath the Archaean/Proterozoic lithosphere of the northern Baltic Shield that had been recently metasomatised. Melting of the carbonated garnet peridotite mantle formed a spectrum of magmas including carbonatite, damkjernite, melilitite, melanephelinite and ultramafic lamprophyre. Pockets of phlogopite metasomatised lithospheric mantle also melted to form potassic magmas including kimberlite. Depth of melting, degree of melting and presence of metasomatic phases are probably the major factors controlling the precise composition of the primary melts formed.

Keywords: Kola Alkaline Carbonatite Province; alkaline ultramafic magmatism, carbonatites; nepheline syenites, kimberlites

1. Introduction

The Kola Alkaline Carbonatite Province (KACP) is located in the northern Baltic Shield, within the Kola Peninsula (Russia) and parts of NE Finland (Fig.1). The province is well-known for its ultramafic, alkaline and carbonatite magmatism (Kogarko, 1987; Woolley, 1989; Arzamastsev, 1994; Kogarko et al., 1995; Bulakh et al., in press). It consists of nineteen alkaline-ultramafic rock complexes, most of which also contain carbonatites, together with two giant nepheline syenite complexes (Lovozero and Khibiny) and numerous dykes and pipes of various ultramafic and evolved alkaline rocks, kimberlites and carbonatites. Calculations indicate that the total volume of magma that formed the KACP was at least 15000 km^3 (Arzamastsev et al., 2001), but this does not take into account the possibility of an eroded lava cover. Although each magmatic group within the KACP has been extensively investigated and discussed individually, this paper aims to discuss all of the magmatic rock groups (ultramafic alkaline rocks, kimberlites, carbonatites and nepheline syenites) together and to suggest a relationship between the different types of magmatism. We present a review of the key petrological and geochemical features of the different magmatic groups and discuss the origin and evolution of the KACP, using recently published papers that contain high quality geochemical data. An Appendix provides a glossary of unusual rock-types found in the KACP.

2. Geology and petrography

The northern Baltic Shield is composed predominantly of tonalite-trondhjemite-granodiorite complexes formed around 2.95-2.90 Ga ago, with subsidiary supracrustal Late Archaean and Early Proterozoic formations (Balagansky et al., 1998). The crust of the region is approximately 40km thick and the present-day lithosphere thickness is estimated at >200km (see review by Artemieva (2003)). During Palaeozoic times, the area was part of Baltica, a continent consisting of present-day Scandinavia, Spitsbergen, Russia and Ukraine. Paleogeographic reconstructions show that Baltica was situated in the southern hemisphere during Devonian times and was moving northward (Torsvik et al., 1996). Several authors have linked the KACP with either a 'North Atlantic Alkaline Province' that includes complexes in Greenland and the Canadian Shield (Vartiainen and Woolley, 1974) or with the extensive Devonian rifting and magmatism on the East European Platform (Kramm et al., 1993). The age of the KACP magmatism is much more restricted than that of the so-called 'North Atlantic Alkaline Province' and is much closer to the ages of the East European Platform Devonian magmatism. The existence of a ENE-WSW trending rift system on the Kola Peninsula (sometimes called the Kontozero rift) was first suggested by Kukharenko (1967) from the general alignment of several KACP massifs. This trend also encompasses the outcrops of Devonian volcano-sedimentary units (Arzamastsev et al., 1998). However, the generally N-S to NE-SW orientation of the KACP dyke swarms on the south coast of the Kola Peninsula argues for an approximately E-W extensional stress field at the time of their emplacement. Kukharenko et al. (1971) and Vartiainen and Paarma (1979) suggested that the presence of several carbonatite complexes and dyke swarms on the south coast of Kola was related to NNW-SSE trending 'Kandalaksha deep fracture system', which may be associated with the Mezen rifts beneath Arkhangelsk.

The lithospheric mantle beneath the Kola Peninsula is represented by mantle xenoliths such as spinel lherzolites and spinel wehrlites (Arzamastsev and Dahlgren, 1994; Beard et al., in prep). These lithologies show evidence of metasomatism, as they contain 1-3% amphibole and ca. 1% phlogopite, together with rare fluorapatite and picroilmenite. Kimberlites in Arkhangelsk (eastern end of the White Sea) contain spinel peridotite and garnet peridotite xenoliths (Sablukov et al., 2000), with rarer phlogopite clinopyroxenites, again indicative of metasomatic enrichment. The lower continental crust of the Kola and Arkhangelsk region is composed mainly of mafic garnet granulites (Markwick and Downes, 2000; Kempton et al., 2001) that are at least 2.4 Ga old (Downes et al., 2000). Metasomatic phlogopite of 2.0 Ga age is present in some of these granulite xenoliths (Kelley and Wartho, 2000).

The Devonian magmatism was preceeded by several earlier periods of alkaline magmatic activity in the northern Baltic Shield (see review by Bulakh et al., in press). Nepheline syenite massifs of late Archaean age are found in the eastern part of the Kola Peninsula at Sakhariok and Kuljok. Three early Proterozoic (ca. 2.0 Ga) alkaline massifs with associated carbonatites are found in North Karelia (Tiksheozero and Eletozero) and western Kola (Gremyakha-Vyrmes). Potassic magmatism also occurred in Kola and Karelia at approximately 1.7-1.8 Ga, followed by emplacement of lamproitic dykes in Karelia at approximately 1.2 Ga. Uvad'ev (1980) reported similar ages on alkaline lamprophyre dykes in the Kandalaksha Gulf. Elsewhere on the Baltic Shield (e.g. Fen in southern Norway, Alnö in eastern Sweden, and the Kuopio-Kaavi kimberlites of eastern Finland), there is evidence for late Proterozoic alkaline ultramafic magmatism at around 600 Ma. There are reports of similar ages for dykes within the Kandalaksha region (e.g. Rukhlov, 1999). Thus, the Kola-Karelia region was the site of sporadic alkaline and carbonatitic magmatism long before the main Devonian KACP magmatic event.

2.1 Dyke swarms and pipes

Two major Devonian dyke swarms are exposed on the south coast of the Kola Peninsula. One swarm is located in the north-west part of the Kandalaksha Gulf and the other occurs on the Turiy Peninsula (Fig. 1). Together they comprise more than 1000 bodies. Detailed descriptions are given by Ivanikov (1977) and Rukhlov (1999). From field relations, confirmed by the sparse age determinations (Fig. 2), dyke emplacement appears to have occurred in two stages in Early and Late Devonian times. The Early Devonian dyke magmatism comprises alnöites, aillikites, damkjernites and carbonatites, together with monticellite kimberlites and ultramafic lamprophyres (Mahotkin et al., 2003). The Late Devonian magmatism, particularly developed in the Turiy Peninsula, consists of dykes and pipes of kimberlites, alkaline and melilite picrites, melilites, nephelinites and carbonatites (Ivanikov et al., 1998). Some of the dykes and pipes contain crustal and mantle xenoliths that yield insights into the nature of the lithosphere beneath the region (Kempton et al., 2001; Beard et al., in prep).

