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Kola alkaline province in the Paleozoic: evaluation of primary mantle magma composition and magma generation conditions

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Abstract. This paper is an attempt to estimate quantitatively the chemical composition and volume of magma, the reactivation of which resulted in the formation during the Paleozoic of the northeastern part of the Baltic Shield in the Kola alkaline province. In contrast to the known models, a gravity-based method of 3-D density modelling was used to evaluate the extent of alkaline magmatism in the province and, accordingly, to estimate the volume of mantle magma produced during the Paleozoic cycle of activity. During the early period of study, along with sample collection and geochemical analyzes, the deep structure of the province was investigated, and 3-D density models were derived for all alkaline intrusions of the province to a depth of 22.5 km. The next step included the high-precision determinations of trace element concentrations in the rocks using an ICP-MS method as a basis for calculating the weighted mean concentrations of these elements in the rocks of the province, deriving models for mantle rock melting, and estimating the geodynamic consequences of these mantle processes. The calculations showed that the total volume of the Paleozoic magma produced in the NE part of Fennoscandia had been 15000±2700 sq. km. The calculated composition of the magma that might have been melted from the mantle of an intermediate composition revealed that a significant amount of incoherent elements must have been added to the primary mantle material. It is shown with a high degree of certainty that the primitive magma was produced in the Kola Province because of the low melting degree of the substrate (0.3–0.5%) whose composition answered to a phlogopite (± amphibole) bearing garnet lherzolite residing at a depth of a garnet mantle. The enrichment degree of this substrate was calculated to have been 3 times higher than the mean contents of incompatible elements in the primitive mantle. It is shown that the process of magma generation involved a significant portion of the NE Fennoscandian lithosphere ca. 400 km across and 120 km in depth, that is, covered the entire depth of the mantle garnet lherzolite. This areal estimate agrees with the area of Paleozoic igneous rocks in the region. The estimated depth correlates with the PT conditions of the mantle xenoliths found in the dikes and breccia pipes of the region.

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1. Introduction

The research work done in the last decade furnished new proofs that the main factor responsible for continental magmatism in areas of ancient shields and their frames had been the reactivation of the upper mantle as result of a plume–lithosphere interaction and/or rifting [*Baker et al.,* 1997;

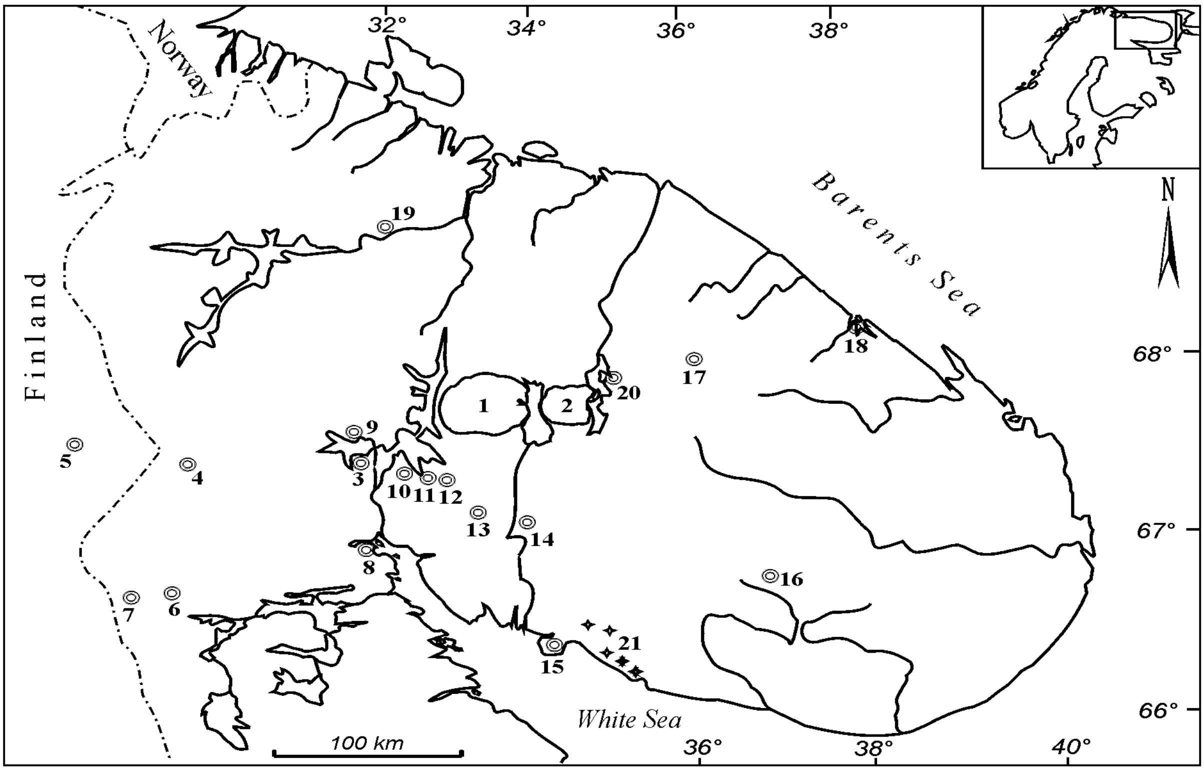

Figure 1. Location map for the distribution of the products of Paleozoic magmatism in the NE Baltic Shield. Intrusions: 1) Khibiny, 2) Lovozero, 3) Niva, 4) Kovdor, 5) Sokli, 6) Vuoriyarvi, 7) Sallanlatva, 8) Kandaguba, 9) Mavraguba, 10) Afrikanda, 11) Ozernaya Varaka, 12) Lesnaya Varaka, 13) Salmagora, 14) Ingozero, 15) Turii Mys, 16) Pesochnyi, 17) Kontozero, 18) Ivanovka, 19) Sebl'yavr, 20) Kurga; 21) Terskii coast dikes and diatremes.

Bell and Simonetti, 1996; *Kerr et al,* 1995, 1996; *Thompson and Gibson,* 1991, 1994; *Toyoda et al.,* 1994; *White and McKenzie,* 1989, 1995]. The results of deep seismic sounding combined with high-accuracy isotopic geochemical studies of mantle magmatic rocks and hypoxenoliths provided a basis for deriving models of magma generation in the mantle [*Keen et al.,* 1994; *McKenzie and O'Nions,* 1991; *Ryabchikov,* 1998; *White and McKenzie,* 1995; *Williamson et al.,* 1995]. Based on the latest experimental data, these models are good enough to determine the behavior of chemical elements for the partial melting of mantle rocks and to estimate the compositions and, in some cases, the volumes of the melting products [*McKenzie and Bickle,* 1988; *Niu,* 1997; *Walter,* 1998; *Winter,* 1995]. At the same time these approaches are liable for random assumptions because of the uncertainty of some data for magma generation in the mantle. This circumstance calls for deriving models based on alternative approaches to determining the volumes and compositions of mantle magmas.

This paper is an attempt to estimate the chemical composition and volume of the mantle, the melting of which resulted in the formation in Paleozoic time of the NE portion of the Baltic Shield in the Kola alkaline province and to evaluate the composition of the source melts. In contrast to the models mentioned above, we used a method of 3-D density modeling based on geophysical data [*Glaznev et al.,* 1996].

The aims of this study were:

– to evaluate the volumes of the Paleozoic alkaline magmas in the region, including the calculation of the volumes of different types of rocks in the study area. The main results of this work, based on the study of the crust and mantle structure in the region and on the calculation of 3-D density models for all alkaline rock intrusions to a depth of 22.5 km, were reported earlier [*Arzamastsev et al.,* 1998a; *Arzamastsev et al.,* 2000a];

– to collect samples of plutonic, dike, and volcanic rocks for a geochemical study and perform high-precision determinations of trace elements concentrations using an ICP-MS method in the laboratory of the University of Granada following the procedure described in [*Bea,* 1996];

– to calculate the weighted average concentrations of trace elements in the rocks of the province, use the results to calculate the mean compositions of the source magmas, and compare the resulting compositions with the least differentiated rocks of the province;

– to carry out a petrologo-geochemical modeling including the calculation of the probable concentrations of trace elements in the source mantle melts (based on experimental data reported in literature), compare them with the calculated contents in the source Paleozoic magmas of the Kola Province, and calculate the potential volumes of the zone of Paleozoic magma generation for the given degrees of mantle rock melting.

2. Geology of the Kola Paleozoic Igneous Province in Terms of the Model Applicability

The Kola Province occupies the northeastern region of the Baltic Shield and is made up of the world largest plutons of agpaite syenites and numerous intrusions of alkalic ultrabasic rocks with carbonatites (Figure 1). Volcanic rocks of Paleozoic age are scarce, are significantly reduced, and occur mainly as remnants in the collapse calderas of the Kontozero, Lovozero, Khibiny, and Ivanovka massifs [*Arzamastsev et al.,* 1998b]. The widespread dike swarms and diatremes originated at the same time with the intrusion of plutons. The Kola alkalic intrusions rank among the well known geological objects; they were described by many investigators [*Bussen and Sakharov,* 1972; *Galakhov,* 1975; *Gerasimovskii et al.,* 1966; *Kukharenko et al.,* 1965, 1971]. For this reason we prefer to dwell on some principal features which define the applicability of a model for calculating the composition of mantle rocks for this region.

1. The province of study includes almost all products of the Paleozoic igneous activity including intrusions, dike swarms, and diatremes. The present-day level of the geological and geophysical knowledge of the Kola region [*Mitrofanov et al.,* 1995] and of the adjacent areas of the Barents and White seas [*Grachev,* 2000a] suggests the minimum probability of discovering any new occurrences of Paleozoic igneous activity. This supposition is proved by the latest findings of alkaline rocks on the Barents Sea coast (Ivanovka Massif) [*Rusanov et al.,* 1993], in the area of Lake Imandra (Niva intrusion) [*Arzamastsev et al.,* 2000b], and in the Kandalaksha area (Kandaguba Massif) [*Pilipyuk et al.,* 1998], whose contribution to the total volume of alkaline rocks in the province is not higher than 1%.

2. The level of the geological knowledge is high enough to reconstruct with a high degree of detail the internal structure of virtually all alkaline intrusions. Because most of the massifs were known to contain rare-metal ores, the area of all intrusions was covered by a large-scale geological survey, and the massifs were drilled to depths of 200–2000 m.

3. All products of Paleozoic igneous activity were emplaced during a relatively short time interval of 380–360 million years [*Kramm et al.,* 1993]. This suggests that they originated during one strictly limited period of tectonomagmatic reactivation. This period was preceded by a long amagmatic period of the Baltic shield history, which lasted more than 1.3 billion years. No magmatic post-devonian events have been registered in the NE part of Fennoscandia.

4. The isotopic and geochemical characteristics of the Paleozoic plutonic and subvolcanic rocks of the province suggest the minimum contribution of crustal material in the origin of the alkaline rocks [*Beard et al.,* 1998; *Kramm and Kogarko,* 1994; *Zaitsev and Bell,* 1995] and in the origin of their parental magmas as a result of the direct melting of the old mantle material depleted in the course of the Archean and Proterozoic crust formation [*Arzamastsev et al.,* 1998b].

The above features place the Kola Province into the number of the most promising regions where the reconstruction of the initial composition of the mantle is permissible.

3. Calculation of the Volumes of Paleozoic Magmatism in the Baltic Shield

We calculated the volumes of the alkaline ultrabasic intrusions using the results of our 3-D density modelling based on geophysical data, which enabled us to determine the geological structure of the intrusions to a depth of 22 km. The essence of the regional density modelling of the Earth's crust under the Baltic shield and the technique of the 3-D density modelling of alkaline intrusions were discussed earlier [*Arzamastsev et al.,* 2000a; *The Structure of the Baltic Shield Lithosphere,* 1993]. The interpretation of gravity data aimed at determining the structure of the central-type massifs consisted of two stages: first to calculate a regional density model for the crust and the gravity field it produced, and second to interpret the local gravity anomalies produced by density inhomogeneities in the upper crust.

Our calculation of a detailed density model for the upper crust was based on the method and calculation technique offered by V. N. Strakhov [*Strakhov,* 1990, 1999] for solving a general inverse linear problem. In our practical use of this method we introduced some additions to improve the convergence of the iteration solution of our 3-D inverse problem. To pick out local high-gradient anomalies, we used our own version of dispersion filtering, close in its sense to the known methods of adaptive filtering [*Nikitin,* 1979]. The spacing of our grid for calculating a 3-D density model was 2×2 km in plan, and the vertical interval was specified using a discrete series of the grid nodes: 0, 1.0, 2.0, 3.5, 5.0, 7.0, 9.0, 11.0, and 14.0 km. The accuracy of solving the inverse gravity problem was chosen to be ±0.25 mgal. This accuracy was sufficient for the accuracy of the density solution to be ±10 kg/m^3. This algorithm of the calculation and visualization of the results was used to write computer programs to have the results of modelling in a graphic form.

In our calculation of volumes we included all known occurrences of alkaline-ultrabasic and carbonatite magmatism (Kovdor, Turii Mys, Afrikanda, Sebl'yavr, Vuoriyarvi, and other intrusions), the huge alkaline rock complexes of Khibiny and Lovozero, and also volcanic rocks from the Kontozero caldera. In view of the fact that the volume of the Paleozoic alkaline dikes was hard to calculate, we assumed, using the swarms of alkaline lamprophyre dikes, known from the Kandalaksha River shore and from the Neblo Mt. area, their volume to be 10% of the total volume of the alkaline–ultrabasic intrusions. It is obvious that the error of determining the dike volume may be as high as 50% or even higher.

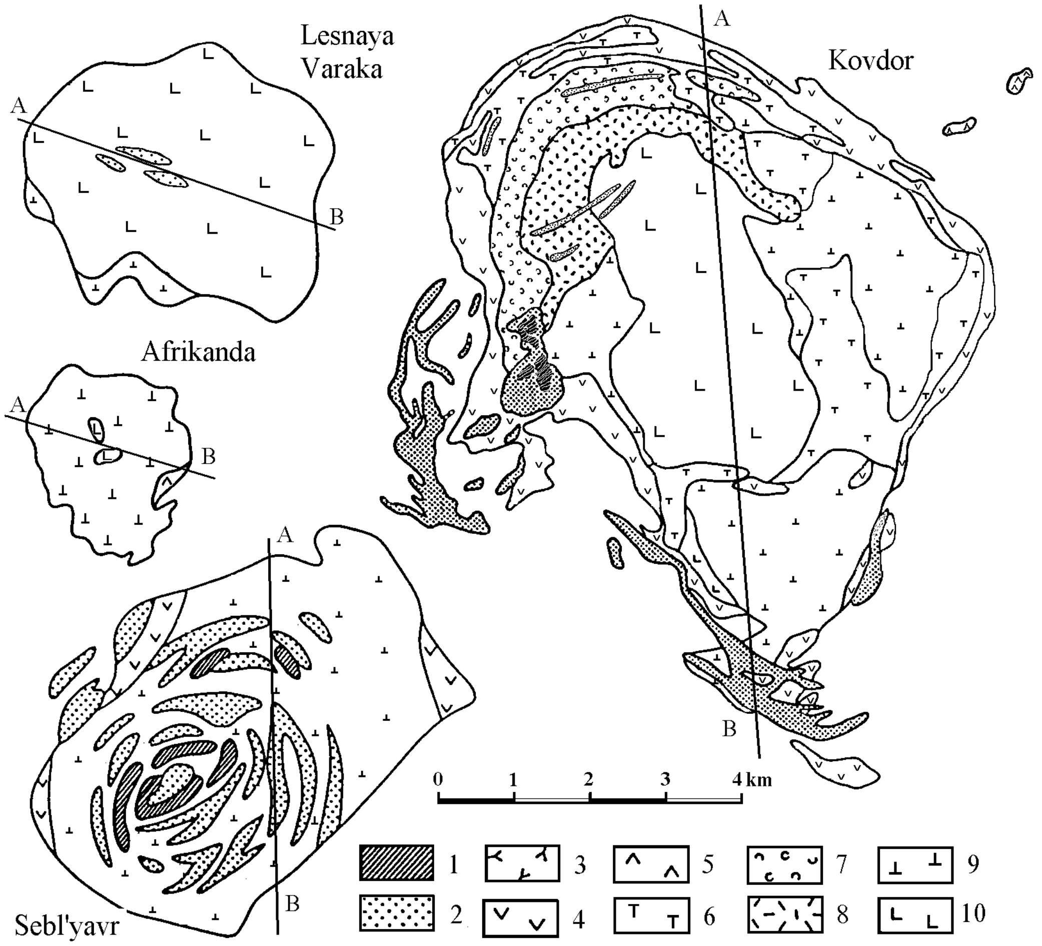

Figure 2. Schematic maps showing the geologic structure of the Kola carbonatite massifs, modified after *Ternovoi* [1977] and *Kogarko et al.* [1995]: (1) phoscorite, (2) carbonatite, (3) nepheline syenite, (4) ijolite, (5) melteigite, (6) melilite rocks, (7) melilite-monticellite-olivine rocks, (8) phlogopite-diopside-olivine rocks, (9) pyroxenite, (10) peridotite and dunite. The A-B lines show the orientations of the density sections given in Figure 3.

3.1. Intrusions of Alkaline-Ultramafic Rocks and Carbonatites

The results of our density modeling suggest substantial differences in the deep structure of the carbonatite intrusions (Figure 2). The objects of our study included subvertical bodies of a cylindrical form (Sebl'yavr, Kovdor), intrusions with a near-surface magma chamber and a lateral feeding channel (Lesnaya Varaka, Afrikanda), lopolithlike intrusions (Salmagora, Turii Mys), and bodies that were actually the apical parts of large alkaline ultramafic intrusions (Sokli) (Figure 3). The results of our density modeling revealed that most of the intrusions had narrow necks in the zones of high-density rocks, which can be interpreted as transition zones between the magma chambers and the feeding channels. Considering the above mentioned limitations of the method in terms of the accuracy of solving an inverse gravity problem, the estimates of the lower limits of the chambers may vary as much as 15–20%, the general pattern remaining valid.

