Труды Карельского научного центра РАН
№ 7. 2015. С. 74–84
DOI: 10.17076/geo164

УДК 552.321 + 551.71

Sm-Nd AND U-Pb ISOTOPIC STUDY OF THE NYASYUKKA DIKE COMPLEX, KOLA PENINSULA, RUSSIA

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The Nyasyukka dike complex forms a NW-trending dike swarm in the Archean bedrock of the Murmansk Province adjacent to the Pechenga Complex. The dikes are mostly composed of two rock types, kaersutite-bearing peridotites and olivine gabbros. Also a rounded pyroxenite stock has been found in the area. The dikes were generated from ferropicritic parental magma which was similar to Pechenga ferropicrites though having a somewhat higher silica activity. A peridotite sample yielded an internal Sm-Nd isochron with an age of 1956 ± 19 Ma (MSWD = 0.7) and an initial ε_{Nd} value of +1.4 ± 0.4. This is consistent with the baddeleyite age of 1941 ± 3 Ma, showing that the Nyasyukka dikes are ca. 40 Ma younger than the Pechenga ferropicrites. The pyroxenite stock shows geochemical and Nd isotopic evidence for significant crustal contamination. We also present isotopic and geochemical data for olivine gabbro-norite from the Tuloma River area, supporting the earlier view that there exist dikes of the Nyasyukka type in this area.

Keywords: Paleoproterozoic Pechenga structure, Dike of peridotite-olivine gabbro complex, Sm-Nd and U-Pb isotopic dating, baddeleyite, zircon.

В. Ф. Смолькин, Е. Хански, Х. Хухма, Ж. А. Федотов. Sm-Nd и U-Pb ИЗОТОПНЫЕ ИССЛЕДОВАНИЯ НЯСЮККСКОГО ДАЙКОВОГО КОМПЛЕКСА, КОЛЬСКИЙ ПОЛУОСТРОВ, РОССИЯ

Нясюккский дайковый комплекс образует дайковый рой СЗ-простирания в архейских породах Мурманской области, прилегающих к Печенгской структуре. Дайки в основном сложены из двух типов пород – керсутитсодержащих перидотитов и оливиновых габбро. В этом районе также были найдены пироксениты штокообразной формы. Дайки были сформированы за счет ферропикритовой родительской магмы, которая была подобна печенгским ферропикритам, но имела несколько более высокую активность кремнезема. Образец перидотита дал внутреннюю Sm-Nd изохрону с возрастом 1956 ± 19 млн лет (СКВО = 0,7) и первичное ε_{Nd} отношение +1,4 ± 0,4. Это согласуется с возрастом бадделеита 1941 ± 3 млн лет, показывая, что нясюккский дайковый рой на 40 млн лет моложе печенгских ферропикритов. Для пироксенитового штока получены геохимические и Nd изотопные свидетельства значительной коровой контаминации. Мы также представляем изотопные и геохимические данные для оливиновых габброноритов района р. Туломы, поддержав ранее высказанное мнение о том, что в этом районе существуют дайки нясюккского типа.

Ключевые слова: Палеопротерозойская Печенгская структура, дайковый комплекс перидотитов-оливиновых габбро, Sm-Nd и U-Pb изотопные данные, бадделеит, циркон.

Introduction

Several generations of mafic dike have been found in the Archean TTG (tonalite-trondhjemite-granodiorite) gness bedrock in the area outside the northeastern margin of the Paleoproterozoic Pechenga-Varzuga Belt in the Kola Peninsula [Smolkin, 1993, 1997; Fedotov, 1995; Arzamastsev et al., 2009] (Figs. 1, 2). Their abundance may reach 5 volume percent of the bedrock. The dikes are divided into two major groups: the younger Paleozoic, unaltered dolerites and the older Paleoproterozoic, variously metamorphosed dike complexes. No apparent volcanic or deep-seated, intrusive counterparts have been found for the first group, while close compositional analogues for the Paleoproterozoic dikes have been recognized among the volcanic and intrusive rocks occurring in the adjacent Pechenga-Varzuga Belt. On the basis of their mineralogical and chemical composition, age and orientation, Fedotov [1995] subdivided the Paleoproterozoic dikes into four dike complexes, which are from oldest to youngest: 1) gabbro-norites, 2) quartz-bearing metadolerites, 3) picritic dolerites, and 4) high-Fe-Ti metadolerites and metapicrites. The last type includes kaersutite-bearing peridotites and olivine gabbros of the Nyasyukka dike complex, which have earlier been regarded as comagmatic with the ore-bearing gabbro-wehrlite intrusions and ferropicritic volcanic rocks of the Pechenga Group [Fedotov et al., 1974; Fedotov, 1995; Smolkin, Borisova, 1995].

