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# Rb–Sr and Sm–Nd isotopes in garnet pyroxenite xenoliths from Siberian kimberlites: an insight into lithospheric mantle

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Rb–Sr and Sm–Nd isotope compositions of seven garnet pyroxenite xenoliths from Udachnaya and Mir kimberlites, Siberia, are presented. Five of them are websterites, and the other two are clinopyroxenites. The websterite suite is divided into two groups (Group A and Group B) according to their mineral chemistry. Group B websterites are characterized by presence of jadeite-rich clinopyroxene and pyrope-poor garnet. The Garnet-orthopyroxene geobarometry indicates that Group A were produced in deep positions of the cratonic mantle (up to diamond stability field) and Group B websterites are formed at lower pressure (ca. 19 kb).

Probably, the Rb–Sr isotope system was re-equilibrated at the time of kimberlite emplacement at 367 Ma. The initial Sr isotope compositions differs from one group to the other. The initial ratio $^{87}Sr/^{86}Sr$ (0.70272–0.70338) for Group A is lower than that of Group B (0.70485–0.70737). The Sm–Nd isotope system in all samples gives apparent isochron ages considerably older than that of the emplacement of host kimberlites. Group A websterites and clinopyroxenites are apparently younger (1223–582 Ma) than those of Group B (1550–1465 Ma). The origin of garnet pyroxenites is suggested as crystal accumulation from LREE-enriched melts which episodically added into peridotite-dominated lithospheric mantle. These melts played also a role of metasomatic agent to the host peridotites. A delaminated lower crustal protolith has probably been involved in Group B origin.

The Sm–Nd isotope study reveals a systematic increase of initial $^{143}Nd/^{144}Nd$ with time. A vairable Sm–Nd isotope data suggest that peridotites and pyroxenites in lithospheric mantle beneath the Udachnaya area were in isotopic equilibrium, but not beneath the Mir area where peridotites depleted in initial Nd isotope composition.

## Introduction

The investigation of isotope compositions of mantle xenoliths carried by kimberlite magmas is an important tool for our understanding of the evolution and composition of cratonic mantle. Numerous studies in this field were carried out during the last two decades. It is now common knowledge that cratonic mantle is more heterogeneous than oceanic mantle due to isolated evolution since mid-Archaean (i.e. Pearson et al., 1995 and reference there). Isotope systems of xenoliths record a complex history of cratonic mantle, including subduction related events. At present time the origin of eclogitic part of cratonic mantle is modelled in two ways: 1). Consider this part as fragments of subducted oceanic crust, and 2) as cumulates from deep mantle melts. Evidence supporting both models has been reported from eclogites in the South African and Sibe-

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rian cratons (Neal et al., 1990; Viljoen et al., 1996; Snyder et al., 1997). Many xenoliths of low-temperature garnet peridotite in Siberian kimberlites exhibit Sm-Nd isochron ages of garnet-clinopyroxene pairs considerably older than the emplacement of the host kimberlites (McCulloch 1989; Pearson et al., 1995; Gunther and Jagoutz 1997). The meaning of these age relation of xenolith formation is still uncertain (Pearson et al., 1995).

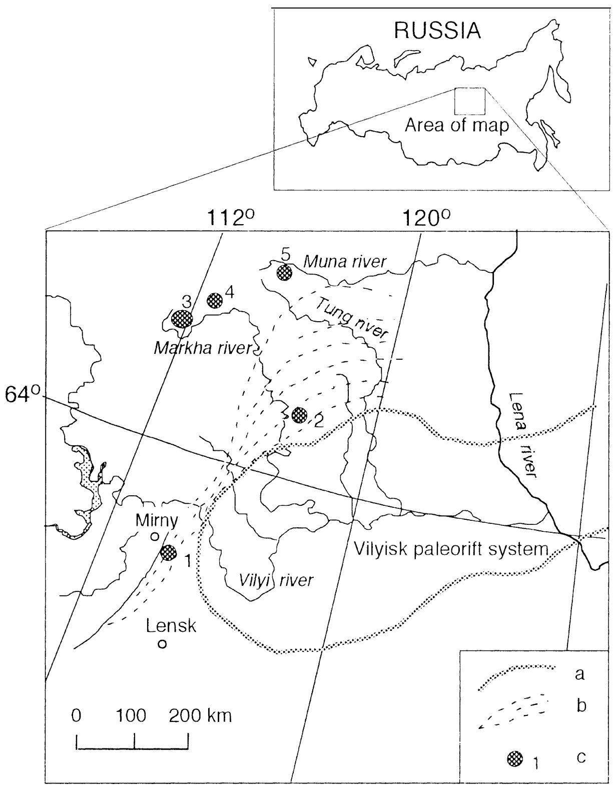


**Figure 1.** Schematic map of the southern part of the Siberian kimberlite province (after Tomshin et al., 1998). a) Boundary of Vilyisk paleorift system. b) Traces of the Viluisk-Markhinskya deep faults zone. c) Kimberlite fields; 1, Malo-Botyobia; 2, Nakyn; 3, Alakit; 4, Daldyn; 5, Verkhne-Myna. Mir and Udachnaya pipes are located in the Malo-Botuobia and Daldyn kimberlite fields respectively.

Garnet pyroxenites constitute a small portion of mantle xenoliths in kimberlites, around 3% in the Udachnaya pipe, Siberia (Sobolev, 1990). Compared with peridotites and eclogite suites, they are not well characterized geochemically. Nd isotope compositions of two garnet websterite xenoliths together with two eclogite xenoliths from the Obnazhennaya pipe, Siberia, were reported by McCulloch (1989). Their isotopic character was interpreted as evidence of early earth differentiation. In this paper we present and discuss Sr and Nd isotope compositions of minerals in seven garnet pyroxenite xenoliths in the Udachnaya (six) and Mir (one) kimberlite pipes (Fig. 1). Geological descriptions of the pipes are given elsewhere (i.e., Pearson et al., 1995; Snyder et al., 1997).

