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Diamondiferous xenoliths from crustal subduction: garnet oxygen isotopes from the Nyurbinskaya pipe, Yakutia

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Abstract: Oxygen isotopic ratios suggest that many and possibly all eclogite xenoliths from kimberlites are representatives of subducted crust. Such oxygen data from all diamond pipes studied to date form an approximate bell-shaped distribution curve centered on that of the mantle, with a significant number of values both below and above mantle, indicative of high- and low-temperature (resp.) hydrothermal seawater processing of the protoliths prior to subduction.

The Nyurbinskaya pipe of Yakutia, a newly developed diamondiferous kimberlite, has yielded an unprecedented array of xenoliths, each containing diamonds. Some 121 of these diamondiferous samples were selected for this study. Garnets were separated from the different types of diamondiferous xenoliths, including mostly eclogites, but also some garnet websterites (pyroxenites), and peridotites. The $\delta^{18}O$ ratios of the majority of the peridotitic garnet samples lie within the range of the average mantle, except for one with a $\delta^{18}O$ value of 6.57 ‰. Garnets from xenoliths of websterite paragenesis, in general, have $\delta^{18}O$ values above 6.0 ‰, with two samples as high as 7.3 and 8.59, and only two samples as low as 5.9 and 6.0 ‰. Eclogitic garnets have a range of $\delta^{18}O$ from 4.7 to 9.7 ‰, with > 80 % above 6 ‰, but still within the general range reported for garnets from eclogite xenoliths from the Siberian platform (2.5 and 8.0 ‰). There does not appear to be any correlation between the major-element composition of the garnets and their $\delta^{18}O$ values. These eclogitic garnet $\delta^{18}O$ values form a rather steep-sided, near Gaussian distribution, centered about 6.6 ‰. These new garnet oxygen-isotope ratios are not only additional evidence for subduction of oceanic crust but also evidence for a major involvement of the upper, low-temperature metasomatized portion of the crustal section. These eclogites, garnet websterites, and peridotites have also experienced extensive late-stage mantle metasomatism, with inhomogeneities in some garnet, typical of many diamondiferous xenoliths.

Key-words: kimberlite, xenolith, eclogite, diamond, garnet, oxygen isotopes, subduction.

Introduction

Diamondiferous xenoliths in kimberlites are representatives of various mantle levels and provide important information about mantle petrology and conditions of diamond formation. Although peridotitic xenoliths are dominant in kimberlites and P-type (peridotitic) diamonds are far more abundant than E-type (eclogitic), recovered diamondiferous eclogite xenoliths are significantly more abundant world-wide than are diamondiferous peridotites, perhaps, a function of weakness of olivine-bearing rocks during diamond recovery crushing and processing (*e.g.* Sobolev *et al.,* 1984). In contrast to garnets from most mantle peridotites, which reportedly have $\delta^{18}O$ values in a narrow range, +5.36 ± 0.18 (1 SD; Lowry *et al.,* 1999), many mantle eclogite xenoliths have $\delta^{18}O$ values that are significantly outside of the range accepted as normal for mantle rocks (*e.g.*, Taylor & Anand, 2004). Garnets in mantle eclogites range from +2.3 ‰ to +9.2 ‰ (*e.g.* Deines *et al.,* 1991; Mattey *et al.,* 1994). By analogy with rocks from ophiolite sequences (Gregory & Taylor, 1981), eclogites with $\delta^{18}O$ values above those of "common mantle" are thought to represent subducted oceanic crust that has been altered by interaction with hydrothermal fluids at temperatures <~ 350 °C; in contrast, eclogites with lower $\delta^{18}O$ values represent mafic rocks that have interacted with higher-temperature hydrothermal fluids.

Numerous early studies of oxygen isotope ratios of southern African eclogites were among the first to indicate this possibility of subduction of oceanic crust for the origin of some mantle eclogites. These include studies on the Roberts Victor kimberlite (Garlick *et al.,* 1971; Jagoutz *et al.,* 1984; MacGregor & Manton, 1986; Ongley *et al.,* 1987), as well as Bellsbank (Neal *et al.,* 1990; Caporuscio,

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Table 2. Representative garnet compositions in diamondiferous xenoliths from the Nyurbinskaya pipe.

