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Evidence for deep mantle convection and primordial heterogeneity from nitrogen and carbon stable isotopes in diamond

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ABSTRACT

Diamond, as the deepest sample available for study, provides a unique opportunity to sample and examine parts of the Earth's mantle not directly accessible. In order to provide further constraints on mantle convection and deep volatile cycles, we analysed nitrogen and carbon isotopes and nitrogen abundances in 133 diamonds from Juina (Brazil) and Kankan (Guinea). Host syngenetic inclusions within these diamonds indicate origins from the lithosphere, the asthenosphere-transition zone and the lower mantle.

Juina and Kankan diamonds both display overall carbon isotopic compositions within the current upper mantle range but the $\delta^{13}C$ signatures of diamonds from the asthenosphere-transition zone extend toward very negative and positive values, respectively. Two Kankan diamonds with both lower mantle and asthenosphere-transition zone inclusions (KK-45 and KK-83) are zoned in $\delta^{13}C$, and have signatures consistent with multiple growth steps likely within both the lower mantle and the asthenosphere-transition zone illustrating the transfer of material through the 670 km seismic discontinuity.

At a given locality, diamonds from the upper and the lower mantle show similar $\delta^{15}N$ distributions with coinciding modes within the range defined by typical upper mantle samples, as one might expect for a well stirred reservoir resulting from whole mantle convection.

Kankan diamonds KK-11 (lower mantle), KK-21 and KK-92 (both lithospheric) display the lowest $\delta^{15}N$ values (-24.9%, -39.4% and -30.4%) ever measured in terrestrial samples, which we interpret as reflecting primordial heterogeneity preserved in an imperfectly mixed convective mantle.

Our diamond data thus provide support for deeply rooted convection cells, together with the preservation of primordial volatiles in an imperfectly mixed convecting mantle, thereby reconciling the conflicting interpretations regarding mantle homogeneity derived from geochemical and geophysical studies.

1. Introduction

The dynamic and compositional structure of the mantle is critical to understand the evolution of our planet. Mantle convection provides the central framework linking geochemistry, geophysics, mineral physics and geology. Noble gas and radiogenic lithophile element geochemistry of mid-ocean ridge basalts (MORB) and oceanic island basalts (OIB) lead to the suggestion that distinct reservoirs exist (e.g. Allègre et al., 1986; Hilton and Porcelli, 2003; Hofmann, 2003; Ballentine et al., 2005; Kurz et al., 2009). The difference between chondrites and most terrestrial rocks in $^{142}Nd/^{144}Nd$ has been interpreted as resulting from early global differentiation of the Earth's mantle composed of an incompatible element-depleted source of MORB and a complementary enriched reservoir located deeply within the mantle (e.g. Boyet and Carlson, 2005; O'Neil et al., 2008). This has been taken as evidence for layered mantle convection (often assumed to be separated at 670 km depth) but the size and depth of these reservoirs remain mostly unconstrained.

Seismic tomography studies have shown that some slabs subduct through the 670 km seismic discontinuity down to the core–mantle boundary (e.g. Fukao et al., 1992; Grand, 1994; Van der Hilst et al., 1997; Masters et al., 2000; Lay, 2007), providing

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Table 1
Chemical and mineralogical characteristics of Juina diamonds. This includes measurements of $\delta^{13}C$ by mass spectrometry in dual inlet mode, $\delta^{15}N$ and nitrogen content (N_{bulk}) by mass spectrometry in static mode, $[N]_{FTIR}$ and % of B defect by infrared spectroscopy for Juina diamonds. Errors on $\delta^{13}C$ are better than $\pm 0.1‰$ (2σ), and $\pm 0.5‰$ (2σ) for $\delta^{15}N$ except when blank contributed to more than 20%, in which case a Monte Carlo correction was applied.