## Samples

Five of the seven samples are garnet websterites, and the other two are garnet clinopyroxenites. The garnet websterites are very fresh, and are medium to coarse grained. They are garnet-dominant, and consisted of 35-50% garnet and two pyroxenes in variable amounts (Table 1 and Fig. 2). The exception is sample m153/72 from the Mir pipe, containing slightly altered orthopyroxene as a major phase. The garnets usually contain oriented rutile needles. Medium grained samples display weak layered texture, with segregation of minerals

**Table 1.** Petrographical data of garnet pyroxenites

| Sample<br>Websterites | Mode<br>Gar-Cpx-Opx | Texture |
|---|---|---|
| Uv 21/91 GrB | 45-20-35 | Medium grained, mostly 2-4mm, little metamorphic segregation or layered txt, Opx or Cpx rich layers or glomerocrysts. |
| Uv 403/84 GrB | 50-35-15 | Medium grained, 1-4mm, Gar or Cpx rich layer or segregations. |
| Uv 22/91 GrA | 50-20-30 | Coarse grained , mostly 3-5mm, Gar up to 8mm. |
| Uv 143/86 GrA | 42-25-33 | Medium-coarse grained, Cpx slightly altered. |
| m153/72 GrA | 35-25-40 | Coarse grained, 2-10mm, Opx slightly altered. |
| Clinopyroxenites | | |
| Uv /m89 | 30-70 | Medium grained, Cpx altered (50%)<br>Phlogopite 2%. (modally metasomatised). |
| Uv 364/89 | 30-70 | Coarse grained, Cpx mostly fresh,<br>Gar strongly fractured. |

Note: Gar, Garnet; Cpx, Clinopyroxene; Opx, Orthopyroxene

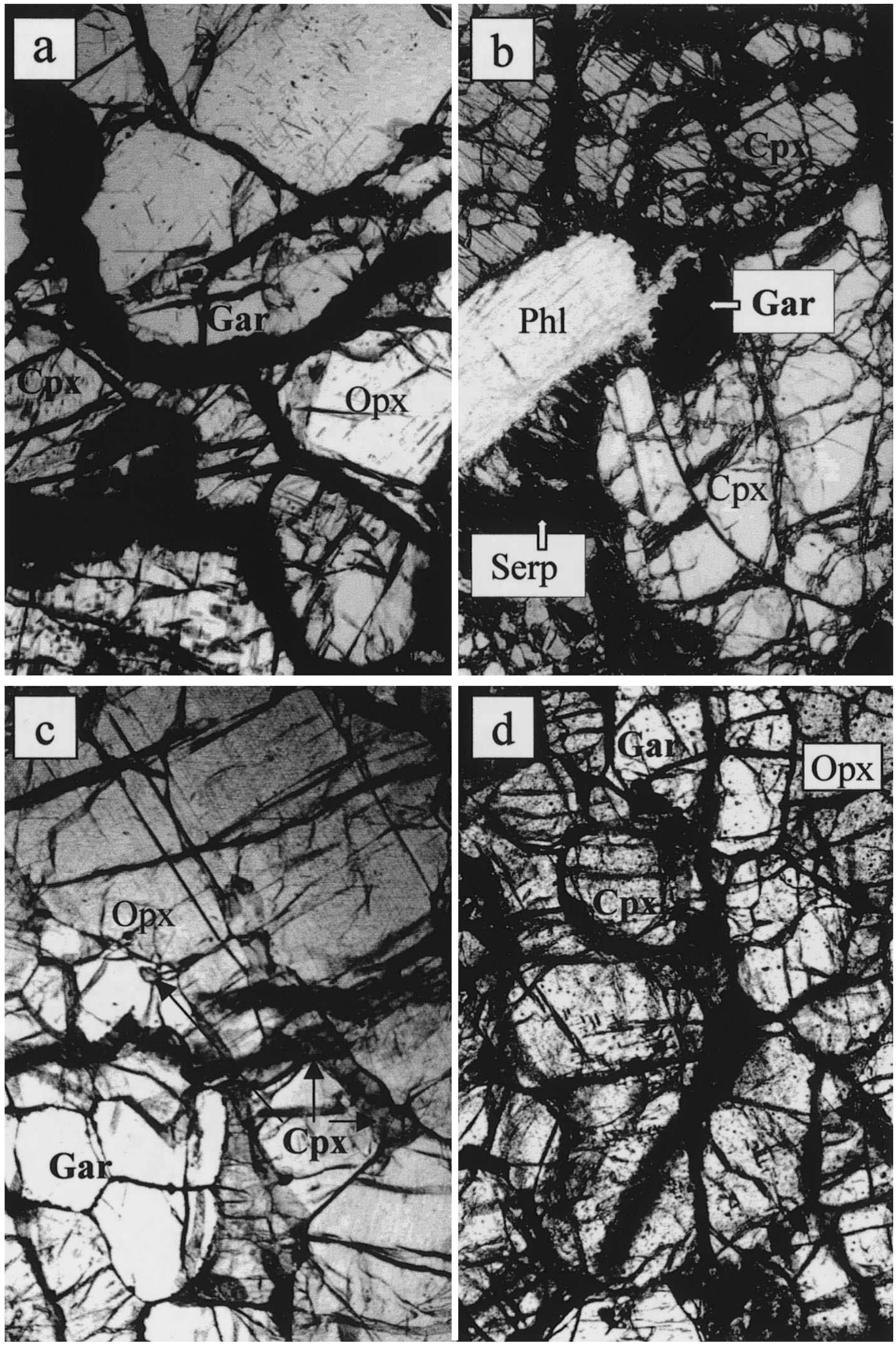


**Figure 2.** Photomicrograph of garnet pyroxenite xenoliths (Gar, Garnet; Opx, Orthpyroxene; Cpx, Clinopyroxene; Phl, Phlogopite; Serp, Serpentine.)
a) Sample Uv22/91 Group A garnet websterite
b) Sample Uv/m89 garnet clinopyroxenite, modally metasomatised
c) Sample Uv21/91 Group B garnet websterite
d) Sample Uv403 Group B garnet websterite
The field of view is 6 mm on the long axis of each photograph.

into discontuous short layers or glomerocrysts. The garnet clinopyroxenites are medium to coarse grained, and consisted of 30% purple garnet and 70% emerald green Cr–diopside. Sample Uv/m89, which often contains altered clinopyroxene, is modally metasomatised. It contains about 2% of phlogopite (Fig. 2b).

### Sample preparation and analytical techniques

Pieces of xenolith cores were crushed and mineral concentrates were roughly separated. These concentrates were crushed again and pure mineral grains were hand-picked under the binocular microscope. The minerals were then leached in similar way to that described by Pearson et al. (1995). The leached concentrates were washed by ultra-pure water and powdered using tungsten mill. The weights of samples used for isotope analysis were 150–200 mg for garnet and 50–100 mg for clinopyroxene. Samples were dissolved in HF-HCl-$HNO_3$ mixture in Teflon jars (Savillex beakers). Several garnets were dissolved in high-pressure bomb.

