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A secretive mechanical exchange between mantle and crustal volatiles revealed by helium isotopes in ^{13}C-depleted diamonds

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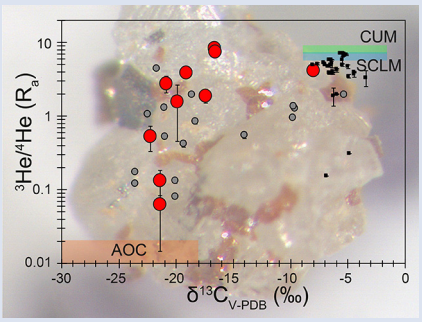
Abstract



Fluid inclusions trapped in fast-growing diamonds provide a unique opportunity to examine the origin of diamonds, and the conditions under which they formed. Eclogitic to websteritic diamondites from southern Africa show ^{13}C-depletion and ^{15}N-enrichment relative to mantle values (δ^{13}C = -4.3 to -22.2 ‰ and δ^{15}N = -4.9 to +23.2 ‰). In contrast the ^{3}He/^{4}He of the trapped fluids have a strong mantle signature, one sample has the highest value so far recorded for African diamonds (8.5 ± 0.4 R$_a$). We find no evidence for deep mantle He in these diamondites, or indeed in any diamonds from southern Africa. A correlation between ^{3}He/^{4}He ratios and ^{3}He concentration suggests that the low ^{3}He/^{4}He are largely the result of ingrowth of radiogenic ^{4}He in the trapped fluids since diamond formation. The He-C-N isotope systematics can be best described by mixing between fluid released from subducted altered oceanic crust and mantle volatiles. The high ^{3}He/^{4}He of low δ^{13}C diamondites reflects the high ^{3}He concentration in the mantle fluids relative to the slab-derived fluids. The presence of post-crystallisation ^{4}He in the fluids means that all ^{3}He/^{4}He are minima, which in turn implies that the slab-derived carbon has a sedimentary organic origin. In short, although carbon and nitrogen stable isotope data show strong evidence for crustal sources for diamond-formation, helium isotopes reveal an unambiguous mantle component hidden within a strongly ^{13}C-depleted system.

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Introduction

Placing diamond-formation into context of large scale tectonothermal processes, such as subduction and plume-lithosphere interaction, is fundamental to understanding the deep terrestrial carbon cycle (Shirey *et al.*, 2013). Diamond is a chemically simple mineral comprised largely of C and trace N (~0.025 %) incorporated as single nitrogen atoms substituting for carbon (Kaiser and Bond, 1959). The origin of diamond-forming fluids is commonly addressed using the stable isotope values of carbon and nitrogen, where coupled δ^{13}C-δ^{15}N values can indicate diamond growth from mantle-derived fluids (Cartigny *et al.*, 2014). However, many datasets require the contribution of crustal sources for the C and/or N, such as eclogitic diamonds from Dachine (Smith *et al.*, 2016). Sometimes, C-N isotope systematics do not fully resolve the origin of the diamond-forming fluids. For instance, eclogitic diamonds from Jwaneng (Cartigny *et al.*, 1998) and Orapa (Cartigny *et al.*, 1999) show crust-like low δ^{13}C values yet have mantle-like negative δ^{15}N values (Fig. 1), and C and N isotope systems can be decoupled during diamond-formation (Mikhail *et al.*, 2014; Hogberg *et al.*, 2016).

Diamonds can trap fluid during their growth, either along the diamond fibres, between interlocking polycrystalline grains, and surrounding diamond-hosted mineral inclusions (Navon *et al.*, 1988; Jacob *et al.*, 2014). As well as providing the only direct samples of metasomatic fluids from the mantle (Weiss *et al.*, 2015), the trapped fluids enable the application of noble gas isotope tracers to resolve the origin of diamond-forming fluids (Burgess *et al.*, 1998; Gautheron *et al.*, 2005; Broadley *et al.*, 2018; Timmermann *et al.*, 2018, 2019a,b). Here we combine C-N isotope and nitrogen abundance data from southern African diamondites with He isotope data from micro-inclusions in the same sample to investigate the origin of carbonaceous fluids in the mantle. These new data shed light on the number of discrete sources required for the generation of carbonaceous high-density fluids responsible for diamond-formation in the SCLM.