All alkaline-ultramafic intrusions were found to have a multiphase structure which reflects the successive intrusion of an alkaline ultramafics–foidolite–carbonatite series. It was believed earlier [*Epshtein and Kaban'kov,* 1984; *Epshtein et al.,* 1972; *Frolov,* 1972; *Kukharenko et al.,* 1965; *Landa,* 1976; *Samoilov,* 1977] that most of carbonatite intrusions had a zonal structure with carbonatite dominating in the top of the magma column, underlain by foidolite which is replaced at a deeper level by a zone of ultramafic rocks. Accordingly, the poorly eroded massif must show carbonatites, and the highly eroded ones, the rocks of the alkaline-ultramafic series. The results of our modeling confirmed this observation: the established relationship between the modern forms of the bodies and the depths to the bottoms of the magma chambers suggests that initially most of the Kola carbonatite intrusions had the form of a lenticular symmetrical stock with a distinct transition from the magma chamber to the feeding

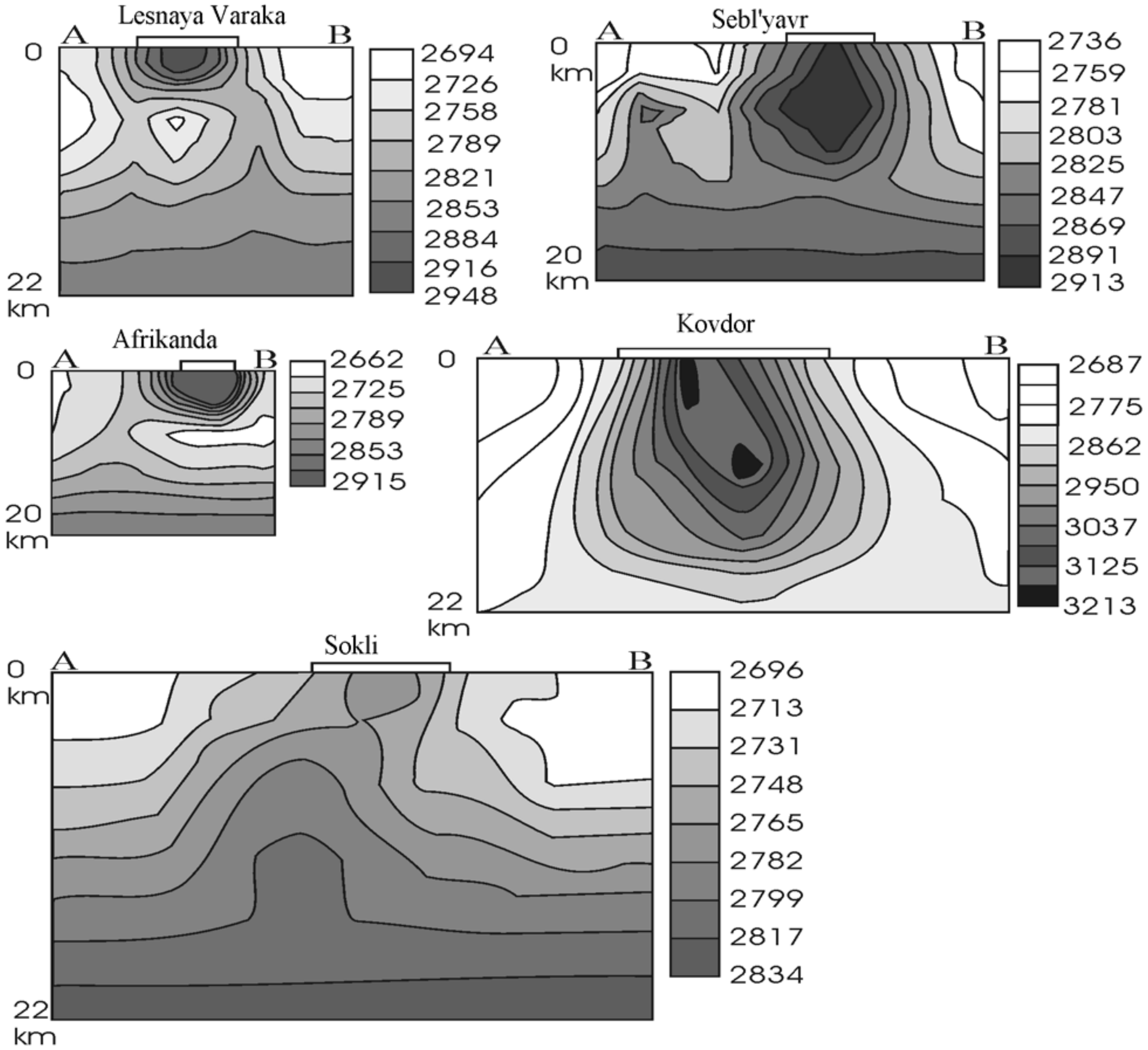

Figure 3. Density distribution in the Kola carbonatite massifs. See Figure 2 for the orientations of the section lines.

channel, the diameters of the latter being 1/5 to 1/3 of the maximum sizes of the intrusions [*Arzamastsev et al.,* 2000a]. The apical part of this hypothetical intrusion seems to be represented in the Sokli Massif, where the carbonatites are associated with a large swarm of alkaline lamprophyre dikes, the fact typical of the poorly eroded intrusions. We used the Sebl'yavr and Kovdor intrusions, which preserved the large parts of their magma reservoirs, to reconstruct their sizes. We found that a ratio between the initial heights of the chambers and their diameters must have been 2:1, and the vertical lengths of the reservoirs, 15–20 km (Figure 3).

Using the data available on the deep structure of the intrusions, we calculated, for each of them, the volumes of their near-surface magma chambers, of their eroded parts, and of their feeding channels connecting the zone of magma generation and the shallow magma reservoir. The results of our calculations are presented in Table 1. We assumed that there had been no intermediate magma chambers in the crust or upper mantle. The circumstantial evidence of this is provided by isotopic data [*Arzamastsev et al.,* 1998b; *Kramm and Kogarko,* 1994], suggesting an insignificant role of crustal contamination which would have been observed in the case of the long standing of mantle magma in crustal chambers.

Proceeding from the fact that most of the intrusions have a concentrically zoned structure, as follows from geological observations and from the results of our density modelling, a truncated cone was assumed as an acceptable approximation of their forms (Figure 4). We used the following parameters of the approximation form:

(1) the height of the magma chamber estimated from the results of the density modeling as a distance from the surface

Table 1. Calculated volumes of alkaline–ultramafic intrusions of the Kola Province

	Massif area, km^3	Surface radius R$_1$, km	Chamber base radius R$_2$, km	Chamber height h$_1$, km	Chamber volumes, km^3	Feeder radius, km	Feeder length h$_3$, km	Feeder volume, km^3	Erosion height h$_2$, km	Erosion volume, km^3
Kovdor	37.5	3.43	5.0	7.0	782.6	1.0	41	128.7	1.0	16.0
Lesnaya	13.1	2.04	1.0	4.5	33.6	0.2	51	31.7	10.5	59.6
Ozernaya	0.8	0.50	0.5	4.0	3.1	0.1	51	16.0	11.0	3.8
Afrikanda	5.0	1.26	1.0	4.0	16.0	0.2	51	32.0	11.0	23.8
Salmagora	38.0	3.48	2.0	6.5	155.3	0.4	49	60.9	8.5	139.9
Sokli	31.0	3.14	5.0	6.0	629.0	1.0	43	135.0	3.0	40.3
Turii Mys	43.0	3.70	3.0	4.5	157.6	0.6	51	95.1	10.5	195.6
Sebl'yavr	20.0	2.52	4.0	6.5	437.3	0.8	42	105.5	2.0	17.3
Vuoriyarvi	20.0	2.52	2.0	5.0	79.9	0.4	50	62.8	10.0	86.6
Sallanlatva	6.0	1.38	1.0	5.0	22.2	0.2	50	31.4	10.0	26.0
Kovdozero	1.6	0.71	0.5	5.0	5.8	0.1	50	15.7	10.0	6.9
Kandaguba	1.0	0.56	0.5	5.0	4.4	0.1	50	15.7	10.0	4.3
Ivanovka	5.0	1.26	1.0	5.0	20.0	0.2	50	31.4	10.0	21.7
Kurga	30.0	3.09	2.5	5.0	243.8	0.5	45	70.7	5.0	65.0
Iivara	18.0	2.39	3.0	4.5	204.4	0.6	46	86.7	6.0	46.8
Kontozero	65.0	4.55	4.5	3.0	126.0	0.9	53	149.8	13.0	366.6
Total volume, km^3	–	–	–	–	2921±290	–	–	1069±320	–	1120±340

Note. The total volume of intrusions including the volumes of their shallow chambers, feeders, and eroded portions amounts to 4040±950 km^3.

erosion level to the depth level of the transition to the feeding channel (h$_1$);

(2) the radius of the intrusion at the surface (R$_1$) found from the computed area of the massif. The latter and the outcrop areas of various rock types were computed from map data [*Kukharenko et al.,* 1965, 1971];

(3) the radius of the magma chamber bottom (R$_2$) at the level where it changes to a feeding channel estimated from the results of the density modelling. The maximum diameter of the chamber (R$_3$) was calculated for intrusions of a lenticular form. In this case the volume was calculated as the sum of volumes of two truncated cones;

(4) Considering that the total volume of the magma chamber included its eroded portion, the volume of the latter was calculated using the radius of the intrusion near the surface (R$_1$), the radius of the apical portion taken as 0.25 R$_1$, and the height h$_2$ estimated as a difference between the height of a hypothetical carbonatite intrusion (15 km) [*Arzamastsev et al.,* 2000a] and the height of the magma chamber h$_1$;

(5) The volumes of the feeding channels were calculated using a formula for cylindrical bodies having a diameter measuring 0.25 of the bottom diameter of the intrusion and a height (h$_3$) equal to a distance from the bottom of the magma chamber to the zone of magma generation residing at a depth of ca. 55 km, as estimated in [*Arzamastsev and Dalgren,* 1993].

The volumes of the rocks making up the intrusions (dunite, pyroxenite, melilitholith, foidolite, and carbonatite) were estimated on the basis of their proportions at the eroded surface (Table 2) and of the results of the density modeling. For some intrusions (Sokli), the presence of silicate rocks in the uneroded portion of the massif was taken into account. It was assumed that the feeder was filled with the rock whose composition was similar to olivine melteigite porphyry. According to [*Arzamastsev and Arzamastseva,* 1990; *Kochurova and Ivannikov,* 1976; *Kukharenko et al.,* 1971], the latter represents the average composition of the alkaline-ultramafic province.

With the adopted method of approximating the forms of the alkaline intrusions, the errors of calculating their volumes were 10–15% for the magma chambers and approximately 30% for the zone of the feeder and for the eroded portion. The calculated total volume of all carbonatite intrusions of the province, including the volumes of their shallow chambers, feeders, and eroded portions, amounted roughly to 4000±1000 km^3.

3.2. Khibiny and Lovozero Massifs

The volumes of these massifs were calculated using the following geological evidence on their structure at the present-day erosion level (Figure 5) and the results of geophysical interpretation based on the 3-D density modeling [*Arzamastsev et al.,* 1998a].

1. The southeastern, southern, and western contacts of the Lovozero Pluton are subvertical to a depth of 4 km in the zone of nepheline syenites and grow gentler beginning with the depths of 8–10 km (Figure 6). The northern and northwestern contacts are more gentle: the dips vary within

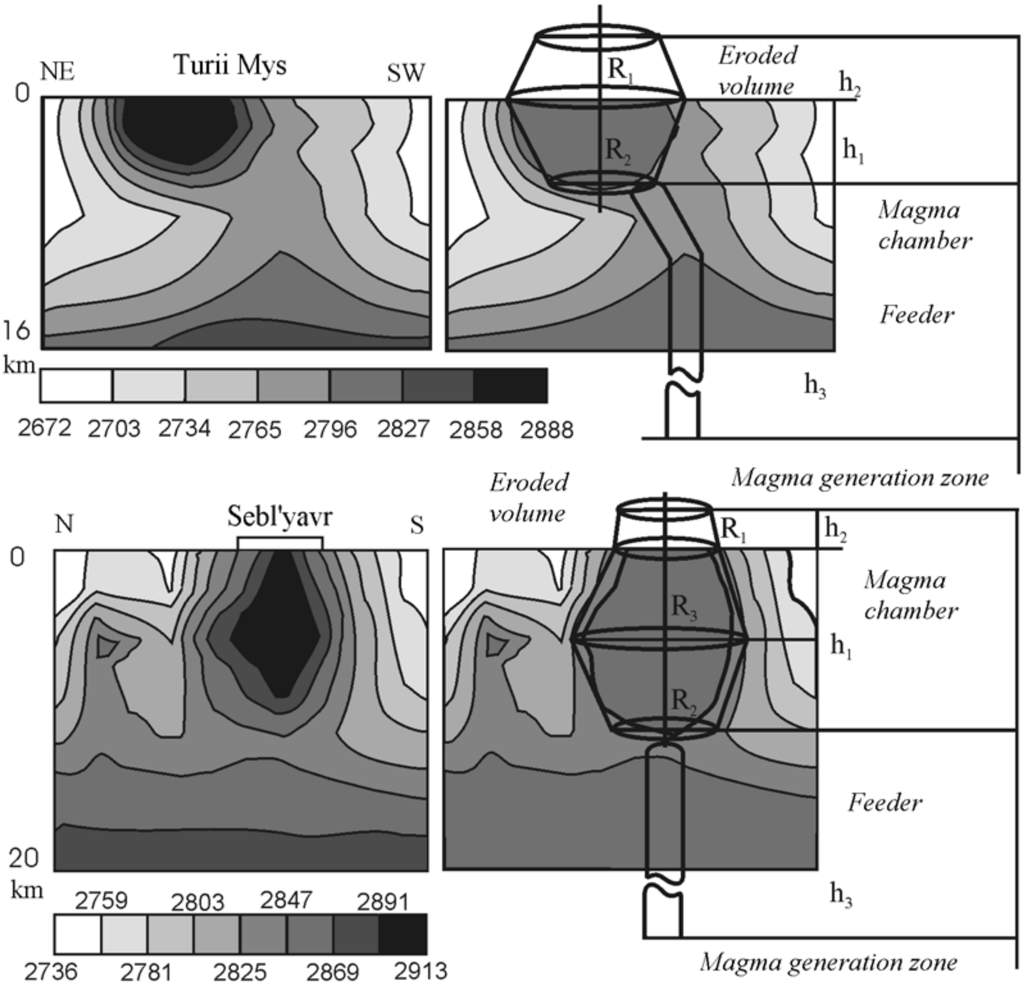

Figure 4. Examples of calculating the volumes of alkaline-ultramafic intrusions in the Kola Province from the results of density modeling shown for the Turii Mys and Sebl'yavr intrusions. The density values are given in kg/km^3.

50–60° near the surface and within 30–40° at depths of 4–5 km. At greater depths the contact is subvertical to a depth of 9–10 km.

2. The Lovozero Pluton consists of two zones of different densities at a depth greater than 2 km (Figure 6). The southwestern zone is made up of rocks with densities of 2660–2750 kg/m^3, these values being typical of nepheline syenite. A local negative density anomaly was recorded in the central part of the pluton in the Lake Sedyavr area. This anomaly marks a body of alkaline and analcime syenites with a density of 2580–2630 kg/m^3. This region seems to host a feeder for the nepheline syenite intrusion. The northeastern zone consists of rocks with a density higher than 2800 kg/m^3. According to field geology and drilling data, the top of the zone is composed of the remnants of alkaline volcanic rocks of the Lovozero suite of Devonian age, and also of the alkaline-ultramafic rocks similar to those known from the Khibiny Massif [*Arzamastsev et al.,* 1998a].

3. The conic-circular structure of the Khibiny Pluton persists within the depths accessible for observation, namely to a depth of 12.5 km. The eastern contact in the region of a carbonatite stock is subvertical to a depth of 3–4 km and tends to become suddenly gentler at a depth of 4–5 km. The western and southern contacts dip inward at an angle of 65–70° to a depth of 4 km. The position of the contact is as gentle as 30° in a depth interval of 4–6 km and becomes as steep as 50–60° below a depth of 7 km.

4. The results of our study suggest that the alkaline-ultramafic rocks are more abundant in the Khibiny Pluton than it was believed earlier [*Galakhov,* 1975]. The results of our density modeling show that boreholes reached merely the roof of a thick zone of alkaline ultramafics showing a positive density anomaly and extending along the entire northern sector of the massif (Figure 6). The holes drilled through the khibinites intersected thick zones composed of peridotite, pyroxenite, melilitolite, and ultrabasic foidolite xenoliths. The western sector of the pluton, which according to *Snyatkova et al.* [1986] is marked by a combination of gravity and mag-

Table 2. Ratio of rocks in the Kola intrusions and their portions in the total volume of the products of alkaline-ultramafic magmatism

	Dunite	Pyroxenite	Melilite rocks	Melteigite	Ijolite	Melteigite + ijolite	Nepheline syenite	Carbonatite	Nephelinite, melilitite
Rock index	PRO	PRX	MML	FOM	FOI	FO	SFN	CC	NFM
Kovdor	9.0	12.0	3.5	–	–	9.5	0.5	3.0	–
Lesnaya	10.0	2.0	–	–	–	1.0	–	0.1	–
Ozernaya	–	–	–	0.8	–	–	–	–	–
Afrikanda	0.5	3.5	–	1.0	–	–	–	–	–
Salmagora	13.0	8.0	5.6	–	–	9.5	–	1.9	–
Sokli	–	–	–	–	–	–	–	9.4	–
Turii Mys	–	2.0	21.0	–	–	19.0	–	1.0	–
Sebl'yavr	–	14.0	–	–	–	2.0	–	4.0	–
Vuoriyarvi	1.0	11.0	–	–	–	6.0	–	2.0	–
Sallanlatva	–	–	–	1.5	3.5	–	–	1.0	–
Iivara	–	–	–	6.0	12.0	–	–	–	–
Kovdozero	–	–	–	1.0	–	–	–	–	–
Kandaguba	–	–	–	–	1.0	–	–	–	–
Ivanovka	–	3.0	–	2.0	–	–	–	–	–
Kurga	6.0	18.0	–	–	–	–	6.0	–	–
Kontozero	–	4.0	–	–	–	–	1.0	–	60.0
Total area of intrusions, km^2	39.5	77.5	30.1	12.3	16.5	47.0	7.5	22.4	60.0
Percentage of rock in intrusion area, %	12.63	24.78	9.62	3.93	5.27	15.03	2.40	7.16	19.18
Total volume of rock, km^3	510.3	1001.3	388.9	158.9	213.2	607.2	96.9	289.4	775.2

Note. The total volumes of the rocks were calculated taking into account their eroded volumes and the results of the density modeling to a depth of 22.5 km.

netic anomalies, was found to include a large zone of alkaline ultramafics which extends as far as 15 km along a contact between the massive and the trachitoid khibinites. In contrast to the northern zone, the analysis of the structure of the southwestern part of what is known as an "ijolite–urtite arc" showed the absence of positive density anomalies at low levels. This confirms the trend revealed by drilling that the ijolite-melteigite intrusion pinches out at a depth of ca. 3 km.