Borodin et al (1976) presented geochemical analyses of the wide variety of rock-types that form the dykes and concluded that the lamprophyre dykes are closely related to the alkaline-ultramafic complexes. They also suggested that the silicate magmas that formed the dykes were not closely related to kimberlites. Carbonatite and ultramafic lamprophyre dykes from Kandalaksha were investigated by Beard et al. (1996) and Mahotkin et al. (2003), whilst Kalinkin et al. (1993) and Beard et al. (1998) studied pipes of sparsely diamoniferous kimberlite and melilitite from the Terskiy coast. The petrogenesis of the melilitite-carbonatite-nephelinite dyke series of the Turiy coast was discussed by Ivanikov et al (1998). Sindern et al (2004) have recently studied a suite of late-stage alkaline picrite, monchiquite, nephelinite and phonolite dykes from the Khibiny complex. A monticellite kimberlite dyke near Kandalaksha was regarded by Beard et al. (1998) as showing some similarities to ultramafic lamprophyres. The diamondiferous kimberlite pipes of the Arkhangelsk region (Mahotkin et al., 2000; Beard et al., 2000) are also Devonian in age and probably belong to the KACP magmatism, despite being situated much further east (Fig. 1).

2.2 Ultramafic-alkaline carbonatite complexes (UACC)

The phoscorite-bearing ultramafic alkaline carbonatite complexes (UACC) of the KACP have been extensively reviewed by Bulakh et al (in press), Krasnova et al (in press) and Wall and Zaitsev (in press). The UACC are multiphase central intrusions with circular or elliptical exposures and concentrically zoned structures (Kukharenko et al., 1965; Kogarko et al., 1995). Their centres contain a series of ultramafic cumulus rocks, whereas melilite-bearing rocks and strongly silica-undersaturated feldspathoidal rocks (foidolites) occur nearer to the periphery. In some complexes a multistage phoscorite-carbonatite series forms concentrically zoned stockworks. Dyke rocks are mostly alkaline and nepheline syenites along with monchiquites, tinguaites and ultramafic lamprophyres, which crosscut all other rock-types. The distribution of rock-types within the various complexes is shown in Table 1. The only complex in which all the above-mentioned rocks are found is Kovdor, which is the best exposed occurrence and also the one that has been studied in most detail (Krasnova and Kopylova, 1988; Balaganskaya, 1994; Krasnova, 2001). Table 2 shows details of the sequence of magmatic rocks within the Kovdor complex (Liferovich, 1998). Verhulst et al (2000) presented a detailed study of the petrology and geochemistry of Kovdor. A review of the phoscorite and carbonatite occurrences in Kovdor is given by Krasnova et al. (in press).

Several recent papers have dealt with the Kola UACC. The Kandaguba massif was investigated by Pilipiuk et al (2001). Balaganskaya et al. (1999a), Brassinnes et al (2003 and in press) and Karchevsky and Moutte (in press) produced new data on the Vuoriayarvi complex, Vartianen (1980) and Lee et al (in press) have discussed the Sokli complex, Zaitsev et al (in press) and Sitnikova (2004) have reported on the Sallanlatvi complex, and Afrikanda has been studied by Chakhmouradian and Zaitsev (in press). The Turiy UACC (Fig. 1) was also the subject of a recent major study by Dunworth and Bell (2001), while Karchevsky (in press) deal with the phoscorite-carbonatite part of this complex. Lapin (1979), Bulakh et al. (1998) and Balaganskaya et al (2000) studied the Seblyavr complex. Arzamastsev et al (2000a) gave details of gravity and density modelling of the size and shape of the hidden portions of all the major UACC intrusions.

The ultramafic rock group includes cumulates composed of olivine and clinopyroxene, with minor cumulus Ti-rich magnetite and perovskite and intercumulus Ti-garnet, amphibole, phlogopite, apatite and calcite. Proportions of cumulus and intercumulus phases vary widely, and cumulate textures have often been obliterated by replacement of clinopyroxene by late magmatic mica and amphibole. Melilitic rocks are also highly unusual cumulate lithologies in which the proportions of major minerals vary widely, including cumulates with >85% melilite (melilitolites). The most abundant rock-type is turjaite, which consists of cumulus melilite, nepheline, clinopyroxene and phlogopite, with accessory olivine, Ti-rich magnetite, Ti-garnet, amphibole, perovskite and minor apatite and calcite. Foidolites form a series of cumulates with differing proportions of cumulus clinopyroxene, nepheline/cancrinite and rarer melilite, forming melteigites, ijolite-urtites and urtites. The rocks are highly heterogeneous in terms of textures, grain-size and mineral composition. Interstitial calcite is normally in equilibrium with nepheline, indicating that it is a primary igneous mineral.

Carbonatites occur in all periods of formation of the UACC, including the early magmatic one in which phoscorites are absent, in a late magmatic phase where they are found intimately related with phoscorites, and in a post-magmatic period (see Table 2). Early carbonatites form dykes up to 150 m wide, cross-cutting the ultramafitolites, foidolites and fenites. In addition to calcite or dolomite, they contain feldspathoids, biotite/phlogopite, clinopyroxene/amphibole and titanite. In some cases they have both clear contacts with host silicate rocks but elsewhere they gradually merge into cumulate clinopyroxenite or melteigite-ijolite (Kukharenko et al., 1965; Ternovoy et al., 1969). This indicates that at least some of the carbonatites are cumulate igneous rocks and, as shown in Afrikanda, genetically linked with silicate rocks (Chakhmouradian and Zaitsev (in press). In the later evolution of the UACC, several stages of magmatic phoscorite-carbonatite series were formed. The phoscorites are composed of magnetite, forsterite, clinopyroxene, apatite and carbonate in different proportions, with magnetite usually dominant. Calciocarbonatites of the first stages of these phoscorite-carbonatite series (Table 2) contain forsterite, clinopyroxene, monticellite, phlogopite, amphibole, apatite and magnetite. Those associated with the later stages are composed of calcite-dolomite and dolomite with forsterite and tetraferriphlogopite (Table 2). The carbonatites of the latest stages are composed of Fe-carbonates (Fe-rich dolomite, ankerite and siderite). They show pegmatitic textures and contain Ba, Sr, Nb and REE mineralisation and quartz. They were formed at the end of the late-magmatic period and in the post-magmatic one as pegmatitic and hydrothermal facies (Bulakh et al., 1998; Wall et al., 2001). Geological, mineralogical, geochemical and isotopic evidence shows that there are genetic links between phoscorite and carbonatite (Sokolov 1983; Balaganskaya, 1994; Zaitsev and Bell, 1995; Subbotin and Subbotina, 2000; Krasnova et al., in press; Demeny et al., in press). The phoscorite-carbonatite rock series represents the result of complex differentiation of a carbonate-silicate melt that was extremely rich in iron and phosphorus. The early cumulates in each magma portion were forsterite/diopside, magnetite and apatite (forming phoscorite), whereas the later ones were dominated by carbonate minerals.