Sr and Nd isotope analyses were performed at the Division of Earth and Planetary Science, Graduate School of Science, Hokkaido University. The sample dissolution and separation of Sr and Nd were carried out by the method of Kagami et al. (1989). Total procedural blanks were checked several times during the analysis. Nd and Sm blank concentrations were stable and low, never exceeding 60 pg and 30 pg, respectively. Sr and Rb blanks were higher and variable (from 0.3 to about 1 ng) than Nd and Sm blanks for unknown reasons. Blank influence on the Sr isotope ratios for garnets with Sr higher than 1 ppm was negligible. In the case of garnets with 0.5 ppm of Sr, the blank influence was around 1% (1 ng-highest possible blank/200 mg-sample). Garnets with very low Sr contents were excluded from consideration. A Finnigan MAT 262 mass spectrometer equipped with seven collectors, operating in static mode (Orihashi et al., 1998), was used for the isotope analysis. The measured $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were normalized to $^{86}Sr/^{88}Sr=0.1194$ and $^{146}Nd/^{144}Nd=0.7219$, respectively. During this study, analytical results for standards were as follows: SRM 987 $^{87}Sr/^{86}Sr=0.710257$ ($\pm11$), La Jolla $^{143}Nd/^{144}Nd=0.511847$ ($\pm8$). Concentrations of Rb, Sr, Sm and Nd were analyzed by the isotope dilution method. The precision are within 0.5% established by 10 separate analyses of Jb-1a standard. Major-element analyses of minerals were carried out by electron microprobe.

### Mineral chemistry and geothermometry

Based on the mineral compositions (Fig. 3 and Table 2) the websterite suite can be divided into two groups (A and B). The first group includes three samples (Uv22/91, m153/72 and Uv143/86) which contain magnesian garnets (16.8–21.2 wt% MgO) and jadeite-poor clinopyroxenes. They are comparable to Group A eclogites of

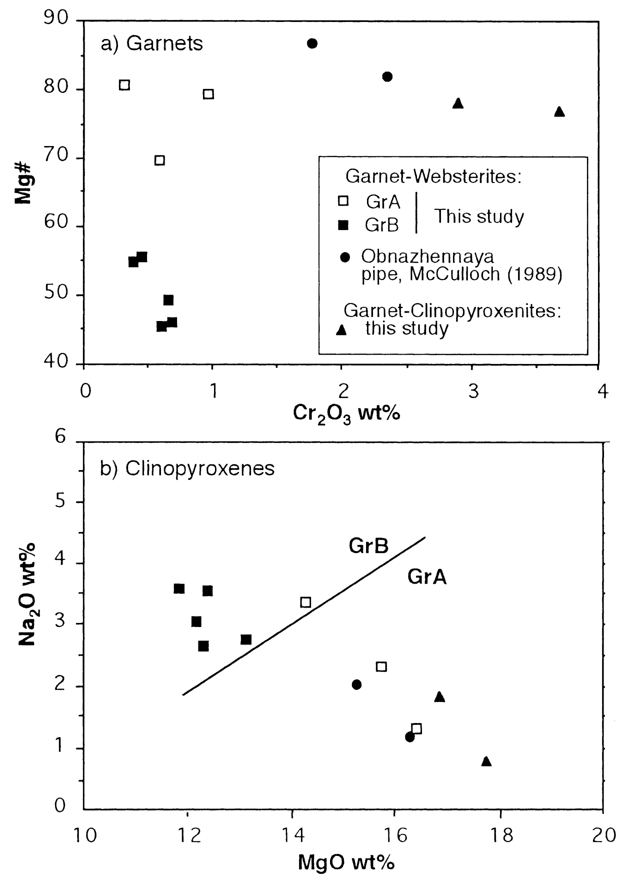


**Figure 3.** Composition of garnets (a) and clinopyroxenes (b) of garnet-pyroxenite xenoliths. Classification boundary between GrA (Group A) and GrB (Group B) for clinopyroxenes after Taylor and Neal (1989).

the classification of Taylor and Neal (1989) and Snyder et al. (1997). The other two websterites (Uv403 and Uv21/91) show a high FeO content in garnet (19.26–23.1 wt%) and clinopyroxene compositions that falling in the field of Group B eclogites by Taylor and Neal (1989) (Fig. 3). Orthopyroxenes in the latter samples exhibit a zoning for $Al_2O_3$, decreasing from core to rim. The two groups above are referred as Group A (Gr A) and Group B (Gr B) websterites in the forthcoming chapters. The garnet-clinopyroxenites are similar to peridotite than the eclogite suite in mineral color and chemical signatures. Their garnets contain as much as 2.9–3.7 wt% $Cr_2O_3$.

Using mineral compositions in Table 2, P-T equilibrium conditions were estimated by the garnet-clinopyroxene thermometer of Ellis and Green (1979), the two-pyroxene thermometer of Brey and Kohler (1990) and the garnet-orthopyroxene geobarometer of Nickel and Green (1985). Estimated pressure and temperature are ca. 19 Kbar, 790–830°C for the Group B websterites and 26–46 Kbar, 760–1060°C for Group A

**Table 2.** Major element compositions of main constituent minerals of garnet pyroxenite xenoliths in wt %

| Sample | U v403/84 | | | | Uv21/91 | | | | Uv22/91 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mineral | Gar | Cpx | OpxCore | OpxRim | Gar | Cpx | OpxCore | OpxRim | Gar | Cpx | Opx |
| $SiO_2$ | 40.45 | 52.01 | 55.66 | 55.51 | 39.65 | 52.50 | 54.09 | 54.72 | 41.46 | 54.2 | 56.91 |
| $TiO_2$ | 0.04 | 0.59 | 0.01 | 0.01 | 0.03 | 0.66 | 0.01 | 0.02 | 0.19 | 0.09 | 0.05 |
| $Al_2O_3$ | 22.19 | 5.76 | 1.55 | 1.28 | 21.53 | 6.11 | 1.52 | 1.21 | 22.14 | 1.71 | 0.43 |
| $Cr_2O_3$ | 0.47 | 0.36 | 0.07 | 0.08 | 0.65 | 0.57 | 0.14 | 0.11 | 0.58 | 0.21 | 0.03 |
| FeO | 18.61 | 5.79 | 12.27 | 12.32 | 23.11 | 5.69 | 16.17 | 15.97 | 13.26 | 3.39 | 8.47 |
| MnO | 0.54 | 0.05 | 0.06 | 0.08 | 0.21 | 0 | 0.12 | 0.12 | 0.31 | 0.06 | 0.09 |
| MgO | 13.06 | 13.09 | 29.70 | 30.13 | 10.60 | 11.89 | 27.56 | 27.78 | 16.79 | 16.42 | 32.73 |
| CaO | 4.72 | 20.00 | 0.25 | 0.14 | 4.35 | 18.60 | 0.25 | 0.23 | 4.76 | 21.46 | 0.30 |
| $Na_2O$ | 0.01 | 2.69 | 0.01 | 0.01 | 0.01 | 3.58 | 0.05 | 0.04 | 0.02 | 1.32 | 0.01 |
| $K_2O$ | 0.0 | 0.02 | 0.0 | 0.0 | 0.0 | 0.02 | 0.0 | 0.0 | 0.0 | 0.03 | 0.0 |
| Total | 100.09 | 100.36 | 99.57 | 99.55 | 100.14 | 99.62 | 99.91 | 100.20 | 99.52 | 98.90 | 99.02 |
| Mg# | 55.58 | 80.12 | 81.19 | 81.34 | 44.99 | 78.84 | 75.24 | 75.62 | 69.30 | 89.62 | 87.32 |
| Ca# | | 52.33 | | | | 52.92 | | | | 48.43 | |