It follows from the above that the results of our 3-D density modelling were good enough to determine the structure of the Khibiny and Lovozero plutons to a depth of ca. 12 km, which is sufficient for estimating the total volumes of the magma reservoirs of these plutons and clarifying the volumetric relations of their rocks. Taking into account the circular configuration of these intrusions in plan, their total volume can be approximated as a sum of truncated cones, whose radii R_1–R_n and heights h_1–h_n are known (Figure 6). The calculations of the rock proportions in the total volume was performed on the basis of the density modelling within the areas outlined for the Khibiny and Lovozero plutons to the depths of 10.1 and 11.9 km, respectively. The results of our calculations are presented in Table 3. We assumed a priori that the radii of the feeding channels for these intrusions were 3 km for Khibiny and 1 km for Lovozero, these values being roughly 10% of the surface diameters of the intrusions. The channels have lengths equal to a distance between the bottom of the magma chamber and the zone of magma generation, which was inferred to reside at a depth of 55 km [*Arzamastsev and Dalgren,* 1993]. Taking into account the depth of erosion estimated by *Virovlyanskii* [1975] to be not more than a few kilometers, and also the numerous outliers of sedimentary and volcanic rocks that had formerly composed the roofs of the plutons, it can be assumed that the portion of the eroded rocks in the total volumes of the intrusions was approximately 10%.

Taking into account the approximated forms of the Khibiny and Lovozero massifs, the errors of calculating their volumes are not higher than 10% for their magma chambers, 30% for the feeders, and 40% for the eroded rocks. The calculated total volumes of the Khibiny and Lovozero massifs, including the volumes of the shallow chambers, feeders, and eroded rocks, were found to be 9100±1400 km^3 and 1600±250 km^3, respectively.

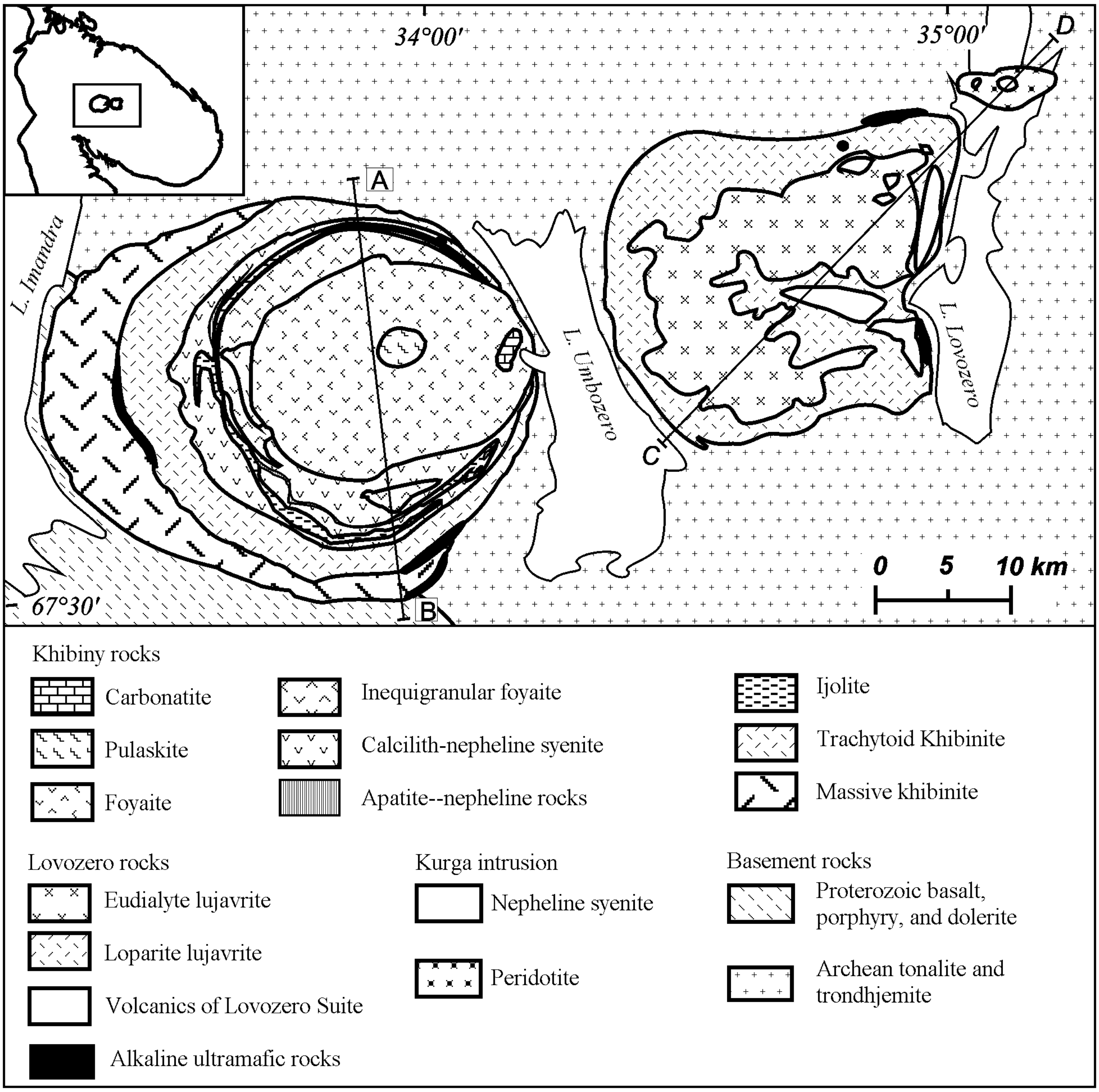

Figure 5. Schematic map showing the geologic structure of the Khibiny and Lovozero plutons based on the data reported by *Bussen and Sakharov* [1972], *Galakhov* [1975], and *Gerasimovskii et al.* [1966] and the results of this study.

4. Compositions of the Primary Magmas of the Paleozoic Phase of Tectono-Magmatic Reactivation

We calculated the average weighted concentrations of trace elements using the geochemical data obtained from analyzing the samples of the main varieties of Paleozoic igneous rocks in the Kola region. Our petrochemical data set included 1070 analyzes for the Khibiny Massif, 280 analyzes for the Lovozero Massif, 360, for the carbonatite intrusions, 230 analyzes for the volcanic rocks of the Lovozero and Kontozero suites, and 350 analyzes for the Paleozoic dikes and diatremes. The mean contents of trace elements were calculated using 116 analyzes of the representative samples of rocks collected in the above mentioned sites. Some of our chemical analyzes are presented in Tables 4 to 11.

The procedure of calculating the average weighted compositions of the primary magmas consisted in computing first the mean contents of elements for each rock type and then the concentrations of elements, taking into account the rock volumes and densities. Apart from the rocks of the alkaline-

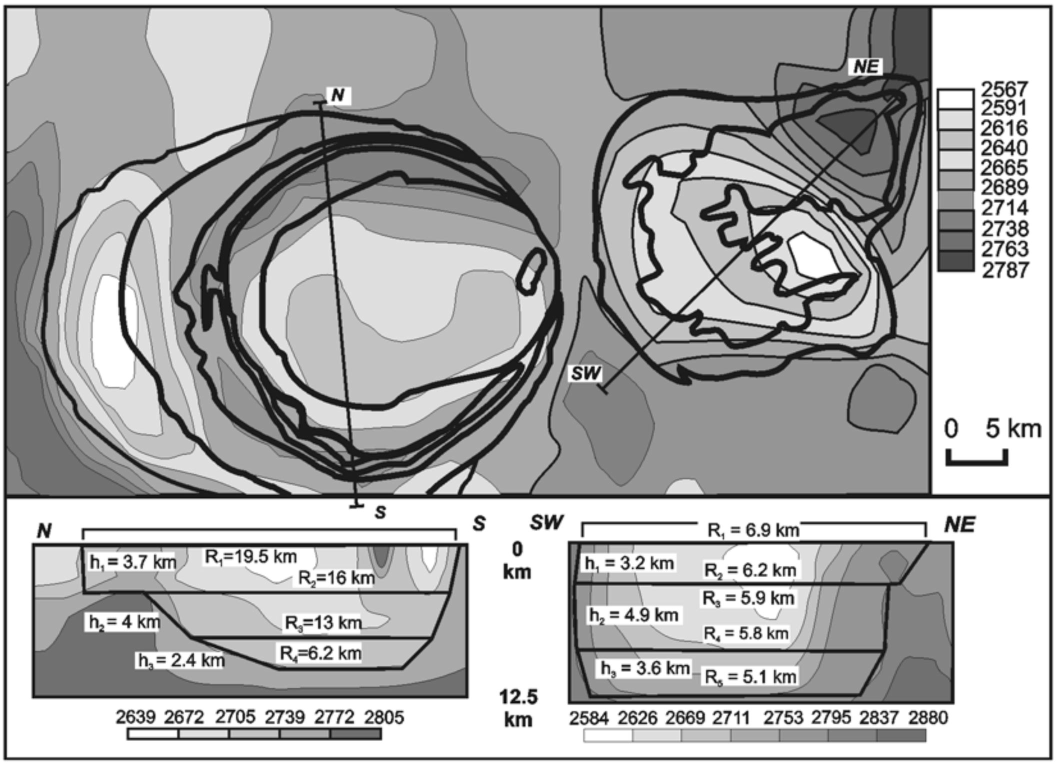

Figure 6. Map of density distribution at a depth of 3.8 km in the Khibiny and Lovozero massifs from the results of 3-D modeling. The contour lines show the boundaries of the rocks on the ground surface. The density sections show the contour lines used to calculate the volumes of the intrusions. The densities of the rocks are given in kg/m^3.

ultramafic and phonolite series, calculations were made for the rocks of the Khibiny and Lovozero massifs (Table 12). Attempts to determine the compositions of the latter were made earlier, including high-precision techniques [*Bussen and Sakharov,* 1972; *Gerasimovskii et al.,* 1966; *Kukharenko et al.,* 1971]. The recent data on the age, geologic structure, and geochemistry of the Khibiny and Lovozero massifs suggest that they are composed of the rocks of two series: alkaline-ultramafic and phonolite ones [*Arzamastsev et al.,* 1998a; *Galakhov,* 1988]. From this standpoint the mean composition of the Khibiny rocks calculated earlier [*Kukharenko et al.,* 1971] does not give an idea of the composition of the primary magma of this unique massif. Moreover, our estimates of the mean compositions of the Khibiny and Lovozero rocks (Table 12) are different markedly from the earlier estimates [*Kukharenko et al.,* 1971], because our calculations included a significant volume of the alkaline-ultramafic rocks from a depth of more than 2 km in the northern part of the Khibiny Massif and in the northeastern part of the Lovozero Massif. As a result, the chemical compositions of both massifs were displaced toward the higher contents of femic components and also of P, Cr, Ni, Co, Sc, and V.

Primary magmas of the alkaline-ultramafic series. To improve the reliability of our estimate of the average composition of the alkaline-ultrabasic magma, we compared our average weighted composition of the alkaline-ultramafic intrusions with the compositions of the contemporaneous rocks of the province representing the most primitive mantle magmas. The characteristics ascertaining the magmas to be most primitive and least differentiated mantle melts were (1) the magnesium number #mg>68 found experimentally for the magnesium number of primary mantle melts [*Eggler,* 1989], (2) the relatively high contents of Ni and Cr, and (3) the mineralogical and petrographic evidence of the mantle origin of rocks, such as the presence of mantle xenoliths and/or of the xenocrysts of high-pressure phases (chrome diopside, Cr-bearing magnesian garnet, and chromite).

The most probable candidates, compositionally resembling the primary magmas of the Kola alkaline-ultramafic series, have been found in the Paleozoic volcanics and dikes, which were emplaced prior to and after the emplacement of the intrusions during a period of 405–360 Ma, respectively [*Arzamastsev et al.,* 1998b; *Kramm et al.,* 1993]. We distinguished the following groups of rocks.

1. The alkaline-ultramafic volcanic rocks of the Lovozero and Kontozero suites, as the earliest manifestations of the Paleozoic volcanic activity in the region. The alkaline picrites and ankaramites show #mg = 0.72–0.81, Ni = 160–520 ppm, Cr = 143–1100 ppm, and Co = 21–100 ppm. Some samples were found to contain chrome diopside xenocrysts.

2. The olivine and pyroxene melteigite porphyry, found in the satellites of large carbonatite intrusions and emplaced

Table 3. The ratio of the rocks and their portions in the volumes of the Khibiny and Lovozero plutons

	Rock portion in pluton volume	Chamber volume, km^3	Eroded volume, km^3	Feeder volume, km^3	Total volume, km^3
	Khibiny				
Khibinite	0.23	1640	164	292	2097
Foyaite	0.17	1212	121	216	1550
Inequigranular syenite	0.08	571	57	102	729
Pulaskite	0.05	357	36	64	456
Calcilithic nepheline syenite	0.09	642	64	114	821
Peridotite	0.06	428	43	76	547
Pyroxenite	0.08	571	57	102	729
Melilitholith	0.02	143	14	25	182
Ijolite	0.17	1212	121	216	1550
Melteigite	0.03	214	21	38	274
Carbonatite	0.02	143	14	25	182
Total volume of the pluton	1.00	7132±710	713±285	1272±385	9117±1380
	Lovozero				
Lujavrite, differentiation product	0.26	337	34	37	407
Foiyaite, differentiation product	0.19	246	25	27	297
Eudialite lujavrite	0.09	116	12	13	141
Poikilitic sodalite and analcime syenites	0.13	168	17	18	203
Murmanite lujavrite	0.01	13	1	1	16
Alkaline syenite	0.05	65	6	7	78
Alkaline-ultramafic rocks	0.21	272	27	30	329
Ankaramite of Lovozero Suite	0.04	45	5	5	55
Basalt of Lovozero Suite	0.02	32	3	4	39
Total volume of pluton	1.00	1294±130	129±50	141±40	1565±220

Note. The total volume of the rocks was calculated from the eroded surface and as a result of density modeling to a depth 14.5 km.

during the main stage of magmatic activity. In spite of the extensive development of these rocks in different areas of the Kola Peninsula (Turii Mys, Ivanovka, Ozernaya Varaka), the melteigite porphyry showed poor variations in the contents of petrogenic and trace elements (Tables 4 and 5). Except for the samples from Ozernaya Varaka, showing some indications of fractionation, the melteigite porphyry samples yielded #mg = 67–76, Ni = 140–610 ppm, and Cr = 310–820 ppm.

3. The olivine melanephelinite dikes and diatremes are spread over the entire territory of the Kola Peninsula, commonly concentrating in the frames of the alkaline intrusions. Geological data suggest that they were emplaced during the terminal phase of magmatic activity. Most of the dikes are poorly differentiated, as indicated by the presence of xenoliths and xenocrysts of mantle origin [*Arzamastsev and Belyatskii,* 1999], which could be preserved only under the condition of a relatively rapid rise of nephelinite magma from the zone of its generation. On this basis, the variety of olivine melanephelinite from the Namuaiv diatreme in the Khibiny Massif (Sample 1635/297.8) is comparable in terms of its Mg number and Ni and Cr contents with the most primitive magma.

Therefore we believe that the above mentioned three groups of rocks are most consistent with the primary magmas that were generated during a relatively short period of magmatic activity in northeastern Fennoscandia.

The REE distribution patterns for all types of the distinguished rocks are presented in Figure 7a. The partition coefficients $(La/Yb)_N$ vary within 28.4 and 53.4 with a regular growth of $(La/Yb)_N$ from the early (volcanic) to the latest (dike) rocks. Comparison with the average weighted composition of the plutonic alkaline-ultramafic rocks of the province, calculated with due account for the geophysical data, showed that their REE contents were close to those in the melteigite porphyry, this supporting the earlier assumption that these rocks are close to the average composition of the alkaline-ultramafic rocks [*Kukharenko et al.,* 1971].

