Geochemical Perspectives Letters

Plume-lithosphere interaction, and the formation of fibrous diamonds

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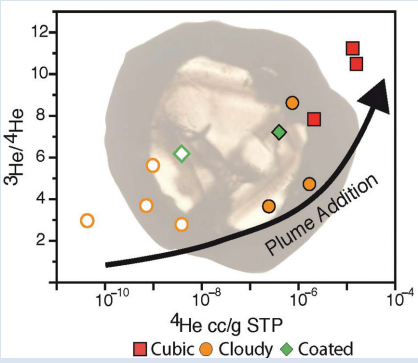
OPEN ACCESS
doi: 10.7185/geochemlet.1825

Abstract



Fluid inclusions in diamond provide otherwise inaccessible information on the origin and nature of carbonaceous fluid(s) in the mantle. Here we evaluate the role of subducted volatiles in diamond formation within the Siberian cratonic lithosphere. Specifically, we focus on the halogen (Cl, Br and I) and noble gas (He, Ne and Ar) geochemistry of fluids trapped within cubic, coated and cloudy fibrous diamonds from the Nyurbinskaya kimberlite, Siberia. Our data show Br/Cl and I/Cl ratios consistent with involvement of altered oceanic crust, suggesting subduction-derived fluids have infiltrated the Siberian lithosphere. $^3He/^4He$ ranging from 2 to 11 R_A, indicates the addition of a primordial mantle component to the SCLM. Mantle plumes may therefore act as a trigger to re-mobilise subducted carbon-rich fluids from the sub-continental lithospheric mantle, and we argue this may be an essential process in the formation of fluid-rich diamonds, and kimberlitic magmatism.

Received 5 May 2018 | Accepted 14 September 2018 | Published 1 October 2018

Introduction

Diamond formation events within the sub-cratonic lithospheric mantle (SCLM) are related to metasomatism, often coeval with tectonothermal events, such as subduction and plume emplacement (Haggerty, 1999; Gurney *et al.*, 2010). These fluids can be trapped as microinclusions along the surfaces of diamond fibres and surrounding diamond-hosted mineral inclusions (Navon *et al.*, 1988; Nimis *et al.*, 2016; Skuzovatov *et al.*, 2016). Diamond-hosted fluids therefore represent the only direct samples of mantle fluids, and provide a unique insight into the composition of carbonaceous fluids from the mantle.

Fluids trapped in diamonds are categorised into four major compositional groups, distinguishable on a ternary plot for K + Na (saline), Al + Si (silicic), and Ca + Mg + Fe (high- and low-Mg carbonatitic) (Klein-BenDavid *et al.*, 2009). The four compositional end members are considered to form either *via* immiscible separation of hydrous and carbonatitic fluids within the SCLM (Schrauder and Navon, 1994), or *via* the interaction of a parental saline fluid with the lithosphere, producing silicic and carbonatitic fluids (Weiss *et al.*, 2015). Saline fluids in diamonds have been shown to have high concentrations of Cl of up to ~40 wt. % (Izraeli *et al.*, 2001; Klein-BenDavid *et al.*, 2007). Diamonds from Canadian kimberlites, previously shown to contain saline inclusions (Tomlinson *et al.*, 2009) have highly elevated Br/Cl and I/Cl values, suggesting parental fluids may have been introduced to the SCLM during ancient subduction-related processes (Johnson *et al.*, 2000).

Halogens and noble gases are concentrated in surface reservoirs, and have distinguishable elemental/isotopic ratios within different reservoirs, making them sensitive tracers of subduction-related metasomatism (Broadley *et al.*, 2016). Here we report halogen abundance (Cl, Br and I) and noble gas isotopic (He, Ne and Ar) data from a suite of cubic, cloudy and coated diamonds from the Nyurbinskaya kimberlite, Nakynsky field, Siberia (Fig. S-1). The Nyurbinskaya kimberlite contains a higher proportion of eclogitic diamonds, relative to other Siberian kimberlites – potentially indicating the diamonds have a subduction-related origin (Spetsius *et al.*, 2008). We combine halogen and noble gases to explore the origin(s) of diamond-hosted fluids within the Siberian SCLM.

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Halogen Geochemistry

The range of Cl (0.5-20.3 ppm), Br (2.7-168.6 ppb) and I (0.1-2.1 ppb) concentrations within the diamonds (n = 7; Table S-1) are higher than previously reported measurements of Siberian fibrous diamonds (Burgess *et al.*, 2002). Halogen concentrations are higher in cubic diamonds indicating that halogens are predominantly sited within microinclusions, given the greater proportion of inclusions in the cubic diamonds compared to the coated or cloudy samples.