2.3 Alkaline syenite magmatism

This is represented by the Khibiny and Lovozero alkaline syenitic plutons (Kogarko, 1987), the Kurga intrusion (Kogarko et al., 1995) and the Niva syenite intrusion (Arzamastsev et al., 2000b). The volumetric importance of these massifs was shown by Arzamastsev et al. (2001) whose detailed calculations suggest that the total volume of the two massifs formed 70% of the total volume of magma in the KACP. The Khibiny pluton is the largest with an exposed area of 1327 km^2. It is a multiphase intrusion, with a concentrically zoned structure formed by layered intrusive bodies (Kukharenko et al., 1965). Its periphery consists of alkaline syenites, giving way to various types of nepheline syenite (khibinites and rischorrites), followed by ijolite-melteigite-urtites and foyaites towards the centre. A stock-like body of carbonatite cuts the foyaites (Dudkin et al., 1984; Zaitsev, 1996). Contacts between intrusions are usually gradual. Only the ijolite-melteigite-urtite intrusion has rather sharp contacts, showing complicated relations with the later intrusions (Ivanova et al., 1970). Xenoliths of ultramafic and melilite-bearing rocks occur along its outer contacts (Galakhov, 1975, 1988; Schpachenko and Stepanov, 1991), interpreted as relics of an earlier ultramafic-alkaline intrusion (Dudkin et al., 1986; Balaganskaya and Savchenko, 1998). These ijolites are similar in composition to the ijolite-urtite arc (Kostyleva-Labuntsova et al., 1978). Numerous late-stage dykes of alkali picrite, monchiquite, nephelinite and phonolite cut the Khiniby massif (Sindern et al., 2004).

The Lovozero multiphase nepheline-syenite pluton has an exposed area of 650 km^2. It has the form of a broad-based lopolith that can be traced geophysically down to 7 km (Schablinsky, 1963). Early nepheline and nosean syenites form about 5% of its area. The main pluton area (77%) comprises a regular alternation of urtite, foyaite and lujavrite layers from a few centimeters to hundreds of meters in thickness. Rocks of the eudialyte lujavrite suite represent a third phase and form about 18% of the pluton area. Rare alkaline lamprophyre dykes cut all the earlier rocks (Bussen and Sakharov, 1972; Kogarko et al., 1995; 2002).

The Kurga complex is a lopolith that can be traced to 4.5 km depth (Arzamastsev et al., 1999). Its exposed area is about 30 km^2 and is elliptical in shape. From the center to the margin, the complex consists of cumulate olivinites, wehrlites and clinopyroxenites; the central part is cut by stocks of alkaline and nepheline syenites (Kukharenko et al., 1971; Kogarko et al., 1995).

2.4 Alkali basaltic and carbonatitic extrusive rocks

Eruptive volcanic rocks are rare within the KACP, but xenoliths of alkali basaltic lavas up to several hundred meters long occur within the Khibiny and Lovozero massifs (Gerasimovsky et al., 1966; Galakhov, 1975; Bussen and Sakharov, 1972; Kogarko et al., 1995). These xenoliths are thought to form part of the roof complex into which the plutonic rocks were intruded. A small volcanic series interpreted as a carbonatite-melanephelinite palaeovolcano has been identified at Kontozero (Pyatenko and Osokin, 1988). The total thickness preserved within a circular depression in Kontozero is approximately 3km. Remnants of the lava pile have been found in Ivanovka on the northern coast of the Kola Peninsula (Arzamastsev et al., 1998; 2002). They are nepheline basalts and alkaline trachyte or phonolite lavas, up to 40m thick and extending for a few hundred meters.

Chemical analyses of the effusive silicate rocks are given by Arzamastsev et al (1998). Age determinations (Table 3) suggest that they are 20-30 Ma older than the intrusive rocks, but Kirichenko (1962) reported Upper Devonian – Lower Carboniferous plant fossils within the sedimentary sequences accompanying the lavas in Lovozero and Kontozero. The original thickness of the lava pile is one of the unknown factors in estimating the volume of magma that formed the KACP, and the volume calculated by Arzamastsev et al. (2001) does not contain any value for eroded extrusive rocks. A conservative estimate, based on a 2km thick pile of lavas covering an area 200km in diameter, yields an additional volume of 60000 km^3 for the erupted material.

3. Geochronology

Rb-Sr dating of many of the alkaline complexes led Kramm et al. (1993) to the conclusion that the KACP was formed during a relatively short time interval of 360 - 380 Ma. Further studies, using techniques such as Ar-Ar, U-Pb and Sm-Nd, have generally confirmed this interval but have also allowed it to be slightly broadened (Arzamastsev et al., 1999, 2002; Arsamastsev & Belyatsky, 2000). A recent review of the subject is given by Kramm and Sindern (in press) and our brief discussion here generally agrees with these authors. Table 3 gives a review of the available age determinations. Figure 2 shows a histogram of age determinations of KACP magmatic rocks, derived from Table 3, in which the vast majority of the results still fall between 360 and 380 Ma. The ages of the Kola kimberlites is poorly known, but one of the associated melilitites at Terskiy Bereg has been dated at 365±16 Ma and a monticellite kimberlite dyke near Kandalaksha has yielded an age of 382±14 Ma (Beard et al., 1998). However, Delenitsyn et al. (2001) determined ages of 457±46 Ma (Sm-Nd isochron) and 465±12 Ma (Rb-Sr isochron) on separated minerals from the Yermakovskaya-7 kimberlite pipe in Tersky Bereg. The Arkhangelsk kimberlites are also constrained to be Devonian by fossil evidence (Sablukov, 1984; Makhotkin et al., 2000). Therefore we consider that the kimberlite magmatism is an integral part of the KACP event.