In contrast to the rare earth elements, variations in the contents of other trace elements are more significant (Figure 7b), which stems, first, from the variations in the distribution of the accessory phases, such as apatite (P, Sr) and perovskite (Ti, Nb, Ta, Th), and, secondly, from the higher mobility of lithophile elements (Li, Rb). Nevertheless, the rocks of the initial, main, and terminal phases of magmatic activity show a regular, slow increase in the concentrations of most of incoherent elements in the rocks of the late phase. To sum up, our comparison shows that the

Table 4. Representative chemical analyses and densities of the alkaline-ultramafic intrusions of the Kola Province

	Dunite				Pyroxenite					Turjaite		Melteigite		
Massif	KVD	KVD	LSV	SLM	AFR	AFR	VUO	VUO	SLM	KVD	KVD	KVD	KVD	KVD
Sample	4/400	4/898	Z-6	SL-23	AFR-5	AFR-6	93/192	282/223	SL-24	227/43	252/100	7/394	7/348	5/740
Density, kg/m^3	3350	3360	3660	3210	2960	3020	2990	2980	3010	2920	2900	3020	2960	3010
SiO_2	37.81	37.25	38.74	38.58	37.68	32.17	43.21	44.37	39.33	41.25	41.10	44.10	48.24	38.35
TiO_2	0.24	0.30	0.35	0.52	1.69	7.19	4.14	2.93	3.86	0.79	0.47	1.26	0.22	1.29
Al_2O_3	1.20	1.16	0.38	0.96	3.36	7.41	3.88	4.47	7.05	10.90	8.02	10.15	1.24	4.01
Fe_2O_3	1.48	3.47	3.74	4.90	4.48	10.95	7.15	5.78	6.90	3.74	2.68	4.37	2.46	8.78
FeO	9.01	9.26	11.22	6.07	4.81	9.41	4.36	3.91	9.12	4.38	3.22	6.19	3.43	12.36
MnO	0.20	0.20	0.23	0.24	0.13	0.22	0.14	0.13	0.21	0.10	0.09	0.15	0.17	0.21
MgO	44.05	45.61	43.30	39.67	8.81	9.18	12.60	12.78	8.41	10.10	9.90	10.27	14.76	14.41
CaO	4.17	1.17	0.69	3.38	28.87	15.95	22.48	22.32	20.98	19.60	26.40	14.47	22.50	14.68
Na_2O	0.10	0.07	0.03	0.08	0.82	1.55	0.50	0.64	1.68	4.65	3.78	4.56	1.43	0.46
K_2O	0.05	0.14	0.03	0.51	0.06	1.29	0.21	0.49	0.37	2.10	1.35	2.54	0.77	2.02
P_2O_5	0.03	0.01	0.04	0.04	8.05	1.01	0.19	0.58	0.38	0.05	0.07	0.12	1.76	0.08
CO_2	0.24	0.18	0.16	0.10	0.20	0.27	0.36	0.73	0.30	0.28	0.40	0.21	1.73	0.68
$S_{tot.}$	0.08	0.02	0.02	0.05	0.21	0.25	n.a.	0.03	n.a.	n.a.	n.a.	n.a.	n.a.	0.01
F	0.01	0.01	0.01	0.01	0.40	0.07	0.03	0.05	0.02	0.06	0.05	0.07	0.18	0.07
H_2O	0.72	0.58	0.50	3.96	0.47	3.07	0.44	0.67	1.33	1.42	1.86	0.88	0.89	2.18
Total	99.39	99.43	99.44	99.07	100.04	99.99	99.69	99.88	99.94	99.42	99.39	99.34	99.78	99.59
Mg#	0.90	0.90	0.87	0.92	0.77	0.64	0.84	0.85	0.62	0.80	0.85	0.75	0.88	0.68

	Ijolite					Nepheline syenite	Melteigite porphyry				Ankaramite	Olivine nephelinite
Massif	KVD	KVD	SLN	SLN	KVD	KVD	OZV	OZV	TUR	IVN	LVZ	KHI
Sample	5/610	7/30	25/15	26/151	27/65	MK-10	13-	8-OV	3011	M-9-87	107/111	1635/295.8
Density, kg/m^3	2860	2800	2850	2900	2910	2680	2890	2880	2890	2930	–	–
SiO_2	44.56	44.44	41.93	41.25	42.92	51.83	40.76	45.40	40.00	40.58	44.27	34.48
TiO_2	0.13	0.34	0.73	0.78	1.92	0.82	3.05	0.85	2.20	4.93	4.62	2.83
Al_2O_3	19.56	12.50	15.94	16.20	7.20	16.52	8.98	3.87	10.24	7.42	7.82	8.29
Fe_2O_3	1.17	0.22	4.48	6.57	4.56	2.18	6.91	3.55	8.00	6.98	3.14	6.70
FeO	2.01	7.43	6.71	4.67	7.92	4.70	7.02	6.76	5.43	7.51	10.96	3.76
MnO	0.10	0.18	0.17	0.13	0.14	0.12	0.19	0.24	0.16	0.20	0.19	0.20
MgO	5.66	5.26	5.35	5.62	11.86	3.38	10.39	8.97	9.67	12.22	12.35	13.89
CaO	9.52	14.74	11.16	11.30	17.40	4.44	14.32	22.67	15.22	11.66	9.85	15.23
Na_2O	9.94	7.29	8.53	8.77	2.67	8.58	2.80	2.52	4.99	2.83	2.49	0.92
K_2O	4.04	2.69	2.84	2.99	0.64	3.64	2.43	0.34	1.35	1.38	1.34	4.62
P_2O_5	0.79	1.00	0.76	0.67	0.20	0.54	0.55	3.41	0.33	0.93	0.50	0.91
CO_2	0.81	1.10	n.a.	0.59	0.80	0.44	0.64	0.26	0.64	0.44	0.11	2.45
$S_{tot.}$	0.01	n.a.	0.04	0.05	n.a.	0.10	0.06	0.01	0.22	0.17	0.14	0.11
F	0.06	0.05	0.04	0.03	0.06	0.10	0.21	0.20	0.23	0.04	0.14	0.33
H_2O	1.15	0.81	0.85	0.41	1.29	1.86	1.51	0.62	0.80	2.05	1.56	4.60
Total	99.51	98.05	99.53	100.03	99.58	99.25	99.82	99.67	99.48	99.34	99.48	99.32
Mg#	0.83	0.56	0.59	0.68	0.73	0.56	0.73	0.70	0.76	0.74	0.67	0.87

Note. Here and in the tables that follow: KVD – Kovdor, AFR – Afrikanda, VUO – Vuoriyarvi, SLN – Sallanlatva, OZV – Ozernaya Varaka, IVN – Ivanovka, TUR – Turii Mys, LVZ – Lovozero, KHI – Khibiny; n.a. – not analyzed; n.d. – not discovered. Mg# = Mg/(Mg+Fe^{2+}).

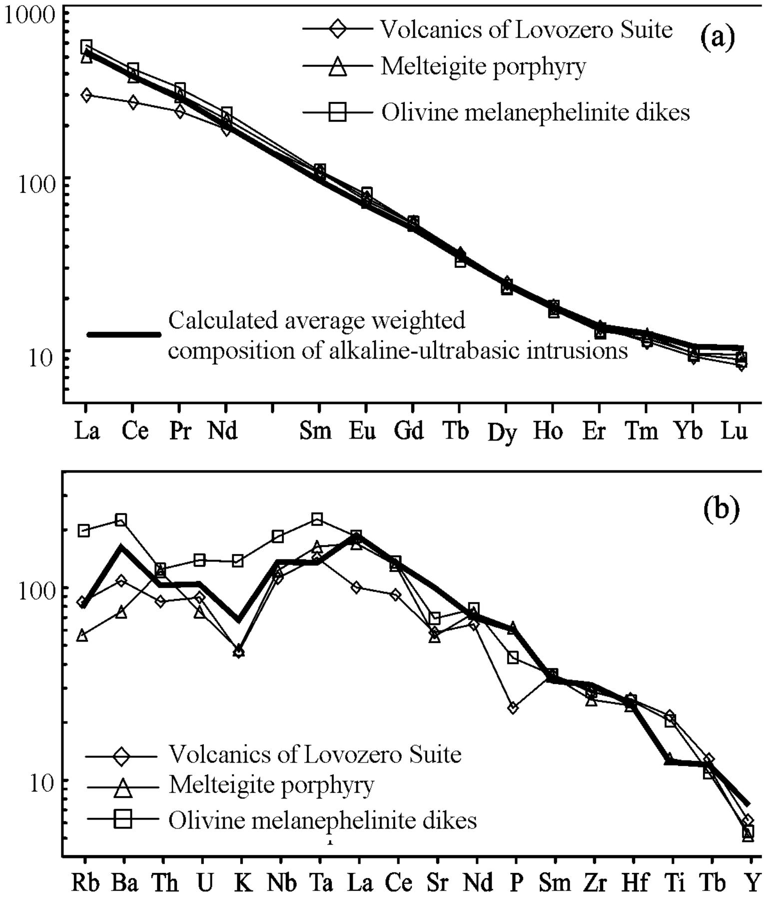

Figure 7. Chondrite (a) and primitive mantle (b) normalized trace element distribution in the Kola rocks of average compositions compared with their distribution in the undifferentiated rocks of the region. The normalizing factors for REE were used after *Evensen et al.* [1978] and *Hofmann* [1988].

average weighted contents of the majority of trace elements in the plutonic alkaline-ultramafic rocks, calculated with due allowance for geophysical data, agree with the values of the most primitive magmas of the alkaline-ultramafic series of the province, being most close to the contents in the olivine melteigite porphyry.

Primary magma of the phonolite series. Proceeding from the fact that the products of the phonolite magma were found only in the Khibiny and Lovozero massifs, the basis for calculating the mean composition of the phonolite magma was, first, the analytical data for the samples of all types of agpaite syenites from these intrusions and, secondly, the results of our 3-D density modeling, which allowed us to calculate the average weighted contents of trace elements. The results are presented in Table 12. The phonolite magma was found to have a high agpaitic coefficient, (Na+K)/Al = 1.09, and high LILE and HFSE concentrations, higher than the average values for alkaline-ultramafic magmas. We could not compare our average weighted composition of phonolite magma with the compositions of phonolite from the dikes in the surroundings of the Kovdor, Vuoriyarvi, and Ivanovka massifs because of the great scatter of many trace element contents in the latter.

5. Composition of the Paleozoic Mantle

The data available for the concentration of petrogenic and trace elements in the rocks of the Kola Province are sufficient to estimate the composition of the mantle which was reactivated in Paleozoic time and served as a source of alkaline magma. The data available today for the composition of the mantle, the PT conditions of magma generation, the phase equilibria at high pressures, as well as for the distribution patterns of trace elements, are good enough to get correct results not only through modeling the conditions of komatiite magma generation [*Herzberg and Zhang,* 1997; *Vrevskii,* 2000; *Walter,* 1998; *Wei et al.,* 1990], but also for the melting of moderately enriched mantle rocks [*McKenzie and O'Nions,* 1991; *Niu and Hekinian,* 1997; *Pickering-Witter and Johnson,* 2000; *Walter et al.,* 1995].

It is known that the concentration of a trace element in magma C_L is a function of the following variables: (1) the element concentration in the initial rock C_o (wt.%); (2) the melting degree F (the amount of melt relative to the initial rock); (3) melting type (partial, fractional, etc.); (4) the number of mineral phases involved in the melting process; (5) the mineral–melt partition coefficient D. The initial sub-

Table 5. Contents of trace elements in the representative samples of rocks from the alkaline-ultramafic intrusions of the Kola Province (ppm)

	Dunite				Pyroxenite					Turjaite		Melteigite		
Massif	KVD	KVD	LSV	SLM	AFR	AFR	VUO	VUO	SLM	KVD	KVD	KVD	KVD	KVD
Sample/Hole	4/400	4/898	Z-6	SL-23	AFR-5	AFR-6	93/192	282/223	SL-24	227/43	252/100	7/394	7/348	5/740
Li	n.d.	n.d.	2.58	3.32	n.d.	4.80	n.d.	n.d.	6.22	n.d.	n.d.	n.d.	n.d.	n.d.
Rb	4.53	5.83	0.94	18.7	5.05	25.0	10.4	13.5	11.7	47.3	35.8	69.6	23.4	63.0
Cs	n.d.	n.d.	0.08	0.29	n.d.	0.11	n.d.	n.d.	0.14	0.36	0.20	0.61	0.12	0.75
Sr	74.5	34.3	7.67	160	1525	1313	399	424	1103	1998	3050	358	563	298
Ba	21.1	111	12.3	152	20.6	25.7	151	280	801	1011	951	401	103	937
Sc	7.82	7.49	7.09	8.80	14.9	14.4	79.0	62.8	46.2	12.6	2.34	28.5	97.5	13.5
V	20.8	21.1	20.8	58.3	177	210	142	135	355	73.1	41.6	171	191	190
Cr	1462	1977	2124	2725	23.2	10.2	30.3	33.1	38.6	3.96	5.07	1083	51.1	30.4
Co	112	120	168	93.9	35.8	69.0	35.8	31.1	2.4	36.7	35.1	49.6	12.9	69.1
Ni	1480	1636	1432	1961	40.6	29.7	59.8	45.8	54.5	145	85.4	321	21.5	231
Y	1.49	n.d.	0.69	2.38	66.9	25.9	27.9	16.1	29.4	3.18	3.76	6.20	10.3	3.51
Nb	8.64	8.12	3.00	10.3	31.6	379	208	66.8	238.3	12.7	10.8	18.8	18.5	32.4
Ta	0.41	0.48	0.38	0.44	1.89	41.7	20.4	7.12	13.7	0.86	0.73	0.46	0.93	2.80
Zr	21.0	27.3	6.31	80.9	419	472	456	584	425	98.5	25.8	113	190	210
Hf	0.55	0.70	n.d.	1.93	12.9	5.72	18.0	21.9	11.9	2.88	0.68	2.99	4.78	2.59
U	0.29	0.25	n.d.	0.43	1.53	6.19	3.28	1.13	5.38	0.22	0.24	0.45	0.50	0.83
Th	0.95	0.65	0.29	0.48	7.36	72.7	15.9	8.30	12.2	0.81	0.88	1.07	3.80	2.30
La	5.16	1.69	0.95	5.39	354	475	224	85.7	172	28.5	42.6	21.2	42.5	8.25
Ce	11.1	4.60	1.66	10.1	551	1037	502	197	368	52.9	76.2	50.0	99.6	18.5
Pr	1.24	0.60	0.17	1.13	53.0	111	57.5	23.0	43.2	5.71	8.08	6.09	12.2	2.32
Nd	3.37	0.96	0.55	4.08	189	386	222	89.0	142	19.9	27.4	22.1	47.7	8.14
Sm	0.60	0.20	0.11	0.70	31.1	44.2	35.5	14.0	20.2	2.69	3.74	3.57	7.30	1.58
Eu	0.23	0.10	0.02	0.21	9.23	10.1	9.26	3.70	5.36	0.52	0.84	0.95	1.99	0.36
Gd	0.32	n.d.	0.08	0.65	24.8	23.2	24.1	9.38	13.8	1.62	2.06	2.28	5.15	1.02
Tb	0.05	n.d.	0.02	0.09	3.18	2.31	2.70	1.08	1.74	0.16	0.22	0.28	0.59	0.14
Dy	0.32	n.d.	0.09	0.47	16.0	8.19	10.9	4.68	7.64	0.71	0.90	1.42	2.59	0.77
Ho	0.06	0.01	0.02	0.10	2.74	1.10	1.52	0.75	1.23	0.13	0.14	0.26	0.41	0.14
Er	0.19	n.d.	0.05	0.26	5.92	2.14	2.65	1.46	2.70	0.28	0.32	0.63	0.90	0.40
Tm	0.03	0.02	0.01	0.04	0.67	0.25	0.31	0.19	0.36	0.04	0.04	0.10	0.13	0.07
Yb	0.21	0.09	0.06	0.24	3.50	1.48	1.67	1.16	2.03	0.25	0.23	0.67	0.93	0.42
Lu	0.03	0.02	0.01	0.04	0.49	0.21	0.23	0.17	0.27	0.04	0.03	0.12	0.14	0.08
(La/Yb)$_N$	17.4	13.3	11.7	15.7	71.1	226.4	94.2	52.0	59.6	81.9	128.5	22.3	32.0	13.9

strate subject to melting can be primitive mantle [*Hofmann,* 1988], depleted mantle [*McDonogh and Sun,* 1995], and also metasomatized mantle enriched in incompatible elements. Because the contents of elements in depleted mantle and in primitive mantle were calculated using the composition of chondrite CI [*Evensen et al.,* 1978] and were found to be 1.5 and 2.51, respectively, the results of modeling are applicable to both compositions, differing merely in the general amount of magma enrichment in incoherent elements. In all of the models calculated here we used the composition of primitive mantle as the initial mantle substrate (Tables 13 and 14). In our calculations we used the partition coefficients of olivine and orthopyroxene after [*Beattie,* 1994], of clinopyroxene after [*Johnson,* 1998], and of garnet after [*Johnson,* 1998; *Prinzhofer and Allegre,* 1985] (Tables 13 and 14). The values of the amphibole partition coefficients were used after [*White,* 1997].

The concentrations of elements in the products of partial melting C_L were calculated using the standard formulas [*Rollinson,* 1993]:

$$C_L/C_o = 1/[D_0 + F(1-P)],$$

where D_0 is the bulk partition coefficient in the initial mantle rocks before melting, and P is the bulk partition coefficient calculated for the minerals producing the melt.

The composition of the restite C_S was calculated using the formula

$$C_S/C_o = D_0/[D_0 + F(1-P)].$$

The models of the Rayleigh fractional melting were calculated by the formulas

$$C_L/C_o = 1/D_o(1 - PF/D_0)^{(1/P-1)},$$

Table 5. (continued)

	Ijolite					Nepheline syenite	Melteigite porphyry				Ankaramite	Olivine nephelinite
Massif	KVD	KVD	SLN	SLN	KVD	KVD	OZV	OZV	TUR	IVN	LVZ	KHI
Sample/Hole	5/610	7/30	25/15	26/151	27/65	MK-10	13-OB	8-OV	3011	M-9-87	107/111	1635/295.8
Li	n.d.	n.d.	n.d.	n.d.	5.21	43.4	3.60	4.20	16.0	12.3	40.8	14.4
Rb	54.6	63.7	50.1	52.9	15.5	131	64.2	7.91	35.5	36.4	53.4	133.2
Cs	0.04	0.01	0.04	n.d.	n.d.	0.94	0.68	0.12	n.d.	0.46	1.12	2.25
Sr	281	730	359	388	429	1039	918	1106	1148	1543	1233	1461
Ba	129	163	76.2	67.1	210	1101	1047	31.6	444	574	759	1567
Sc	22.3	11.6	8.01	13.5	49.7	10.7	39.6	11.9	27.7	30.5	29.1	27.5
V	85.4	175	101	94.9	294	124	246	200	216	409	357	259
Cr	5.16	76.0	13.3	19.6	409	55.4	143	59.1	338	564	1025	613
Co	7.55	23.0	31.6	33.1	53.7	18.9	51.1	32.5	53.3	70.8	73.3	48.9
Ni	7.55	30.8	19.4	18.2	130	31.9	68.3	24.4	159	405	468	266
Y	4.66	7.21	6.25	6.33	10.6	12.5	14.8	20.5	15.8	43.1	28.2	24.6
Nb	20.4	65.3	16.3	16.3	16.1	52.8	163	29.0	87.1	70.5	79.9	131
Ta	2.16	3.99	0.54	0.81	0.73	2.87	13.9	2.05	5.76	5.05	5.85	9.28
Zr	264	283	58.2	55.4	82.8	155	218	164	182	609	321	266
Hf	5.41	4.79	1.71	1.80	3.24	3.73	6.53	3.55	5.20	14.9	8.16	6.35
U	0.50	1.54	0.49	0.44	0.38	1.68	1.53	0.83	1.55	2.39	1.87	2.92
Th	7.02	17.2	1.86	2.33	1.31	8.56	14.7	12.2	6.84	7.08	7.12	10.5
La	32.0	55.4	21.6	22.6	18.5	52.1	133	169	91.3	86.5	70.9	131
Ce	70.2	118	40.0	44.1	36.2	88.7	273	315	160	216	169	248
Pr	7.93	13.1	4.42	4.99	4.19	8.40	28.9	34.1	16.1	29.0	21.7	28.8
Nd	28.7	46.0	15.5	18.3	16.1	27.3	100	116	55.6	131	88.2	106
Sm	4.22	5.94	2.55	3.12	2.92	3.99	12.8	15.1	7.92	26.0	15.7	15.7
Eu	1.12	1.45	0.80	0.91	0.97	0.78	3.09	3.60	2.09	7.23	4.17	4.36
Gd	2.69	3.47	2.06	2.33	2.52	2.84	7.65	11.1	4.99	19.4	10.9	10.8
Tb	0.30	0.37	0.25	0.28	0.37	0.39	0.88	1.28	0.64	2.29	1.39	1.18
Dy	1.32	1.48	1.31	1.38	2.07	2.16	3.86	5.26	3.31	10.4	6.58	5.79
Ho	0.20	0.27	0.25	0.25	0.40	0.44	0.65	0.82	0.61	1.71	1.10	0.98
Er	0.42	0.71	0.58	0.57	0.99	1.26	1.43	1.87	1.44	3.62	2.52	2.13
Tm	0.06	0.10	0.09	0.08	0.15	0.19	0.18	0.25	0.20	0.45	0.31	0.27
Yb	0.50	0.72	0.60	0.54	0.93	1.22	1.09	1.50	1.19	2.60	1.67	1.67
Lu	0.08	0.12	0.11	0.10	0.14	0.18	0.17	0.25	0.18	0.34	0.23	0.22
$(La/Yb)_N$	45.0	54.3	25.4	29.5	14.0	30.0	86.1	76.2	54.1	23.4	29.9	55.0

$$C_S/C_o = (1 - PF/D_0)^{1/P}/(1 - F)$$

for the derivates and the restite, respectively.