| Sample | m 153/72 | | | Uv143/86 | | | Uv364/89 | | Uv/m89 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Mineral | Gar | Cpx | Opx | Gar | Cpx | Opx | Gar | Cpx | Gar | Cpx |
| $SiO_2$ | 42.6 | 55.2 | 57.2 | 41.96 | 55.18 | 57.81 | 41.57 | 55.16 | 41.75 | 55.23 |
| $TiO_2$ | 0.06 | 0.27 | 0.04 | 0.13 | 0.23 | 0.06 | 0.57 | 0.24 | 0.28 | 0.11 |
| $Al_2O_3$ | 22.67 | 3.38 | 0.90 | 22.78 | 4.79 | 0.62 | 19.76 | 1.87 | 20.06 | 0.99 |
| $Cr_2O_3$ | 0.96 | 0.6 | 0.04 | 0.32 | 0.25 | 0.04 | 2.93 | 0.82 | 3.71 | 0.72 |
| FeO | 9.42 | 1.44 | 4.97 | 9.03 | 2.77 | 5.39 | 9.33 | 2.76 | 9.73 | 2.07 |
| MnO | 0.44 | 0.04 | 0.03 | 0.24 | 0.04 | 0.07 | 0.48 | 0.07 | 0.52 | 0.08 |
| MgO | 20.21 | 15.75 | 36.36 | 21.24 | 14.27 | 35.20 | 17.83 | 16.75 | 18.37 | 17.65 |
| CaO | 4.28 | 20.91 | 0.19 | 3.75 | 18.41 | 0.52 | 6.85 | 20.45 | 6.29 | 22.62 |
| $Na_2O$ | 0.03 | 2.27 | 0.05 | 0.06 | 3.36 | 0.13 | 0.11 | 1.77 | 0.03 | 0.79 |
| $K_2O$ | 0.0 | 0.02 | 0.0 | 0.0 | 0.02 | 0.01 | 0.0 | 0.03 | 0.0 | 0.01 |
| Total | 100.38 | 99.81 | 99.84 | 99.51 | 99.31 | 99.85 | 99.44 | 99.92 | 100.76 | 100.31 |
| Mg# | 79.27 | 95.12 | 92.88 | 80.75 | 90.18 | 92.09 | 77.31 | 91.54 | 77.10 | 93.83 |
| Ca# | | 48.82 | | | 48.11 | | | 46.73 | | 47.94 |

Note: Gar, Garnet; Cpx, Clinopyroxene; Opx, Orthopyroxene.

(Fig 4). Pressures for Group B samples estimated by using $Al_2O_3$ contents of orthopyroxene rims are 22–23 kbar. The formation temperature of clinopyroxenites was estimated as 910–1005°C under assumed pressure of 25 Kbar. It is noted that calculated temperature for the sample Uv143/86 using the garnet–clinopyroxene equation is 200°C higher than that estimated from two-pyroxene solvus (Fig. 4). The difference of estimated temperatures can be caused by the wrong assumption for equilibrium mineral assemblage, as discussed later.

## Isotope geochemistry

The concentrations of Sm and Nd in the websterite clinopyroxenes (1.23–11.15 ppm and 16.7–77 ppm respectively) significantly exceed those of mantle eclogites from Siberia (Snyder et al., 1997) as well as peridotites (Pearson et al., 1995), but are comparable with those in Group A eclogites from Bellsbank (Neal et al., 1990) and in group 2 eclogites from the Orapa kimberlite (Viljoen et al., 1996). Measured $^{143}Nd/^{144}Nd$ isotope ratios of clinopyroxenes differ significantly from that of co-existing garnets, and they range between 0.51518–0.51697 for garnet and 0.51097–0.51221 for clinopyroxene (Table 3). Clinopyroxenes of Group A samples have higher Nd isotope ratios than of Group B. The $^{147}Sm/^{144}Nd$ ratios of garnets (0.52–1.09) are also much higher than those of clinopyroxenes (0.024–0.11). Clinopyroxenes with the lowest $^{147}Sm/^{144}Nd$ (sample Uv143/86) have the highest $^{143}Nd/^{144}Nd$, and co-exist with garnets having the highest $^{147}Sm/^{144}Nd$. The Sr isotope ratios of minerals differ from one group to the other (Table 3 and Fig. 5), being slightly enriched in Group B (0.70485–0.70737) and depleted in Group A (0.70272–0.70338) at the age of host kimberlite emplacement (367 Ma; Kinny et al., 1997). The Rb–Sr isotope system in several samples yield ages close to the kimberlite emplacement/eruption age of 367 Ma suggesting that Rb–Sr isotopes were re-equilibrated at that time. Garnet and clinopyrexene in the phlogopite-bearing clinopyroxenite (Uv/m89) does not show the significant difference in $^{143}Nd/^{144}Nd$ ratio, as do the minerals in the websterites (Table 3). However, $^{147}Sm/^{144}Nd$ ratio of garnet in the sample of Uv/m89 is high (0.443). Both minerals in this sample have negative $\varepsilon_{Nd}$ values at the time of kimberlite emplacement. Clinopyroxene from the another clinopyroxenite sample (Uv364/89) has a slightly radiogenic/depleted Nd isotope ratio and $\varepsilon_{Nd}$(t) of +5. Initial (367 Ma) Sr isotope ratios of clinopyroxenite are non-radiogenic (0.70284–0.70369).

In all xenoliths, the Sm–Nd isotope data for garnet and clinopyroxene gives ages, considerably older than the emplacement age of the host kimberlite (Table 4 and Fig. 6). Two compositionally similar and low-pressure Group B xenoliths give a Middle Proterozoic age (1550–1465 Ma). Among the Group A, one xenolith (Mir pipe) gives 1223 Ma, and the other two samples, later Proterozoic ages of 641–616 Ma. The phlogopite-bearing garnet clinopyroxenite sample gives the youngest age

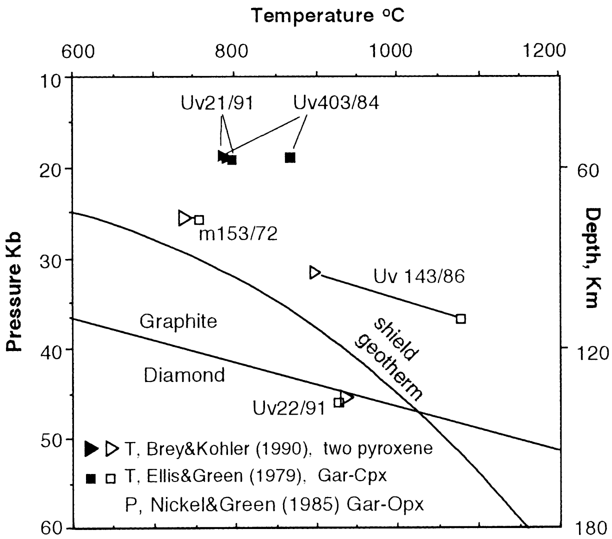


**Figure 4.** P–T diagram for garnet-websterite xenoliths from Siberian kimberlites. Data are compared to approximate 40 mW/m² shield geotherm (Pollack and Chapman (1977) and diamond stability boundary (Kennedy and Kennedy, 1976). Open symbols are GrA, filled-GrB. Gar, Garnet; Cpx, Clinopyroxene; Opx, Orthopyroxene.