In addition to the Archean bedrock adjacent to the Pechenga Complex, Nyasyukka-type mafic-ultramafic dikes have been encountered elsewhere in the Kola Peninsula. Borisova [1989] desribed an occurrence ca. 100 km southeast of Pechenga, in the Tuloma River area southwest of Murmansk (see Fig. 1). Also dikes of this affinity have been found in the Monchegorsk area close to the north-western end of the Imandra-Varzuga supracrustal belt where they penetrate Archean gneisses and a Paleoproterozoic mafic layered intrusion [Dokuchaeva et al., 1989]. In addition, dike rocks of the Nyasyukka type have been recognized in the Sydvaranger area in northeastern Norway

Fig. 1. Location of the Nyasyukka dike complex (Fig. 2) in the Archean basement on the NE side of the Pechenga Complex. Also shown is the site of sample T-33 in the Tuloma River area SW of Murmansk

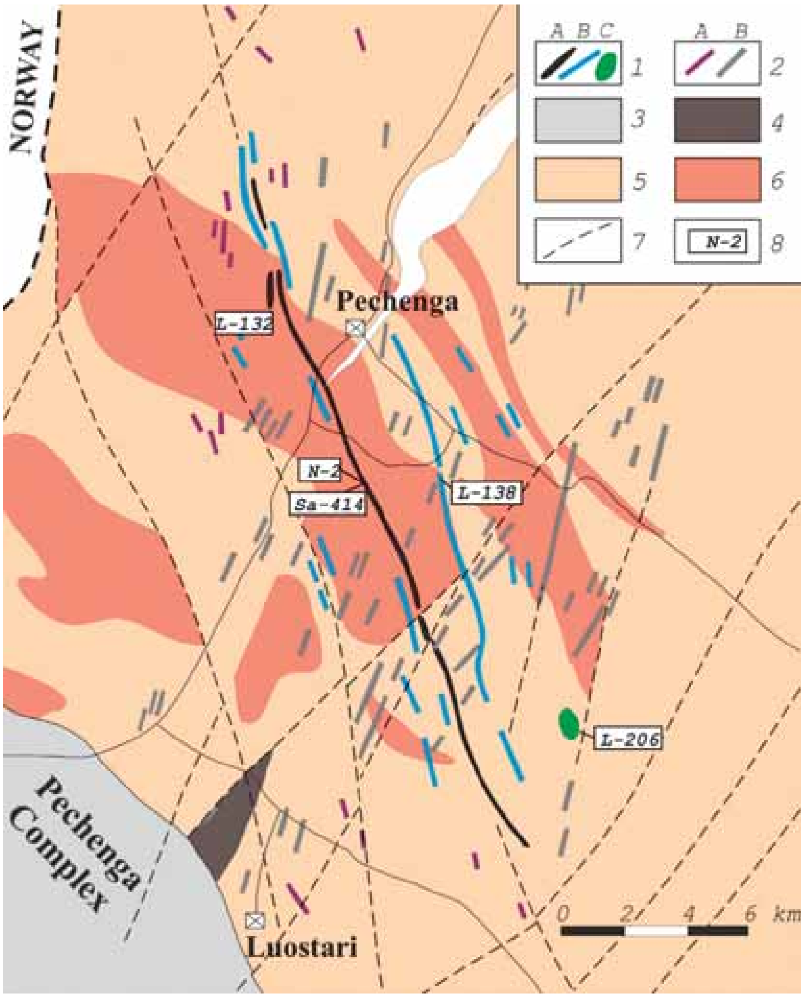

Fig. 2. Map showing dike rocks and sampling sites around the Pechenga village [modified after Smolkin, 1993]. Legend:

1) a – peridotite, b – olivine gabbro, c – olivine pyroxenite of the Nyasyukka dike complex; 2) a – dolerite, b – quartz dolerite; 3) sedimentary and volcanic rocks of the Pechenga Complex; 4) Mt. Generalskaya mafic layered intrusion; 5) Archean amphibolite, gneiss, high-Al schist; 6) Archean granite; 7) fault; 8) sampling site

[Smolkin, Borisova, 1995]. Thus the Nyasyukka type dikes are known to occur in a zone having a NW-SE extension of more than 300 kilometers.

The potential genetic link between the Nyasyukka dike complex and the Pechenga Ni-Cu-bearing intrusions has important geotectonic and economic implications. In order to evaluate whether the Nyasyukka dikes form isotopically a coherent group and are comagmatic with the ferropicritic magmatism of the North Pechenga Group [Smolkin, 1993; Melezhik, Hanski, 2012], we undertook a geochemical and Sm-Nd isotopic study of representative samples from the Nyasyukka dikes occurring near the Pechenga village (see Fig. 1). Also included was one olivine gabbro-norite sample from the Tuloma area.

The Nyasyukka dike complex

Among the dikes found in the Archean bedrock on the NE side of the Paleoproterozoic Pechenga Complex, there is a somewhat heterogeneous, but geochemically correlative group of mafic to ultramafic dikes, which have been assigned to the Nyasyukka dike complex (see Fig. 2). It was named after the Nyasyukka village (called Näsykkä in Finnish). Currently the number of known dikes exceeds 40. They form a NNW-trending and steeply dipping swarm occurring within an area of 30 x 40 km^2 and extending from the Luostari railway station to the coast of the Barents Sea.

There is also another dike swarm in the area, which is NNE oriented, thus forming an angle of 45° with the Nyasyukka dike complex. These dikes are more evolved and composed of gabbro diabases and quartz gabbros [Smolkin, Borisova, 1995].

The dike-forming process was affected by deep differentiation in stoging magma, which resulted in the concentration of dikes of different composition in different subswarms. Three parallel series are distinguished (see Fig. 2). The western and eastern series are composed predominantly of olivine gabbro forming dikes that vary in thickness from 30 to 130 meters and in length from 1 to 8 kilometers. The central series contains dikes that are composed of plagioclase- and kaersutite-bearing peridotites and are 40–150, sometimes 200 meters thick and up to 22 km long, occuning together with some smaller dikes having the same composition. In addition to these linear dike bodies, a plagioclase-bearing olivine pyroxenite stock is located at the southern termination of the eastern series (see Fig. 2).