The PT conditions for the generation of nephelinite magmas in the Kola Province estimated using mantle xenoliths [*Arzamastsev and Dalgren,* 1993] show that alkaline-ultrabasic magmas might have been produced in the conditions of the mantle facies of spinel and garnet lherzolites. In the sections that follow we describe the calculations of the melting models:

(1) for normal primitive mantle (Tables 13 and 14) having the composition of spinel or garnet peridotite;

(2) for enriched mantle in which the concentrations of elements were 3 times as high as those in the primitive mantle; the versions here were for the melting of spinel and garnet peridotite, both containing amphibole and phlogopite.

5.1. Models for the Melting of Normal Primitive Mantle

Melting of spinel peridotite. In this version we considered the melting of primitive mantle having the composition ($Ol_{0.578}$ + $Opx_{0.27}$ + $Cpx_{0.119}$ + $Spl_{0.033}$) [*McKenzie and O'Nions,* 1991] in the melting interval of 0.1–15%, for which the compositions of the melts and complementary restites are controlled in the interval of spinel stability [*Robinson and Wood,* 1998; *Walter et al.,* 1995] (pressure 1.5–2.8 GPa) by the cotectic $Ol_{0.10}$ + $Opx_{0.15}$ + $Cpx_{0.55}$ + $Spl_{0.20}$. The resulting compositions of the melts (Figure 8) showed, in contrast to the average compositions for the Kola Province, the low contents of light REE and a poorly fractionated distribution pattern $(La/Yb)_N < 9$, this pattern being controlled by the amount of dissolving clinopyroxene.

Table 6. Contents of petrogenic elements and densities in the representative samples of alkaline and ultramafic rocks from the Khibiny Massif

Rock	PRD	PRD	PRX	PRX	PRX	PRX	MML	MML	FOM	FOM	FOI	FOI	CC
Sample/Hole	1010	A-1044	1010	A-1036	A-1038	A-1087	1010	1010	455	466	1072	455	603
Depth, m	1052	–	1186	–	–	–	1059	1165	345	552	530	402	23
Density, kg/m^3	3350	3330	3300	3120	3090	3020	2850	2820	3020	2990	2830	2850	2860
SiO_2	38.26	43.62	39.52	41.60	41.37	37.53	28.01	29.98	37.56	44.00	43.48	44.81	2.89
TiO_2	3.51	3.41	7.25	4.91	4.18	2.90	6.01	2.84	7.73	4.60	2.67	1.97	0.01
Al_2O_3	4.29	5.21	9.17	5.92	7.37	11.09	6.12	3.58	3.38	3.64	18.85	17.44	0.98
Fe_2O_3	10.31	5.41	8.00	4.33	8.90	5.90	15.57	10.51	11.60	9.20	4.88	5.31	3.62
FeO	5.25	7.06	7.00	11.25	5.22	4.04	5.83	5.18	11.81	9.13	3.17	3.19	2.05
MnO	0.28	0.19	0.28	0.23	0.23	0.17	0.26	0.29	0.61	0.33	0.16	0.21	0.91
MgO	19.93	17.85	7.01	11.67	13.38	6.49	9.20	16.58	7.17	8.32	3.35	3.94	0.88
CaO	12.60	9.36	11.74	11.20	9.09	18.40	23.43	28.46	14.68	13.41	7.70	7.91	41.75
Na_2O	0.65	2.26	4.56	3.47	3.18	5.69	1.35	0.67	3.30	4.02	10.58	10.74	1.24
K_2O	2.06	2.91	2.36	2.11	3.60	1.78	0.86	0.04	0.81	1.46	4.45	3.78	0.12
P_2O_5	0.42	0.36	1.25	0.38	0.36	2.97	0.77	0.37	0.99	0.27	0.65	0.22	0.11
CO_2	0.38	0.14	0.32	0.23	0.32	0.96	0.49	0.35	0.05	0.05	0.31	0.07	38.96
$S_{tot.}$	0.16	0.03	0.19	0.12	0.04	0.40	0.04	0.02	0.10	0.10	0.03	0.05	0.42
Cl	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.01
F	1.06	0.45	0.32	0.60	0.91	0.14	0.58	0.16	0.20	0.36	0.09	0.07	0.35
LOI	0.68	1.01	0.48	1.52	1.32	1.27	1.53	0.46	0.33	1.08	0.20	0.48	0.17
Total	99.84	99.27	99.45	99.54	99.47	99.73	100.05	99.49	100.32	100.46	100.57	100.19	94.47
#Mg	87	82	64	65	82	74	74	85	52	62	65	69	43

Note. PRD – peridotite, PRX – pyroxenite, MML – melilite rock, FOM – melteigite, FOI – ijolite, CC – calcitic carbonate; n.a. – not analyzed.

The greatest differences were observed in the distribution of heavy REE which showed, with their total elevated content, an extremely low fractionation degree $(Sm/Yb)_N < 2$. Similar results were obtained for the version of fractional melting.

Melting of garnet peridotite. The melting of mantle rocks with the composition of ($Ol_{0.60} + Opx_{0.20} + Cpx_{0.08} + Grt_{0.12}$) [*McKenzie and O'Nions,* 1991] requires a higher pressure (>2.8 GPa), at which, in the melting interval of 0.1–15%, the compositions of the melts and complementary restites are controlled by the cotectic $Ol_{0.05} + Opx_{0.05} + Cpx_{0.36} + Gr_{0.54}$. It should be noted that cotectic relationships are hard to determine at different PT conditions and can be estimated very roughly [*Walter et al.,* 1995]. At the same time the composition of the cotectic is not essential because at low degrees of melting, the partitioning of trace elements between the melt and the restite takes place in accordance with their own D values.

In contrast to the version with spinel, both the partial and fractional melting of garnet peridotite produce melts with a high degree of REE fractionation $(La/Yb)_N = 50–130$ (F = 0.1–0.5%) (Figure 9, a and b). Comparison with the composition of primary magma in the Kola Province shows a similarity of the REE distribution to the compositions of melts with low degrees of melting (F = 0.1–1.0%), however the threshold total REE content in the models for the melting of "normal" primitive mantle (that is, with F→ 0%) is many times lower than that observed in the magmas of the province. A specific feature of the model discussed is a similarity between the composition of the restite obtained for 1-per cent melting and the composition of depleted mantle after [*McKenzie and O'Nions,* 1991].

The models of the partial and fractional melting of trace elements (Figure 9, c and d) showed higher variations. This might have been caused by the higher mobility of some elements and by the less exact calculation of partition coefficients. Nevertheless, the data obtained for the majority of trace elements were similar to those for REE and showed the significantly higher Nb, Ta, Zr, Hf, and Y contents in the Kola primary melts, as compared to their threshold contents in the model melts with low melting degrees.

5.2. Models for the Melting of Enriched Metasomatized Mantle

Inasmuch as the above models showed a low probability of getting melts enriched in incompatible elements, resembling the contents observed in the primary magmas of the Kola Province from the melts produced by the normal primitive mantle, this version was aimed to calculate the melting of mantle rocks, in which the contents of incompatible elements

Table 7. Contents of trace elements in the representative rock samples of the alkaline-ultramafic series from the Khibiny Massif (ppm)

Rock	PRD	PRD	PRX	PRX	PRX	PRX	MML	MML	FOM	FOM	FOI	FOI	FOI	CC
Sample/Hole	1010	A-1044	1010	A-1036	A-1038	A-1087	1010	1010	455	466	301/500	1072	455	603
Depth, m	1052	–	1186	–	–	–	1059	1165	345	552	–	530	402	23
Li	8.01	36.6	22.3	46.1	84.3	2.60	5.97	7.53	12.2	28.4	6.01	28.5	7.90	8.86
Rb	138	115	86.0	113	208	23.9	58.5	1.13	15.9	37.7	29.8	23.4	34.4	8.40
Cs	2.60	1.30	0.60	1.52	2.20	0.32	0.79	0.03	0.32	0.22	0.32	3.62	0.19	0.09
Sr	1126	893	2194	995	1485	748	5933	539	2544	3237	1012	31.3	1352	3595
Ba	1364	558	852	432	521	187	1063	49.4	168	1114	248	357	335	4993
Sc	23.9	21.4	20.0	28.2	21.1	19.0	42.0	24.0	26.5	22.3	1.32	2.50	19.5	6.08
V	506	213	428	251	265	242	298	83.1	673	739	230	1.80	276	14.4
Cr	1277	1131	135	800	724	23	158	1061	112	39.1	35.3	72.8	51.4	33.9
Co	98	81	46	66	63	28	84	102	65	75.6	14.0	2.6	16.0	12.9
Ni	1018	915	134	428	568	38	278	994	104	61.9	9.9	37.4	29.1	31.9
Y	27.7	19.7	86.6	30.4	33.6	45.9	30.5	18.3	63.0	36.0	27.2	41.8	24.1	316
Nb	73	39	371	104	95	154	312	157	261	169	173	215	110	40.3
Ta	5.41	2.55	28.0	7.64	5.75	6.83	23.3	15.1	31.2	16.4	13.7	15.8	7.98	0.62
Zr	345	220	744	481	453	429	480	173	812	814	275	929	565	2.05
Hf	8.74	5.94	18.0	10.3	11.1	12.2	12.5	4.59	19.8	24.8	7.86	25.3	12.9	1.22
U	1.56	0.41	1.57	1.76	1.86	3.05	4.45	2.97	0.85	0.20	0.26	3.68	1.08	2.46
Th	5.04	2.67	23.4	9.09	7.22	6.10	27.9	19.2	3.99	0.85	1.89	23.2	3.19	533
La	85.6	62.0	380	102	102	143	251	128	222	108	109	119	69.4	2909
Ce	176	138	747	223	216	255	465	270	441	250	230	238	150	3144
Pr	20.3	16.5	88.9	26.4	24.8	28.1	49.2	28.9	50.8	30.7	25.1	27.3	16.6	413
Nd	79.9	68.4	323	105	99.0	112	173	103	190	116	89.3	97.6	62.2	1787
Sm	13.7	11.6	49.5	18.0	16.7	22.0	23.3	13.3	30.4	19.9	14.2	16.8	10.4	379
Eu	3.9	3.3	14.3	5.1	4.7	7.1	6.2	3.5	9.0	5.8	3.96	1.68	3.04	118
Gd	10.8	8.47	33.1	13.2	12.0	20.6	13.8	7.50	22.8	13.8	11.3	11.2	7.63	269
Tb	1.39	1.03	4.37	1.65	1.64	2.82	1.66	0.90	3.08	1.9	1.48	1.73	1.05	31.8
Dy	6.42	4.99	21.0	7.57	7.71	12.2	7.85	4.20	14.6	9.1	6.54	9.44	5.26	105
Ho	1.04	0.81	3.42	1.22	1.34	1.88	1.18	0.69	2.46	1.6	1.14	1.97	0.93	15.2
Er	2.45	1.85	7.83	2.63	3.04	4.03	2.67	1.64	5.61	3.6	2.44	5.31	2.37	30.3
Tm	0.28	0.21	0.86	0.31	0.37	0.44	0.29	0.20	0.66	0.5	0.29	0.81	0.32	3.82
Yb	1.54	1.21	4.80	1.82	2.19	2.40	1.66	1.20	4.06	3.2	1.53	4.71	2.20	25.0
Lu	0.21	0.17	0.60	0.27	0.30	0.32	0.22	0.18	0.59	0.6	0.17	0.70	0.34	3.42

Note. See Table 6 for the rock codes.

were taken to be n times higher than in primitive mantle.

Melting of spinel peridotite. In this version we modeled the melting of amphibole-bearing spinel peridotite $Ol_{0.59} + Opx_{0.21} + Cpx_{0.10} + Spl_{0.05} + Amph_{0.05}$, close to the mineral composition of the mantle rock from a diatreme in the Khibiny Massif [*Arzamastsev and Dalgren,* 1993]. The plots presented in Figure 10, a and b, show a substantial difference of the REE distribution pattern in the model magma from that observed in the rocks of the Kola Province. The melts obtained for both the partial and the fractional melting of threefold enriched primitive mantle yielded poorly fractionated spectra in the region of Sm–Lu $(Sm/Yb)_N < 1.8$. The distribution of the other trace elements (Figure 10, c and d) shows that the melting of the substrate of this composition cannot give the Rb and Nb concentrations observed in the primary magmas of the province.

Melting of garnet peridotite. We calculated a melting model for two compositions: $Ol_{0.59} + Opx_{0.20} + Cpx_{0.08} + Grt_{0.08} + Phlog_{0.05}$ and $Ol_{0.59} + Opx_{0.20} + Cpx_{0.08} + Grt_{0.08} + Phlog_{0.02} + Amph_{0.03}$. The existence of these mineral associations is controlled by the stability of phlogopite and/or amphibole in the presence of garnet and clinopyroxene in mantle conditions. *K. Sato and E. Ito* [1997] proved the stability of phlogopite in garnet harzburgite in the mantle underlying a craton at pressures growing as high as 5 GPa. On this basis they suggested the possibility of phlogopite formation as a secondary mineral produced by the reaction of garnet with the rising metasomatic fluid flow. It was supposed earlier [*Dawson and Smith,* 1982] that inasmuch as the stability of amphibole in the mantle is limited by a narrow pressure range, corresponding to a spinel facies depth, this mineral, in contrast to phlogopite, cannot be a receptacle of incoherent elements in deep zones of the mantle.

Table 8. Contents of petrogenic elements in the representative rock samples from the phonolite series of the Khibiny Massif

Rock	SFNX	SFNX	SFNX	SFNX	SFNX	SFNX	SFNR	SFNR	SFNF	SFNF	SFNF	SAP	SAP
Sample (Hole/depth)	Z-1	A-1035	A-1037	A-1042	A-1046	A-1049	455/890	818/637	2237	A-1014	A-1029	642/210	642/397.7
SiO_2	54.24	51.98	53.67	54.07	42.70	47.89	48.48	50.54	53.03	55.22	56.98	58.69	60.59
TiO_2	0.69	0.22	0.50	0.75	14.81	4.78	1.30	0.81	0.75	0.66	0.17	0.50	0.40
Al_2O_3	20.62	23.16	22.41	22.14	8.46	11.30	23.54	22.03	20.60	20.85	21.14	18.68	18.28
Fe_2O_3	3.14	2.66	1.26	1.30	3.37	5.40	2.08	2.17	2.01	1.28	1.30	0.44	0.41
FeO	1.03	2.00	2.07	2.46	2.64	4.58	1.94	1.96	2.19	2.87	2.07	2.85	2.67
MnO	0.18	0.17	0.12	0.15	0.32	0.62	0.12	0.12	0.17	0.21	0.10	0.09	0.09
MgO	0.40	0.14	0.54	0.41	0.96	1.45	0.40	0.80	0.71	0.84	0.23	0.72	0.32
CaO	1.06	0.66	1.16	0.76	14.06	6.50	0.96	1.25	2.76	0.63	0.39	1.89	1.38
Na_2O	11.21	12.20	11.16	10.67	5.08	6.97	9.12	8.30	9.52	9.68	7.31	7.54	7.20
K_2O	5.63	5.03	5.36	5.45	2.47	4.24	11.19	10.99	5.98	5.44	8.28	5.61	5.63
P_2O_5	0.12	0.09	0.11	0.09	1.53	0.66	0.31	0.15	0.16	0.20	0.02	0.16	0.09
CO_2	0.06	0.05	0.01	0.01	0.09	3.03	0.02	0.05	0.20	0.78	0.14	0.77	0.84
$S_{tot.}$	0.18	0.09	0.03	0.04	0.02	0.11	n.a.	n.a.	0.02	0.13	0.07	0.18	0.14
Cl	0.06	0.012	0.037	0.035	0.027	0.004	0.06	n.a.	0.41	0.007	0.03	0.43	0.04
F	0.14	0.08	0.13	0.13	0.69	0.56	0.04	0.07	0.11	0.23	0.05	0.05	0.05
LOI	0.88	1.09	0.80	0.83	0.71	1.14	0.17	0.70	1.05	0.51	1.15	0.68	1.22
Total	99.64	99.63	99.37	99.30	97.94	99.23	99.73	99.94	99.67	99.54	99.43	99.28	99.35

Note. SFMX – agpaite syenite from the peripheral part of the massif, SFNF – agpaite syenite from the central part of the massif, SAP – pulaskite, SFNR – calcilithic nepheline syenite; n.a. – not analyzed.

However, *Niida and Green* [1999] showed that the stability of pargasite amphibole was controlled by the bulk content of Na_2O+K_2O in the mantle rocks: at $T=1000°C$, it is limited by pressure of 2.6 GPa and 0.33 wt.% Na_2O+K_2O, and grows higher at 2.9–3.0 GPa and 1.17 wt.% Na_2O+K_2O, thus extending into the garnet stability region. Moreover, *Niida and Green* [1999] discovered that the Na_2O content in pargasite was also a function of pressure. Our calculations of the melts from the unenriched primitive mantle, quoted above, show that at low melting degrees (F = 0.1–0.5%) the content of K_2O alone rises as high as 0.5–1.1 wt.%. On the other hand, pargasite from the harzburgite xenoliths in the Khibiny Massif contains 2.91–3.10 wt.% Na_2O. Therefore it can be assumed that under the PT conditions of magma generation in the Kola Province the mantle rocks might have contained not only phlogopite but also amphibole.

