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Article *in* Geology · March 2001

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Geochem stry of k mberl tes from the Nakyn field, S ber a: Ev dence for un que source compos t on

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ABSTRACT

Two newly discovered kimberlite pipes in the Nakyn field, Siberia yield Rb-Sr isochron ages of ca. 364 Ma, similar to emplacement ages of other major diamond-bearing pipes on the Siberian platform. Unlike any other Siberian kimberlites, however, the rocks from the Nakyn field show some similarities to South African group II (micaceous) kimberlites in their mineralogy and chemical compositions. Several key geochemical ratios (TiO_2/K_2O, 0.43; Nb/Zr, 0.4) in the Nakyn kimberlites are the same as for group II, whereas others such as Ba/Nb (0.95) and Ni/MgO (45.2) are intermediate between groups I and II, and La/Nb (0.58) ratios are similar to group I kimberlites.

The Nakyn kimberlites are unique in having concentrations of incompatible elements two to three times lower than kimberlites from any cratonic area worldwide, coupled with higher Sm/Nd (0.21) and Lu/Hf (0.06) and lower La/Yb (25.8). Ranges of initial Sr and Nd isotope composition are very narrow in the Nakyn kimberlites, at $\epsilon_{Nd}(t)$ +0.9 to −0.7 and $^{87}Sr/^{86}Sr(t)$ 0.7059–0.7068. These compositions are closer to group I than to group II kimberlites, but they require a source with higher Rb/Sr and lower Sm/Nd ratios than Group I kimberlites from both Siberia and South Africa. The trace element and isotope signatures of the Nakyn kimberlites appear to indicate a specific source located within the lithospheric mantle, distinct from that of other Siberian kimberlites.

Keywords: kimberlite, geochemistry, Siberia, Sr, Nd, isotopes.

INTRODUCTION

Kimberlites are a rare ultrabasic and ultrapotassic rock type, derived from deeper levels in the mantle than any other magma. Hence, kimberlite compositions are an important source of information on deep mantle compositions and melt-generation processes. Previous studies show that basaltic and micaceous varieties of southern African kimberlites differ in their isotopic and geochemical character, and are thus divided into groups I and II, respectively (Smith, 1983; Smith et al., 1985). The chemical and isotopic contrasts between the two groups are inferred to reflect different compositions of their mantle sources. Trace element ratios in group I kimberlites are generally similar to those of oceanic island basalts (Smith et al., 1985). They also have relatively high initial $^{143}Nd/^{144}Nd$ isotope ratios and low initial $^{87}Sr/^{86}Sr$ ratios compared to group II kimberlites. Origin of group I rocks from convectively mixed (asthenospheric) mantle is generally accepted, but the position of the source remains unknown. Opinions are divided between a site just below cratonic lithosphere, or within a transitional zone between the upper and lower mantle (Smith, 1983; Ringwood et al., 1992; Taylor et al., 1994; Haggerty, 1994). Isotopic signatures of group II kimberlites (low initial $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ratios) indicate an origin by melting of a source within the lithospheric mantle that is characterized by a long-term time-integrated enrichment in incompatible elements (Smith, 1983; Tainton and McKenzie, 1994; Taylor et al., 1994). It has also been argued that Group II kimberlites could originate from the transition zone, the enriched component in their source being contributed by subducted pelagic sediments and terrigenous material (Ringwood et al., 1992).

Recent studies have shown that middle Paleozoic kimberlites from the Siberian platform are isotopically and geochemically similar to South African basaltic kimberlites (Nowell et al., 1998; Agashev et al., 2000) and can be classified as group I rocks. No group II kimberlites have been reported from Siberia, and their occurrence thus far is restricted to South Africa (Mitchell, 1995). The Botuobinsk Enterprise recently discovered two new kimberlite bodies in the Nakyn field on the Siberian platform. Here we present the first Sr and Nd isotope and geochemical data and age estimates for kimberlites from the Nakyn field and compare them to group I and II kimber-