Peridotites of the Nyasyukka complex are olivine cumulates with interstitial amphibole (kaersutite), plagioclase, and clinopyroxene. They are medium- to coarse-grained rocks with a massive or porphyritic texture, the latter being caused by large, poikilitic amphibole crystals. The volumetric abundance of the main minerals is the following: olivine 25–40 %, augite 11–45 %, kaersutite 4–40 %, plagioclase 0.3–8 %. Minor minerals include bronzite, biotite, magnetite, ilmenite, and apatite. *Olivine gabbros* are medium-grained, massive rocks having a wide variation in the relative proportions of the major minerals. Olivine had crystallized before pyroxene, and plagioclase is xenomorphic with respect to the mafic main minerals. There is often a orthopyroxene-amphibole corona at the contact between olivine and plagioclase. The stock-forming, olivine-bearing *pyroxenites* (pyroxenite cumulates) have the following modal composition: olivine 10–25 %, plagioclase 8–17 %, augite 60–63 %, biotite 1–3 %.

The NW-trending dikes in the Tuloma River area are 300 to 1200 m long, 10 to 60 m wide, non-differentiated, and composed of olivine-bearing *melagabbros* or *gabbro-norites* [Borisova, 1989]. The modal abundance of their primary magmatic minerals varies as follows: olivine 5–15 %, bronzite 2–15 %, augite 15–25 %, plagioclase 10–30 %, kaersutite 0.5–1 %.

The rocks of the Nyasyukka dike complex have some features, including the presence of primary magmatic amphibole, kaersutite, which they share with the gabbro-wehrlite intrusions in the Pechenga-Varzuga Belt. There are, however, mineralogical distinctions, which indicate some differences in the respective parental magma compositions. Orthopyroxene is present in the Nyasyukka dikes but has not been found in the Pechenga rocks, suggesting a higher silica activity in the magma parental to the former rocks. Olivine and plagioclase typically coexist in the olivine gabbros of the Nyasyukka complex whereas the gabbroic rocks of the Pechenga intrusions commonly lack olivine or contain only a small amount of olivine.

Samples and analytical methods

Geological sampling and mineralogical research were carried out by V. F. Smolkin and Zh. A. Fedotov, geochemical research was made by E. Hanski, and isotopic Sm-Nd analysis by H. Huhma.

The sampling sites are shown in Figs. 1 and 2. For isotope and trace element analyses, six whole-rock samples were collected from the Nyasyukka area: three plagioclase-bearing kaersutite peridotites (samples N2, L-132 and SA-414) from the central ultramafic dike, an olivine gabbro (L-138) representing one of the eastern gabbroic dikes, and plagioclase-bearing olivine pyroxenite (L-206) from the above-mentioned stock-like body (see Fig. 2). In addition, one olivine gabbro-norite sample (T-33) was picked from the Tuloma River area (see Fig. 1). Mineral separates of olivine, clinopyroxene, kaersutite, orthopyroxene and plagioclase, obtained using standard heavy liquid and magnetic methods, were analyzed from sample L-132 and plagioclase and clinopyroxene from sample L-206.

For U-Pb dating using conventional thermal mass spectrometry (TIMS), a 50-kg sample (P-27) was taken from close to the contact of an olivine gabbro dike located near the Kirikovan open pit. It consists of large grains of partly amphibolized pyroxene (45–50 vol.%), tabular grains of partly chloritized plagioclase (45–50 vol.%), and also biotite (3–5 vol.%), magnetite and ilmenite (2–3 vol.%). Another sample (P59) was picked from the same spot for in situ dating using SHRIMP (sensitive high-resolution ion microprobe).

Whole-rock analyses were performed in the chemistry laboratory of the Geological Survey of Finland at Espoo (currently Labtium). Concentrations of major elements and Cr, Ni, Sc, V, Cu, Pb, Zn, S, As, Rb, Ba, Sr, Ga, Nb, Zr, Y were measured by the XRF method using a Philipps PW1480 equipment. For determination of concentrations of rare earth elements (REE) and Y, Sc, Zr, Hf, Nb, Th, and U, inductively coupled plasma mass spectrometry (ICP-MS) was utilized.

Sm-Nd isotopic analyses were carried out in the geochronological laboratory of the GTK (Espoo). Chemical preparation of samples for the Sm-Nd isotopic analysis was made using the methodology described by Hanski et al. [2001] and isotopic ratios were measured using a VG sector 54 thermal ionization mass spectrometer. The concentrations were measured using a mixed ^{150}Nd/^{149}Sm spike without aliquoting. The estimated error in ^{147}Sm/^{144}Nd is 0.3 % and ^{143}Nd/^{144}Nd is normalized to ^{146}Nd/^{144}Nd=0.7219. The average value for the La Jolla standard was ^{143}Nd/^{144}Nd = 0.511850 ± 10 (1σ, n=15).

Zircon extraction and U-Pb isotopic analysis were performed by T. B. Bayanova in the Collective Use Center of the Geological Institute, Kola Science Center RAS (Apatity). Chemical procedure of zircon dissolution followed the method of Krogh [1973], and plotting of the U-Pb isotopic data and age calculations were carried out using the Isoplot software of Ludwig [1991, 1999] and applying the decay constant of Steiger and Jäger [1977]. All errors are reported at the 2 level. Isotopic analyses were made on a 7-channel Finnigan-MAT-262 (RPQ) mass spectrometer.