The REE distribution plots (Figure 11, a and b) show an agreement between the real composition of primary magma in the Kola Province and the melts obtained through the melting of enriched mantle material containing, apart from olivine, orthopyroxene, clinopyroxene, and garnet, also phlogopite (up to 5%), or phlogopite (2%) and amphibole (3%). The results that were most close to the calculated ones were obtained for the 0.3–0.5% fractional melting of phlogopite–amphibole peridotite (Figure 11, b), the Kola magma composition fitting the range of the latter. The results of modelling the concentrations of the other trace elements (Figure 11, c and d) yielded, like in all of the other models, a wide scatter of values, which allows one to merely surmise the generation of the Kola magmas as a result of the low-degree partial melting of phlogopite–amphibole peridotite (<1%). At the same time the presence of a negative P and Ti anomaly in the primary magma of the Kola Province suggests the potential presence of apatite and perovskite in the initial mantle rocks. Of particular significance are the high contents of Nb, Ta, Zr, and Hf in the Kola primary magmas, which are 5 to 10 times higher than their threshold concentrations in the model melts of enriched mantle.

6. Discussion of Results

6.1. Compositions and Generation Conditions of Primary Magmas

Our calculated average weighted contents of rare earth elements in the primary ultramafic magmas of the Kola Province agree with the values reported for some varieties of the most primitive magmas of the region [*Beard et al.,* 1998; *Ivanikov et al.,* 1998; *Rukhlov,* 1997] and also with their mean contents in alkaline lamprophyres [*Rock,* 1987] and in the most primitive melanephelinite melts from other alkaline provinces [*Le Bas,* 1987; *Rock,* 1987]. The results obtained for the other trace elements showed, as reported earlier [*Kogarko,* 1984], a significant enrichment of the mean composition of the Kola phonolite mantle magma in Nb, Ta, Zr, and Hf (Figure 12, a). At the same time no positive HFSE anomaly was found in the primitive alkaline-ultramafic magmas of the region. Comparison with the less differentiated rocks of the Meimecha-Kotui Province [*Arndt*

Table 9. Contents of trace elements in the representative rock samples of the phonolite series from the Khibiny Massif (ppm)

Rock	SFNX	SFNX	SFNX	SFNX	SFNX	SFNX	SFNR	SFNR	SFNF	SFNF	SFNF	SAP	SAP
Sample (Hole/depth)	Z-1	A-1035	A-1037	A-1042	A-1046	A-1049	455/890	818/637	2237	A-1014	A-1029	642/210	642/397.7
Li	31.3	15.7	17.8	18.8	36.0	110	7.42	14.8	15.6	57.1	8.03	14.9	26.3
Rb	162	83.7	68.5	58.4	83.6	128	234	286	66.1	388	156	96.6	92.0
Cs	1.89	1.94	1.34	1.45	2.22	1.98	4.03	6.63	1.45	3.79	1.15	1.72	1.69
Sr	2711	1005	1318	1209	2600	3522	687	561	1500	450	907	936	309
Ba	1469	570	1029	1033	404	1312	905	1738	1316	572	366	1633	485
Sc	1.24	1.68	3.39	2.49	4.80	5.52	2.97	3.90	1.74	1.90	0.19	2.04	1.72
V	43.6	28.7	38.4	55.6	278	198	68.3	69.5	79.5	18.2	41.4	46.8	34.2
Cr	34.3	19.6	11.1	21.3	14.9	16.1	19.6	15.8	35.9	23.4	24.5	38.1	33.3
Co	2.84	1.47	1.77	1.52	3.71	4.62	3.89	4.08	5.14	2.41	2.49	3.96	2.75
Ni	7.11	4.80	4.55	4.98	9.62	5.73	4.31	5.35	11.1	6.00	10.4	10.0	8.96
Y	51.2	18.8	21.7	19.5	387	212	6.60	7.86	15.8	21.2	6.02	12.9	8.19
Nb	225	184	140	156	1627	895	90.2	117	150	103	55.1	102	79.9
Ta	9.49	11.1	9.14	11.8	243	81.5	3.37	3.63	9.94	5.52	1.24	8.58	6.74
Zr	638	309	520	621	2367	1456	161	291	238	251	204	254	223
Hf	15.0	6.13	10.6	13.3	72.1	36.9	3.22	4.98	4.55	5.46	3.55	5.34	4.64
U	8.93	3.84	3.42	2.57	7.00	14.6	1.54	2.50	2.18	1.51	1.06	3.52	3.66
Th	30.7	12.5	10.0	9.07	26.1	64.8	5.60	6.90	14.4	9.37	7.32	16.5	18.1
La	163	77.9	79.3	73.4	2906	844	35.9	33.9	184	159	28.7	98.7	60.6
Ce	352	165	161	144	5437	1792	60.9	58.3	266	276	33.8	165.0	98.9
Pr	32.9	19.4	18.0	18.4	528	238	6.28	5.41	20.5	25.7	3.32	14.3	8.91
Nd	108	72.8	64.8	68.6	2075	876	20.7	17.7	58.3	77.7	9.29	42.8	27.1
Sm	16.2	11.2	9.8	0.5	347	131	2.75	2.42	6.51	9.13	1.19	5.28	3.24
Eu	4.50	3.14	2.76	2.99	94.2	35.8	0.68	0.64	1.71	1.89	0.30	1.35	0.89
Gd	12.8	7.51	6.53	7.05	215	82.0	1.89	1.78	3.83	5.07	0.83	3.09	1.97
Tb	1.85	1.02	0.96	0.96	28.3	11.1	0.27	0.27	0.54	0.74	0.15	0.45	0.29
Dy	9.81	4.99	4.99	4.85	124	52.6	1.47	1.62	3.05	4.13	1.00	2.55	1.64
Ho	1.84	0.83	0.90	0.85	18.2	8.44	0.28	0.33	0.58	0.73	0.23	0.49	0.32
Er	4.41	2.04	2.25	2.12	37.4	19.0	0.74	0.85	1.54	1.99	0.76	1.30	0.88
Tm	0.63	0.24	0.29	0.28	3.77	2.17	0.10	0.12	0.21	0.28	0.12	0.19	0.14
Yb	3.45	1.36	1.69	1.67	19.2	11.7	0.65	0.75	1.43	1.76	0.72	1.16	0.87
Lu	0.46	0.17	0.24	0.23	2.29	1.49	0.09	0.11	0.21	0.26	0.11	0.18	0.14

Note. See Note in Table 8 for the legend.

et al., 1995, 1998] (Figure 12, b) revealed that the distribution of trace elements in the Kola alkaline-ultramafic magmas resembled that in alkaline picrites and melanephelinites. The primitive magmas of both provinces showed a negative K anomaly, which, along with the low Rb contents, seems to have been related to the fractionation, prior to lava flow, of a K-bearing phase, probably phlogopite. Our model calculations show that the Kola primary magmas, rich in incoherent elements, could not be derived from primitive mantle even in the case of critically low melting degrees. Therefore the most probable case was the melting of enriched mantle, the composition of which had been altered by the process of mantle metasomatism. Based on the estimates obtained for the Meimecha-Kotui Province [*Arndt et al.,* 1998] and on the model calculation of carbonatite magma melting [*McKenzie and O'Nions,* 1991], we assumed that the degree of the rock enrichment might have been 3 times higher than the mean contents of incompatible elements in primitive mantle.

It appears that the existence of the enriched mantle substrate was related to the processes of a plume–lithosphere interaction, which produced extensive zones of metasomatized mantle. According to the results of studying mantle xenoliths, the mineral composition of mantle in zones of mantle metasomatism differs by the presence of amphibole, phlogopite, rutile, ilmenite, and apatite, in addition to olivine, orthopyroxene, clinopyroxene, spinel, and garnet [*Haggerty,* 1995; *Konzett et al.,* 2000]. There is numerous evidence proving the existence of metasomatized mantle in regions of alkaline magmatism [*Bailey,* 1987; *Wyllie,* 1995; *Yaxley et al.,* 1998], the Kola alkaline Province being one of them [*Tolstikhin et al.,* 1999]. The direct proofs of the existence of the zones of mantle metasomatism in the region are the findings of spinel harzburgite xenoliths, containing pargasite and phlogopite, in a diatreme from the Khibiny Massif [*Arzamastsev and Dalgren,* 1993].

Our modeling of the behavior of trace elements during

Table 10. Contents of petrogenic elements in the representative samples from the Lovozero Massif

Rock	SA	SA	SA	SFS	SFS	SFS	SFNDL	SFNDL	SFNDF	SFNDF	SFNDF	SFNDF	SFNLE	SFNLE	SFNLE	SFNLE	SFNLE	SFNLE
Sample/Hole	903	903	903	145	193	143	202	100	215	109	901	A-1210	7	7	1510-g	1571-d	A-1208	A-1209
Depth, m	978	1195	827.5	138	268	80	94.7	57.8	371.3	64.7	993.4	–	8.7	128.3	–	–	–	–
SiO_2	52.58	50.65	51.61	56.34	53.64	54.11	54.16	51.62	53.99	54.02	52.14	59.24	54.25	53.19	52.03	52.76	55.64	55.71
TiO_2	1.29	0.87	2.16	0.62	0.52	1.09	0.89	1.20	0.62	0.47	1.52	0.48	1.14	1.10	1.28	1.28	0.83	0.72
Al_2O_3	19.54	20.93	19.47	18.13	21.92	19.96	14.64	13.37	21.53	19.62	19.40	20.05	13.61	14.12	16.54	14.09	14.87	17.33
Fe_2O_3	2.63	3.03	1.72	2.32	2.68	3.87	9.05	9.94	4.27	3.41	3.55	2.08	5.61	5.26	6.47	8.20	4.85	4.55
FeO	1.60	1.35	3.28	0.71	1.52	0.82	2.44	2.32	0.88	0.80	1.33	0.82	3.42	3.21	1.71	1.73	2.37	1.56
MnO	0.37	0.21	0.40	0.30	0.20	0.18	0.28	0.34	0.13	0.18	0.32	0.11	0.45	0.45	0.55	0.51	0.44	0.27
MgO	0.91	0.37	0.94	0.27	0.25	0.96	1.21	1.43	0.36	0.41	0.51	0.12	0.87	1.24	0.92	0.94	1.85	0.32
CaO	1.15	1.64	0.90	0.86	0.49	1.20	2.37	2.07	0.19	1.49	0.79	0.35	1.51	1.32	1.34	2.07	1.80	0.92
Na_2O	8.65	9.50	10.07	10.67	10.76	10.14	7.98	10.50	10.76	10.68	13.26	6.88	10.31	11.70	8.82	7.93	9.85	9.93
K_2O	3.54	2.07	4.57	6.04	5.51	5.73	4.28	4.50	6.32	6.10	5.13	7.66	4.79	4.52	5.91	5.46	4.59	5.05
P_2O_5	0.28	0.38	0.17	0.45	0.06	0.34	0.09	0.05	0.24	–	0.08	0.02	0.10	0.05	0.06	0.04	0.02	0.02
CO_2	0.59	1.17	0.63	0.75	0.62	0.30	–	0.23	–	0.21	0.20	0.06	–	–	–	–	0.18	0.07
$S_{tot.}$	0.48	0.07	0.44	0.29	0.08	0.21	0.05	0.04	0.01	0.02	0.03	0.05	0.22	0.17	0.11	0.14	0.04	0.07
Cl	0.01	0.01	0.01	0.29	0.15	0.05	0.07	0.04	0.05	–	1.09	0.01	–	–	0.15	0.17	0.23	0.30
F	0.14	0.06	0.21	0.32	0.03	0.23	0.03	0.06	0.12	0.05	0.08	0.01	0.10	0.21	0.16	0.14	0.39	0.02
LOI	5.46	6.99	2.92	0.79	0.95	0.65	1.67	1.54	0.96	1.89	0.82	1.65	1.15	1.18	1.60	2.50	0.78	1.23
Total	99.22	99.30	99.50	99.15	99.38	99.84	99.21	99.25	100.43	99.35	100.25	99.59	97.53	97.72	97.65	97.96	98.73	98.07

Note. SA – alkaline syenite, SFS – poikilitic sodalite syenite, SFNDF – foyaite (differentiated), SFNDL – lujavrite (differentiated), SFNLE – eudialyte Lujavrite, ANK – ankaramite, BAS – alkaline basalt.

Table 11. Contents of trace elements in the representative samples of rocks from the Lovozero Massif (ppm)

Rock	SA	SA	SA	SFS	SFS	SFS	SFNDL	SFNDL	SFNDF	SFNDF	SFNDF	SFNDF	SFNLE	SFNLE	SFNLE	SFNLE	SFNLE	SFNLE
Sample/Hole	903	903	903	145	193	143	202	100	215	109	901	A-1210	7	7	1510-g	1571-d	A-1208	A-1209
Depth, m	978	1195	827.5	138	268	80	94.7	57.8	371.3	64.7	993.4		8.7	128.3				
Li	133	82.9	43.5	60.4	28.0	56.7	29.4	40.3	27.2	52.2	28.7	12.4	62.8	96.7	111	96.0	92.0	8.28
Rb	19.6	22.3	50.9	124	138	31.5	62.6	40.7	77.0	89.6	60.1	215	83.7	112	59.5	88.5	47.2	105
Cs	9.56	25.8	1.23	1.61	1.91	1.26	0.64	2.04	1.11	2.38	0.98	2.03	1.98	1.81	2.88	1.44	0.94	0.94
Sr	738	1073	900	808	364	1447	257	381	304	54.1	126	168	1334	1271	5925	5862	1355	940
Ba	290	179	229	642	338	985	126	209	112	147	41.6	523	403	403	1715	732	537	346
Sc	10.0	8.04	11.1	13.6	11.3	11.4	10.9	11.0	14.0	11.3	14.5	4.55	15.1	15.2	15.0	14.2	14.7	16.2
V	50.1	46.7	33.8	12.0	15.4	60.1	243	195	42.4	11.6	54.5	5.98	69.8	65.2	78.8	117	72.2	49.0
Cr	3.95	13.6	23.8	7.43	24.2	14.3	3.49	5.02	2.87	0.15	3.19	17.8	13.6	4.63	8.22	7.22	9.11	18.8
Co	2.82	2.05	2.78	0.92	1.25	2.81	2.92	3.70	0.71	0.44	1.22	0.40	4.90	3.11	5.92	6.01	3.55	2.17
Ni	4.79	7.68	11.3	3.92	5.94	7.41	5.73	4.00	2.69	1.57	4.61	5.57	13.9	9.09	5.51	5.20	22.1	11.2
Y	24.9	28.7	13.8	61.9	14.2	36.4	8.45	19.1	15.7	0.80	2.99	4.89	368	300	232	250	356	296
Nb	488	460	334	690	260	327	228	461	645	372	301	271	890	643	813	527	516	328
Ta	25.8	24.6	23.6	48.5	14.5	21.1	19.4	36.9	65.1	14.6	12.3	10.4	76.2	60.8	57.6	42.5	47.5	34.8
Zr	619	591	628	4693	1799	1311	1704	2410	1229	467	737	451	6769	6894	6887	6831	7374	7435
Hf	17.7	18.5	17.0	97.3	38.1	29.5	57.7	77.5	31.5	12.0	19.9	10.0	234	191	178	177	239	214
U	6.75	6.90	5.28	16.2	8.78	5.43	3.45	8.22	5.24	4.18	5.50	5.01	12.8	11.3	18.4	20.6	5.31	3.64
Th	51.4	64.8	12.5	44.6	15.2	36.2	27.2	42.4	55.6	15.2	13.3	11.9	45.0	27.6	34.5	24.1	8.92	7.51
La	110	138	54.3	209	17.5	116	262	234	550	9.39	12.1	11.7	284	244	195	236	157	147
Ce	183	304	121	376	38.8	262	531	493	1115	19.4	28.8	25.7	635	517	464	507	370	341
Pr	17.5	33.8	13.6	36.7	4.86	29.0	50.6	47.4	119	1.90	3.49	2.77	72.6	56.8	52.1	56.1	50.2	45.1
Nd	63.5	120	48.4	128	19.3	104	141	139	325	6.08	13.1	9.46	273	217	205	209	215	199
Sm	11.0	19.2	7.83	22.0	4.71	17.9	12.0	14.1	24.6	0.65	2.21	1.56	67.1	53.2	50.5	49.1	61.3	55.4
Eu	2.97	5.05	2.09	6.02	1.43	5.01	2.33	3.14	4.30	0.13	0.56	0.39	21.1	16.7	16.4	15.5	20.0	19.0
Gd	7.74	12.3	5.21	16.8	3.78	12.3	6.79	8.14	13.6	0.36	1.37	1.13	66.4	51.9	43.6	44.0	62.6	57.6
Tb	1.17	1.60	0.68	2.54	0.61	1.65	0.64	1.00	1.31	0.04	0.17	0.14	11.3	9.10	7.38	7.51	10.7	9.73
Dy	6.40	8.16	3.58	14.7	3.67	8.63	2.30	4.22	5.48	0.19	0.81	0.72	77.8	60.8	46.2	47.4	72.2	64.8
Ho	1.15	1.37	0.65	2.85	0.73	1.57	0.38	0.75	0.76	0.03	0.14	0.13	16.9	13.1	9.22	9.71	15.1	13.7
Er	2.71	3.05	1.55	7.37	1.90	3.78	0.99	2.05	1.77	0.08	0.34	0.32	45.6	36.0	23.9	25.5	41.1	36.6
Tm	0.36	0.41	0.22	1.14	0.28	0.53	0.21	0.38	0.27	0.01	0.05	0.05	6.60	5.31	3.51	3.74	5.79	5.31
Yb	1.73	2.19	1.23	5.97	1.60	2.97	1.72	2.76	1.55	0.07	0.42	0.29	37.5	29.4	18.7	20.0	32.8	29.6
Lu	0.24	0.30	0.19	0.82	0.22	0.40	0.36	0.53	0.23	0.01	0.08	0.04	5.17	4.13	2.45	2.74	4.51	4.01

Note. See Table 10 for the rock codes.