A clinopyroxenite and an early carbonatite of the Seblyavr intrusion have yielded Rb-Sr ages of 410±7 and 408±7 Ma (Balaganskaya et al., 1999b; Gogol & Delenitsyn, 1999), whilst volcanic rocks of the Kontozero caldera and Lovozero were dated by Rb-Sr at 461±39 and 446±56 Ma, respectively (Arzamastsev et al., 1998). These older ages may represent earlier phases of activity but it is possible that the samples may contain contaminants from the surrounding Precambrian basement that have caused these older ages. Kramm and Sindern (in press) have suggested that the Ar-Ar ages of 378-395 Ma for carbonatite and hornblendite xenoliths from the Kandalaksha Gulf (Beard et al., 1996) may be due to excess argon. A much younger age (252 Ma) has been obtained on a sample from Salmagora (Table 2) but this is considered to be spurious, particularly as other samples from the same intrusion have yielded ages within the 360-380 Ma age range (Table 3). Thus, further studies of the ages of KACP magmatism have largely supported the assertion of Kramm et al. (1993) that the magmatic event was of relatively short duration.

4. Geochemistry

4.1 Major element geochemistry

Table 4 presents geochemical data for a selection of silicate dyke and pipe rocks of the KACP, all of which are assumed to represent true magmatic liquids (i.e. have not undergone cumulus processes). The loss on ignition (LOI) is included in the total in these analyses, so recalculation to anhydrous compositions would raise the SiO_2 content to some extent. Nevertheless, on the Total Alkalis vs Silica diagram (Fig. 3) the dykes and pipes largely fall in the foidite field, as they mostly have significantly lower SiO_2 contents than common silica-undersaturated magmas such as basanites and nephelinites. They also generally have low total-alkali contents (<5 wt%), although some evolved melilitites and melanephelinites (< 7 wt% MgO) have higher total alkali contents. These latter approach the compositions of nepheline syenites (Fig. 3). Within the dykes and pipes, sodic types are more abundant than potassic ones (Fig. 4), with the potassic rocks tending to be melilitites, damkjernites and kimberlites. Among the dyke rocks, CaO/Al_2O_3 ratios range from 1 to >5, with the higher values being from kimberlites and damkjernites, greatly exceeding the ratios shown by typical ocean-island basaltic magmas and MORB (Fig. 5). This indicates that the KACP magmas were derived from a mantle source with high CaO/Al_2O_3 ratios (e.g. one enriched in carbonate).

The MgO-SiO_2 diagram (Fig. 6) shows that many of the dyke rocks are highly magnesian (>12 wt% MgO) and silica-undersaturated (20-40 wt% SiO_2). When other rock-types such as carbonatites, phoscorites, nepheline syenites and cumulates are plotted on the MgO-SiO_2 diagram, the cumulate rocks appear as mixtures of their constituent minerals (i.e. between diopside, olivine, nepheline, calcite, dolomite, phlogopite and melilite). There are complete compositional trends between carbonatites and olivinites, and between carbonatites and pyroxenites, suggesting that many of the plutonic carbonates are cumulates. Phoscorites also plot between calcite and one or more mafic silicate phases (forsterite, diopside and phlogopite) and may therefore be cumulates. In constrast, the nepheline syenites form a fractionation trend to high SiO_2 and low MgO, and overlap with the more evolved foidolite dykes (Fig. 6).

4.2 REE and incompatible trace elements

Figure 7 shows chondrite-normalised REE abundances of primitive mafic alkaline rocks (including kimberlites) from the KACP (Table 4). Their patterns are all remarkably similar and show strong LREE enrichment with La/Yb between 70 and 200. Their LREE abundances are much higher than those of OIB, indicating a more extreme metasomatism in the mantle source or a much smaller degree of partial melting, whereas the HREE abundances are often lower than OIB, suggesting the presence of residual garnet. Significantly, carbonatites from the KACP have extremely similar REE patterns to those of the silicate magmas. This observation, however, does not help in distinguishing the origin of the carbonatites.

The REE compositions of nepheline syenites from the Khibiny and Lovozero plutons (Arzamastsev et al., 2001) show both higher and lower patterns than those of the supposed parental magma of the UACCs (Fig. 8). This is probably related to the extensive fractional crystallisation and accumulation that the evolved magmas have undergone, and the relative abundances of REE-bearing minerals in the cumulate rocks. However, with the exception of a few rock-types which show slight MREE depletion (probably due to titanite fractionation), the REE patterns in the evolved rocks are parallel to those of the mafic and ultramafic parental magmas.

Mantle-normalised incompatible trace element diagrams for primitive silicate magma compositions from the KACP (Fig. 9) show that they are enriched in strongly incompatible elements relative to ocean island basalts (Sun & McDonough, 1989), although kimberlites and melilitites show a trough at Zr. Both potassic and sodic magmas show very similar trace element patterns. Such strong enrichment would be hard to explain even by small degrees of melting (0.1-3%) of an undepleted garnet peridotite mantle. Most likely the source contains additional metasomatic phases. Arzamastsev et al (2001) suggested the presence of phlogopite and amphibole, together with possible apatite and perovskite, in the mantle source of the KACP magmas.

Figure 10 shows mantle-normalised trace element diagrams for carbonatite dykes from Kola, i.e. those representing a magmatic liquid rather than a cumulate (Verhulst et al., 2000; Dunworth and Bell, 2001; Mahotkin et al., 2003). They show distinct troughs at Rb and Nb, although in all other trace elements they are identical to melilitites and/or kimberlites, including the trough at Zr. However, some carbonatite dykes from Turiy (Ivanikov et al., 1998) are more enriched in Sr and the REE, and do not show the same Nb trough (Fig. 10). Thus there appear to be at least two “end-member” types of carbonatite magmas within the KACP, those with depletion in Nb and those that show enrichment in this element. It is not clear what the petrogenetic significance of this observation is, as these do not seem to correlate with any other feature (e.g. age, mode of emplacement, etc).

When the trace element diagrams of nepheline syenites are compared with that of a typical ultramafic lamprophyre or UACC parent magma (Fig. 11), many of the patterns are remarkably similar, although some of the evolved rock-types actually have lower overall trace element contents. This indicates that both crystal fractionation and crystal accumulation have occurred. Some highly evolved nepheline syenites from Khibiny show extreme enrichment in the REE and Nb, but with conspicuous troughs at Zr, Sr, Rb and Ba. We suggest that this pattern probably results from fractionation of alkali feldspar and a Zr-bearing phase such as eudialyte.