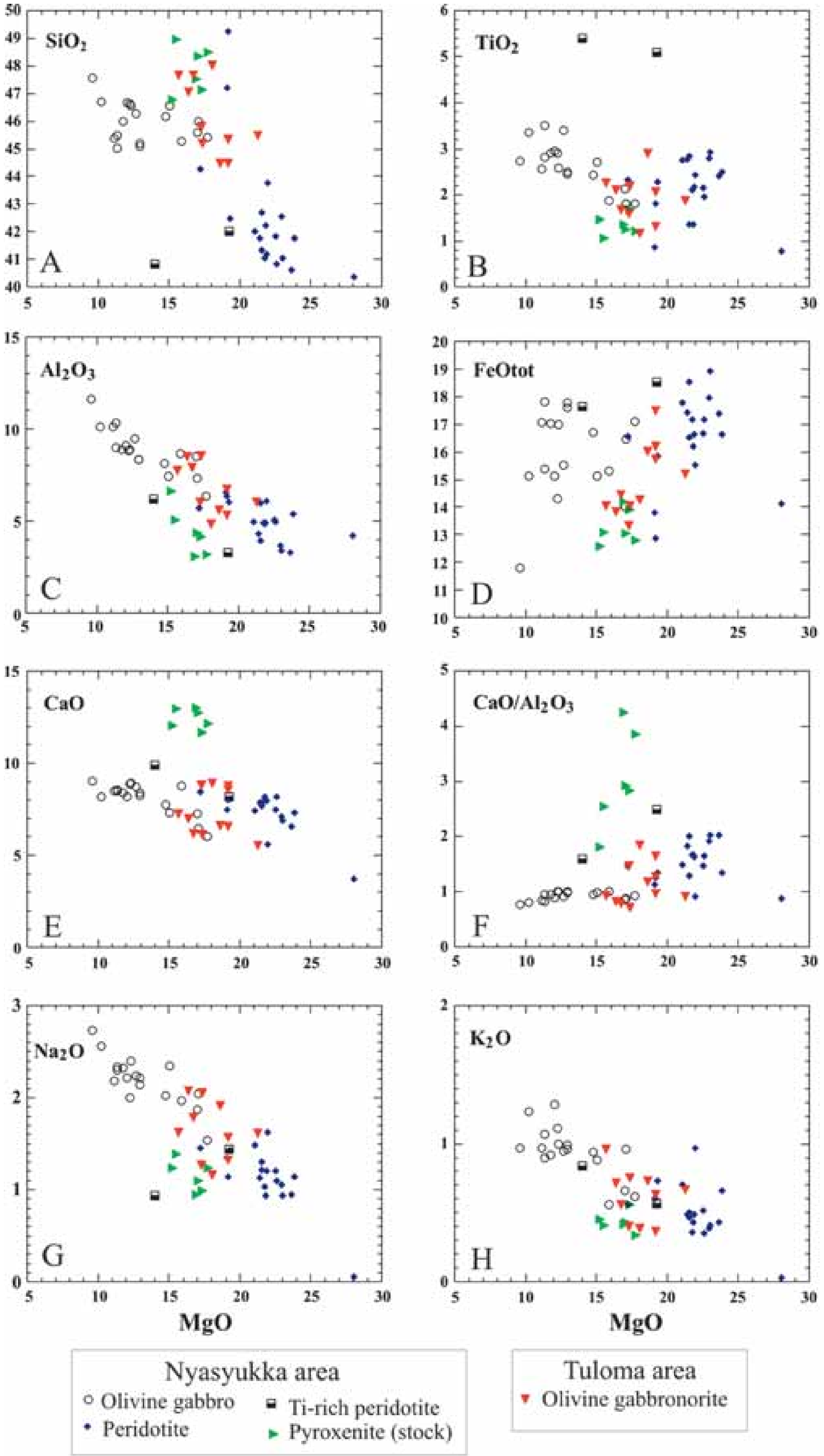

Fig. 3. Major element compositions of rocks from the Nyasyukka dike complex and dikes from the Tuloma River area

In situ U-Pb zircon analyses were conducted in the *VSEGEI's Centre of Isotopic Research* (CIR) on a SHRIMP II mass spectrometer. The analysis method is described by Williams [1998] and Larionov et al. [2004]. The measured isotope ratios were corrected using zircon standard TEMORA from leucogabbro of Eastern Australia.

Geochemistry

Chemical analyses of the dike samples are shown in Tab. 1. Based on these and more abundant major element data reported by Smolkin [1993], Fedotov [1995], and Borisova [1989], Fig. 3 was constructed, displaying major components plotted against MgO. The samples are divided into the following five groups marked with their own symbols: peridotites, olivine gabbros, and Ti-rich peridotites from the Nyasyukka area, pyroxenites of the stock-like body from the same area, and olivine gabbro-norites from the Tuloma area. As shown in these diagrams, the rocks form an extensive differentiation series with the MgO content varying from 28 to 10 wt. %. Most of the samples have a high FeO_{tot} content analogous to the ferropicritic rocks [Smolkin, 1992; Hanski, 1992]. Another feature shared by the ferropicrites is high TiO_2 resulting in low Al_2O_3/TiO_2 ratios, which fall generally below 5 in the Nyasyukka rocks.