The Br/Cl and I/Cl ratios for the fluids progress from mantle-like signatures towards elevated Br/Cl values (Fig. 1). Similar Br/Cl signatures have been previously measured in fibrous diamonds from Canada (Johnson *et al.*, 2000; Burgess *et al.*, 2009). The above mantle Br/Cl and I/Cl values in Canadian diamond-fluids were attributed to either the subduction of volatiles into the SCLM or fractionation of halogens during the separation of immiscible fluids (Burgess *et al.*, 2009). The latter process was considered most feasible given the lack of a known subduction component with similar Br/Cl and I/Cl values (Burgess *et al.*, 2009).

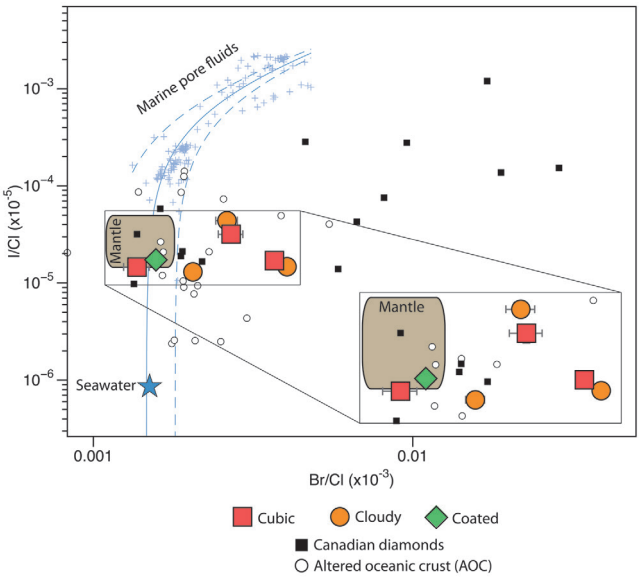

Figure 1 Log-log plot of I/Cl *vs.* Br/Cl (mol/mol) for the Nyurbinskaya diamonds. Seawater, average mantle, marine pore fluids, altered oceanic crust fluids (AOC) and Canadian diamonds are shown for reference (Johnson *et al.*, 2000; Muramatsu *et al.*, 2007 and references therein; Kendrick *et al.*, 2012; Chavrit *et al.*, 2016). Nyurbinskaya diamonds range from mantle values towards enriched Br/Cl, similar to AOC and Canadian diamonds suggesting there has been an input of Br-rich fluids to the Siberian lithosphere. Uncertainties are 1σ when shown and are often smaller than symbol size.

However, the separation of immiscible fluids during diamond formation would likely lead to combined fractionation of both Br/Cl and I/Cl ratios. The I/Cl ratio is expected to be fractionated to a greater degree given that halogen fractionation is most likely controlled by differences in solubility in the aqueous fluid, which increases from NaCl < NaBr < NaI, leading to the heavier halogens being concentrated in the brine fraction, relative to the lighter halogens (Bureau *et al.*, 2000). Fractionation should therefore result in a steeper profile of Br/Cl and I/Cl than that measured in the Nyurbinskaya and Canadian diamonds (Johnson *et al.*, 2000). The I/Cl of Nyurbinskaya diamonds are also consistently mantle-like, suggesting fractionation during diamond formation is not the main mechanism controlling the increase in Br/Cl. To explain the relative enrichment in Br without an associated enrichment of I, is therefore more consistent with mixing between two distinct components (mantle-like + high Br/Cl component; Fig. 1).

A potential high Br/Cl source is the fluid fraction trapped within altered oceanic crust (AOC) (Chavrit *et al.*, 2016). High Br/Cl in AOC fluids is attributed to phase separation of saline fluids during seawater-basalt interaction, and/or the sequestering of Cl into alteration minerals (Chavrit *et al.*, 2016). This process fractionates Br/Cl, whereas I/Cl ratios remain mostly intermediate between mantle and seawater values. This suggests that interaction between seawater and the oceanic crust with a mantle composition predominantly controls I/Cl, without affecting Br/Cl, given that seawater and mantle have indistinguishable Br/Cl values. Higher than mantle I/Cl in AOC may indicate a limited degree of fractionation or the presence of an I-rich sedimentary component (Fig. 1; Chavrit *et al.*, 2016). Whilst Nyurbinskaya and Canadian diamonds generally range from mantle values towards higher Br/Cl and I/Cl, some diamonds have I/Cl lower than the mantle, which could not be formed from the same fractionation process responsible for the elevated Br/Cl and I/Cl and may therefore signify a subducted AOC component in the parental fluids (Fig. 1).

