

Ocean-island basalt–like source of kimberlite magmas from West Greenland revealed by high $^3\text{He}/^4\text{He}$ ratios

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ABSTRACT

The depth of origin of kimberlite magmas remains controversial. Hypothesized sources include the asthenosphere, the lower part of the upper mantle, and the lower mantle. Based on Sr-Nd isotope systematics, kimberlites are divided into two groups. Group 1 kimberlites have Sr-Nd isotope compositions similar to bulk earth. These compositions are consistent with a kimberlite source that is either a relatively unfractionated ocean-island basalt (OIB)–like source, or a mixture of depleted mid-oceanic-ridge basalt and enriched mantle components. In order to distinguish between these two possibilities, we performed noble gas analyses on olivine crystals separated from extremely fresh kimberlites from South and West Greenland. We detected OIB-like (Loihi-type) high $^3\text{He}/^4\text{He}$ ratios of up to 26.6 R_A in kimberlites. This clearly indicates that group 1 kimberlite magmas have a source similar to that of mantle plumes, implying that the source of kimberlite magma is in the lower mantle.

Keywords: kimberlite, source, ocean-island basalt, $^3\text{He}/^4\text{He}$ ratio, lower mantle.

INTRODUCTION

Because kimberlites are known to transport diamonds to the surface, it has been generally thought that the kimberlite magma source is located at a depth of more than 150 km (e.g., Dawson, 1980). However, there are several competing hypotheses concerning the depths from which kimberlite magmas are derived. Among the proposed sources are the asthenosphere, the lower part of the upper mantle, and the lower mantle (e.g., Dawson, 1972; DePaolo, 1988; Ringwood et al., 1992; Smith, 1983). Although some mineral inclusions in diamonds are considered to have formed in the lower mantle (e.g., Harte and Harris, 1994), the depth of origin of the source materials from which kimberlites derive remains contentious.

Wagner (1914) proposed that two types of kimberlites (basaltic and micaceous) could be recognized petrographically. Based on Sr-Nd isotope systematics, kimberlites have been divided into two groups (Smith, 1983). The group 1 kimberlites have Sr and Nd isotope ratios close to bulk earth values, whereas group 2 kimberlites have relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ values that plot in the enriched mantle field (Smith, 1983). Since there are fundamental differences between the

group 1 and group 2 kimberlites, Mitchell (1995) proposed that the name kimberlite be discontinued when referring to the latter and that they instead be termed orangeites. These “orangeites” can be explained on the basis of old recycled lithospheric materials. On the other hand, the Sr-Nd isotope systematics indicate that group 1 kimberlite magmas are possibly derived from a relatively unfractionated source, but they do not exclude the hypothesis that their sources involve mixing between mid-oceanic-ridge basalt (MORB) source mantle and enriched components. Solid isotope systematics, such as Sr, Nd, and Pb isotopes, cannot distinguish between these two possibilities.

In this respect, noble gas isotopes can be used to distinguish between relatively unfractionated material, such as the primitive ocean-island basalt (OIB; mantle plume) source and MORB magmas mixed with enriched, possibly recycled, crustal components. Noble gas isotope systematics, as revealed in the $^3\text{He}/^4\text{He}$ ratio (e.g., Graham, 2002; Kaneoka, 1983), are distinctly different in these contrasting situations. OIBs like those from Hawaii (Loihi-type) and Iceland show $^3\text{He}/^4\text{He}$ ratios up to 43 R_A (Breddam and Kurz, 2001) (R_A is the $^3\text{He}/^4\text{He}$ of air), i.e., higher than the typical MORB value of $(8 \pm 1) R_A$, whereas enriched crustal components are characterized

by lower than MORB values. In MORBs (e.g., Allégre et al., 1983), as well as OIBs from Loihi (dunites) and Iceland (glasses; Trierloff et al., 2000), $^{129}\text{Xe}/^{132}\text{Xe}$ ratios higher than the atmospheric value (0.983) have been observed, whereas crustal components show $^{129}\text{Xe}/^{132}\text{Xe}$ ratios similar to the atmospheric value. If kimberlite magmas are derived from a relatively unfractionated source, such as those of primitive OIBs, they would show higher $^3\text{He}/^4\text{He}$ ratios than the MORB value and similar $^{129}\text{Xe}/^{132}\text{Xe}$ ratios to those observed in OIBs. Thus, we can separate the signatures from mixtures between MORB magmas and enriched components, which would show systematically lower $^3\text{He}/^4\text{He}$ ratios than the MORB value and a different trend in Xe isotope systematics than that of OIBs.