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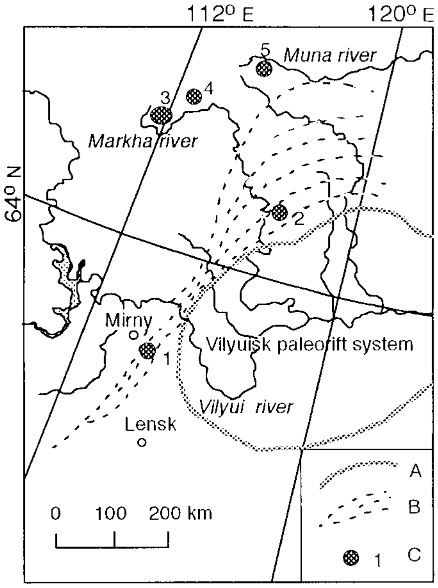

Figure 1. Schematic map of southern part of Siberian kimberlite province (after Tomshin et al., 1998). A—Boundaries of Vilyui paleorift system, B—Vilyui-Markha deep fault zone, C—kimberlite fields: 1—Malo-Botyobia; 2—Nakyn; 3—Alakit; 4—Daldyn; 5—Verkhne-Muna.

lites. The data show that the Nakyn kimberlites are the first rocks geochemically similar to group II to be reported from Siberia. In addition, they have unique trace element signatures, which were probably inherited from their mantle source.

GEOLOGICAL BACKGROUND, SAMPLES AND AGE DETERMINATION

The Nakyn kimberlite field is located in the east of the Siberian platform, in the Vilyui-Markha deep fault zone, a northeast-trending structure associated with the middle Paleozoic Vilui rift system (Fig. 1). The well-known Mir pipe (Malobotuobia kimberlite field) also is located in that zone ~350 km southwest of the Nakyn field, a magmatic complex that includes tholeiitic and alkaline basalts, kimberlites, and explosion breccias (Tomshin et al., 1998). Only two kimberlite pipes (Botuobinskya and Nurbinskaya) have been discovered; both are diamondiferous. The kimberlites originally intruded an early Paleozoic terrigenous-carbonate sequence and were covered by Jurassic terrigenous sediments 30–80 m thick.

Samples for this study were taken from drill cores, from 120–420 m below the surface. They are hard, dense, but serpentinized rocks containing abundant serpentinized olivine xenocrysts up to 1 cm and largely fresh phlogopite in the groundmass. Cr-rich spinel is the most abundant accessory oxide phase in the rocks; there are very subordinate amounts of ilmenite and perovskite. Low contents of the latter two minerals are considered typical of

TABLE 1. AVERAGE MAJOR ELEMENT COMPOSITIONS OF KIMBERLITES

	1	2	3	4
SiO_2	32.56	37	32.6	28.1
TiO_2	0.46	1.4	1.7	1.22
Al_2O_3	3.52	3.8	2.7	2.45
Fe_2O_3	6.11	8	9.2	7.85
MnO	0.12	0.2	0.2	0.14
MgO	27.97	26.7	29.1	28.3
CaO	9.63	6.9	8.3	11.95
Na_2O	0.01	0.2	0.3	0.03
K_2O	1.23	3.3	1	0.57
P_2O_5	0.45	1	0.7	0.48
LOI	18.15	11.1	14.2	18.86

Note: 1—Nurbinskaya, this study. 2, 3.—South Africa group II and I respectively (Taylor et al., 1994). 4.—Siberia group I (Agashev et al., 2000). LOI is loss on ignition. Oxides in wt%.

group II kimberlites (Smith et al., 1985). No direct data on inclusions in diamonds from the Nakyn field are available. Studies of heavy mineral concentrates have found both Cr-rich spinel and garnet with compositions corresponding to those normally found as inclusions in diamonds, chrome-spinel being more abundant than garnet.

For age determination by the Rb-Sr isochron method, fresh phlogopite grains were handpicked under microscope. The isochron defined by the three acid-leached phlogopite fractions and a whole-rock kimberlite gives an age of 364 ± 9Ma for the Botuobinskaya pipe, with an initial Sr isotope ratio of 0.70611. An acid-leached phlogopite separate, a phlogopite-rich groundmass separate, and a whole-rock kimberlite sample from the Nurbinskaya pipe yield an isochron with an age (364 ± 5 Ma) identical to that from Botuobinskaya, and an initial ratio of 0.7059. The age estimates we obtained fall within the range of 353–367 Ma defined earlier for the main Siberian diamondiferous kimberlite emplacement event (Kinny et al., 1997).