**Table 3.** Rb–Sr and Sm–Nd isotope compositions of the minerals of garnet pyroxenite xenoliths

| Sample | Rb | Sr | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ | $^{87}Sr/^{86}Sr$,t | Sm | Nd | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd$ | $\varepsilon^{Nd}_{t}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Websterites GrB | | | | | | | | | | |
| Uv21/91Cpx | 3.46 | 80.08 | 0.125 | 0.705506±10 | 0.704855 | 7.835 | 43.03 | 0.1101 | 0.511312±12 | -22 |
| Uv21/91Gar | 0.053 | 0.6502 | 0.2378 | 0.708624±44 | 0.707374 | 3.324 | 3.024 | 0.6653 | 0.516972±11 | 62.6 |
| Uv403/84Cpx | 6.08 | 299.7 | 0.0587 | 0.705655±12 | 0.705349 | 11.15 | 77.81 | 0.0866 | 0.510914±11 | -27.3 |
| Uv403/84Gar | 0.398 | 2.95 | 0.3907 | 0.708292±15 | 0.706256 | 0.306 | 0.354 | 0.5237 | 0.515181±38 | 34.3 |
| Websterites GrA | | | | | | | | | | |
| Uv22/91Cpx | 1.47 | 39.11 | 0.1088 | 0.703509±11 | 0.702942 | 1.23 | 16.73 | 0.0443 | 0.512110±10 | -3.1 |
| Uv22/91Gar | 0.382 | 0.453 | 2.441 | 0.715554±24 | 0.702833 | 0.479 | 0.36 | 0.804 | 0.515304±39 | 23.6 |
| Uv143/86Cpx | 0.472 | 149.42 | 0.0091 | 0.703433±16 | 0.703385 | 3.01 | 75.73 | 0.024 | 0.512211±8 | -0.2 |
| Uv143/86Gar | | | | 0.705064±30 | | 0.567 | 0.315 | 1.09 | 0.516524±46 | 34 |
| m153/72Cpx | 2.855 | 278.78 | 0.0296 | 0.703033±21 | 0.702879 | 3.034 | 16.69 | 0.1099 | 0.511505±11 | -18 |
| m153/72Gar | 0.173 | 1.6218 | 0.3092 | 0.704493±14 | 0.702868 | 0.668 | 0.629 | 0.6426 | 0.515781±12 | 40.7 |
| Clinopyroxenites | | | | | | | | | | |
| Uv/m89Cpx | 0.721 | 157.07 | 0.0133 | 0.703445±12 | 0.703376 | 1.076 | 7.694 | 0.0845 | 0.511281±14 | -21.2 |
| Uv/m89Gar | | | | | | 0.777 | 1.06 | 0.4436 | 0.512651±32 | -11.3 |
| Uv/m89Wr | 21.14 | 79.34 | 0.771 | 0.707708±13 | 0.703690 | 1.01 | 6.81 | 0.0888 | 0.511234±12 | -22.4 |
| Uv364/89Cpx | 2.65 | 196.6 | 0.03904 | 0.703044±14 | 0.702841 | 2.516 | 11.05 | 0.1378 | 0.512753±9 | 5 |

t=367 Ma.
Note: Gar, Garnet; Cpx, Clinopyroxene. Concentrations of Rb, Sr, Sm and Nd in ppm.

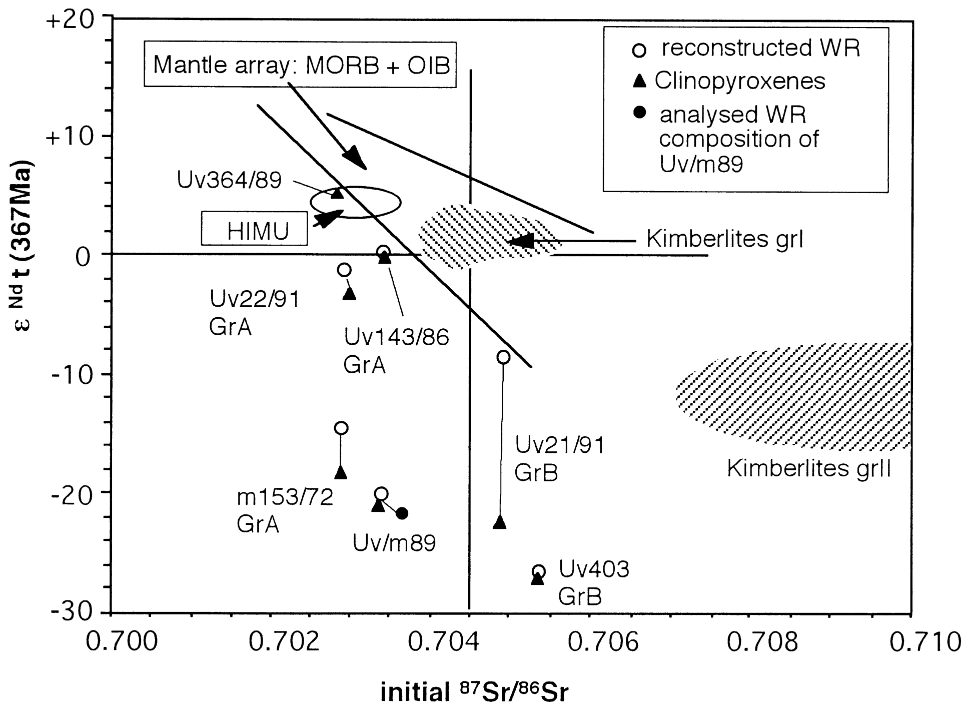


**Figure 5.** Sr–Nd isotope composition of clinopyroxenes and reconstructed WR of garnet–pyroxenite xenoliths from Siberian kimberlites, calculated at the time of kimberlite emplacement (367 Ma). Most of garnets have $\varepsilon_{Nd}>20$ and are not shown. Fields of MORB and OIB including HIMU (High $\mu$mantle source, $\mu={}^{238}U/{}^{204}Pb$) after Hofmann (1997). In half the cases, reconstructed WR Nd isotope compositions do not resemble these of Cpx. Sample Uv21/91 has the most marked difference between WR and Cpx composition. WR composition reconstructed assuming that all REE reside in Gar and Cpx. Densities of 3.9 g/cm$^3$ for Gar and 3.3–3.2 for Cpx and Opx respectively were used in calculations. Analyzed WR composition of sample Uv/m89 differs from the reconstructed value, indicating presence of a metasomatic phase (phlogopite). Fields of kimberlites of grI (Group I) and grII (Group II) after Smith (1983) and (Agashev et al., 2000).