SAMPLES

As yet, there have been quite few noble gas studies on kimberlites (Tolstikhin et al., 2002), the reason being that most kimberlites are severely altered rocks, affected by low-temperature processes in which the primary noble gas signatures are eliminated. This paper concerns unusually fresh hypabyssal kimberlite samples from two localities in western Greenland. Two samples (101243-2, 101243-3) are from Pyramidefjeld, South Greenland, and were exposed as a sill and dated around

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TABLE 1. NOBLE GASES IN OLIVINES FROM SOUTH AND WEST GREENLAND KIMBERLITES

Sample No. (Weight)	⁴ He (10 ⁻⁶)	²⁰ Ne (10 ⁻¹²)	³⁶ Ar (10 ⁻¹²) (cm ³ STP/g)	⁸⁴ Kr (10 ⁻¹²)	¹³² Xe (10 ⁻¹²)	³ He/ ⁴ He (R/R _A)	³⁸ Ar/ ³⁶ Ar	⁴⁰ Ar/ ³⁶ Ar	¹²⁹ Xe/ ¹³² Xe	¹³⁶ Xe/ ¹³² Xe
South Greenland										
101243-2a (0.832 g)	1.35	11.3	91.1	2.11	0.088	4.79	0.1843	2790	0.992	0.373
-2b (0.826 g)	0.096	16.1	N.A.*	N.A.	N.A.	0.1	0.0009	23	0.015	0.015
101243-3a (0.812 g)	1.28	31	155	7.11	0.393	4.63	N.A.	N.A.	N.A.	N.A.
-3b (1.31 g)	0.62	14.8	42.4	2.52	0.458	0.47	0.1892	5810	1.002	0.354
						9.14	0.0007	50	0.018	0.01
						0.14	0.184	5930	0.999	0.344
						9.73	0.0037	218	0.013	0.006
						0.81				
West Greenland										
KIM 1a (0.827 g)	0.72	1>	69.2	1.76	0.078	19	0.184	1120	N.A.	N.A.
1b (1.19 g)	0.68	18.5	9.34	0.72	0.025	0.2	0.0017	72		
						20.8	0.185	8840	1.031	0.342
						0.3	0.0021	124	0.027	0.02
KIM 6a (0.800 g)	0.031	1>	48.6	1.05	0.023	17.7	0.185	2170	1.009	0.331
6b (1.03 g)	0.097	11.6	22.3	1.96	0.184	1.1	0.0024	31	0.015	0.023
						17.8	0.186	2820	1.009	0.332
						0.7	0.0008	16	0.024	0.008
KIM 9a (0.835 g)	0.058	2.43	120	1.91	0.019	26.6	0.1845	886	N.A.	N.A.
9b (1.25 g)	2.26	3.62	9.59	0.3	0.027	1.1	0.0008	5		
						23.2	0.184	5680	1.018	0.345
						1.2	0.0011	28	0.016	0.016
KIM 12 (0.800 g)	1.01	59.1	12.5	0.91	0.026	5.85	0.185	11500	1.046	0.35
						0.1	0.0034	77	0.019	0.01
KIM 15 (0.345 g)	2.19	23.7	326	7.98	0.233	6.1	0.1835	1800	1.02	0.334
						0.12	0.001	31	0.021	0.016