CHEMICAL COMPOSITION

Compared to group I kimberlites from South Africa, the Nakyn samples have somewhat greater Al_2O_3 and CaO contents and distinctly lower contents of Fe_2O_3, TiO_2, and P_2O_5 (Table 1 and Appendix Table 1[1]. Most Nakyn samples also have distinctly lower TiO_2 contents and higher K_2O contents than other Siberian kimberlites, such as those from Udachnaya. The relationship between the TiO_2 and K_2O contents provides an important distinction between group I and group II kimberlites (Smith et al., 1985). Rocks from the Nurbinskaya pipe plot well within the field of South African group II kimberlites, whereas

[1]GSA Data Repository item 200125, Major and trace elements and Sr and Nd isotope composition of the Nakyn kimberlites, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org or at www.geosociety.org/pubs/ft2001.htm.

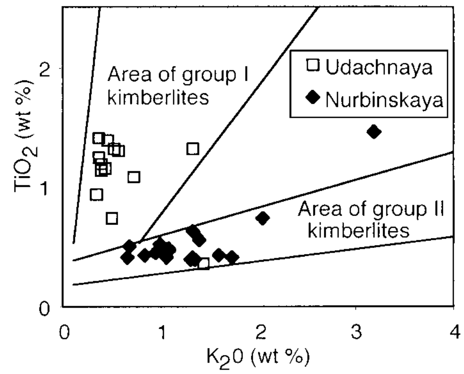

Figure 2. TiO_2-K_2O relationships in Nurbinskaya and Udachnaya kimberlites in comparison with South African group I and II kimberlites. Sources of data: Vasilenko and Zinchuk (1995), Smith et al. (1985), and this study.

most kimberlites from Udachnaya, a typical Siberian pipe, plot within the group I field (Fig. 2). However, the Nakyn samples also appear to differ significantly from group II rocks in their SiO_2, Ca_2O, Fe_2O_3 and K_2O contents.

Concentrations of incompatible trace elements in the Nurbinskaya pipe kimberlites are significantly lower than those reported from other kimberlites (Fig. 3). Typically, they are 20%–80% lower than in the Udachnaya pipe (group I) and make up about one-third of those in the group II kimberlite from Finsch, South Africa. The differences with other kimberlites are less dramatic for more compatible elements (Ni, Cr, Y), but their contents tend to be lower as well. In addition to lower concentrations, the primitive mantle normalized trace-element pattern of average Nakyn kimberlite has significant differences with that for the Udachnaya rocks (Fig. 3). Udachnaya kimberlites feature a strong negative K anomaly, and have different slopes of the pattern segments between Sr and Pb. By comparison, the shape of the Nakyn trace element pattern in Figure 3 is similar to that of the group II Finsch kimberlites (Fraser and Hawkesworth, 1992). In the Nakyn kimberlites, the key geochemical ratios TiO_2/K_2O (0.43) and Nb/Zr (0.4) are the same as in group II kimberlites (Table 2). Others such as Ba/Nb (0.95) and Ni/MgO (45.2), are intermediate between groups, whereas La/Nb (0.58) is similar to group I. However, Sm/Nd (0.21), La/Yb (25.8), and Lu/Hf (0.06) ratios are almost outside the range of any kimberlites. Overall, in terms of major and trace element composition, the Nakyn kimberlites are clearly distinct from other Siberian kimberlites. The Nakyn rocks have significant similarities to group II kimberlites, but some chemical signatures set them apart from most other kimberlites worldwide as demonstrated by Sm/Nd and Lu/Hf ratios (Table 2).