**Table 4.** Apparent isochron and model ages of garnet pyroxenite xenolith

| | Isochron ages Ma | | Nd Model ages Ma | | | |
|---|---|---|---|---|---|---|
| Sample | Rb-Sr | Sm-Nd | CHUR Cpx | DM Cpx | CHUR Gar | DM Gar |
| Uv21/91 | | 1550 | 2321 | 2692 | 1408 | 1288 |
| Uv403/84 | | 1465 | 2294 | 2600 | 1186 | 998 |
| Uv22/91 | 363 | 642 | 529 | 937 | 670 | 557 |
| Uv143/86 | | 616 | 373 | 748 | 664 | 587 |
| m153/72 | 351 | 1223 | 1983 | 2409 | 1074 | 935 |
| Uv/m89 | 395 | 582 | 1853 | 2215 | 805 | |
| Uv364/89 | | | | 799 | | |

Parameters used for calculation of the model ages: CHUR; Chondritic Uniform Reservoir $^{143}Nd/^{144}Nd=0.512638$, $^{147}Sm/^{144}Nd=0.1967$ (DePaolo and Wasserburg 1976). DM, Depleted mantle; $^{143}Nd/^{144}Nd=0.51315$, $^{147}Sm/^{144}Nd=0.2135$ (after Pearson et al., 1995). Cpx, Clinopyroxene; Gar, Garnet.

(582 Ma).

## Discussion

Siberian craton is inferred to have been stabilized about 3.2 Ga (Pearson et al., 1995). After the stabilization, the following mantle processes should be noted. Judging from the Sm–Nd isotope composition and isochron age, McCulloch (1989) explained the origin of a suite of eclogites and garnet websterites from Obnazhonnaya pipe as an ancient mantle melt, stored in cratonic mantle. This melt was produced at 2.6 Ga from a strongly depleted source which was probably an early earth differentiate.

Gunther and Jagoutz (1997) discussed the high variability of Sm–Nd apparent ages ranging from ca. 840 Ma to ca. 2.0 Ga. of garnet peridotites from Yakutia (Siberia). They demonstrated that total concentrations

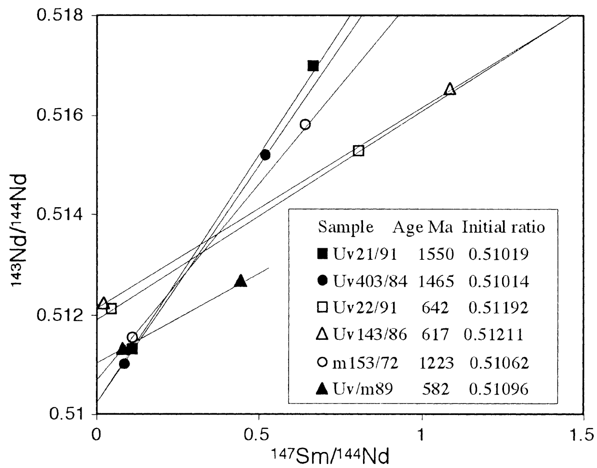


**Figure 6.** Two point Gar-Cpx isochron diagram of garnet-pyroxenite xenoliths. Garnets have higher isotope ratios than Cpx in all of the samples. Sample Uv/m89 is clinopyroxenite. Among the websterites, samples with higher difference in $^{147}Sm/^{144}Nd$ ratios between Cpx and Gar give the youngest ages.

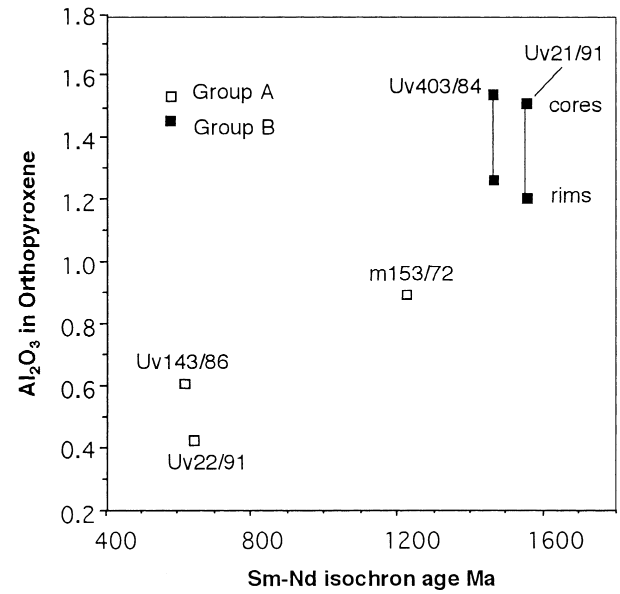


**Figure 7.** Plot of $Al_2O_3$ content in Opthopyroxene vs Sm-Nd apparent isochron age of garnet-websterite xenoliths.

of Sm and Nd in garnet and clinopyroxene have decreased with rejuvenation of apparent isochron ages estimated by garnet-clinopyroxene pairs. In the model by Gunther and Jagoutz (1997), the Sm-Nd isotope system of garnet peridotites started to close at around 2 Ga, and closed at 1680 Ma. The rocks with younger ages than 1680 Ma, except one sample, are explained by difference of intensity in re-equilibration induced by increase in mantle heat flow probably related to kimberlite eruption at ca. 367 Ma. The sample with the lowest Sm and Nd contents, the youngest age and the highest difference in Sm/Nd ratios between clinopyroxene and garnet were explained to represent states more close to re-equilibrated ones. They accepted the calculated closure temperature for Nd in clinopyroxene of a grain size of 2.8 mm of 860°C by Sneeringer et al. (1984).