4.3 Noble gas studies

More than 300 rocks and minerals from the KACP have been studied for noble gas concentrations (He, Ne and Ar) and isotope systematics (Tolstikhin & Marty, 1998; Tolstikhin et al., 1999, 2002). The highest ^{3}He concentrations measured in any terrestrial sample, 4×10^{-9} cc/g, with a rather low $^4He/^3He$ ratio of $3.3x10^4$, were measured in a magnetite separate from a Seblyavr clinopyroxenite (Kamensky et al., 2000). From the noble gas compositions, Tolstikhin et al. (2002) considered that the KACP magmatism was related to a lower mantle plume with an initial $^4He/^3He$ of 3 x 10^4. On the basis of the noble gas abundances in the principal terrestrial reservoirs (Tolstikhin & Marty, 1998), the contribution of the lower mantle in KACP parental melts was estimated to be 1.8 wt.%. This implies that heat from the plume caused melting of the upper mantle, possibly including metasomatised subcontinental lithosphere (Tolstikhin et al., 1999, 2002).

4.4 *Radiogenic isotope ratios*

Kukharenko et al. (1965) and Galakhov (1975) first suggested a mantle origin for the parental melts within the KACP from petrologic and geochemical data. This was later supported by Sr and Nd radiogenic isotope studies (Kramm et al., 1993; Kramm, 1993; Kramm & Kogarko, 1994; Beard et al., 1996; 1998; Rukhlov, 1999; Verhulst et al., 2000; Dunworth and Bell, 2001). Table 5 gives the data sources and values for the initial isotope ratios of radiogenic Sr and Nd, for a wide variety of rocks from the KACP. Initial $^{87}Sr/^{86}Sr$ ratios at 380 Ma for intrusive silicate rocks from the ultramafic alkaline complexes and the nepheline syenites vary from 0.7030 to 0.7049, whilst the carbonatites show variations from 0.7030 to 0.7041. ε_{Nd}^t values (t = 380 Ma) determined for intrusive silicate rocks in the KACP vary from +5.5 to +0.9, excluding an ijolite from Kovdor with $\varepsilon_{Nd}^t = -3.5$; for Kola carbonatites ε_{Nd}^t is +7.3 to +0.4. Table 5 indicates that for some intrusions such as Kovdor and Turiy, there is a large range of initial isotopic compositions, suggesting open system behaviour, whereas in other intrusions (e.g. Vuoriyarvi) the isotopic compositions are much more clustered, indicating a closed system for magma evolution.

Figure 12 shows the age-corrected Sr-Nd results for all analysed rocks from the KACP using data from Table 5, Dunworth and Bell (2001) and Mahotkin et al. (2003). Most of them plot in the Depleted Mantle field, with low $^{87}Sr/^{86}Sr$ and high ε_{Nd}^t values. They appear to diverge from a depleted end-member that has been suggested to be the Devonian equivalent of FOZO (Bell and Rukhlov, in press). The detailed variations in isotope compositions have previously been explained by mixing of melts from two, three or even four mantle and crustal sources (Kramm, 1993; Kramm et al., 1993; Zaitsev & Bell, 1995; Verhulst et al., 2000; Arzamastsev et al., 2000b; Dunworth & Bell, 2001; Mahotkin et al., 2003; Sindern et al., 2004). Potassic samples are distinguished on Fig. 12 and most of them show either higher $^{87}Sr/^{86}Sr_i$ ratios or lower ε_{Nd}^t than the sodic rock-types. Crustal contaminants could include the lower crust, represented by granulite xenoliths from Kandalaksha (Kempton et al., 2001).

5. Discussion

5.1 General considerations

Igneous rocks of the KACP can be broadly classified into four groups: (a) primitive mantle-derived silicate magmas, such as kimberlites, melilitites, nephelinites, ultramafic lamprophyres; these are mostly found as dykes and pipes; (b) evolved alkaline and nepheline syenites found as large plutons and as dykes cross-cutting the alkaline ultramafic complexes; (c) cumulate rocks, including olivinites, clinopyroxenites, foidolites, melilitolites etc; these are found in the alkaline ultramafic complexes and as xenoliths in nepheline syenites; (d) calcite carbonatites found within the UACC (together with dolomitic carbonatites and phoscorites) and also forming dykes and xenoliths. The relationship between all these rock-types can be investigated using the petrological and geochemical data presented above. Borodin et al (1976) suggested that there were three parental magmas within the KACP that had been derived from progressively deeper sources: alkali basaltic, alkali ultramafic and kimberlitic.

One very important consideration about KACP rocks is that they show a very strong tendency to low SiO_2 contents, much lower than most common alkaline magmas, as shown in the TAS diagram (Fig. 3). This indicates an extremely low degree of partial melting in the source mantle. The abundance of magmatic carbonate suggests that the primary magmas were derived from a carbonated mantle and the effect of the presence of carbonate in the mantle may enhance the degree of silica undersaturation of the magmas formed from it. The KACP rocks also have much more enriched REE patterns compared to OIB (Fig. 7), again indicating a lower degree of melting than normal. The low HREE abundances of all primitive rock-types (Fig. 7) indicate the presence of residual garnet, and the presence of diamonds in the Terskiy kimberlites (Kalinkin et al., 1993) are a clear indication that at least some of the magmas were generated at depths >120km. It may be significant that damkjernites and kimberlites show the lowest HREE contents (Fig. 7) and are thought to come from the greatest depths.

Initial Sr and Nd isotope ratios of most of the rock-types (UACC, syenites, carbonatites) fall in the Depleted Mantle field (Fig. 12) and the magmas must therefore have been derived from a time-integrated Rb- and LREE-depleted mantle source. The metasomatic enrichment of the upper mantle (deduced from the trace element enrichment) probably took place in Late Proterozoic or Early Palaeozoic times, as suggested by Artemieva (2003). The spread of data requires slight variations within this mantle source, with one end-member being rather depleted (ε_{Nd}^{t} = 6; $^{87}Sr/^{86}Sr$ = 0.703) and another being closer to Bulk Earth (ε_{Nd}^{t} = 2; $^{87}Sr/^{86}Sr$ = 0.704). In contrast, many of the pipes and dykes, particularly the potassic ones, have isotopic compositions that are quite different from those of the majority of the KACP magmas, indicating either a source with a significantly different isotopic composition or a different extent of alteration.