Sample	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	Total	Groups
N-4	40.4	0.28	22.0	0.11	18.6	0.26	11.9	6.03	0.10	99.69	G1
N-21	39.5	0.34	21.3	0.15	20.4	0.40	11.7	4.29	0.10	98.03	G1
N-52	39.3	0.26	21.8	0.09	19.5	0.50	11.6	5.19	0.11	98.24	G1
N-68	39.8	0.31	21.5	0.06	19.3	0.36	10.3	7.07	0.14	98.77	G1
N-79	39.9	0.29	21.5	< 0.03	21.4	0.34	10.3	5.14	0.12	99.03	G1
N-89	39.5	0.33	21.4	0.06	21.8	0.44	10.7	4.53	0.12	98.80	G1
N-20	39.7	0.21	21.6	0.16	18.8	0.53	8.5	9.74	0.14	99.32	G2
N-25	40.1	0.39	21.9	0.16	16.7	0.40	11.6	7.55	0.14	98.88	G2
N-100	39.8	0.35	21.1	0.09	19.2	0.39	10.6	7.32	0.15	98.89	G2
N-107	39.9	0.83	21.0	0.13	17.4	0.37	11.2	8.08	0.20	99.11	G2
N-108	39.9	0.27	21.5	0.09	18.4	0.34	11.2	7.35	0.10	99.22	G2
N-11	40.1	0.36	21.3	0.08	19.5	0.25	12.4	5.14	0.13	99.23	G3
N-105	39.6	0.50	21.6	0.09	19.5	0.53	11.3	5.66	0.13	98.80	G3
N-141	40.5	0.25	21.8	0.13	18.6	0.31	13.3	4.65	0.12	99.62	G3
N-132	40.5	0.26	21.9	0.04	18.4	0.44	13.2	5.12	0.10	99.99	G3
N-137	39.9	0.27	21.7	0.13	18.9	0.36	12.0	5.99	0.12	99.41	G3
N-3	39.9	0.32	21.7	0.04	20.5	0.35	12.0	4.30	0.10	99.19	G3
N-14	40.3	0.48	21.6	0.11	15.1	0.22	12.3	9.99	0.18	100.25	G4
N-15	41.3	0.24	22.9	0.18	9.2	0.13	14.7	11.57	0.16	100.34	G4
N-66	41.7	0.54	22.5	0.20	9.8	0.20	16.0	8.96	0.12	100.00	G4
N-72	41.2	0.37	22.7	0.05	11.0	0.24	12.1	12.71	0.14	100.54	G4
N-150	40.8	0.46	21.9	0.08	12.6	0.21	13.9	9.23	0.15	99.29	G4
N-17	40.7	0.36	22.2	0.07	10.0	0.13	9.12	17.8	0.19	100.60	G5
N-22	40.5	0.22	22.0	0.08	10.3	0.14	9.95	16.4	0.11	99.71	G5
N-31	40.7	0.20	22.4	0.15	8.73	0.11	9.32	17.5	0.09	99.23	G5
N-64	39.7	0.51	21.6	0.11	12.9	0.05	6.87	17.7	0.19	99.59	G5
N-75	40.3	0.38	22.1	0.09	10.5	0.16	10.8	13.9	0.15	98.33	G5
N-138	40.1	0.34	21.8	0.07	12.3	0.18	10.4	14.0	0.16	99.41	G5
N-157	40.3	0.36	21.9	0.05	10.8	0.12	8.30	17.3	0.18	99.45	G5
N-6	41.1	0.24	22.3	0.19	16.3	0.25	15.9	3.40	0.10	99.75	G6
N-7	41.1	0.24	22.1	0.18	16.5	0.38	16.1	3.37	0.11	100.01	G6
N-8	41.1	0.25	22.1	0.11	16.7	0.33	15.5	3.74	0.10	99.90	G6
N-9	41.1	0.26	22.0	0.05	16.9	0.41	15.6	3.51	0.10	100.08	G6
N-16	41.0	0.30	22.0	0.02	16.2	0.41	16.6	2.73	0.12	99.35	G6
N-24	40.4	0.27	21.9	0.04	17.5	0.36	14.5	3.87	0.11	98.87	G6
N-67	41.1	0.24	22.5	0.12	16.1	0.33	16.1	3.39	0.11	100.03	G6
N-104	41.0	0.38	22.5	0.06	13.7	0.33	17.3	3.47	0.12	98.85	G6
N-145	41.0	0.22	22.9	0.09	16.2	0.38	16.3	3.39	0.11	99.80	G6
N-151	40.7	0.25	22.0	0.16	16.6	0.50	15.1	4.01	0.11	99.42	G6
N-47	42.2	0.42	23.1	0.09	9.24	0.37	21.1	3.06	0.13	99.61	G7
N-53	41.6	0.49	22.8	0.10	12.2	0.42	19.2	2.44	0.22	99.35	G7
N-86	41.3	0.29	22.4	0.01	13.1	0.39	18.1	4.04	0.13	99.79	G7
N-109	42.4	0.35	23.3	0.04	7.85	0.40	21.7	3.60	0.09	99.74	G7
N-129	41.6	0.51	22.1	0.13	13.5	0.24	18.8	3.33	0.15	100.41	G7
N-156	41.9	0.29	22.2	0.92	6.89	0.31	21.9	3.88	0.08	98.43	G7
N-70	41.4	0.03	17.2	7.62	7.42	0.47	20.1	6.02	< 0.03	100.27	G8
N-114	40.4	0.25	14.9	10.4	7.43	0.53	19.2	5.99	0.06	99.14	G8
N-125	41.1	0.10	17.2	7.53	7.77	0.48	18.8	6.73	0.00	99.64	G8
N-134	40.5	0.10	14.7	10.7	7.24	0.40	18.8	6.63	0.03	99.12	G8