Note: "a" and "b" with the same sample No. indicate samples from the same block. All analyses were performed by the crushing method. Abundance includes about 10% uncertainty. Abundances were corrected for blanks. Blanks are as follows (in cm³STP): ⁴He, (1-2) × 10⁻¹¹; ²⁰Ne, (1-3) × 10⁻¹²; ³⁶Ar, (1-3) × 10⁻¹²; ⁸⁴Kr, (2-3) × 10⁻¹⁴; ¹³²Xe, (4-6) × 10⁻¹⁶. The uncertainty in an isotope ratio is shown below each value as one sigma. The ³He/⁴He [R] is normalized by that of air (R_A: 1.4 × 10⁻⁶). Except for a subsample (101243-3a), ³⁸Ar/³⁶Ar ratios show lower values than that of air (0.188), which might have been caused by mass fractionation before and/or during intrusion of a kimberlite magma at a shallow depth.

*N.A.: not applicable.

200 Ma (Andrews and Emeleus, 1975; Emeleus and Andrews, 1975; Escher and Watt, 1976). Five samples (KIM 1, KIM 6, KIM 9, KIM 12, KIM 15) are from Sarfartoq, West Greenland, and were exposed as boulders at the foot of hills and inferred to have been derived from dikes, as revealed by their textures. They are reported to have intruded around 600 Ma based on K-Ar ages of phlogopites in kim-

berlites (Larsen et al., 1983). Both sets of samples are representative of group 1 kimberlites. They are extremely fresh, and almost all olivines in these kimberlites are not serpentinized. The olivine macrocrysts range from 0.5 mm to 3 mm in diameter and compose more than 70% of the rock modally. Other components, such as phlogopites, clinopyroxenes, and orthopyroxenes, are also present. Since pyroxenes are observed sparsely as small angular crystals with sizes of <0.1 mm, they might be mostly xenocrysts. The exceptional freshness of these samples might be due to their derivation from kimberlite sills that have been exposed to the surface relatively recently during deglaciation in Holocene time.

RESULTS

The noble gas data obtained are summarized in Table 1, where sample suffixes "a" and "b" indicate subsamples from the same block. Samples had generally high He concentrations (>10⁻⁷ cm³STP/g; STP indicates standard temperature and pressure), except for sample 121243-2b, and variable amounts of Xe (10⁻¹²-10⁻¹⁴ cm³STP/g). He, Ar, and Xe isotope compositions were variable among samples, but showed significant mantle signatures (see following). Since Ne isotope data did not have sufficient precision for discussion, they are not shown in Table 1.

THE ³He/⁴He RATIO

As shown in the ³He/⁴He-⁴He diagram (Fig. 1), most samples from West Greenland (KIM 1a, 1b; KIM 6a, 6b; KIM 9a, 9b) have ³He/⁴He ratios of greater than 15R_A. It should be noted that the observed ⁴He concentrations for a and b subsamples are quite variable in some samples, but for all samples, both a and b subsamples show almost the same ³He/⁴He ratio within their 2σ analytical uncertainty. This suggests that the concentration of noble gases is largely controlled by the amount of fluid and/or melt inclusions in olivine crystals, but that the isotopic composition is homogeneous throughout each sample. Hence, the reproducible ³He/⁴He ratio for subsamples a and b represents the primary signature of the magma. Sample KIM 9a has the highest ³He/⁴He ratio

EXPERIMENTAL PROCEDURES

For noble gas analyses, olivine crystals with sizes of 0.5 mm to 1 mm were separated by handpicking. The olivines were then cleaned by immersion in 1N HNO₃ at 60 °C for 30 min. Each sample weighed around 1 g, and the crushing method was used to de-gas the olivines. The crushing efficiency for each sample is estimated to have been around 30% based on our previous experiments for olivine samples. Noble gas isotopes were analyzed on a VG-5400 mass spectrometer at the Earthquake Research Institute, University of Tokyo. Details about analytical procedures are described by Hanyu et al. (1999).