Most of the samples of the Nyasyukka area form more or less coherent trends in the diagrams with peridotites and olivine pyroxenites occupying their high-MgO and lower-MgO ends (see Fig. 3). However, there are two exceptions: the pyroxenite samples from the stock differ from the other analyzed samples in having high CaO (and Sc) and CaO/Al_2O_3 due to the large fraction of cumulus clinopyroxene (see Figs. 3, e–f). Two peridotite samples are exceptionally rich in TiO_2 (>5 wt. %) (see Fig. 3, b) and consequently have extremely low Al_2O_3/TiO_2 ratios of less than 1.2. In most diagrams, the Tuloma River samples plot somewhere between the peridotites and olivine gabbros from the Nyasyukka area. Due to their high SiO_2, they form a field on the SiO_2 vs. MgO plot (see Fig. 3, a) that does not overlap the fields of the other samples.

Figures 4 illustrates mantle-normalized REE diagrams extended with Th, U, Nb, and Ta. It shows that the dikes cannot be distinguished on the basis of their REE characteristics: all are strongly enriched in LREE compared to HREE. One of the samples, L-206 from the pyroxenite stock, displays pronounced negative Nb and Ta anomalies in Fig. 4. With the exception of this sample, the analyzed rocks of the Nyasyukka dike complex have similar immobile trace element characteristics to those of the Pechenga ferropicrites, including high LREE and HFSE. The similarity does not extend to mobile elements (Sr, K, Rb, Ba, Na), which occur in higher abundances in the dikes compared to the ferropicritic intrusions and volcanic rocks (not shown here).

Sm-Nd and U-Pb isotopes

The Sm-Nd isotopic results are presented in Tab. 2. In Fig. 5, the analytical data are plotted on two $^{147}Sm/^{144}Nd$ vs. $^{143}Nd/^{144}Nd$ diagrams in order to distinguish the samples and analyzed sample materials from each other. The whole-rock and mineral analyses of the peridotite sample L-132 yield an isochron with an age of 1956 ± 19 Ma (MSWD = 0.7) and an initial ε_{Nd} value of +1.4 ± 0.4.

Table 1. Major and trace element analyses for dike rocks from the Nyasyukka (№ 1–4) and Tuloma areas (№ 5)

	1	2	3	4	5
Sample	SA-414	L-132	L-138	L-206	T-33
SiO_2 (wt %)	42.48	41.04	45.26	48.96	45.35
TiO_2	2.29	2.11	1.87	1.05	2.06
Al_2O_3	6.02	4.90	8.68	5.08	6.71
Fe_2O_3	3.96	1.91	2.22	1.45	2.43
FeO	12.30	15.46	13.30	11.77	13.55
MnO	0.21	0.22	0.22	0.19	0.20
MgO	19.33	21.77	15.92	15.54	19.20
CaO	8.06	8.16	8.74	12.95	8.57
Na_2O	1.43	1.03	1.97	1.39	1.57
K_2O	0.73	0.36	0.56	0.41	0.63
P_2O_5	0.21	0.13	0.15	0.07	0.16
S (ppm)	1360	1150	100	2400	1100
Cu	253	258		135	
Cr	1996	2510		955	
Ni	991	1097		217	
Sc	39.1	36.8	30.8	50.8	24
V	360	292	240	353	320
Sr	232	210		221	
Ba	197	114		161	
Rb	25.4	10.1	15.1	10.7	19.1
Zr	179	68.5	102	58.5	101
Hf	3.99	2.27	3.16	1.58	2.8
Ta		0.62	0.99	0.26	0.92
Nb	13.4	9.64	14.5	4.21	13.6
Th	2.61	1.26	1.64	1.08	2.03
U	0.66	0.32	0.38	0.20	0.39
La	18.0	9.90	14.3	9.62	14.4
Ce	42.3	24.1	33.7	22.5	33.4
Pr	5.75	3.30	4.66	2.99	4.33
Nd	24.3	15.3	20.3	13.4	18.7
Sm	5.67	3.68	4.86	2.67	4.11
Eu	1.79	1.13	1.55	0.85	1.27
Gd	5.81	3.73	5.23	2.86	4.39
Tb	0.88	0.50	0.69	0.40	0.62
Dy	4.32	2.51	3.89	2.12	3.10
Ho	0.70	0.46	0.68	0.38	0.58
Er	1.78	1.10	1.61	0.97	1.56
Tm	0.19	0.13	0.23	0.14	0.20
Yb	1.35	0,87	1,44	0,88	1.15
Lu	0.18	0.13	0.20	0.12	0.18
Y	19.8	12.4	18.8	10.7	15.7

Rock types. 1–2, amphibole-bearing peridotite, 3, olivine gabbro; 4, clinopyroxenite; 5, olivine gabbro-norite. (REE, Rb, Hf, Ta, Nb, Th, U analyzed by ICP-MS, other components by XRF).