To assess the possible effects of weathering on the trace element patterns, we examined

TABLE 2. COMPARISON OF KEY GEOCHEMICAL RATIOS

	1	2	3	4
Ni/MgO	45.2	49	40	42.4
TiO_2/K_2O	0.43	0.42	1.7	1.58
Nb/Zr	0.4	0.48	1.1	1.1
Ce/Sr	0.11	0.32	0.24	0.3
La/Nb	0.58	1.43	0.55	0.55
Ba/Nb	16.9	26	—	5.14
Sm/Nd	0.206	0.123	0.142	0.135
Lu/Nf	0.06	0.021	0.021	0.029
La/Yb	25.8	170	—	180

Note: 1—Nurbinskaya, 2, 3—South Africa group II and I, respectively, 4—Siberia group I. Ratios for South African kimberlites after Taylor et al. (1994). Ba/Nb and La/Yb ratios for group II are estimates after Mitchell (1995). Sm/Nd and Lu/Hf ratios for South Africa are from Nowell et al. (1999). Siberia group I after Nowell et al. (1998) and Agashev et al. (2000). Nurbinskaya kimberlites were analyzed for trace elements by inductively coupled plasma–mass spectrometry at Niigata University following the procedure of Eggins et al. (1997).

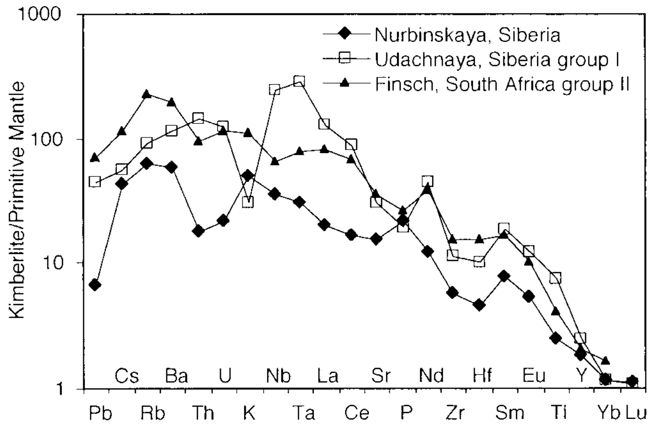

Figure 3. Primitive mantle-normalized trace element patterns of the Nurbinskaya kimberlite (average, *n* = 9) compared to average kimberlites from Udachnaya (*n* = 2) and Finsch (*n* = 16) pipes. Data sources: Udachnaya—Nowell et al. (1998), Agashev et al. (2000), Finsch—Fraser and Hawkesworth (1992), Nurbinskaya—this study. Primitive mantle values are from McDonough and Sun (1995).

ratios of inert to mobile trace elements assuming the order of mobility: Sr, Rb > Ba > La, Ce > P, Zr > Nb established by Taylor et al., (1994). No systematic changes in the ratios of elements with distinct mobility are seen in the Nurbinskaya kimberlites. Some elemental ratios are lower (e.g., Ce/Sr = 0.11), others (e.g., La/Nb = 0.58) are in the range of unaltered kimberlites (see Taylor et al., 1994).

Rb-Sr AND Sm-Nd ISOTOPE SYSTEMATICS

The $^{143}Nd/^{144}Nd$ isotope ratios measured in the Nakyn kimberlites are within the range of Siberian kimberlites (Nowell et al., 1998; Agashev et al, 2000). However, their $^{147}Sm/^{144}Nd$ ratios (0.122–0.125) are higher than those in other kimberlites, from Siberia and worldwide. As a result, initial Nd isotope ratios at the time of emplacement (364 Ma) of the Nakyn samples are below those of many other Siberian kimberlites and are close to the bulk silicate earth (BSE) composition at that time, with a very limited range of $\epsilon_{Nd}(t)$ from +0.9 to −0.7 (Fig. 5). Initial $^{87}Sr/^{86}Sr$ isotope compositions (0.7059–0.7068) are moderately radiogenic relative to the BSE composition. On the ϵ_{Nd} vs. $^{87}Sr/^{86}Sr$ plot at the time of emplacement, the Nakyn data plot between the fields of South Africa groups I and II kimberlites, being closer to group I (Fig. 4). Although some Nakyn samples partially overlap the field of other Siberian kimberlites, as a group they appear to have distinctly lower $\epsilon_{Nd}(t)$ and higher initial $^{87}Sr/^{86}Sr$ values.