In the present study we also found the same result in Sm-Nd system for coexisting garnet and clinopyroxene. Namely, garnet websterites produced at higher temperature showed stronger variations in Sm/Nd ratios between coexisting minerals and younger apparent ages than rocks of the same family formed at lower temperatures. Therefore we will consider a possibility that high variability of apparent ages of our samples (582-1550 Ma) depends on different intensity of re-equilibration as discussed by Gunther and Jagoutz (1997). However the pressure is also an important factor, as can be seen from the correlation between $Al_2O_3$ content in orthopyroxene and isochron age (Fig. 7) in our samples. Isotope data obtained in this study show general accordance with the model described above, but it is still difficult to propose a general history for all samples. We will try to interpret the isotope composition of each sample separatedly before reaching any conclusions.

The Group B garnet websterites and a sample of Group A (m153/72) show significant differences in Nd isotope composition between coexisting garnet and clinopyroxene (Table 3 and Fig. 6). The difference in $\varepsilon_{Nd}$ at the time of kimberlite emplacement is more than 58. This requires an evolution of minerals in a closed system during long period of time, as their apparent isochron ages of 1550-1223 Ma indicate. Their LREE-enriched compositions and enriched initial Nd isotope signature, suggest that those samples represent an old enriched material and/or a derivative from such an old enriched precursor, if the apparent isochron age is reliable. The Group B websterites also possess a radiogenic Sr isotope signature (Fig. 5). Their protolith, therefore, can be lower continental recycled crust materials. This idea may be supported by Figure 8, a plot of initial ratio versus isochron age of rock specimens. Group B websterite xenoliths fall on one of the possible evolution lines (the most enriched line) of 3.08 Ga old Daldyn series granulites which cropout in the Anabar shield (Spiridonov et al., 1994). The shallow position of Group B in the lithospheric mantle (Fig. 4) and zoned orthopyroxene in $Al_2O_3$ may support the above hypothesis. Although the meaning of ages around 1.5 Ga of Group B websterites is not yet understood, the ages may suggest an episode of phase transformation of the recycled crustal materials under the mantle condition. If the difference in an estimated tempera-

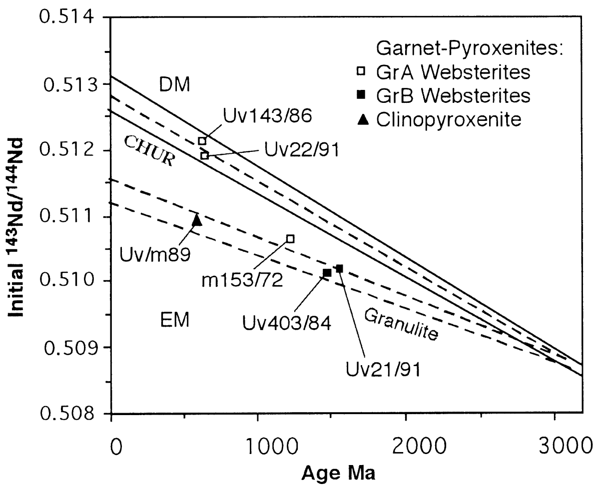


**Figure 8.** Initial $^{143}Nd/^{144}Nd$ ratio vs apparent isochron age diagram for garnet-pyroxenite xenoliths from Siberian kimberlites. Evolution lines calculated for 3 particular samples of Daldyn series granulites using data from (Spiridonov et al., 1994) shown as dashed lines and all samples used are the same age of 3.1 Ga. CHUR, Chondritic Uniform Reservoir; DM, Depleted Mantle; EM, enriched mantle. CHUR and DM evolution lines calculated using values given in Table 4.

ture for Group B (Fig. 4) suggests disequilibrium event, one of the ages may be influenced by re-equilibration episode.

Minerals of sample m153/72 in Group A have the lowest $^{87}Sr/^{86}Sr$ ratios (Table 3 and Fig. 5) and high Mg# values (see Table 2). The petrological and isotopic features of the sample suggests a mantle origin of this websterite. It may be a cumulate from a depleted (asthenospheric) mantle melt, in which the Sm-Nd isotope system was closed at 1.22 Ga (Table 4) when it developed a non-radiogenic Nd isotope ratio.

Other samples of Group A of late Proterozoic age (Uv22/91 and Uv143/86) require different origin, because their clinopyroxenes have Nd isotope compositions close to Bulk Earth (Fig. 5), and the $^{147}Sm/^{144}Nd$ ratio is distinctly different between coexisting minerals. The differences are greater than those in the samples of GrB and m153/72 (Table 3). The ratio (Sm/Nd)Gar/(Sm/Nd)Cpx is 18.1 and 42.9 for samples Uv22/91 and Uv143/86, respectively. These values are inconsistent with an idea of simple crystallization process becouse the value of mineral/melt partition coefficients (DSm/DNd)Gar/(DSm/DNd)Cpx is 5.7 (D-values from Halliday et al., 1995). The whole rock $^{147}Sm/^{144}Nd$ ratio of sample Uv22/91 was calculated using mineral modes (Table 1), Sm and Nd concentrations (Table 3) and mineral densities (Fig. 5) and gave 0.09. This low value suggests crystallization of the minerals from a LREE-enriched melt with asthenospheric Nd isotope composition, followed by disequilibrium re-distribution of Sm and Nd between garnet and clinopyroxene. An alternative way of achieving this Sm and Nd distribution pattern is fractional crystallization under high pressure condition where garnet was the first solid phase and clinopyroxene crystallized later from evolved melt. The reconstructed whole rock composition of the sample Uv143/86 still has a very low $^{147}Sm/^{144}Nd$ ratio (0.034). Hence, a precursor with very low Sm/Nd ratio is necessary. However, the garnet of the sample Uv143/86 has the highest Sm/Nd ratio (Table 3), and a hybrid nature, therefore, for this sample can be proposed. According to recent experimental data (Kogiso et al., 1997) Nd is more strongly incorporated into the aqueous fluids released by dehydration of subducted ocean crust than Sm. $^{147}Sm/^{144}Nd$ ratio of dehydrated MORB in this process is 0.264. Considering the very high $^{147}Sm/^{144}Nd$ ratio (up to 0.68) of some mantle eclogites (Snyder et al., 1997), fluid released from such restite should possess a very low Sm/Nd ratio and is assigned to be a precursor of clinopyroxene of this sample.

The garnet-clinopyroxenite sample Uv/m89 shows no pronounced difference in Gar-Cpx Nd isotope composition (Table 3) and has the youngest apparent age (582 Ma in Table 4). Both minerals and whole rock show enriched Nd isotope signature, and the whole rock has low Sm/Nd ratio. Therefore it is possible to speculate that this sample may have been derived from an ancient LREE-enriched melt, having a Clinopyroxene CHUR (Chondritic Uniform Reservoir) Nd model age of 1.85 Ga (Table 4). The garnet has high $^{147}Sm/^{144}Nd$ ratio (0.44) at given comparatively low Nd isotope ratio. To explain this inconsistency, re-equilibration (not long before the kimberlite emplacement) is required. In the same manner as described by Gunther and Jagoutz (1997) this process led to decreasing Nd isotope ratio of garnet, hence lowering the isochron age. Additionally Shimizu et al. (1997) show that rims of Udachnaya peridotitic garnets were enriched in Sm over Nd relative to core, probably by reaction with a melt of kimberlite affinity. Thus, we propose that the re-equilibration mentioned above was probably accompanied by a metasomatic agent and Sm/Nd ratio of garnet was increased, and lowered the isochron age.