Table 2. Sm-Nd concentration and isotopic data for whole rocks and mineral separates (for analytical techniques, see Hanski et al., 2001)

Sample		Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	ε_{Nd} (1940 Ma)
L-132	peridotite[1]					
	Whole rock	3.71	15.38	0.1460	0.512062±10	1.3
	Plagioclase	0.45	3.25	0.0828	0.511242±10	1.1
	Augite	4.24	13.08	0.1958	0.512692±10	1.2
	Kaersutite	15.42	62.27	0.1497	0.512109±10	1.3
	Cpx+Opx	2.41	7.54	0.1934	0.512670±10	1.4
	Opx	0.25	1.07	0.1417		
N2	peridotite[1]					
	Whole rock	5.21	22.75	0.1383	0.511961±10	1.4
SA-414	peridotite[1]					
	Whole rock	5.77	24.48	0.1424	0.511995±10	1.1
L-138	gabbro[1]					
	Whole rock	4.94	21.23	0.1407	0.511986±10	1.2
L-206	pyroxenite[1]					
	Whole rock	3.09	13.80	0.1353	0.511697±11	-3.1
	Plagioclase	0.47	3.030	0.0869	0.511040±30	-3.9
	Augite	3.10	11.02	0.1698	0.512133±10	-3.2
T-33	gabbro-norite[2]					
	Whole rock	4.48	19.78	0.1370	0.11879±10	0.0

[1] Nyasyukka, [2] Tuloma.

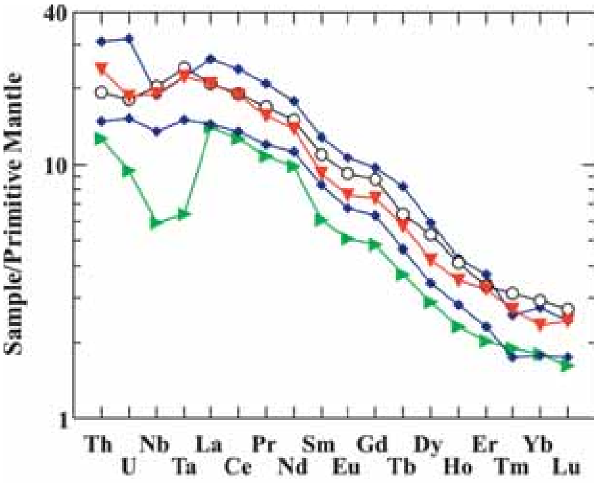

Fig. 4. Primitive-mantle normalized extended REE diagram for whole-rock dike analyses. For symbols, see Fig. 3

The two other peridotite samples from the same dike, N2 and SA-414, plot on the same isochron. The olivine gabbro sample L-138 also plots on the isochron and is most probably genetically related to the peridotites of the central dike. Combining the data of all the above-mentioned samples does not change the age result that is provided by sample L-132.

Sample L-206 plots clearly below the isochron defined by sample L-132. The Sm-Nd analyses (less precise) of pyroxene and plagioclase from L-206 indicate that the pyroxenite stock (L-206) is roughly coeval with L-132 (2.0 ± 0.1 Ga). The low initial ε_{Nd} of ca. -3 suggests a significant contribution from old LREE-enriched lithosphere in the genesis of the stock-like pyroxenite represented by sample L-206. This is likely through crustal contamination, which is also compatible with the geochemical data (see Fig. 4).

The whole-rock isotopic analysis on the olivine gabbro-norite (T-33) from the Tuloma River area plots slightly below the L-132 isochron and yields a chondritic initial ratio as calculated at 1940 Ma (Tab. 2). This value is thus slightly lower than that obtained for the two dikes in the Nyasyukka area. The single analysis cannot be used to confirm whether this dike is

Table 3. U-Pb concentration and isotopic data for baddeleyite from an olivine gabbro (Sample P-27)

Fraction	Weight (mg)	Concentrations (ppm)		Pb isotopic composition[1]			Isotopic ratios[2]		Ages (Ma)	Rho
		Pb	U	^{206}Pb/^{204}Pb	^{206}Pb/^{207}Pb	^{206}Pb/^{208}Pb	^{207}Pb/^{235}U	^{206}Pb/^{238}U	^{207}Pb/^{206}Pb	
1	2	3	4	5	6	7	8	9	10	11
1[3]	0.85	129.0	328.4	466	6.7797	6.4842	5.5585	0.3385	1943	0.91
2[3]	0.70	135.4	370.9	638	7.1650	9.436	5.4410	0.3321	1939	0.91
3[3]	0.70	58.3	232.9	353	6.4052	5.3596	3.3823	0.2068	1936	0.82
4[3]	0.85	81.6	384.6	305	6.1690	4.3814	2.7496	0.1679	1938	0.46

[1] The ratios are corrected for blanks of 0.08 ng for Pb and 0.04 ng for U and for mass discrimination 0.12 ± 0.04 %.
[2] Correction for common Pb was determined for the age according to Stacey and Kramers (1975).
[3] Corrected for isotope composition of light cogenetic plagioclase: ^{206}Pb/^{204}Pb =15.316; ^{207}Pb/^{204}Pb = 15.061; ^{208}Pb/^{204}Pb = 34.872.