Samples and Methods

Three main diamond types are recognised; monocrystalline, fibrous and polycrystalline. The latter, also known as diamondites, are a mixture of diamond intergrown with silicates and

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Table 1 Data for southern African diamondites. A full data table including all comparative data is located in the Supplementary Information (Table S-1).

Sample	Location	Para	Minerals	R/Ra	±	^{4}He ccSTP/g	^{3}He ccSTP/g	δ^{13}C (‰)	±	N at.ppm	δ^{15}N (‰)	±
DIA030	SA	W	Gnt	8.5	0.4	1.33 E-07	1.51 E-12	-16.6	0.2	8	+6.4	3.9
DIA053	SA	W	Gnt	2.8	0.7	3.20 E-08	1.18 E-13	-20.8	0.5	56	+2.0	0.7
DIA057B#1	SA			0.1	0.0	6.79 E-07	5.81 E-14	-21.4	0.1	1389		
DIA057B#2	SA			0.1	0.1	6.90 E-07	1.25 E-13	-21.4	0.1	1389		
DIA058B	SA	E	Gnt	3.9	0.2	7.42 E-08	3.84 E-13	-19.1	0.1			
DIA059	SA	W	Gnt	0.5	0.2	1.42 E-07	1.01 E-13	-22.2	0.3	13	+5.3	6.1
DIA073B	SA	W	Gnt	1.9	0.4	8.71 E-08	2.21 E-13	-17.4	0.1	2812	+6.9	0.5
DIA077	SA			7.4	0.5	1.44 E-07	1.43 E-12					
ORF9	Orapa	W	Gnt			2.44 E-08		-5.3	0.1			
ORF12	Orapa					6.72 E-08						
ORF19	Orapa	E	Gnt	4.2	2.7	9.02 E-08	5.11 E-13	-8.0	0.1	255	+5.8	0.1
ORF26#1	Orapa	P + E	Cpx + Gnt			4.22 E-09		-14.6	0.2	38	-4.8	2.2
ORF26#2	Orapa	P + E	Cpx + Gnt					-17.8	0.2	19	+23.2	6.6
ORF28#1	Orapa					5.37 E-08		-4.3	0.1	775	+2.9	0.2
ORF28#2	Orapa							-4.9	0.2	52	+19.7	0.6
ORF41	Orapa					7.77 E-08		-14.8	0.3	1146	+14.7	0.2
ORF57	Orapa	E	Gnt	7.5	0.7	2.24 E-07	2.26 E-12	-16.6	0.2	17	+18.4	3.0
ORF60	Orapa		Chromite					-6.5	0.1	1054	+12.1	0.2
ORF91	Orapa							-20.3	0.3	401	+4.4	0.3
ORF143	Orapa	E	Gnt	1.6	1.1	1.03 E-07	2.17 E-13	-19.9	0.2	647	+10.0	0.2

Abbreviations: W = websteritic, P = peridotitic, E = eclogitic, Gnt = garnet, Cpx = clinopyroxene, SA = southern Africa.

oxides (Kurat and Dobosi, 2000). Seventeen diamondites in this study are from two collections, the Orapa and the southern African diamondites (n = 10 and 7 respectively; Table 1). These samples are described in detail elsewhere (Kurat and Dobosi., 2000; Mikhail *et al.*, 2019; Supplementary Information). The δ^{13}C, δ^{15}N values and N concentrations were obtained using the automated and custom-made Finesse system at the Open University following the method outlined in Mikhail *et al.* (2014). The helium isotope composition of trapped fluids released by *in vacuo* crushing were determined using a ThermoFisher Scientific Helix-SFT mass spectrometer at the Scottish Universities Environmental Research Centre (Carracedo *et al.*, 2019). These data are provided in Table 1.