Mantle xenoliths from Nyurbinskaya show $\delta^{18}O$ values up to +9.65 ‰, higher than typical mantle samples (+5.5 ‰; Mattey *et al.*, 1994). Elevated $\delta^{18}O$ is interpreted as evidence for subduction of oceanic crust, which has undergone low temperature alteration (Gregory and Taylor, 1981). Notably, Br/Cl of AOC fluids decreases with depth in the oceanic crust (Chavrit *et al.*, 2016), suggesting the release of fluids from the upper oceanic crust, where low temperature alteration occurs, may be the potential source of the halogen-rich fluids within the Siberian SCLM. The subduction of AOC fluids can therefore provide a Br/Cl enriched source necessary to explain the signature of the Nyurbinskaya diamonds.

An AOC Br/Cl and I/Cl origin could also account for some of the values measured within other fibrous diamonds (Fig. 1). The extreme Br/Cl and I/Cl measured in some Canadian diamonds cannot be accounted for by the simple addition of AOC-like fluids to the SCLM, suggesting that another process may be responsible for enriching diamond-forming fluids in Br and I relative to Cl. This process may be related to an unknown fractionation process during subduction or within the SCLM, however the processes driving further enrichment of Br and I remain unknown.

Noble Gas Geochemistry

The $^3He/^4He$ of the diamonds released during crushing and laser heating are similar and range from 2.8-11.2 R_A. However, the concentrations of He released during laser heating are 2-4 orders of magnitude lower than that released during crushing (Fig. 2), suggesting the noble gases are primarily hosted within microinclusions and are efficiently released by crushing. The upper range of $^3He/^4He$ in the diamonds is similar to values obtained from Siberian Flood Basalts (<12.7; Basu *et al.*, 1995) indicating that the diamonds contain at least two noble gas components; a low $^3He/^4He$ SCLM component and a high $^3He/^4He$ primitive mantle component, potentially related to the Siberian plume. The $^3He/^4He$ signatures of the diamonds differ according to type, with the cubic diamonds having $^3He/^4He$ extending above the MORB range (8 ± 1 R_A; Graham, 2002), whilst the coated and cloudy diamonds range from MORB-like to lower values. The cubic diamonds therefore appear to be dominated by volatiles associated with the plume-like signature, whilst coated and cloudy diamonds retain more of the original lithospheric signature (4 - 6 R_A; Gautheron

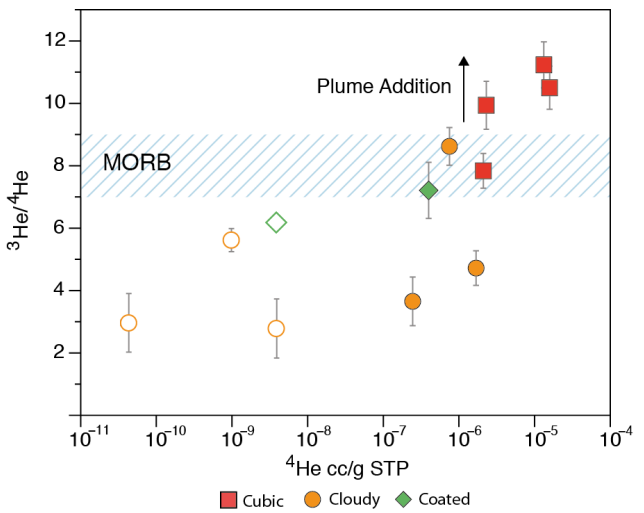

Figure 2 $^3He/^4He$ *vs.* ^4He concentrations from crushing and laser heating (open symbols) of Nyurbinskaya diamonds. $^3He/^4He$ from the cubic diamonds are higher than the cloudy and coated diamonds and plot above MORB values suggesting the diamond-hosted inclusions contain a mixture of lithospheric and deep mantle volatiles. Uncertainties shown are 1σ and for ^4He concentrations are smaller than symbol size.