From the other clinopyroxenite only clinopyroxene was analyzed. This clinopyroxene has Sr and Nd isotope compositions corresponding with HIMU (High U/Pb ratio mantle source) OIB source (Fig. 5), the initial Sr ratio being 0.70284 and $\varepsilon_{Nd}$ +5 at the age of host kimberlite.

In Figure 9 the relationship between Sm-Nd apparent ages and Nd isotope initial ratios of our garnet

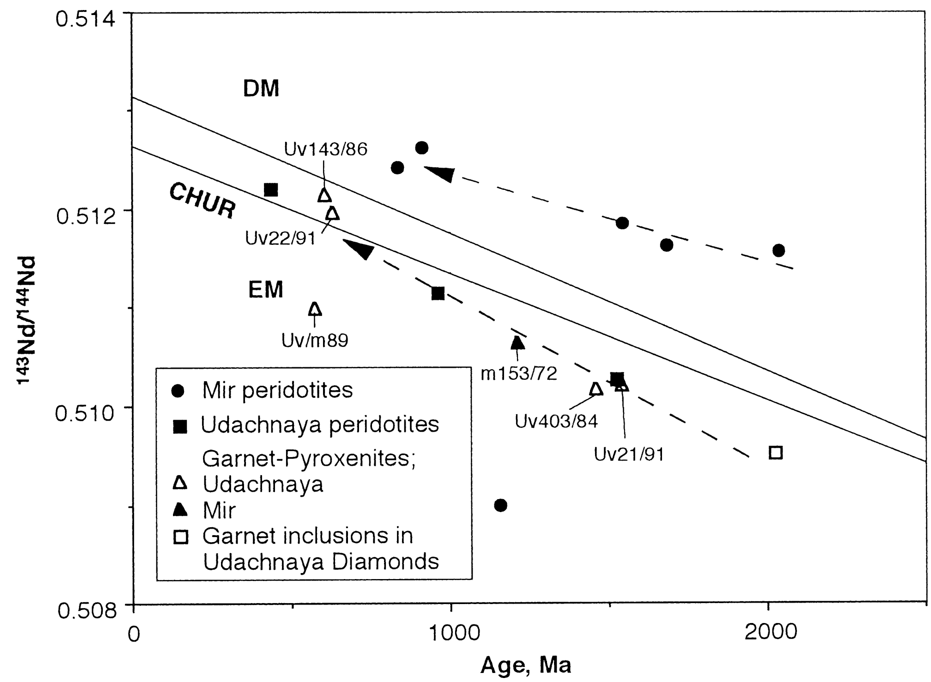


**Figure 9.** Nd isotope evolution diagram for Siberian cratonic mantle. Data for peridotites from Gunther and Jagoutz (1997), garnet inclusions in Udachnaya diamonds from Richardson and Harris (1997) and garnet pyroxenites-this study. Possible evolution trends of cratonic mantle beneath Mir (upper) and Udachnaya (lower) shown as dashed lines. CHUR and DM are the same as in (Fig. 8) and Table 4.

websterites is plotted together with those of the Udachnaya and Mir peridotites (Gunther and Jagoutz 1997) and the initial ratio of garnet inclusions in Udachnaya diamonds from isochron of Richardson and Harris (1997). This relationship provides evidence that peridotites and pyroxenites in lithospheric mantle beneath the Udachnaya was in isotopic equilibrium, but it is not the case beneath the Mir pipe where most of peridotites have depleted initial Nd isotope composition. The isotope compositions of garnet pyroxenites allow to envisage an episode of periodical additions of LREE-enriched melts with asthenospheric mantle isotope signatures to peridotite-dominated lithospheric mantle. These melts can originate directly from the underlying convected mantle as well as from the subducting ocean slab. In the latter case the crystallizing minerals would have lower Sm/Nd ratios. The apparent isochron ages possibly suggest the history of such melt additions, where samples with nearly asthenospheric initial isotope ratios probably show the time close to the emplacement of their parental melts into peridotitic cratonic mantle.

On the other hand samples with evolved isotope composition show the time of resetting of the Sm-Nd isotope system of much older melts, probably of 2.2-2.6 Ga in age as recorded by DM (Depleted Mantle) Nd model ages of their clinopyroxenes (Table 4). These melts, which in many cases underwent the complex history inside the lithospheric mantle, were an ultimate metasomatic agent for the host peridotites. Evidence for the metasomatism has been found in the Udachnaya peridotites and the metasomatic event may have been episodic over the long history of cratonic root (Pearson et al., 1995; Boyd et al., 1997).

## Conclusions

Garnet pyroxenites occur through the lithospheric mantle, from not far below the Moho boundary to the diamond stability field. Their Nd isotope systems record a complex history of the Siberian cratonic mantle. Group B websterite xenoliths have similar mineral compositions, age and shallow position in the cratonic mantle. On the basis of isotope composition of these xenoliths ($\varepsilon_{Nd}$, $-10$ at 1.5 Ga) and slightly radiogenic Sr we propose their origin from enriched precursor, and their protolith can be a delaminated lower continental crustal material. Their 1.5 Ga isochron age may reflects phase transformation and re-equilibration of this material under mantle conditions, although the mantle origin for these samples can not be excluded.

The Group A websterite xenoliths show diversity in the Nd isotope composition and apparent isochron age. Their constituent minerals are MgO rich and have non-radiogenic Sr isotope composition. It seems more likely that they originated as cumulates from a melt with asthenospheric mantle isotopic signatures and low Sm/Nd ratio. This melt, at the same time, was a metasomatic agent for adjacent peridotites. Subsequently some of these samples underwent disequilibrium re-distribution of Sm-Nd between minerals, and resetting of the Nd isotope system. We propose fractional crystallization under high pressure and addition of metasomatic melt/fluid from the downgoing subducted slab, but the nature of such re-distribution process remains enigmatic. The origin of the garnet-clinopyroxenites can be also modeled as asthenospheric mantle melts, which in the case of the phlogopite-bearing sample were ancient, having a Clinopyroxene CHUR (Chondritic Uniform Reservoir) Nd model age of 1.85 Ga. The depleted Sr and Nd isotope composition of clinopyroxene from the other clinopyroxenite suggests crystallization shortly before kimberlite eruption. On the other hand samples with evolved isotope composition show the time of resetting of the Sm-Nd isotope system of much older melts, probably of 2.2-2.6 Ga in age.

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