There is no obvious age progression for the various types of magmatic activity (Table 3; Fig. 2). Thus, all of the magma types were formed in the same series of events over a relatively short time span and over a relatively restricted area, and must therefore be related to some extent. Recent experimental results on the melting of carbonated mantle at 6GPa (Dalton and Presnall, 1998) have shown that kimberlites and carbonatites can be formed from the same source during the same melting event. These authors suggested that there is a strong petrogenetic link between carbonatites, kimberlites and alkaline ultramafic rocks such as ultramafic lamprophyres. Rock (1991) also pointed out that there is a compositional continuum between these magma types. The noble gas systematics (Tolstikhin et al., 2002) suggest an origin related to mantle plume activity.

It is quite possible, therefore, that all of the magmatic rocks seen in the Devonian KACP originated in a single event, triggered by the arrival of upwelling hot material (mantle plume?) beneath the metasomatised Archaean/Proterozoic lithosphere of the Kola region. The influx of heat caused melting of the carbonated garnet peridotite asthenospheric mantle, forming sodic magmas and carbonatites, which evolved to form the UACC and the nepheline syenites. Pockets of phlogopite-metasomatised lithospheric mantle were also melted and formed potassic ultramafic or mafic magmas, which appear to have not evolved to form fractionated magmas. The depth and degree of melting are probably the major factors controlling the precise composition of the melts formed, together with variations in metasomatic phases in the mantle source.

5.2 Origin of silicate dyke rocks (magmatic liquids)

Borodin et al (1976) first suggested that there is a close petrogenetic relationship between the dykes and the ultramafic alkaline complexes. Dyke rocks from the dyke swarms clearly represent magma compositions, rather than the cumulate compositions that characterise the ultramafic-alkaline magmatic complexes, and hence they can be used to investigate the primitive magmas of the KACP. Table 4 shows some compositions of these rocks. All have high MgO (>12 wt%) and are clearly capable of being derived directly from the mantle. They frequently have >500ppm Ni and >1000ppm Cr, supporting this suggestion. Ivanikov et al (1998) suggested that an olivine melilite melanephelinite, derived from depths of at least 80km, was the primary magma for the Turiy dyke series.

On the MgO-SiO_2 diagram (Fig. 6), some of the primitive silicate dyke rocks show a remarkable positive correlation between these oxides. This may relate to mixing between more and less carbonated mantle source regions, or to olivine fractionation causing a decrease in MgO and SiO_2 in such silica-poor magmas. Damkjernites fall within this array, having low silica contents (25-27 wt% SiO_2) and only 10-12 wt% MgO (Table 4). Although they are potassic magmas, they appear to be transitional to true carbonatites as they contain >20% CaO. CaO/Al_2O_3 ratios for silicate dyke rocks range up to 5 (Fig. 5), indicating a very small degree of melting of a carbonated mantle at depth. The damkjernites again have the highest CaO/Al_2O_3, transitional to silico-carbonatites which have CaO/Al_2O_3 ratios >>7.

Mantle-normalised trace element diagrams for rocks from the ultramafic and mafic dykes and pipes (Fig. 9) show that kimberlite, melilitite and damkjernite have the lowest HREE abundances, indicating a lower degree of melting and greater depth of formation. Modelling by Arzamastsev et al (2001) indicates that the spectrum of magmas from kimberlites to nephelinites cannot be derived from small degrees of non-modal partial melting of an undepleted garnet peridotite mantle source. However, the primitive magmas can be modelled as 0.3-0.5% melts of an enriched phlogopite- and amphibole-bearing garnet lherzolite (Arzamastsev et al., 2001). Such mantle rocks have been observed in the xenolith suite from the Arkhangelsk diamondiferous kimberlites (Sablukov et al., 2000). Spinel peridotites from Kola also contain phlogopite, amphibole and apatite (Arzamastsev and Dahlgren, 1994; Beard et al., in prep).

The Sr and Nd isotope ratios of the KACP silicate dyke rocks show a wide range of values (Fig. 12). Many fall in the "Depleted Mantle" field, overlapping the values of KACP carbonatites, UACC and syenites; however, numerous dykes have either much higher $^{87}Sr/^{86}Sr$ or much lower ε_{Nd}^t values, similar to those found among the kimberlites and melilitites (Table 5). Several processes could have given rise to these unusual isotopic ratios. One possibility is that they could have been derived from the mantle lithosphere, in which either phlogopite or amphibole was present. Phlogopite has a high Rb/Sr and over time would cause the region of the mantle in which it was situated to have a high $^{87}Sr/^{86}Sr$. However, mantle phlogopite has very low REE contents and so its effect on the Nd isotope ratio would be limited. In contrast, mantle amphibole has modest Rb/Sr ratios but is often highly LREE-enriched, which would cause low ε_{Nd} values to evolve. The impact of the mantle plume on the lithosphere may have caused these low-solidus domains to undergo partial melting, thus producing a range of sodic and potassic magmas. An alternative possibility is that all the samples with low ε_{Nd}^t values may be contaminated by continental crust, whereas those with high $^{87}Sr/^{86}Sr$ may result from hydrothermal alteration that has affected Sr but not the REE. Without detailed oxygen and Sr isotope measurements of individual phases within the samples, this suggestion cannot be verified. However, it is supported by the leaching experiment of Beard et al. (1996) in which the measured Sr isotope composition of a Kola ultramafic lamprophyre dyke was reduced from 0.711 to 0.709 by leaching in hot acid.

Some melilitites and melanephelinites have low MgO contents (<10 wt%) and must therefore be the products of fractionated magmas (Ivanikov et al., 1998). They are transitional in their Si-Mg compositions to some of the rocks in the syenite intrusions (Fig. 6). They also have much lower Ni and Cr contents (4-20ppm Cr; 35-65 ppm Ni), indicating that they have experienced fractionation of mafic minerals. These samples, however, have Sr and Nd isotope compositions identical to those of the more primitive magmas, demonstrating that fractionation occurred without any contamination by the surrounding crust. Ivanikov et al. (1998) suggested that fractionation of olivine, clinopyroxene, melilite, titanomagnetite, apatite and perovskite would be able to produce the compositions of these more evolved magmas. They also pointed out that such a sequence of crystallising phases would account for the compositions of many of the ultramafic rocks in the UACC. Dunworth and Bell (2001) also suggested that there should be a large volume of olivine- and pyroxene-rich ultramafic cumulates associated with fractional crystallisation within the Turiy complex.