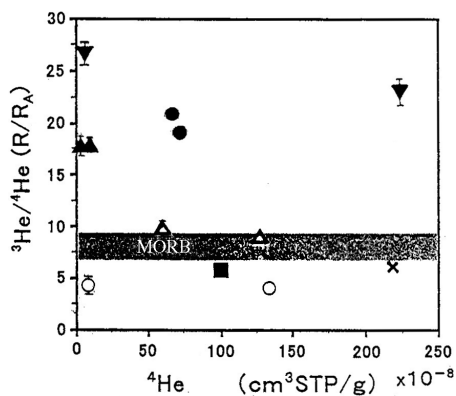


Figure 1. ³He/⁴He-⁴He diagram for kimberlites from South and West Greenland. Open symbol indicates sample from South Greenland and closed symbol from West Greenland. Same symbol indicates data for same sample block. Gray banded area represents ³He/⁴He ratios for mid-ocean-ridge basalts (MORBs). Error bar is expressed as 1σ. STP—standard temperature and pressure; R_A—the ³He/⁴He of air.

of $(26.6 \pm 1.0) R_A$. Such high $^3\text{He}/^4\text{He}$ ratios are similar to those observed in samples from Hawaii (Loihi-type) (e.g., Kaneoka et al., 2002) and Iceland (Hilton et al., 1999), where $^3\text{He}/^4\text{He}$ ratios are as high as 30–38 R_A . In contrast, the South Greenland samples (101243-2a,-2b; 101243-3a,-3b) have $^3\text{He}/^4\text{He}$ ratios of 4.6–9.7 R_A .

It could be argued that such high $^3\text{He}/^4\text{He}$ ratios resulted from in situ production of ^3He by cosmic-ray bombardment. However, in the present study, we used the crushing method to de-gas the samples in order to minimize the effect of components produced in situ by cosmic-ray or nucleogenic and radiogenic processes. Furthermore, the samples used in this study are inferred to have been originally deep enough to be sheltered from cosmic rays and have been exposed to the surface by recent deglaciation, with a maximum exposure time of less than 10^4 yr. Based on a ^3He production rate of 120 atoms $\text{g}^{-1} \text{yr}^{-1}$ by cosmic-ray bombardment of olivine (Niedermann, 2002), we can calculate the cosmogenic ^3He to be 4.4×10^{-14} $\text{cm}^3\text{STP/g}$ for 10^4 yr. Most samples in this study have ^3He concentrations on the order of 10^{-11} – 10^{-12} $\text{cm}^3\text{STP/g}$, thus the contribution of cosmogenic ^3He is almost negligible. ^3He can also be produced from ^6Li through irradiation by the thermal neutrons produced by spontaneous fission of ^{238}U (Mamayrin and Tolstikhin, 1984). However, because ^4He is also produced by alpha decay of U and Th, the resultant $^3\text{He}/^4\text{He}$ ratio of all He produced through these processes is on the order of 10^{-8} , as long as the Li/U ratio of olivines is the same as that of the bulk kimberlite reported in the literature (Muramatsu, 1983). Even if we assume an extreme case of in situ production of ^3He from ^6Li in olivine crystals by irradiation of thermal neutrons originating outside of the crystals, it cannot explain the fact that $^3\text{He}/^4\text{He}$ ratios of subsamples are constant at very different ^4He concentrations (Fig. 1). This is independent important evidence that ^3He is not of cosmogenic nor nucleogenic origin. Consequently, the high $^3\text{He}/^4\text{He}$ ratios must represent the composition at the time of kimberlite magma intrusion at a shallow depth. Although some samples have $^3\text{He}/^4\text{He}$ ratios similar to, or slightly lower than, those of MORBs, they may have been affected by radiogenic components acquired from the surrounding materials at the bottom of the lithosphere and/or during magma ascent processes.

Some olivines in kimberlites might be xenocrysts. However, the high $^3\text{He}/^4\text{He}$ ratios indicate that the magma from which they crystallized is at least related to a deep mantle source. Furthermore, multiple olivine samples separated from the West Greenland kimber-

lites show similarly high $^3\text{He}/^4\text{He}$ ratios. Hence, it is most likely that most olivine crystals with high $^3\text{He}/^4\text{He}$ ratios are related to kimberlite magma.