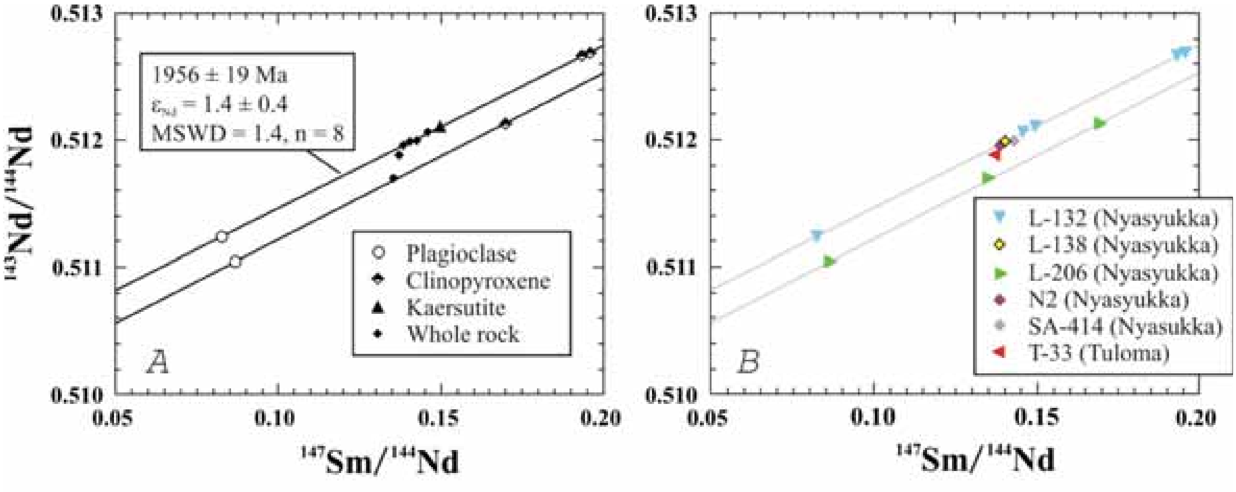

Fig. 5. Sm-Nd isochron diagrams with analyses grouped according to sample type (A) and sample code and location (B)

coeval with the Nyasyukka dike complex but geochemically the former is yet indistinguishable from the latter (see Figs. 3–4).

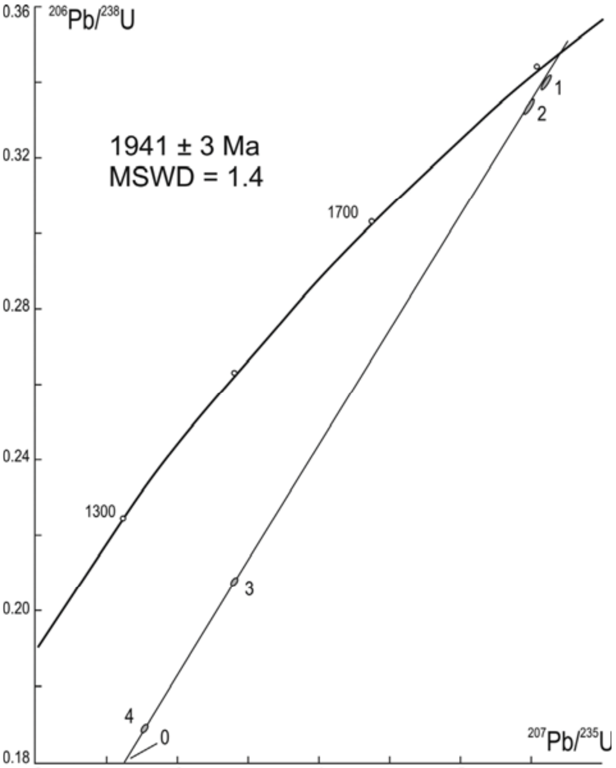

Fig. 6. U-Pb concordia age for baddeleyite from an olivine gabbro of the Nyasyukka dike complex, sample P-27

Sample P-27 from an olivine-gabbro dike yielded lamellar, brown and light brown grains of baddeleyite with an average size of 0.225 x 0.15 mm, and also fragments of metamict zircon grains. Isotopic compositions of four fractions of baddeleyite are listed in Table 6 and plotted on a concordia diagram in Fig. 6, тab. 3, giving an upper intercept age of 1941 ± 3 Ma (MSWD = 1.3). SHRIMP analysis of one dark zircon grain from sample P-59 resulted in a less precise age of 1961 ± 24 Ma, but within error limits, it is comparable with the age obtained by TIMS (Fig. 7, tab. 4).

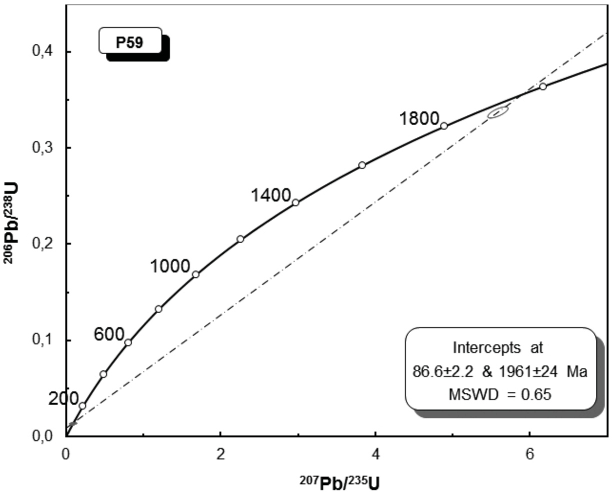

Fig. 7. U-Pb concordia age for zircon from an olivine gabbro, sample P-59 (SHRIMP II). Sample P-59 is a duplicate of sample P-27

Simultaneously, in situ zircon analyses were carried out for ferropicritic lava (1964 ± 12 Ma) and gabbro from the Pilgujärvi intrusion (1985 ± 10 Ma).