DISCUSSION

It is generally assumed that Sr and Nd isotope compositions in kimberlites reflect their primary source compositions (Smith et al., 1985; Taylor et al., 1994). The Sr and Nd isotopic character of the Nurbinskaya rocks require a source with time-averaged Sm/Nd and Rb/Sr ratios respectively similar to and higher than those in the model BSE composition. This implies that the source rocks were enriched in incompatible elements relative to the mid-ocean ridge basalt (MORB)–type and ocean island basalt (OIB)–type asthenospheric mantle, and were stored in the lithospheric mantle, isolated from convective mixing, for a long time before generation of kimberlite magmas.

To assess the storage time in the lithosphere, we calculated model ages for the source enrichment relative to the depleted mantle (DM) model composition of Zindler and Hart (1986). These estimates are based on a common assumption that the Siberian cratonic mantle underwent high degrees of partial melting, mostly in the Archean (Pearson et al. 1995). The Nd_{DM} model age estimates vary between 1.1 and 1.2 Ga. The Sr isotope composition recalculated back to a value of 0.703 requires 0.8–1.1 Ga to develop present-day $^{87}Sr/^{86}Sr$ ratios. We conclude that the source of the Nurbinskaya kimberlites was probably enriched 450–800 m.y. (minimum age) before the generation of the kimberlite magma.

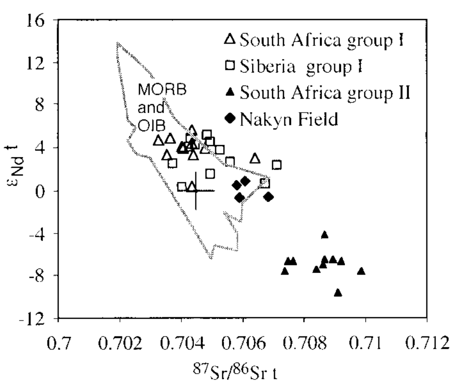

Figure 4. Sr-Nd isotope compositions of Nakyn field (Nurbinskaya and Botuobinskaya pipes) kimberlites compared to South African group I and II kimberlites (Smith, 1983; Kramers et al., 1981), Siberian kimberlites (Nowell et al., 1998; Agashev et al., 2000). Field of main mantle reservoirs: mid-ocean ridge basalt (MORB) and ocean island basalt (OIB) after Hofmann (1997). Cross at ϵ_{Nd} = 0 and $^{87}Sr/^{86}Sr$ = 0.7045 marks position of bulk silicate earth composition.

The low concentrations of incompatible elements in the Nakyn kimberlites compared to other kimberlites worldwide require specific source compositions and/or generation processes. Several factors could be relevant, such as evolution of source composition, degree of partial melting, residual mineralogy, and contamination by entrained crustal and mantle materials.

We consider that the Nurbinskaya kimberlite source evolved in a way similar to that of Group II kimberlites in the model of Tainton and McKenzie (1994). Strong depletion of the cratonic mantle by a high degree of partial melting (komatiite extraction) in the Archean was followed by enrichment in incompatible elements by addition of 4%–10% silicate melt derived from a low degree (0.5%) of partial melting of an asthenospheric-like DM source. On the basis of geochemical similarities, we consider that the source of the Nurbinskaya kimberlites was similar to that of group II kimberlites in terms of enrichment patterns. However, the significantly lower concentrations of incompatible elements in the Nakyn rocks may imply significantly lower incompatible-element abundances in their sources. It is likely that degrees of enrichment by melt addition in their source were less than in the model of Tainton and McKenzie (1994)—i.e., below 4%. The Sr and Nd isotope compositions indicate that storage time in the nonconvecting mantle may be lower as well, though this interpretation depends on parent-daughter isotope ratios in the source.