THE $^{40}\text{Ar}/^{36}\text{Ar}$ RATIO

South and West Greenland samples have $^{40}\text{Ar}/^{36}\text{Ar}$ ratios ranging from ~ 890 to 11,500. It should be noted that KIM 9a, which has the highest $^3\text{He}/^4\text{He}$ ratio, 26.6 R_A , shows the lowest $^{40}\text{Ar}/^{36}\text{Ar}$ ratio among present samples. The South Greenland samples (101243-2, 101243-3) and samples with lower $^3\text{He}/^4\text{He}$ ratios from West Greenland (KIM 12, KIM 15) have high ^{40}Ar concentrations of more than 1.4×10^{-7} $\text{cm}^3\text{STP/g}$, whereas those with high $^3\text{He}/^4\text{He}$ ratios have lower concentrations (Table 1). This suggests that these kimberlites might contain radiogenic components that cause the reduction of their $^3\text{He}/^4\text{He}$ ratio. When we take $^{40}\text{Ar}/^{36}\text{Ar}$ ratios into account together with $^3\text{He}/^4\text{He}$ ratios, kimberlite data are indeed compatible with the mixture of the geologically expected four end members, the OIB (mantle plume) type, the MORB type, the crust (lithosphere) type and the atmosphere type. Although definite numbers are not yet settled, the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the OIB-type end member is generally inferred to be $< 10,000$, whereas that of the MORB type is thought to be around 40,000 (e.g., Graham, 2002). The crust (lithosphere)-type end member might have a variable $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of more than 10,000, depending on the area reflecting individual evolutionary history of the crust (lithosphere). The atmosphere has a $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 296. Kimberlite magmas having plume-type noble gases might have been affected by the other components from the surrounding materials at the bottom of lithosphere and/or during magma ascent processes to the surface, including dike intrusion at a shallow depth.

RELATIONSHIP BETWEEN THE $^{129}\text{Xe}/^{132}\text{Xe}$ AND $^{136}\text{Xe}/^{132}\text{Xe}$ RATIOS

Kimberlite samples have $^{129}\text{Xe}/^{132}\text{Xe}$ and $^{136}\text{Xe}/^{132}\text{Xe}$ ratios greater than those of air (Fig. 2). Samples from West Greenland generally lie on the line defined by MORBs. Since this trend is also observed for OIB samples (Trieloff et al., 2000), the signature is consistent with the interpretation that kimberlite magma has a similar source to that of OIB magmas. In the case of Xe isotope signatures, however, the trend does not exclude a possibility of incorporation of MORB-type materials into kimberlite magmas. It is noteworthy that two samples from South Greenland show no clear ^{129}Xe excess with higher $^{136}\text{Xe}/^{132}\text{Xe}$ ratios compared to air. This could be explained by the incorporation of old crustal or

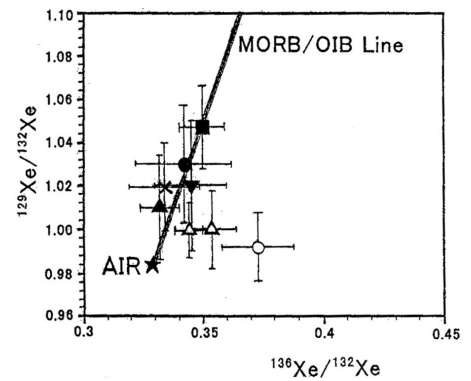


Figure 2. $^{129}\text{Xe}/^{132}\text{Xe}$ vs. $^{136}\text{Xe}/^{132}\text{Xe}$ diagram. Symbols and error bars are same as in Figure 1. Samples from West Greenland lie on line defined by mid-oceanic-ridge basalts (MORBs), which cannot be separated from ocean-island basalt (OIB) trend.

lithospheric components with high $^{136}\text{Xe}/^{132}\text{Xe}$ ratios into the magma resulting from the addition of fissiogenic ^{136}Xe from ^{238}U . This is consistent with the observation that samples from South Greenland have $^3\text{He}/^4\text{He}$ ratios lower than the MORB values. Thus, Xe isotope signatures are also compatible with the mixture of the geologically expected four end members, as suggested by He and Ar isotope systematics.