5.3 Origin of ultramafic alkaline carbonatite complexes

On the $MgO-SiO_2$ diagram (Fig. 6), the cumulate rocks of the UACC plot as mixtures of their constituent minerals. Together with the petrographical evidence for cumulus processes, this indicates that few of the rocks found in the plutonic complexes are true magmatic liquids. Table 4 presents a calculated primitive magma composition for the ultramafic alkaline carbonatite complexes (Arzamastsev et al., 2002). On the TAS diagram (Fig. 3), the proposed parental UACC magmas is a typical silica-undersaturated KACP magma. It falls in the region of the MgO-SiO_2 diagram (Fig. 6) occupied by melilitites and is within the compositional field of the melilitite and ultramafic lamprophyres on the CaO/Al_2O_3 vs SiO_2 diagram (Fig. 5). Furthermore, the parental UACC magma has a REE pattern identical to that of melilitites and carbonatites from the KACP (Fig. 7). It has high Ni (242 ppm) and Cr (393 ppm) contents, again indicating mantle derivation. In terms of their radiogenic isotope ratios, UACC silicate rocks largely overlap the field of carbonatites, syenites and many of the dyke rocks, and so must have been derived from the same mantle source. Crustal contamination may have occurred in a single sample of ijolite from Kovdor that has an unusually low ε_{Nd}^t ratio (Verhulst et al., 2000), but this needs to be confirmed by oxygen isotope analysis.

5.4 Origin of the alkaline syenites

Kogarko (1977a, 1977b, 1979) discussed the origin of nepheline syenites in the KACP and used phase diagram constraints to show that the nepheline syenite minimum composition can appear as a differentiation product from a variety of nepheline-normative parental melts, such as olivine nephelinites, melilitic basalts and alkali basalts. Typical compositions of the nepheline syenites in the Khibiny and Lovozero plutons (Arzamastsev et al., 2001) have low MgO contents (<2 wt% MgO) and extreme enrichment in alkalis (Na_2O > 8 wt%; K_2O > 3.5 wt%). On the TAS diagram (Fig. 3), they plot in the evolved foidite field that has even less SiO_2 than common nepheline syenites. Such extreme compositions could not be derived directly from the mantle, so it is clear that the magmas in these intrusions have undergone extensive fractionation. Ultramafic cumulate rocks are present in the Khibiny and Kurga intrusions, indicating a close relationship. Much more ultramafic rock must be present at depth within the crust, formed of minerals that have been crystallised during this fractionation process. Arzamastsev et al. (2001), using density modelling and borehole core, suggest that about 50% of Khibiny is formed of alkaline ultramafic rocks. The REE pattern of the most evolved nepheline syenites (Fig. 8) is more than an order of magnitude more enriched than that of a typical ultramafic parental magma, suggesting extreme fractionation.

Table 1 shows that syenites are present in more than 50% of the UACC, indicating that such magmas were formed during the evolution of the UACC. During its late magmatic stage, the Kovdor UACC pluton was intruded by dykes of alkaline syenite and nepheline syenite. A xenolith of layered eudialyte syenite found in a dyke in the Turiy area (Beard et al., in prep) indicates the existence of an agpaitic syenitic body at depth, thus forming another link between the UACC and the syenitic plutonic magmatism. On the MgO-SiO_2 diagram (Fig. 6) there is an overlap between the least evolved nepheline syenites and the most evolved foidolites. The similarity of their Sr and Nd radiogenic isotope ratios to those of more mafic rocks in the UACC (Fig. 12) also supports the suggestion that fractional crystallisation was the main process that formed these rocks. Minerals that would fractionate from silica-undersaturated mafic alkaline magmas such as nephelinites include olivine, clinopyroxene, nepheline, melilitite and eventually alkali feldspar (Dubrovsky, 1989). These minerals are the most common constituents of the cumulate rocks in the UACC and in the ijolite-urtite arc within the Khibiny massif.

5.5 Origin of potassic magma types, including kimberlites

Figure 4 shows that there is a continuum of sodic and potassic magma types within the dykes and pipes. The most common potassic magma type is olivine phlogopite melilitite, although damkjernites and kimberlites are also present. Potassic magmas clearly have a different mantle source mineralogy than sodic magmas and derivation from a phlogopite-bearing lithospheric mantle is one possible explanation. Nevertheless, their REE and mantle-normalised trace element patterns are very similar to those of the sodic magmatic rocks, indicating a broadly similar source (Figs. 7 and 9). Although some potassic magmas have Sr and Nd isotope compositions overlapping with the main field of KACP magmatism (Fig. 12), many show much higher $^{87}Sr/^{86}Sr$ or lower ε_{Nd}^t values. These unusual values may be derived from the enriched mantle lithosphere. Such lithosphere may be represented by phlogopite clinopyroxenites that occur with garnet peridotite xenoliths in the Arkhangelsk kimberlites. Alternative explanations could be that these rocks are either hydrothermally altered or contaminated by the Archaean/Proterozoic crust. Beard et al (1998; 2000) discussed the origin of kimberlites in Terskiy Bereg and Arkhangelsk, and concluded that they were formed from a metasomatised mantle source and were associated with impact of a mantle plume on the base of the thick cratonic lithosphere.

5.6 Origin of carbonatites and phoscorites

The evolution and source characteristics of carbonatite magmas in the KACP have been recently reviewed by Bell and Rukhlov (in press). There is a long-standing debate about whether carbonatite magmas are products of liquid immiscibility or can be derived directly from melting of the mantle (or both). However, many recent experimental studies (e.g. Wallace and Green, 1988; Thibault et al., 1992; Dalton and Wood, 1993; Lee and Wyllie, 2000) have demonstrated that carbonatite melts can be formed from carbonated lherzolite at moderate to high pressures. The presence of carbonatites as dykes and as volcanic products (e.g. in Kontozero) indicates that carbonate magmas were present as separate entities in the KACP, but it is not clear whether they were formed separately at mantle depths or exsolved at lower pressures. Evidence for the passage of carbonatite melts through the lithospheric mantle is suggested by the presence of wehrlite xenoliths associated with spinel peridotite xenoliths in a dyke near Kandalaksha (Beard et al., in prep). Wehrlites can be formed by carbonatite metasomatism within the mantle.

The similarities of the REE and trace element patterns for ultramafic alkaline silicate rocks and carbonatite dykes indicate that there is a strong relationship between the two magma types. This is seen in the field relations within the UACC, in which carbonatite rocks grade into silicate rocks. Bell and Rukhlov (in press) point out that fractional crystallisation may be the dominant process in the origin of carbonatites. Primary igneous calcite is common in many silicate rocks within the KACP, e.g. as interstitial phase in the Kovdor ultramafic cumulates (Verhulst et al., 2000), and in dykes associated with the Kandaguba complex (Pilipiuk et al., 2001) and Pinozero dyke swarm (Rukhlov, 1999; Bell and Rukhlov, in press). Many of the carbonatite rocks in the UACC are in fact cumulates, so their compositions represent a mixture between cumulus carbonate minerals and cumulus silicate minerals (Fig. 6). Plutonic silico-carbonatite xenoliths from a ferrocarbonatite sill in the Kandalaksha Gulf were also interpreted as cumulates (Beard et al., 1996). Veksler et al. (1998) analysed melt inclusions in silicate minerals from carbonatite and silicate rocks of Kovdor, and suggested that fractionation of amphibole and phlogopite was an important process during melt evolution. Many olivine-free ultramafic cumulate xenoliths have been found together with the plutonic carbonatite xenoliths in Kandalaksha Gulf (Beard et al., in prep). The mineralogy of these xenoliths includes pargasite, phlogopite, diopside and apatite; they show clear evidence of magmatic layering.