Sample	Paragenesis	$\delta^{13}C$	$\delta^{15}N$	Error $\pm(2\sigma)$	$[N]_{FTIR}$ (ppm)	%B	$[N]_{BULK}$ (ppm)	Inclusions	Main characteristics of inclusion chemistry
1-6	Unknown	−5.0			87	98		Unknown	
1-22	Unknown	−4.4			0			Unknown	
1-24	Unknown	−2.8			0			Unknown	
1-37	Unknown	−5.1			75	97		Unknown	
1-102	Unknown	−4.4	−4.6	1.0	17	90	14	Calcite, Fe-altered	
4-27	Unknown	−4.2			0			Unknown	
5-16	Unknown	−5.6			20	100		Unknown	
5-35	Unknown	−7.8			70	69		Unknown	
5-58	Unknown	−4.9			0			Unknown	
5-59	Unknown	−3.9			0			Unknown	
5-60	Unknown	−4.8			0			Unknown	
5-78	Unknown	−4.6			0			Unknown	
5=80	Unknown	−6.2			61	16		Unknown	
5-105	Unknown	−4.4			0			Unknown	
5-109-2	Unknown				56	100		Unknown	
5-109-3	Unknown				30	38		Unknown	
BZ-208	Unknown	−5.2			14	100		Unknown	
BZ-211	Unknown	−13.0			586	92		Unknown	
BZ-212b	Unknown	−8.5			21	17		Unknown	
BZ-212d	Unknown	−8.5			507	92		Unknown	
BZ-214	Eclogitic?	−11.6			0			Ruby	Hi-Cr, Lo–Al
1-35	Lithospheric P	−5.5	−3.4	0.5	68	100	48	Spinel	Hi-Ti,Fe, Lo–Cr
4-4	Lithospheric P	−3.5			0			Spinel	Hi-Ti,Fe, Lo–Cr
5-55	Lithospheric P	−4.3			n.d.			Spinel	Hi-Ti,Fe, Lo–Cr
BZ-213	Lithospheric P	−3.4	−3.3	0.5	78	27	30	cpx	Hi-Cr
BZ-124	Asthe. B	−12.3	+1	2.0	47	64	510	Majorite, Cpx	Hi-Si at.pfu, Lo-Cr
BZ-127	Asthe. B	−8.4	+0.2	0.5	112	79	77	Majorite	Hi-Si at.pfu, Lo-Cr
BZ-129	Asthe. B	−6.3	+1.2	0.5	0		66	Majorite	Hi-Si at.pfu, Lo-Cr
BZ-209	Asthe. B	−12.1	+3.8	0.5	559	91	750	cpx	Lo-Cr
BZ-215	Asthe. B	−8.8	+1.3	0.5	289	71	166	Majorite	Hi-Si at.pfu, Lo-Cr
BZ-217	Asthe. B	−8.6	+1.2	0.5	101	54	62	Majorite	Hi-Si at.pfu, Lo-Cr
1-1	LM/TZ P	−4.7	−2.1	0.5	361	100	331	Ilmenite	Hi-Mn, Lo-Mg
1-2	LM/TZ P	−4.5			0			Ilmenite	Hi-Mn, Lo-Mg
1-5	LM/TZ P	−4.3	−5.8	0.5	112	95	61	Ilmenite	Hi-Mn, Lo-Mg
1-8	LM/TZ P	−4.2	−8.8	0.5	30	97	125	Ilmenite	Hi-Mn, Lo-Mg
1-30-1	LM/TZ P	−4.9			n.d.			Ilmenite	Hi-Mn, Lo-Mg
1-30-4	LM/TZ P	−10.3	−1.5	0.5	25	86	34	Ilmenite	Hi-Mn, Lo-Mg
1-32	LM/TZ P	−4.2			0			Ilmenite	Hi-Mn, Lo-Mg
1-34	LM/TZ P	−4.2			0			Ilmenite	Hi-Mn, Lo-Mg
4-7-2	LM/TZ P	−9.7			0			Ilmenite	Hi-Mn, Lo-Mg
4-7-3	LM/TZ P	−4.7			0			Ilmenite	Hi-Mn, Lo-Mg
4-101	LM/TZ P	−4.6			0			$CaSiO_3$, olivine	Hi-traces (Ca–Si), Lo-Fo (ol.)
4-102	LM/TZ B?	−4.6			0			SiO_2	almost pure SiO_2
5-107	LM/TZ B?	−4.3	−4.4	0.5	40	95	42	SiO_2	almost pure SiO_2
BZ-237	LM/TZ B?	−5.1	−5.6	0.5	148	97	166	$MgSiO_3$ (Al), majorite	Hi-Al, Lo-Ni (Mg–Si), Hi-Si at.pfu
1-4-3	LM P?	−4.0	−4.0	0.7	124	100	26	fPer, ilmenite	Hi-Fe (fPer), Hi-Mn, Lo-Mg (ilm.)
1-4-4	LM P?	−5.3	−0.8	0.5	410	98	477	fPer, ilmenite	Hi-Fe (fPer), Hi-Mn, Lo-Mg (ilm.)
1-7	LM P?	−4.4			0			fPer, ilmenite	Hi-Mn, Lo-Mg (ilm.)
1-31	LM P	−4.7	−3.2	0.5	41	97	74	fPer	Lo-Fe
1-33	LM P	−4.3			0			fPer	Lo-Fe
1-36	LM P	−5.4	−1.0	0.5	20	52	20	fPer	Lo-Fe
1-38	LM P	−4.2			0			fPer	Lo-Fe