SECULAR VARIATION OF $^3\text{He}/^4\text{He}$ RATIOS AND EVIDENCE FOR THE OIB-LIKE SOURCE OF KIMBERLITES

In order to evaluate the significance of the apparent high $^3\text{He}/^4\text{He}$ ratios more strictly, we need to consider secular variation of the $^3\text{He}/^4\text{He}$ ratio, because the kimberlites have intrusion ages ranging from ca. 600 Ma to 200 Ma. Figure 3 shows the inferred variation of the $^3\text{He}/^4\text{He}$ ratio with the evolution of magma sources of MORBs (depleted reservoir) and OIBs (less-depleted reservoir), along with the data of studied samples. The broad-banded zone for the depleted reservoir shows the inferred $^3\text{He}/^4\text{He}$ ratios of the MORB-source in the case of an open system for He (Seta et al., 2001). As shown in Figure 3, even taking the secular variation of the $^3\text{He}/^4\text{He}$ ratios into consideration, kimberlites from West Greenland have $^3\text{He}/^4\text{He}$ ratios definitely higher than those of MORBs. This suggests that at least some kimberlite magmas might have been derived from a magma source similar to those of OIBs with high $^3\text{He}/^4\text{He}$ ratios (Loihi type). It also implies that kimberlite magmas could be related to mantle plumes. The other noble gas data are also compatible with this conjecture. Furthermore, if mantle plumes are derived from the lower mantle, as is commonly hypothesized (e.g., Hofmann, 1997), the source for kimberlite magmas might lie in the lower mantle. This is compatible with the ob-

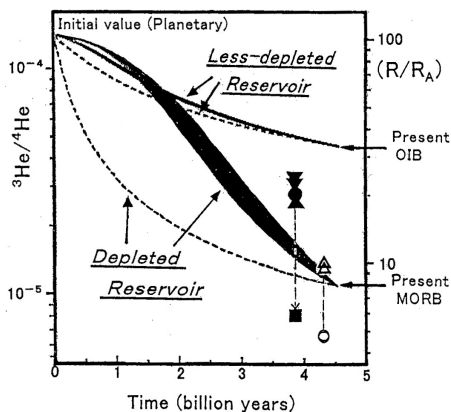


Figure 3. Inferred secular variation of $^3\text{He}/^4\text{He}$ ratio since Earth's formation to present. Dotted line and banded zone labeled "Depleted reservoir" show variation of $^3\text{He}/^4\text{He}$ ratio for mid-oceanic-ridge basalt (MORB) magma source in the case of closed and open systems, respectively. "Less-depleted reservoir" indicates variation of $^3\text{He}/^4\text{He}$ ratio for ocean-island basalt (OIB) magma source in the case of closed and open systems, respectively (modified after Fig. 3 in Seta et al., 2001). Kimberlite data are shown by same symbols as in Figure 1. R_A —the $^3\text{He}/^4\text{He}$ of air.

servation that some mineral inclusions in diamonds have a possible origin in the lower mantle (e.g., Harte and Harris, 1994).

Thus, based on their high $^3\text{He}/^4\text{He}$ ratios, together with the other noble gas isotopic data observed in kimberlites from West Greenland, we conclude that at least some kimberlite magmas might have similar sources to those of Loihi-type OIB and are probably related to those of mantle plumes. Kimberlites might thus play an important role for investigating the chemical state of Earth's deep interior. Due to their relatively rapid ascent and minimal interaction with their wall rocks compared to the other kind of magmas, at least some fresh kimberlites are believed to have retained their primitive volatile components and chemical properties from Earth's deep interior.

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