In contrast to the suggestion that the carbonatite magmas were formed directly from the mantle or from crystal fractionation, Bulakh and Ivanikov (1984) and Ivanikov et al (1998) argued for an origin due to liquid immiscibility from nepheline melilitite magmas. They suggested that the presence of carbonate ocelli in the mafic silicate dykes was consistent with this process. On a large scale, the carbonatites and silicate rocks in the UACC also have similar Sr and Nd isotope ratios (Fig. 12), although detailed studies of Rb-Sr and Sm-Nd systems suggest slightly different sources for carbonatites and silicate rocks of the Khibiny complex (Kramm & Kogarko, 1994; Zaitsev et al., 1997; Sindern et al., 2004). Detailed isotopic studies have shown that KACP carbonatites do not have a uniform isotopic composition and therefore are probably derived from a heterogeneous mantle source (e.g. Verhulst et al., 2000; Dunworth and Bell, 2001). Sr-Nd isotopic data cannot easily distinguish between the two processes of partial melting or liquid immiscibility and, as Bell and Rukhlov (in press) have concluded, there is no overall agreement about whether carbonatites arrive in the crust as carbonate magmas or separate by liquid immiscibility at shallower levels. Possibly both mechanisms have operated, even within the same complex.

Phoscorites are extremely unusual rock-types, associated with carbonatites within the UACC (Krasnova et al., in press). Their mineralogy is highly variable, ranging from almost monomineralic to magnetite-apatite-forsterite/diopside rocks. Such mineralogical variations imply that crystal segregation processes were involved in their formation (i.e. some phoscorites are probably cumulates), but Krasnova et al. (in press) also suggest that liquid immiscibility between phoscorite and carbonatite melts may have played a role. A phoscorite melt would be extremely rich in Fe and P, and would have a very different melt structure from that of a carbonatite melt. Stable isotope data for Kola carbonatite and phoscorite complexes have been presented by Demeny et al. (in press), who suggested that liquid immiscibility may have operated to form some phoscorites (e.g. in Sokli) but the involvement of separate sources is required in other examples (e.g. Turiy).

5.7 Asthenospheric or lithospheric source?

In common with much of the Baltic Shield, the present-day lithospheric thickness beneath the Kola Peninsula is at least 200km (Artemieva, 2003). The presence of rare diamonds in kimberlites of the Terskiy coast (Kalinkin et al., 1993) and Arkhangelsk (Mahotkin et al., 2000) suggests that lithospheric thicknesses were similar in Devonian times. This gives rise to questions concerning the location of the melting that gave rise to the suite of magmas. The general homogeneity in isotopic and REE composition within the non-potassic silicate magmas and the carbonatites argues for a homogeneous source, which is conventionally considered to be the asthenosphere, whereas the isotopic heterogeneity of the potassic magmas (including kimberlites) suggests a lithospheric source. However, kimberlites are usually considered to be formed at greater depths than melilitites, nephelinites or carbonatites. Thus, possibly all KACP magmas were derived from a lithospheric mantle that had been metasomatised prior to melting, which had not had time to develop extensive isotopic heterogeneity except in the regions containing high Rb/Sr phlogopite. The kimberlites were derived from the deepest levels (at least 120 km), which were most metasomatised and heterogeneous, with the nephelinites and melilitites being formed from shallower and more homogeneous regions of the lithosphere. Re-activation of deep lithospheric fractures may have contributed to the uprise of magma.

The trigger for the magmatism is also debateable. Numerous authors have suggested the presence of a mantle plume (e.g. Beard et al., 1998; Dunworth and Bell, 2001; Sindern et al., 2004; Bell and Rukhlov, in press). This would help to explain (a) the short time duration of the magmatism and (b) the large volume of magma produced (between 15000 and 75000 km^3, depending on the original thickness and extent of erupted lavas). The highly silica-undersaturated nature of the magmatism is, however, rather unusual for a plume event and tends to suggest very small degrees of melting of an enriched source, rather than extensive melting related to the impact of a large plume head. Even the He isotopic systematics suggests only a limited role for material actually derived from the lower mantle (Tolstikhin et al., 1999, 2002). Moreover, Meiboom et al (2003) have suggested that high $^3He/^4He$ ratios (= low $^4He/^3He$ ratios) may not be a reliable indicator of the presence of a deep «plume» component.

6. Conclusions

From the data reviewed above, we conclude that most of the magmas within the Kola alkaline province were derived from an upper mantle source (possibly a thick lithosphere), although a lower mantle plume may have initiated the magmatism. A spectrum of magmas from carbonatite to damkjernite to melilitite to ultramafic lamprophyre was derived from melting of metasomatised carbonated garnet peridotite. Most primitive silicate magmas have very similar trace element and isotopic compositions and therefore are derived from a similar mantle source. The most likely 'primitive magma' for the ultramafic-alkaline-carbonatite complexes is a sodic melilitite, olivine melanephelinite or ultramafic lamprophyre. Depth of melting, degree of melting and mineralogy of the mantle source are the key factors in determining the composition of the ultramafic and mafic magmas. Potassic magmas such as kimberlites may have been derived from enriched mantle lithosphere containing residual phlogopite. Cumulate processes were very important in forming the spectrum of alkaline ultramafic rock-types in the ultramafic-alkaline-carbonatite complexes; crystal fractionation processes were important in forming the nepheline and alkaline syenites. Carbonatites may have been formed by direct mantle melting or by liquid immisicibility, but most of them are probably related to crystal fractionation of carbonated alkaline magmas.

7. Acknowledgements

We are very grateful to Lia Kogarko and Frances Wall for their careful reviews of this paper. We wish to record our thanks to the organisers of the annual SVEKALAPKO meetings, held as part of the ESF-funded EUROPROBE project, that enabled Russian and Western colleagues to exchange samples, data and ideas in the congenial surroundings of Lammi (Finland) and Repino (Russia).

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