Low La/Yb and high Sm/Nd ratios indicate relatively small fractionation of the rare earth elements (REE) and possible derivation by higher degrees of partial melting, similar to that observed in basalts. However, major element compositions do not support this proposal, being typically kimberlitic, with high MgO and volatile contents, and low contents of components enriched in basalts, such as TiO_2, FeO, and Al_2O_3. It is also possible that parent magmas of the Nakyn kimberlites were produced by mixing of asthenospheric-type melt and lithospheric melt from the slightly enriched source, particularly considering that their Sr-Nd isotope compositions and La/Nb ratios are closer to those of group I than of group II kimberlites.

Residual mineralogy of the source is another major factor that can modify the magma composition. From the comparatively flat REE patterns and high Lu/Hf ratios, we conclude that garnet did not play an important role in the Nurbinskaya kimberlite source. From the viewpoint of source mineralogy, it is significant that chrome-spinel rather than garnet mostly represents the diamond paragenesis assemblage in these kimberlites. This suggests that the composition of the diamond-bearing section of the lithosphere sampled by kimberlites was dominated by spinel peridotites, or that the kimberlite source was located somewhere in that section. The Cr/(Cr+Al) ratio reflects the degree of depletion, and an increase of this index in the rocks suggests that the spinel stability field extended to a depth of 200 km or more (Canil and Wei, 1992). Kesson and Ringwood (1989) proposed that such Cr-spinel and Cr-rich garnet-bearing peridotites could be a former subducted oceanic spinel-harzburgite. If Cr-spinel–bearing peridotites are accepted as the source rocks, clinopyroxene and phlogopite should be the main enriched components. Mineral/melt distribution coefficients for phlogopite are nearly the same for all REE (Rollinson, 1993), and this helps explain the flat REE pattern of kimberlites. The Sm/Nd and Lu/Hf ratios can be effectively fractionated by residual garnet because Sm and Lu are more compatible in garnet than Nd and Hf. The Nurbinskaya pipe rocks have less fractionated Sm/Nd and Lu/Hf ratios than all other kimberlites (Table 2), supporting our proposal that the source of Nurbinskaya rocks was depleted in garnet.

Crustal contamination is not discussed because average continental crust (Wedepohl, 1995) has higher concentrations of most incompatible elements, and therefore cannot have a role in lowering incompatible element contents in this kimberlite. Contamination by mantle peridotite leads to increases in Ni contents in kimberlites. The samples examined have average 1066 ppm Ni, lower than average Siberian kimberlites (1204 ppm), and therefore cannot contain more peridotite than others in Siberia.

CONCLUSIONS

Study of the Nakyn field kimberlites reveals geochemical features distinct from those of other Siberian kimberlites, but some similarities with South Africa group II kimberlites. The principal similarities with group II kimberlites are the shape of trace element patterns normalized to primitive mantle and low average TiO_2/K_2O ratios (0.43) and Nb/Zr ratios (0.4). However, low incompatible-element concentrations, low La/Yb ratios, and high Sm/Nd ratios set them apart from other kimberlites worldwide and require an origin from a different source or by a different process.

The Sr and Nd isotope compositions of Nakyn kimberlites suggest the presence of a time-averaged incompatible- element-enrichment component in their source, which was isolated from convection at least 450 m.y. before emplacement. Therefore, the enriched component in their source was located in the cratonic mantle. On the basis of geochemical similarities, this evolved in a way similar to the model proposed by Tainton and McKenzie (1994) for group II kimberlites. However, the low incompatible-element concentrations, high Lu/Hf ratios, and low La/Yb ratios require a less enriched source composition and less garnet in the residual mineralogy. Therefore, the Nakyn field kimberlites can have been produced by melting of modally metasomatized chrome-spinel–bearing peridotites and/or by interaction of asthenospheric melts with a slightly enriched component of the lithospheric mantle.

Although emplacement of the Nakyn kimberlites is related to the same middle Paleozoic magmatic cycle as other diamond-bearing kimberlites of the Siberian platform, they carry unique signatures of their source composition.

ACKNOWLEDGMENTS

We thank D. Ionov for a review that helped us to improve the manuscript; E. Takazawa for trace elements analyses; and B. Roser for improvement of the English.

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Manuscript received July 5, 2000
Revised manuscript received December 1, 2000
Manuscript accepted December 1, 2000

Printed in USA

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