Carbon and Nitrogen Geochemistry

δ^{13}C values range from -4.3 to -22.2 ‰ and δ^{15}N range from -4.9 to +23.2 ‰ (Fig. 1). Although they overlap, the southern Africa diamondites have lower mean δ^{13}C (-19.8 *vs.* -12.1 ‰) and higher average δ^{15}N values (+10.6 *vs.* +5.2 ‰) than the Orapa diamondites. There is no systematic relationship between C or N isotope values and the silicate paragenesis, consistent with previous observations (Mikhail *et al.*, 2019). Although mantle-like C and N isotope values are recorded, no sample plots in the mantle field (Fig. 1). Diamondites show ^{13}C-depletion and ^{15}N-enrichment relative to mantle values. The Orapa diamondites have a more pronounced ^{13}C-depletion and ^{15}N-enrichment when compared to the eclogitic and peridotitic monocrystalline diamonds from the same kimberlite (Fig. 1). These data indicate crustal fluids sourced from subducted oceanic sediments or altered oceanic crust (Thomazo *et al.*, 2009). Nitrogen concentrations range from 8–1389 ppm and do not correlate with δ^{13}C or δ^{15}N, consistent with previous observations (Mikhail *et al.*, 2013, 2014, 2019). The lack of correlation between nitrogen concentrations with δ^{13}C or δ^{15}N in both datasets may reflect multiple diamond forming events, or isotopic heterogeneity in the source.

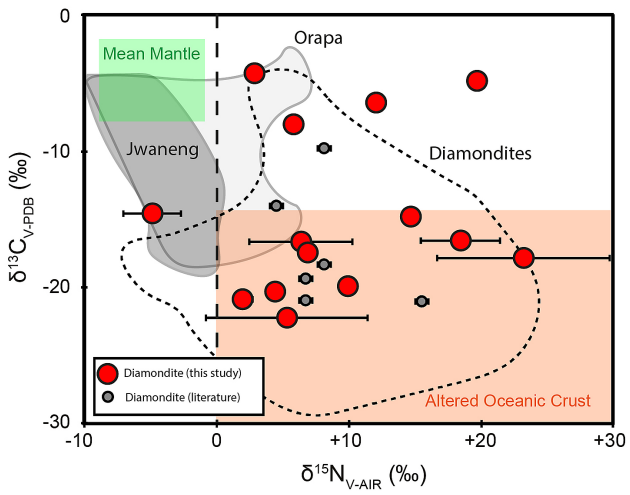

Figure 1 New C and N isotope data for southern African diamondites (red circles) and literature data (grey circles: Gautheron *et al.*, 2005; Burgess *et al.*, 1998) Fields are shown for other diamondites (Mikhail *et al.*, 2013), eclogitic monocrystalline diamonds from Jwaneng (Cartigny *et al.*, 1998) and Orapa (Cartigny *et al.*, 1999), the mean mantle and altered oceanic crustal material (Cartigny *et al.*, 2014).

Helium Isotopes

The ^{3}He/^{4}He ratios range from 0.06 to 8.5 R_a, overlapping, but extending, the range previously measured in southern Africa diamondites (Fig. 2a). The highest ^{3}He/^{4}He in these