Table 12. Weighted average chemical compositions of alkaline intrusions from the Kola Province

	Calculated data					Literature data		
	Alkaline ultrabasic intrusions	Phonolites	Kola Province	Khibiny	Lovozero	Khibiny	Lovozero	Alkaline ultrabasic province
	1	2	3	4	5	6	7	8
SiO_2	36.90	55.06	47.61	48.66	51.96	53.22	53.35	36.38
TiO_2	2.68	0.96	1.63	2.10	1.61	1.05	0.91	3.22
Al_2O_3	7.20	20.53	15.38	17.32	15.67	21.26	17.62	7.94
Fe_2O_3	8.96	2.87	4.56	4.14	5.72	2.59	5.73	8.37
FeO	6.18	2.11	3.76	3.49	3.09	1.58	1.55	6.88
MnO	0.25	0.20	0.22	0.22	0.27	0.18	0.31	0.12
MgO	12.42	0.68	5.35	3.52	3.70	0.65	0.95	14.95
CaO	16.81	1.57	7.88	6.26	4.99	1.80	1.36	14.46
Na_2O	2.92	9.38	6.88	8.20	7.95	9.81	10.11	3.17
K_2O	1.82	6.46	4.70	5.21	4.50	6.52	5.20	1.52
P_2O_5	1.20	0.19	0.61	0.54	0.33	0.29	0.15	0.37
CO_2	1.76	0.00	0.70	0.22	0.10	0.14	0.04	1.80
H_2O	0.90	0.00	0.72	0.12	0.14	0.91	2.72	0.82
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Li	13.5	32.2	24.8	24.2	36.1	20	55	–
Rb	49.4	153.3	112.1	114.9	66.8	220	230	–
Cs	0.64	2.43	1.72	1.89	1.75	3.5	1.62	–
Sr	2094	1476	1728	1398	855	1100	610	1293
Ba	1116	578	797	629	389	1191	690	851
Sc	24.8	4.4	12.2	8.0	17.9	2.7	2.8	2.4
V	104.0	85.3	90.7	137.9	156.2	50	108	440
Cr	293.1	19.7	123.1	143.7	135.1	10	28	–
Co	42.5	3.03	17.2	16.9	18.3	12	5	150
Ni	242.5	6.82	102.2	106.7	77.2	45	12	360
Y	33.6	61.5	50.5	53.2	47.2	27	16	20
Nb	95.8	332.9	238.4	226.8	326.2	150	696	300
Ta	5.46	32.9	21.9	22.4	24.1	20	60	34
Zr	347	922	693	531	1824	640	3480	348
Hf	7.65	24.5	17.8	13.4	51.7	13	83	–
U	2.15	4.49	3.56	2.85	5.71	5	16	15
Th	8.51	19.0	14.9	23.4	24.9	14	35	90
La	131.3	192.0	167.7	206.8	162.3	130	481	–
Ce	249.3	328.4	296.7	322.8	335.9	200	860	–
Pr	27.4	38.6	34.1	39.3	35.3	20	–	–
Nd	96.9	128.0	115.6	143.6	115.6	70	298	–
Sm	14.4	20.4	18.0	25.2	17.0	84	45	–
Eu	3.60	5.27	4.60	6.82	4.55	2.6	11	–
Gd	10.2	12.8	11.8	16.7	12.9	7.5	32	–
Tb	1.26	1.78	1.57	2.19	1.83		6	–
Dy	6.02	9.16	7.91	9.72	10.4	2.4	23	–
Ho	1.05	1.61	1.39	1.61	2.03	1.0	5	–
Er	2.42	3.96	3.34	3.75	5.25	1.1	14	–
Tm	0.32	0.52	0.44	0.47	0.77	–	–	–
Yb	1.83	2.97	2.51	2.81	4.46	1.6	10	–
Lu	0.26	0.41	0.35	0.39	0.65	–	1.8	–

Note. The chemical compositions of the alkaline ultrabasic intrusions (1), phonolites (2), Kola Province (3), Khibiny (4) and Lovozero (5) massifs were calculated taking into account the volumetric ratios of rocks in the intrusions to a depth of 22.5 km. The compositions of the average samples for Khibiny ("Khibiny General") (6), Lovozero (7), and the province as a whole are given after *Bussen and Sakharov* [1972], *Gerasimovskii et al.* [1966], and *Kukharenko et al.* [1971].

Table 13. Concentrations (ppm) and partition coefficients of rare earth elements used in the model calculations

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Calculated average composition for Kola Province	167.7	296.7	34.1	115.6	18.0	4.60	11.75	1.57	7.91	1.39	3.34	0.44	2.51	0.35
Composition of primitive mantle	0.6139	1.6011	0.2419	1.1892	0.3865	0.1456	0.5128	0.094	0.6378	0.1423	0.4167	0.0643	0.4144	0.0637
Composition of enriched mantle	1.8417	4.8033	0.7257	3.5676	1.1595	0.4368	1.5384	0.282	1.9134	0.4269	1.2501	0.1929	1.2432	0.1911
D_{ol}	0.0000088	0.000019	0.000049	0.00009*	0.00045	0.00099*	0.0019*	0.00324	0.01*	0.00927	0.018*	0.027*	0.0366	0.05
D_{opx}	0.0056	0.0058	0.006	0.007	0.0085	0.0078	0.011	0.011	0.015	0.019	0.021	0.025	0.032	0.042
D_{cpx}	0.049	0.07	0.12*	0.178	0.293	0.31*	0.34*	0.36*	0.38	0.387*	0.391*	0.395*	0.4	0.449
D_{garnet}	0.0016	0.005	0.03*	0.052	0.25	0.4	1.00*	1.60*	2.2	2.90*	3.6	4.45*	5.3	5.8
D_{spinel}	0.0002	0.0002	0.0002*	0.0002*	0.0001	0.0002*	0.0002*	0.0002*	0.0002*	0.0002*	0.0002*	0.0002*	0.0012	0.0004
$D_{amphibole}$	0.058	0.116	0.178	0.273	0.425	0.387	0.725	0.779	0.816	0.783	0.699	0.6*	0.509	0.645
$D_{phlogopite}$	0.030	0.034	0.033	0.032	0.031	0.030	0.030	0.03	0.03	0.032	0.034	0.04	0.042	0.046

Note. Primitive mantle composition is given after [*Hofman*, 1988]. Composition of enriched mantle is assumed as a threefold composition of the primitive mantle. D_{ol} and D_{opx} are given after [*Beattie*, 1994], D_{cpx} and D_{garnet} are given after [*Johnson*, 1998; *Salters and Longhi*, 1999]; the data for Yb and Lu were calculated as averages from the data reported by [*Johnson*, 1998], and [*Prinzhofer and Allegre*, 1985]; data for $D_{amphibole}$ are given after *White* [1997].

* The values were calculated using the linear interpolations of the contents of neighboring rare earth elements.

Table 14. Concentrations (ppm) and partition coefficients of the trace elements used in the model calculations

	Rb	Ba	Th	U	K	Nb	Sr	P	Hf	Zr	Ti	Y
Average concentrations calculated for the Kola Province	111.7	793.2	14.82	3.56	36530	238	1723	2892	17.77	692	8997	50.34
Primitive mantle composition	0.5353	6.049	0.0813	0.0203	258.2	0.6175	18.21	95.00	0.2676	9.714	1085	3.94
Enriched mantle composition	1.6059	18.147	0.2439	0.0609	774.6	1.8525	54.63	285	0.8028	29.142	3255	11.82
D_{ol}	0.000044	0.000003	0.000052	0.00002	0.00017	0.00005	0.000063	0.00004	0.001	0.00068	0.0002	0.0098
D_{opx}	0.022	0.0067	0.0056	0.015	0.003	0.015	0.0068	0.01	0.021	0.004	0.1	0.014
D_{cpx}	0.0033	0.0022	0.014	0.013	0.0028	0.0081	0.095	0.2	0.2	0.119	0.34	0.412
D_{garnet}	0.007	0.0007	0.014	0.0059	0.002	0.0538	0.0025	0.1	0.24	0.27	0.29	3.1
D_{spinel}	0.007	0.007	0.03	0.00001	0.0001	0.08	0.0001	0.0001	0.05	0.06	1.2	0.00001
$D_{amphibole}$	0.437	0.282	0.016	0.001	0.35	0.197	0.184	0.001	0.638	0.3	1.5	0.634
$D_{phlogopite}$	3.06	1.09	0.1	0.1	2.0	0.088	0.081	0.001	0.5	0.6	0.9	0.03

Note. The primitive mantle composition is given after *Hofman* [1988]. The enriched mantle composition is taken as a threefold composition of primitive mantle. D_{ol} and D_{opx} are given after *Beattie* [1994] and *White* [1997]; D_{cpx} is given after *Johnson* [1998], *Salters and Longhi* [1999], and *White* [1997]; D_{garnet}, after *Johnson* [1998] and *Salters and Longhi* [1999]; $D_{amphibole}$, after *Irving and Frey* [1984], *Rollinson* [1993], and *White* [1997].

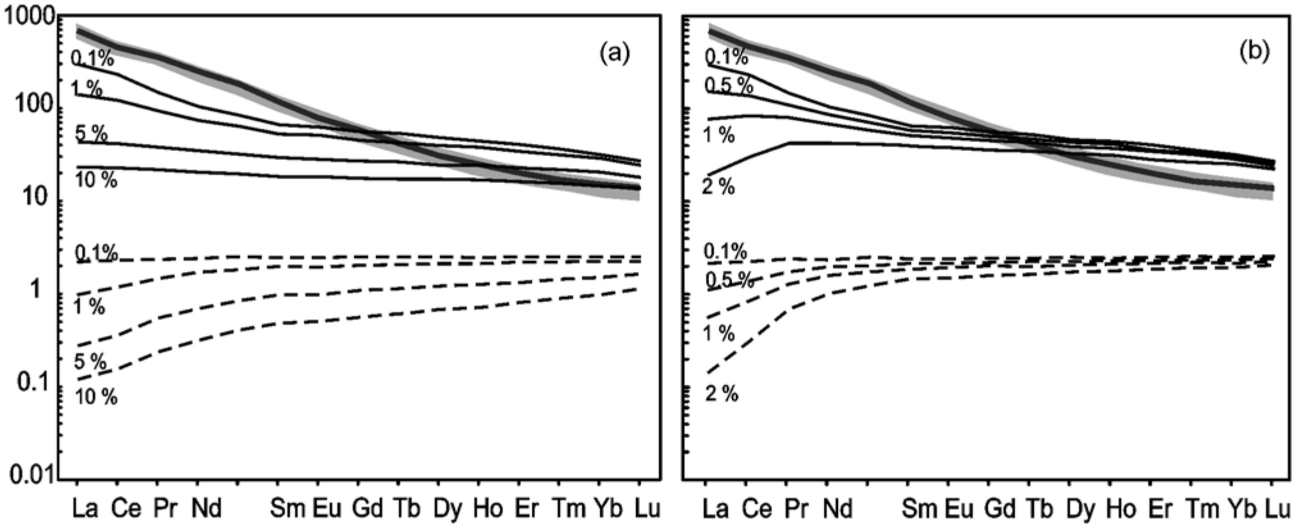

Figure 8. Chondrite-normalized REE distribution in the products of the partial (a) and fractional (b) melting of normal primitive mantle having a composition of spinel peridotite $Ol_{0.578}$ + $Opx_{0.27}$ + $Cpx_{0.119}$ + $Spl_{0.033}$. The thick line is the average composition of primary magmas in the Kola alkaline province, the shaded line denotes the compositions of the alkaline-ultramafic and phonolite series. The thin lines are the model compositions of the melts and complementary restites (broken lines) for the 0.1–10% degrees of melting. The normalizing factors used were after *Evensen et al.* [1978].

the melting of differently enriched mantle rocks of different compositions showed that the generation of primitive magmas in the Kola Province had been favored by the critically low melting degrees of the rocks (0.3–0.5%) whose composition agreed with that of phlogopite-bearing (± amphibole) lherzolite at a garnet mantle depth (>2.8 GPa). The resulting melting degree (≈0.3%) agreed, for the given PT parameters, with the calculations modeling the melting of metasomatized mantle during a mantle plume–lithosphere interaction [*White and McKenzie,* 1995].

6.2. The Volume of the Paleozoic Magma Generation Zone in the Northeastern Baltic Shield

As a result of our calculations, we estimated the total volume of magma generated during the time of Paleozoic tectonomagmatic reactivation. The computed volume (15100±2700 km^3) includes the magmatic systems of the Khibiny (9100±1400 km^3) and Lovozero (1600±250 km^3) massifs, alkaline ultramafic intrusions (4000±1000 km^3), and dikes (400±200 km^3). Experimental data show that nephelinite melts of this type, enriched in incoherent elements, could be generated at the low degrees of mantle melting, not higher than 3–5% [*Edgar,* 1987; *McKenzie,* 1984]. One of the main factors controlling the minimum volume of mantle melt is the ability of the melt to separate from the matrix, which mainly depends on the content of volatiles [*Maaloe,* 1998]. In the case of nephelinite melts, enriched significantly in H_2O and CO_2 [*Schiano et al.,* 1998; *Wyllie,* 1995], the volume of the mantle melt can be as small as 1%. Proceeding from the calculated volume of the Paleozoic magma, the total volume of the partially molten mantle rocks could be 3 to 5 million sq. km with the melting degrees of 0.3% and 0.5%, respectively. It is obvious that these estimates of the volumes of the magma generation zone are minimal, because the calculation was made using the volumes of the melted mantle rocks, whose manifestations are recorded at the level of erosion. At the same time, taking into account the unique features of geophysical anomalies produced by alkaline intrusions, whose identification helps to trace the occurrences of alkaline magmatism to the depth of the lower crust base, we can suppose that our calculations did not include the magmas that had not reached the ground surface but had been conserved in the zone of the Devonian magma generation.

The data available for the Kola Province show that the zone of the lateral propagation of alkaline magmatism in the northeastern part of the Baltic Shield is limited by a circumference with a diameter of about 400 km, corresponding to a distance between the Sokli Massif in the west and the Ivanovka Massif in the east (Figure 1). However, the data available for the PT conditions of the formation of nephelinite magma, based on mantle xenoliths [*Arzamastsev and Dalgren,* 1993] and on the geophysical data for the position of the M discontinuity [*The Structure of the Baltic Shield Lithosphere,* 1993], suggest the zone of Paleozoic magma generation to be a cylinder with a radius of 200 km. The lower limit of the melting region varies from 80 to 120 km depending on the melting degree (0.3% to 0.5%), this depth interval corresponding to the PT conditions of mantle garnet lherzo-

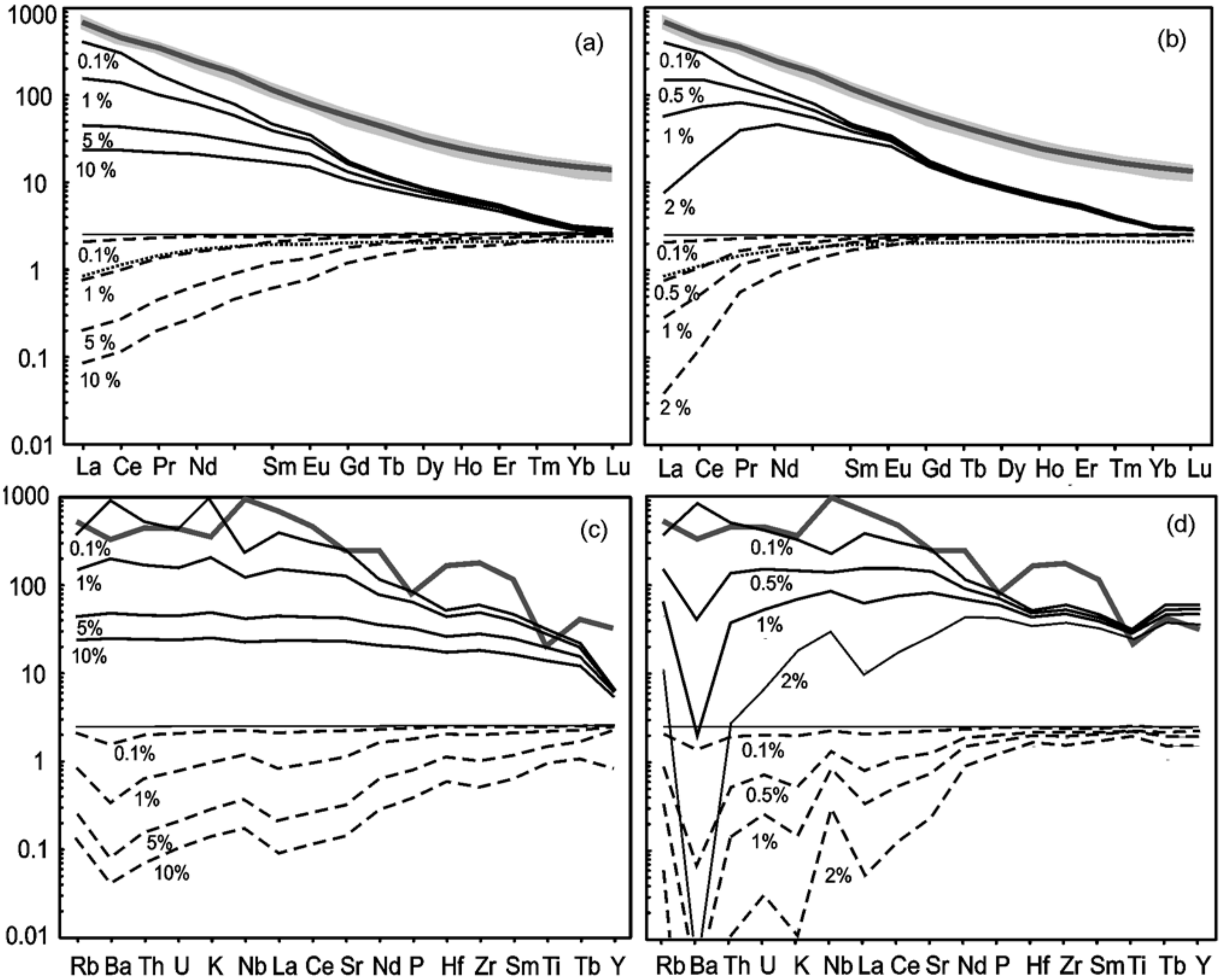

Figure 9. Chondrite-normalized trace element distribution in the products of the partial (a, c) and fractional (b, d) melting of normal primitive mantle having a composition of garnet peridotite Ol$_{0.60}$ + Opx$_{0.20}$ + Cpx$_{0.08}$ + Grt$_{0.12}$. The thick line is the average composition of primary magmas in the Kola alkaline province, the shaded line denotes the compositions of the alkaline-ultramafic and phonolite series. The thin lines are the model compositions of the melts and complementary restites (broken lines) for the 0.1–10% degrees of melting. The dotted lines show the composition of depleted mantle after *McKenzie and O'Nions* [1991]. The normalizing factors used were after *Evensen et al.* [1978] for these and after *Hofmann* [1988] for the other elements.

lite (Figure 13). The position of the lower boundary of the magma generation zone for nephelinite magma is controlled by the PT values for a graphite–diamond phase transition, which corresponds to a depth interval of 140–160 km under the Baltic Shield [*Kennedy and Kennedy,* 1976; *Kukkonen and Peltonen,* 1999].