Approximately 30 % of the diamond crystals have etched channels, rounded edges, and other indications of corrosion (see Fig. 1d).

Methodology

More than 150 samples of mantle xenoliths, mostly diamondiferous, from the Nyurbinskaya pipe were examined for this study. Major-element and modal analyses were performed on garnets in thin sections of each sample. All samples were classified into different varieties of eclogite, websterite, and peridotite, according to their petrographic features and garnet chemistry. The garnet compositions were determined with a Superprobe JXA-8800R electron microprobe at the ALROSA Co Ltd. (Mirny, Russia). Care was taken to analyze only those grains that did not contain inclusions or exhibit alteration. Analytical conditions

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N-52	39.3	0.26	21.8	0.09	19.5	0.50	11.6	5.19	0.11	98.24	G1
N-68	39.8	0.31	21.5	0.06	19.3	0.36	10.3	7.07	0.14	98.77	G1
N-79	39.9	0.29	21.5	< 0.03	21.4	0.34	10.3	5.14	0.12	99.03	G1
N-89	39.5	0.33	21.4	0.06	21.8	0.44	10.7	4.53	0.12	98.80	G1
N-20	39.7	0.21	21.6	0.16	18.8	0.53	8.5	9.74	0.14	99.32	G2
N-25	40.1	0.39	21.9	0.16	16.7	0.40	11.6	7.55	0.14	98.88	G2
N-100	39.8	0.35	21.1	0.09	19.2	0.39	10.6	7.32	0.15	98.89	G2
N-107	39.9	0.83	21.0	0.13	17.4	0.37	11.2	8.08	0.20	99.11	G2
N-108	39.9	0.27	21.5	0.09	18.4	0.34	11.2	7.35	0.10	99.22	G2
N-11	40.1	0.36	21.3	0.08	19.5	0.25	12.4	5.14	0.13	99.23	G3
N-105	39.6	0.50	21.6	0.09	19.5	0.53	11.3	5.66	0.13	98.80	G3
N-141	40.5	0.25	21.8	0.13	18.6	0.31	13.3	4.65	0.12	99.62	G3
N-132	40.5	0.26	21.9	0.04	18.4	0.44	13.2	5.12	0.10	99.99	G3
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N-66	41.7	0.54	22.5	0.20	9.8	0.20	16.0	8.96	0.12	100.00	G4
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N-22	40.5	0.22	22.0	0.08	10.3	0.14	9.95	16.4	0.11	99.71	G5
N-31	40.7	0.20	22.4	0.15	8.73	0.11	9.32	17.5	0.09	99.23	G5
N-64	39.7	0.51	21.6	0.11	12.9	0.05	6.87	17.7	0.19	99.59	G5
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Numerous early studies of oxygen isotope ratios of south-