Discussion

The Nyasyukka dikes show a primary hydrous nature, high FeO_{tot} and TiO_2, low Al_2O_3/TiO_2, and an enrichment in immobile incompatible trace elements, which are all features typical of the Pechenga ferropicritic rocks, and therefore the

Table 4. U-Pb concentration and isotopic data for zircon from an olivine gabbro, sample P-59 (SHRIMP II)

Spot	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	ppm $^{206}Pb^*$	(1) $^{206}Pb/^{238}U$ Age	(1) $^{207}Pb/^{206}Pb$ Age		% Dis-cor-dant	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{206}Pb^*/^{238}U$	±%	err corr
1,1	0.72	719	437	0.63	8.3	85.4 ± 1						0.0816	7.6	0.01334	1.2	.155
1,2	0.39	1250	924	0.76	14.5	86.28 ± 0.77						0.0883	3.8	0.01347	0.89	.233
2,1	0.16	590	966	1.69	171	1872 ±11	1959	± 12	5	0.12018	0.66	5.584	0.96	0.337	0.7	.731
3,1	7.59	774	542	0.72	9.77	86.9 ± 1.5						0.089	22	0.01357	1.7	.079
3,2	1.46	672	363	0.56	7.29	79.8 ± 1.1						0.0783	9.6	0.01245	1.3	.140

Errors are. 1-sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively.
Error in Standard calibration was 0.41 %
(1) Common Pb corrected using measured ^{204}Pb.

parental magma of the Nyasyukka dike complex was similar to ferropicritic magma. However, there are mineralogical differences, such as the presence of orthopyroxene and coexistence of olivine and plagioclase, which suggest some chemical differences in the parental magma compositions. Also, the contents of alkalies are clearly higher in the Nyasyukka rocks at a similar MgO content, which may be related to the parental magma composition or partly also to a more altered nature of the Pechenga ferropicritic rocks.

Within error, the Sm-Nd age of 1956 ± 19 Ma is the same as the Sm-Nd age of 1990 ± 40 Ma obtained previously for the Pechenga ferropicrites [Hanski et al., 1990; Hanski, 1992; Smolkin, 1992] and the U-Pb ages of 1987 ± 5 Ma and 1980 ± 10 Ma determined for zircon and baddeleyite from the Pilgujärvi intrusion, respectively [Smolkin et al., 2003; Skuf'in and Bayanova, 2006]. However, the baddeleyite age of 1941 ± 3 Ma for the Nyasyukka dike complex indicates that the dike complex is younger than the ferropicritic magmatism at Pechenga.

These results confirmed the previous age estimate of ca. 1.97–1.98 Ga obtained by other methods for the Pechenga ferropicritic rocks, and indicates an age difference of ca. 40–45 Ma with respect to the Nyasyukka dike complex.

The initial ratio (ε_{Nd} = +1.4 ± 0.4) obtained for the Nyasyukka dikes is indistinguishable from that of the ferropicritic rocks from the Pechenga Complex (ε_{Nd} = +1.6 ± 0.4) [Hanski et al., 1990; Smolkin, 1992], and hence suggests a similar history of the parental magmas in these two areas. The higher silica activity indicated by the presence of orthopyroxene in the Nyasyukka rocks could be a result of crustal contamination, but the identical initial ε_{Nd} at Pechenga coupled with the trace element geochemical characteristics renders this explanation unlikely.

The general lithological evolution of the Pechenga Group and geochemical characteristics of the tholeiitic, MORB-like volcanism in the upper part of the group suggest that tensional forces led to attenuation of the continental crust and a gradual change of the tectonic setting from an initial cratonic environment to a deep-water environment during the ferropicritic magmatism at ca. 1.98 Ga. Whether this evolution finally resulted in disruption of the continental crust and formation of an embryonic oceanic basin is still unclear. Previous studies of the Nyasyukka dike complex have led to the conclusion that the ferropicritic magmatism manifested itself, not only as lavas and intrusions in the Pechenga supracrustal basin, but also as coeval dike rocks in the Archean basement [Smolkin and Borisova, 1995]. This is compatible with the view that the Pechenga-Varzuga Belt represents an ancient intracratonic rift zone [Smolkin, 1993, 1997]. On the other hand, Melezhik et al. [1994] and Melezhik and Sturt [1994] suggested that the rifting eventually led to the development of a Red Sea-like oceanic basin at the time of the ferropicritic and tholeiitic volcanism of the Pilgujärvi Formation. The age difference between the gabbro-wehrlites of the Pechenga Complex and the intrusions of the Nyasyukka complex, however, means that the setting of the latter cannot be used as a constraint on the geotectonic environment for the ferropicritic magmatism in the Pechenga-Varzuga Belt. In any case, it now seems that geochemically similar though not identical magmatism, represented by the Nyasyukka dike complex, took place in a cratonic environment ca. 40 Ma after the deposition of the ferropicritic volcanic rocks of the Pechenga Group.

These studies became possible as a result of cooperation between scientists from the University of Oulu, Geological Survey of Finland and Russian Academy of Sciences.

We are grateful to Tamara Bayanova for zircon separation and carrying out U-Pb isotope analyses and thank Aelita Pervunina and an anonymous reviwer for their constructive comments on the manuscript.

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