These estimates agree with the data on the sizes of mantle plumes [*Leitch et al.,* 1998] whose periods of igneous activity lasted 10 to 30 Ma. In particular, *Grachev* [2000b] showed that the calculated size of the Kola Paleozoic plume was roughly similar to the products of plume magmatism in Greenland, Columbia, and Arabia.

7. Conclusion

The results of this study of the Paleozoic magmatism in the northeastern part of the Baltic Shield, based on geo-

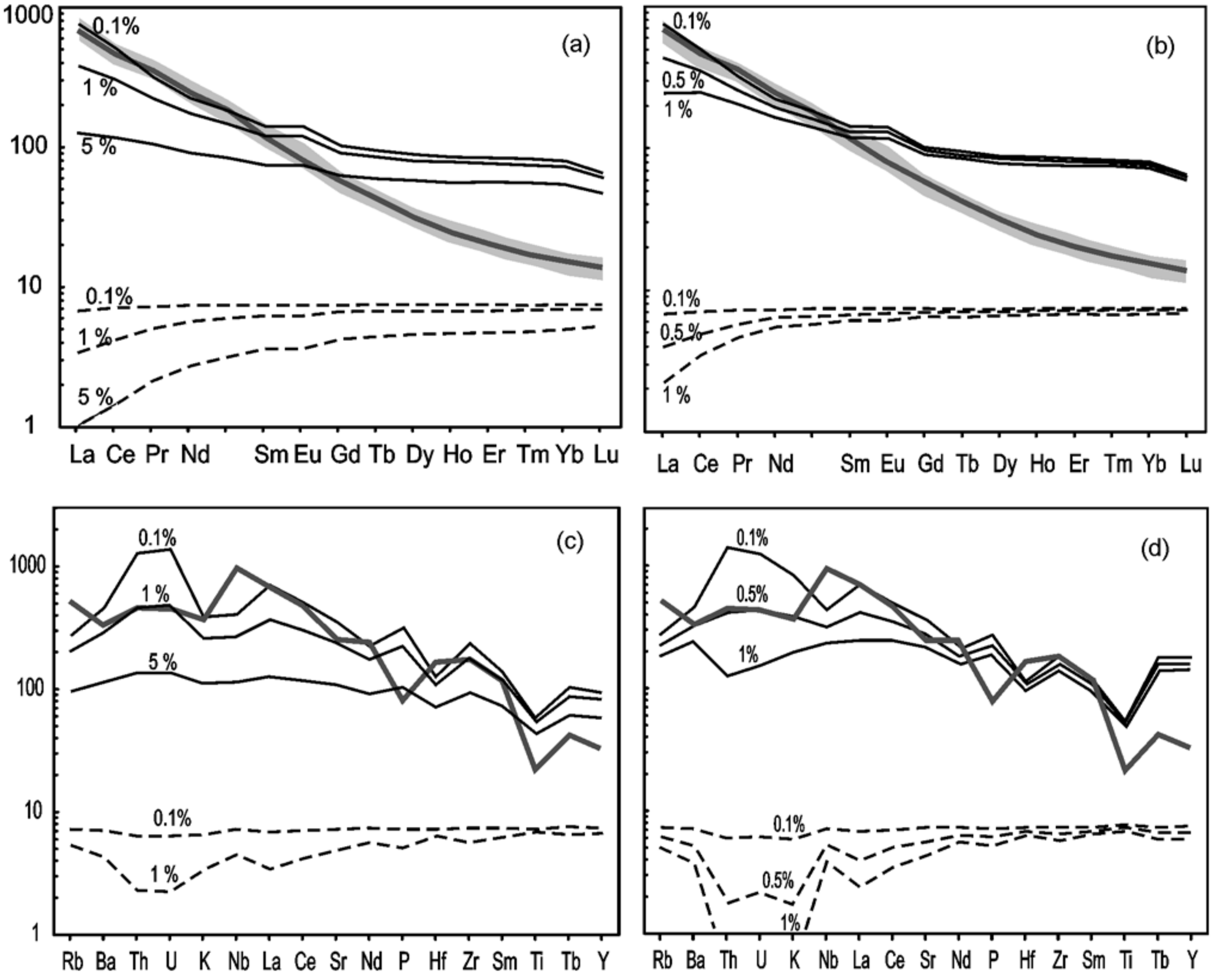

Figure 10. Chondrite-normalized trace element distribution in the products of the partial (a, c) and fractional (b, d) melting of enriched metasomatized mantle having a composition of amphibole-bearing spinel peridotite $Ol_{0.59}$ + $Opx_{0.21}$ + $Cpx_{0.10}$ + $Spl_{0.05}$ + $Amph_{0.05}$. The thick line is The average composition of primary magmas in the Kola alkaline province. The shaded line denotes the compositions of the alkaline-ultramafic and phonolite series. The thin lines are the model compositions of the melts and complementary restites (broken lines) for the 0.1–5% degrees of melting. The normalizing factors used were after *Evensen et al.* [1978] for these and after *Hofmann* [1988] for the other elements.

physical and geochemical data and model calculations, can be summarized as follows.

1. The magma generated during the time of the Paleozoic tectonomagmatic reactivation had a volume of 15,000±2700 km^3. The total volume of mantle rocks melted during a period of 380–360 million years might have been 3 to 5 million sq. km, which corresponds to a region of the reactivated mantle as thick as 40 km under the entire Kola area involved in alkaline magmatic activity.

2. The calculated average weighted composition of the primary magmas in the Kola Province showed its similarity with the average composition of olivine melanephelinite and agreed with the compositions of the most primitive magmas found in the volcanic rocks and small intrusions of the region. The phonolite magma was found to have been enriched in Nb, Ta, Zr, and Hf, whereas no positive HFSE anomaly was found for the primitive alkaline-ultramafic magmas of the region.

3. The modelling of the trace element behavior during the melting of differently enriched mantle rocks having different mineral compositions showed that (a) the primary magmas of the Kola Province could not be derived from the primitive mantle even at critically low melting degrees; (b) the generation of alkaline magma at the PT conditions of spinel stability is highly improbable; (c) the primitive magmas could be produced in the province as a result of the low melting de-

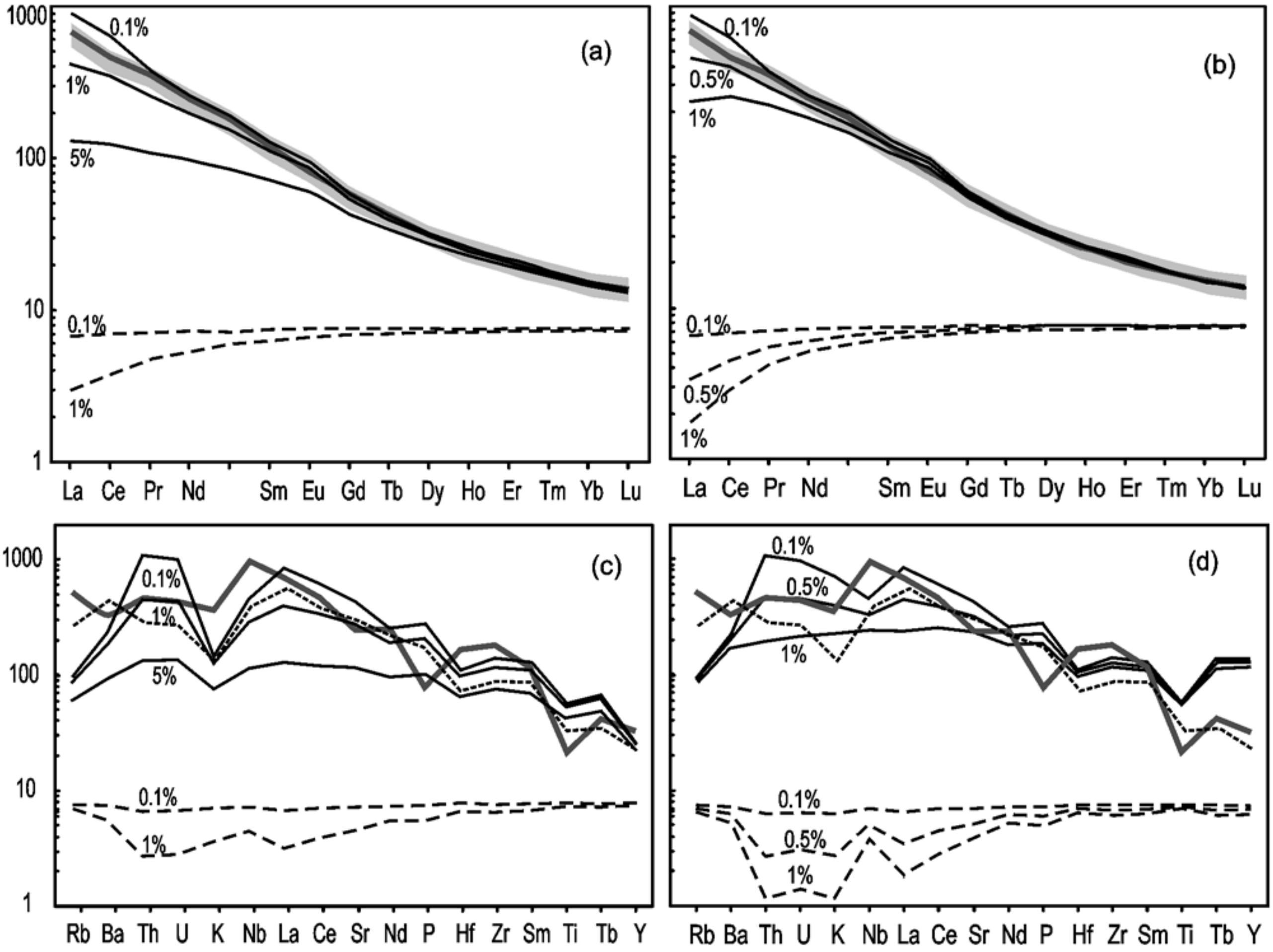

Figure 11. Chondrite-normalized trace element distribution in the products of the partial (a, c) and fractional (b, d) melting of enriched metasomatized mantle having a composition of amphibole- and phlogopite-bearing garnet peridotite $Ol_{0.59} + Opx_{0.20} + Cpx_{0.08} + Grt_{0.08} + Phlog_{0.02} + Amph_{0.03}$. The thick line is the average composition of the primary magmas of the Kola alkaline province, the shaded line denoting the composition of the alkaline-ultramafic and phonolite series. The thin lines are the model compositions of the melts and complementary restites (broken lines) for the 0.1–5% degrees of melting. The normalizing factors used were after *Evensen et al.* [1978] for these and after *Hofmann* [1988] for the other elements.

gree of the rocks (0.3–0.5%), under the conditions of a garnet mantle depth, whose enrichment was 3 times higher than the average contents of incompatible elements in primitive mantle; (d) also involved in melting were the mantle rocks with a composition of phlogopite-bearing (± amphibole) garnet lherzolite.

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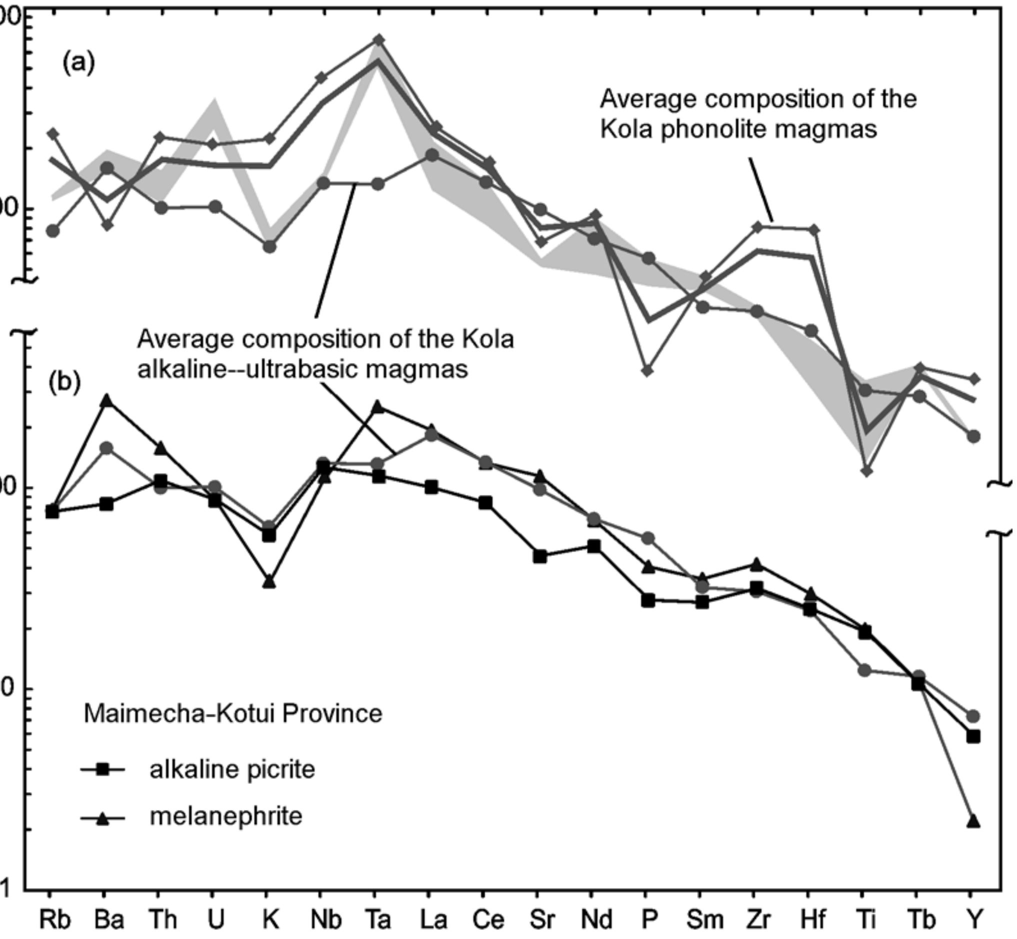

Figure 12. Primitive-mantle normalized trace element distribution in the primary magmas of the Kola Province (thick line) compared to the average compositions of alkaline and ultrabasic lamprophyres (shaded line) [*Rock,* 1987] and the undifferentiated rocks of the Maimecha–Kotui Province [*Arndt et al.,* 1998]. The normalizing factors were after *Hofmann* [1988].

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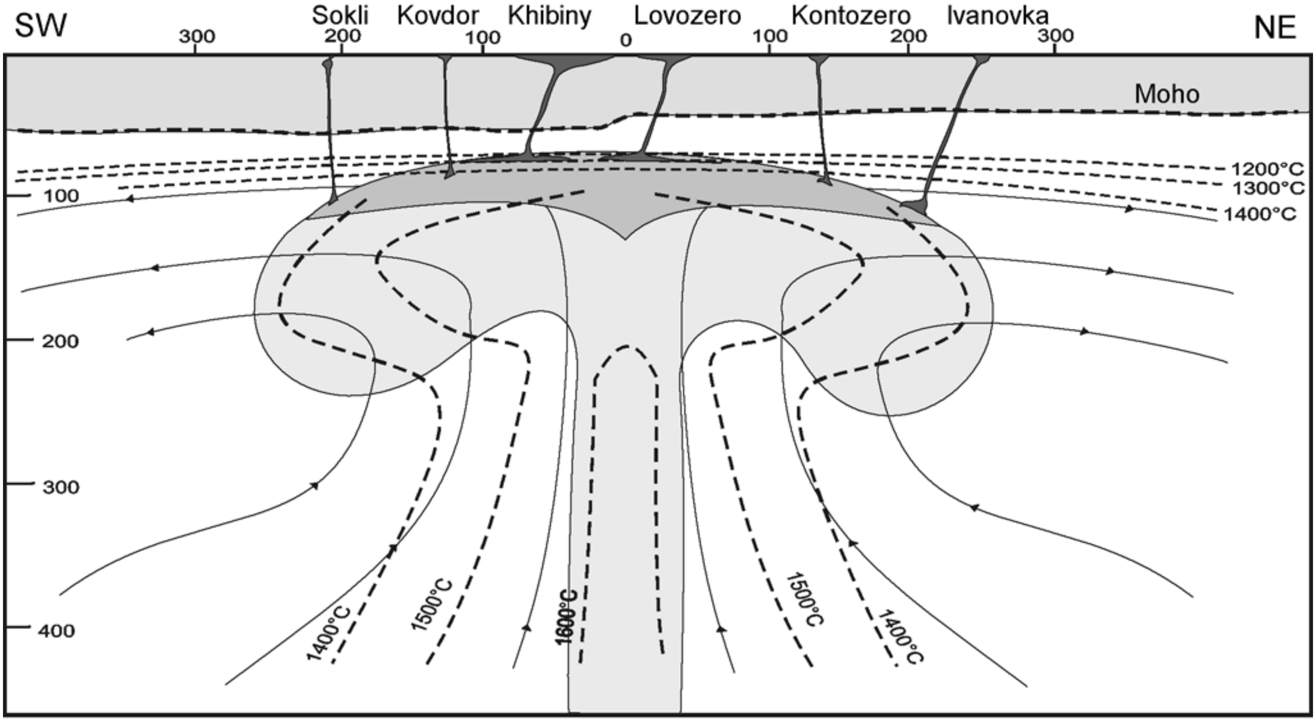

Figure 13. A hypothetical model for the mantle plume–lithosphere interaction in the zone of the Paleozoic alkaline magmatism in the northeastern part of the Baltic Shield, based on the data of *Leitch et al.* [1998], *McKenzie and Bickle* [1988], *Thompson and Gibson* [1991], and *White and McKenzie* [1989].

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