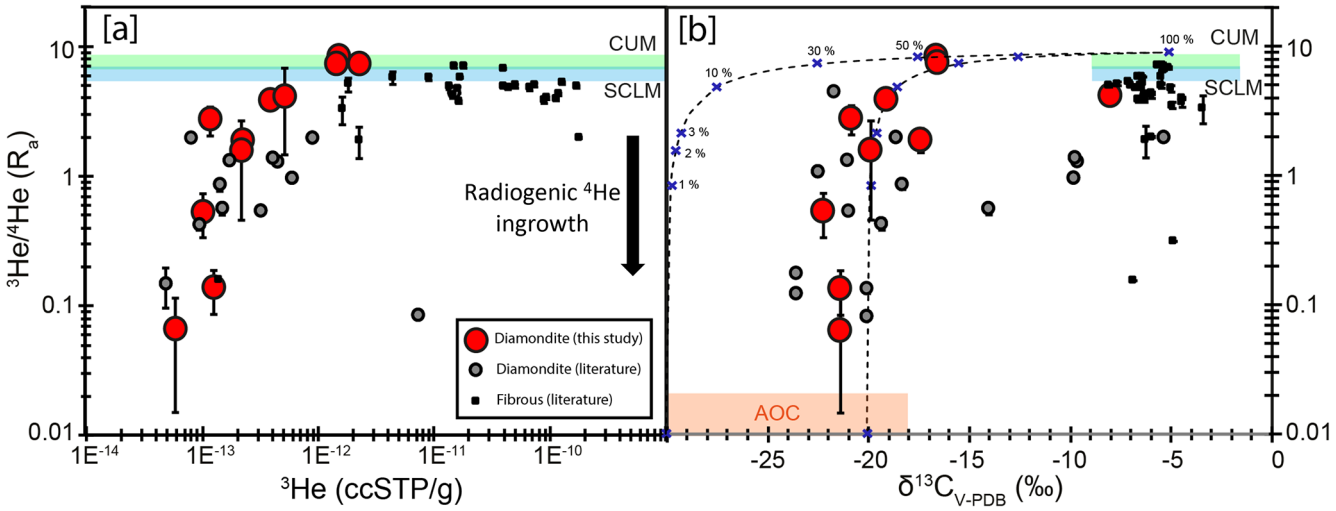

Figure 2 **(a)** Helium isotope systematics of fluids released by *in vacuo* crushing of diamondites. The ^{3}He/^{4}He of modern the convecting upper mantle (CUM) and the sub-continental lithospheric mantle (SCLM) are shown for reference. **(b)** Carbon-helium isotope systematics of southern African diamondites and fibrous diamonds from across southern Africa. The mixing lines are plotted between mantle and crustal fluid sources, the crosses refer to percent of mantle fluid component. The mixing lines plotted in Figure 2b are hyperbolic as $[^4He]_{mantle}/[^4He]_{crust}$ is assumed to be 10. Comparative data are from Burgess *et al.* (1998), Gautheron *et al.* (2005) and Timmermann *et al.* (2018, 2019a).

diamondites (8.5 ± 0.4 R_a) exceeds the highest ratios measured in all other diamondites and fibrous diamonds from southern Africa (Fig. 2a). It is higher than values typical of SCLM (6.1 ± 1 R_a; Gautheron *et al.*, 2005) and modern kimberlite from southern Africa (4.2 R_a; Brown *et al.*, 2012), and overlaps the present day convecting upper mantle (8 ± 1 R_a; Graham *et al.*, 2014).

The southern Africa diamondites formed between kimberlite emplacement and craton stabilisation (91 to >3000 Ma; Gurney *et al.*, 2010). The highly aggregated nitrogen in diamondites is consistent with long mantle residence times (Mikhail *et al.*, 2019), which implies ages far greater than 91 Ma. This leaves open the likelihood that ^{4}He produced by alpha decay of U and Th in the fluid, or recoil of ^{4}He into the fluids, has decreased the ^{3}He/^{4}He (Timmermann *et al.*, 2019a). A strong relationship between ^{3}He/^{4}He and ^{3}He concentration is apparent from Figure 2a and reflects radiogenic ^{4}He production since the fluids were trapped in the diamond. In this case, all ^{3}He/^{4}He ratios are minimum values, although it appears that diamonds with >1 x 10^{-12} ccSTP ^{3}He/g are largely immune to the effect based on Figure 2a. The diamonds studied here are not alluvial, ruling out cosmogenic ^{3}He implantation during surface exposure (*e.g.*, Yakubovich *et al.*, 2019).