changes in pressure do not have major effects (Clayton *et al.,* 1975). Therefore, igneous processes in the upper mantle cannot account for the wide range of $\delta^{18}O$ values of mantle eclogites. The most favored interpretation for the anomalously high- and low- oxygen isotopic values for mantle eclogite xenoliths is as the result of subduction and prograde metamorphism of oceanic lithosphere that has undergone oxygen isotope exchange with hydrothermal fluids prior to subduction (*e.g.*, MacGregor & Manton, 1986; Shervais *et al.,* 1988; Taylor & Neal, 1989; Taylor, 1993; Schulze *et al.,* 2003).

There remains the possibility that the validity of the signatures for crustal origin of $\delta^{18}O$ may not be absolute. All mantle eclogite xenoliths show evidence for metasomatic fluid-induced partial melting of both garnet and clinopyroxene. But, the real question is what was the ultimate source of these fluids? Eiler (2001) found that slab-derived fluids and melts typically have high $\delta^{18}O$ values. It is possible, albeit not very feasible, that such metasomatic fluids may have been sequestered into the mantle where they might have been mixed with 'true' mantle fluids, yet lend their crustal oxygen values to the overall fluid. In fact, with a modern-day interpretation of deep subduction of oceanic slabs and all their ramifications to 'true' mantle chemistry, one should probably begin to doubt the nature of mantle *versus* crustal signatures.

Conclusions

The Nyurbinskaya pipe in the Nakynsky field of Yakutia is the source of an unusual occurrence of a large number of diamondiferous xenoliths exhibiting a wide-range of garnet major-element compositions; they reflect a wide distribution of mafic to ultramafic mantle xenoliths, mostly eclogites, websterites, and pyroxenites.

Oxygen isotopes of garnets in some 121 diamondiferous xenoliths from the Nyurbinskaya pipe display a unique and large range of values, with a predominance of values above that of the accepted mantle range for garnets of $\delta^{18}O$ = 5.3 ± 0.6 ‰ (Valley *et al.,* 1998). For diamondiferous eclogites, this is the first reported occurrence of such an abundance of high $\delta^{18}O$ values in garnets from any kimberlite worldwide. This anomalously wide range and abundance of high $\delta^{18}O$ values of garnets in diamondiferous xenoliths from the Nyurbinskaya pipe, mostly outside of mantle values, is taken as further evidence for crustal protoliths for these rocks. Such conclusions, combined with crustal evidences from several of the other Yakutian kimberlites, are indications for the intense evolution of the mantle beneath the Siberian Platform.

Acknowledgements: This paper was written to honor the celebration of the 100th birthday of Professor and Akademician Vladimir Stephanovich Sobolev. This world-renown scientist was a "Man-Before-his-Time", who made many excellent contributions to metamorphic and mantle petrology, many of which have stood the test of time; yet, others remained to be subsequently proven, such as his predicted presence of diamonds in Yakutia. We thank Prof. M. Arima, B. Harte and N.V. Sobolev for organizing this collection of papers. N. Merkulova and S. Banzeruk, at ALROSA company, performed the work-intensive picking of the garnet separates for oxygen determinations. Sergey I. Mityukhin made the diamondiferous xenoliths available for our study. We also thank our fellow colleagues worldwide for their continued many discussions and educational support. Extensive discussions and reviews by Nikolai V. Sobolev have added immeasurably to the quality of this paper, as has the review by Doug Rumble. Partial support for this study was provided by the Planetary Geosciences Institute at the University of Tennessee and by NSF (EAR 0509639 to JWV).

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