Tracing the Origin of Diamondite-forming Volatiles

Mixing lines in Figure 2b are drawn between oceanic crust-derived fluids with $\delta^{13}C$ = -20 and -30 ‰, and ^{3}He/^{4}He = 0.01 R_a, and mantle-derived fluids with $\delta^{13}C$ = -5 ‰ and ^{3}He/^{4}He = 9 R_a. The mantle ^{3}He/^{4}He end member is slightly higher than the present day upper asthenosphere and lithosphere mantle values, reflecting the temporal evolution of ^{3}He/^{4}He in the mantle (Porcelli and Elliot, 2008).

The spread of data can be explained by mixing between He-rich, high ^{3}He/^{4}He mantle source ($\delta^{13}C$ = -5 ‰) and a He-poor, low ^{3}He/^{4}He crustal component ($\delta^{13}C$ between -15 and -25 ‰). This is strongly supported by the ^{15}N-enrichment in the ^{13}C-depleted samples which best matches altered oceanic crust (Cartigny *et al.*, 2014) or organic material hosted in sedimentary rocks (Thomazo *et al.*, 2009). Furthermore, the prevalence of eclogitic to websteritic silicate inclusions/intergrowths in these diamondites further supports a recycled basaltic component (Mikhail *et al.*, 2019). These observations contrast strongly with the fibrous diamonds which, although they also contain a high density of trapped fluids with evidence of recycled material based on lithophile element geochemistry and Sr-isotopes (Weiss *et al.*, 2015), they commonly show C and N isotope values that are indistinguishable from mantle values (see Fig. 2a,b). Despite significantly lower ^{3}He concentrations, they are thus more likely to be affected by radiogenic ^{4}He ingrowth; the highest ^{3}He/^{4}He southern African diamondites are higher than the highest values measured in fibrous diamonds from southern Africa (Fig. 2a). This suggests that there is no genetic link between the fibrous diamonds and diamondites, and they likely formed in different mantle domains or from isotopically distinct sources.

A mantle origin for the helium trapped in the diamondite fluids is incontrovertible (Fig. 2a), but the incorporation mechanism(s) for He into the high density fluids (HDF) is less clear. Possible mechanisms include the assimilation of He from grain boundaries or small volume mantle melts initiated by the expulsion of slab-derived fluids into the mantle wedge or SCLM. Resolving the origin of the mantle He is hampered by the post-formation ingrowth of radiogenic ^{4}He, and because the ^{3}He/^{4}He ratio of the mantle has reduced over time (*e.g.*, Porcelli and Elliot, 2008). The uncertainty in the diamond age and the He isotope evolution of the mantle makes drawing firm conclusions regarding the source of the mantle He problematic. One prevailing view posits that the southern African kimberlites originate at the edges of large heterogeneities at the core-mantle boundary (Torsvik *et al.*, 2010). This should be evident from high ^{3}He/^{4}He (*e.g.*, Stuart *et al.*, 2003) in kimberlitic fluids. In contrast to Brazilian diamonds (Timmermann *et al.*, 2019b), the absence of ^{3}He/^{4}He above Phanerozoic upper mantle values in fluid-rich diamonds from southern Africa rules likely reflects the formation of the diamonds prior to the generation of the kimberlite melts, and post-formation isolation from kimberlitic fluids. Furthermore, it is conceivable that high ^{3}He/^{4}He ratios (>10 R_a) in some samples (*e.g.*, Siberian fibrous diamonds; Broadley *et al.*, 2018) might reflect the higher ^{3}He/^{4}He of the ancient mantle, as opposed to evidence

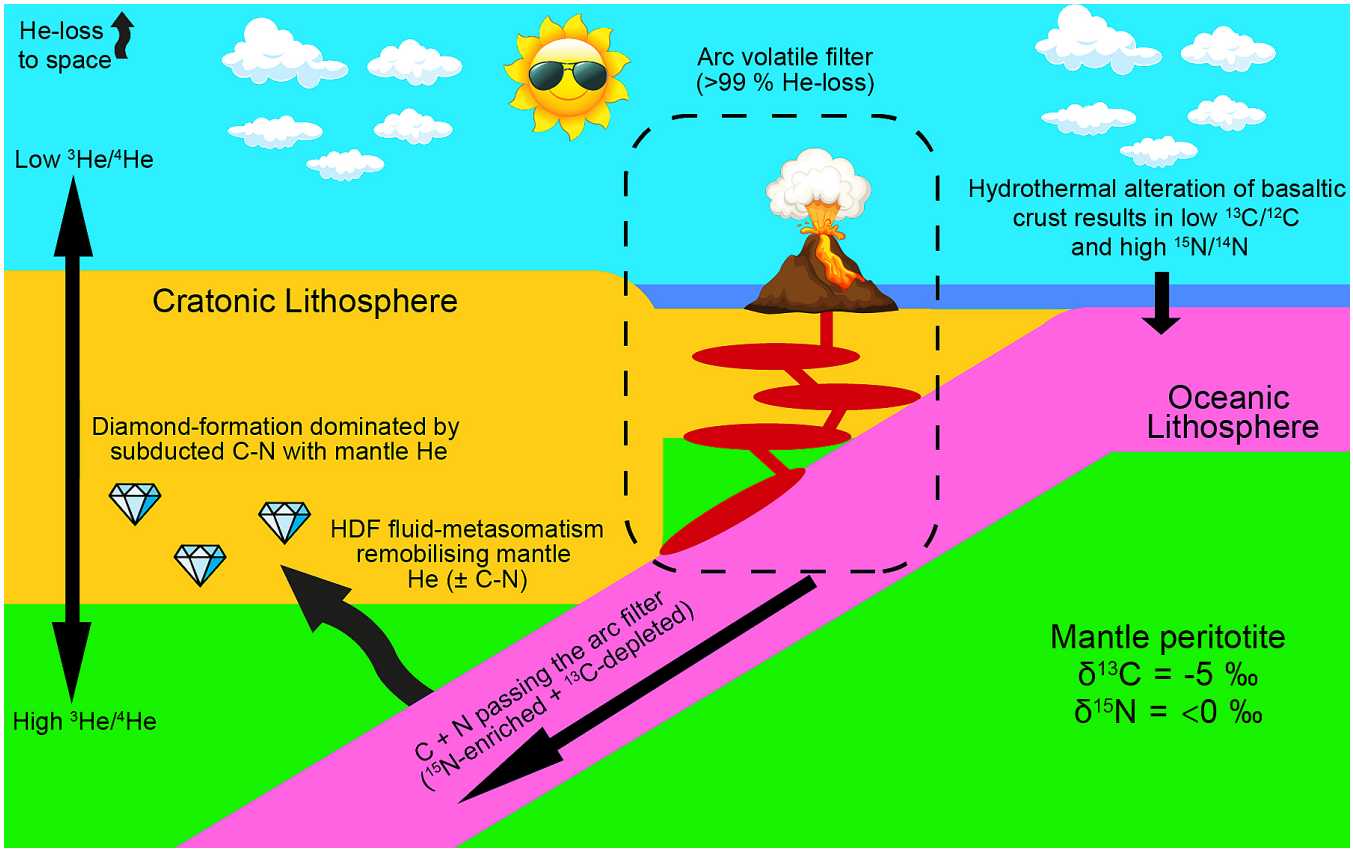

Figure 3 Cartoon illustrating the model discussed in the text. Not to scale.

for the role of mantle plumes in the generation of shallow diamonds. While the highest diamondite $^3He/^4He$ ratios are above modern SCLM values, they do not allow a distinction to be made between an ancient sub-continental lithospheric or a convecting upper asthenospheric mantle source. That said, the absence of $^3He/^4He$ above Phanerozoic upper mantle values in fluid-rich diamonds from all southern Africa rules out a requirement for deep mantle fluids in the generation of diamonds in the SCLM. Diamondites from southern Africa crystallised from HDFs where the C originates from crustal and mantle sources, the N is mostly slab derived, likely from a subducted sedimentary organic component, but the He is largely derived from the upper mantle.

The carbon and nitrogen isotope data (Fig. 1) are consistent with prevailing models for diamondite-formation, whereby high density fluid from a subducting slab interacts with the SCLM (Mikhail *et al.*, 2013, 2019; Jacob *et al.*, 2000, 2014). Mechanically, this journey provides an opportunity for the exchange of material between a subducted fluid acting as a mobilising agent (HDF) with solid residual mantle rocks (illustrated in Fig. 3). This physical interaction can assimilate mantle volatiles into the HDF resulting in hybridisation (where the HDF is now comprised of subducted + mantle volatiles). If the mantle component in the subduction-derived HDF is small, then the diamond-forming media might not reveal this assimilated mantle component in $\delta^{13}C$-$\delta^{15}N$ space (*e.g.*, as shown for most samples in Fig.1). For example, if the subducted carbon has $\delta^{13}C$ = -25 ‰ and assimilated 10 % mantle carbon ($\delta^{13}C$ = -5 ‰) with most of the nitrogen provided by the subducted source ($\delta^{15}N$ > 0 ‰) then the resulting hybrid would have a $\delta^{13}C$ value of -23 ‰ and positive $\delta^{15}N$. Such $\delta^{13}C$-$\delta^{15}N$ values do not suggest mixing between mantle and crustal volatiles because they are within the range of crustal organic carbon and distinct from the canonical mean mantle values for both $\delta^{13}C$ and $\delta^{15}N$ (-5 ± 3 ‰; Cartigny *et al.*, 2014; Mikhail *et al.*, 2014). However, if the ^{13}C-depleted HDF assimilated 50 % mantle carbon and 100 % mantle helium, then the resulting hybrid would have a $\delta^{13}C$ value of -15 ‰ and $^3He/^4He$ > 1 R_a. This scenario matches the data of samples Dia030 (southern Africa) and ORF57 (Orapa) which show elevated $^3He/^4He$ ratios of 8.5 and 7.5 Ra with corresponding $\delta^{13}C$ values (-16.6 ‰; Fig. 2b).

We argue that the C-N isotope data commonly identify a mix of multiple sources. In the case of the southern African and Orapa diamondites, the $\delta^{13}C$-$\delta^{15}N$ systematics reveal that the subducted component dominates over the mantle component (Fig. 1). However, the discrete, but important, mantle component is revealed in the fluid-hosted helium isotope data. The higher ^3He concentration of the mantle fluids compared to slab-derived fluids means that the helium isotopes trace small contributions of mantle-derived volatiles better than C or N isotopes. For example, samples DIA058B (southern African) and ORF143 (Orapa) show elevated $^3He/^4He$ ratios of 3.9 and 1.6 R_a with correspondingly low $\delta^{13}C$ values of -19.1 and -19.9 ‰ (Fig. 2b). Ergo, helium reveals what carbon and nitrogen cannot. When the carbon and nitrogen stable isotope data show strong evidence for crustal sources for diamond formation (Fig. 1), the helium isotopes reveal an unambiguous mantle component hidden within strongly ^{13}C-depleted diamond (Fig. 2b). This observation speaks to the mechanics of fluid migration through the SCLM. Our data require that subducted material percolates though ambient mantle *en route* to the SCLM and results in the mechanical re-mobilisation of primary mantle volatiles (Fig. 3). These data further enhance the notion that the volatile-element components within a diamond-forming HDF do not always share a common origin, and indeed, the C-N-He isotopic systems preserved in mantle diamonds record distinct processes and should not be considered coupled isotopic systems, by default.

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Additional Information

Supplementary Information accompanies this letter at http://www.geochemicalperspectivesletters.org/article1923.

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