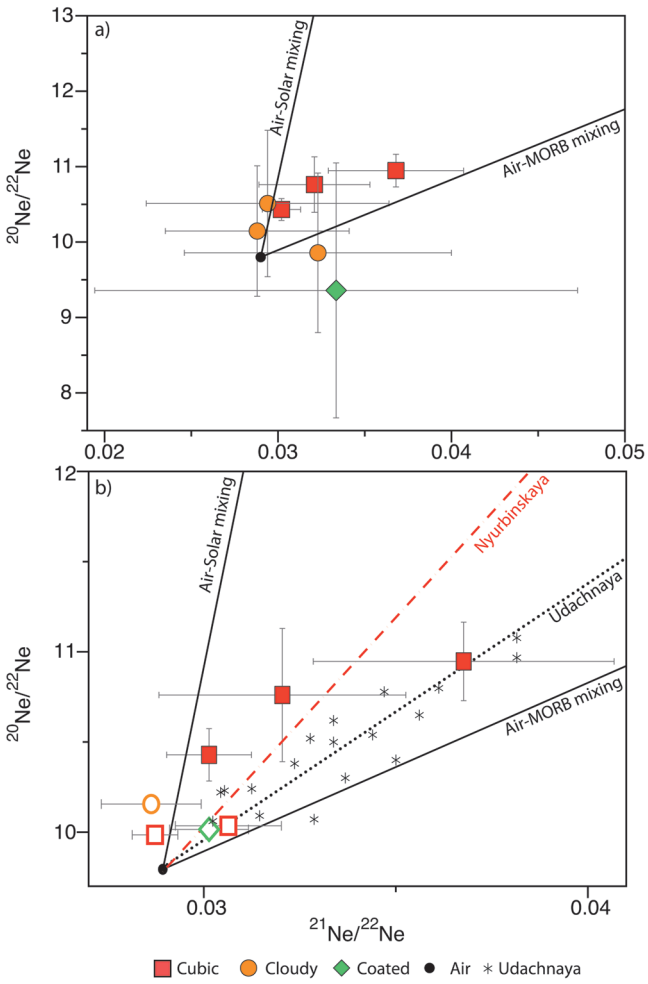

Figure 3 **(a)** Neon three-isotope plot for crushing of Nyurbinskaya diamonds. **(b)** Zoomed in section showing data from laser extraction (open symbols) plus the crushing data from the cubic diamonds. Diamonds show excess in $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ relative to air and plot intermediate between the MORB-Air mixing line and the Solar-Air mixing line. Dashed red line is a regression line fitted through all the Nyurbinskaya diamond data and forced through the atmospheric values. Dashed black line is the trend for Udachnaya olivine xenocrysts (Sumino *et al.*, 2006). Uncertainties are 1σ.

et al., 2005). Some of the coated and cloudy diamonds have lower than SCLM $^3He/^4He$ suggesting the additional input of radiogenic ^4He to the SCLM from a subducted component (Barry *et al.*, 2015).

Neon isotopic ratios from the Nyurbinskaya diamonds further indicate the involvement of a mantle plume in the Siberian SCLM. Diamonds with Ne isotopic ratios distinct from atmosphere (Fig. 3) are intermediate between the Air-MORB mixing line and the Air-Solar mixing line on the $^{20}Ne/^{22}Ne$-$^{21}Ne/^{22}Ne$ isotope diagram. The neon isotope composition of Nyurbinskaya diamonds is similar to those from Udachanaya (Sumino *et al.*, 2006), suggesting that the formation of kimberlites and fibrous diamonds in the Siberian Craton around 360 Ma may be linked to the injection of plume material. The He and Ne isotopic composition of Nyurbinskaya diamonds indicates that they contain a mixture of air and a mantle end member, the latter having high $^3He/^4He$ and mantle-like $^{20}Ne/^{22}Ne$ compositions similar to the Siberian Flood Basalts, with an additional contribution from the low $^3He/^4He$ SCLM (Fig. S-5).

Diamond Formation during Plume-Lithosphere Interaction

The nitrogen aggregation state in diamonds provides a qualitative method to investigate the mantle residence time and temperature of diamonds (Supplementary Information). Nitrogen aggregation states of fibrous diamonds indicate they have short mantle residence times, and ^{40}Ar-^{39}Ar ages of fibrous coats suggests their growth is related to kimberlite magmatism (Taylor *et al.*, 1996; Burgess *et al.*, 2002). Low nitrogen aggregation states determined for Nyurbinskaya cubic and cloudy diamonds (Fig. 4) confirm that they formed not long before emplacement. The core of the coated diamonds however, show nitrogen aggregation states more consistent with a mantle residence age of between 1 Ma and 200 Ma based on a residence temperature of 1200-1300 °C, as estimated from mantle xenoliths in the nearby Udachnaya kimberlite (Boyd *et al.*, 1997). Individual FTIR measurements on the coats of the fibrous samples show low degrees of N aggregation, indicating fibrous coats formed around the same time and resided at similar mantle temperatures, as the cubic diamonds.

Cubic diamonds, which are most abundant in microinclusions and have very short mantle residence times, have the most plume-like noble gas signature suggesting that the fluids may be related to the influx of deep mantle volatiles triggering diamond growth. In contrast, the optically clearer diamond cores of the coated stones have a consistently larger percentage of nitrogen B centres suggesting a longer residence time as well as potentially acting as seeds for the growth of fibrous coats. It should be noted that given the temperature range estimated for the Siberian SCLM at the time of Nyurbinskaya kimberlite formation, all except some of the cloudy diamonds could have mantle residence as low as 5 Ma and therefore may be related to the same metasomatic event(s). Three cubic diamonds that have similar nitrogen contents and aggregation states as the coated diamonds may indicate that even the cubic diamonds retain older diamond cores (*i.e.* seeds), or that the higher temperatures associated with plume accelerated the nitrogen aggregation state over short time scales (Fig. 4).

Therefore, the Siberian lithosphere experienced at least two episodes of diamond growth. The formation of fibrous diamonds in particular requires the precipitation of carbon

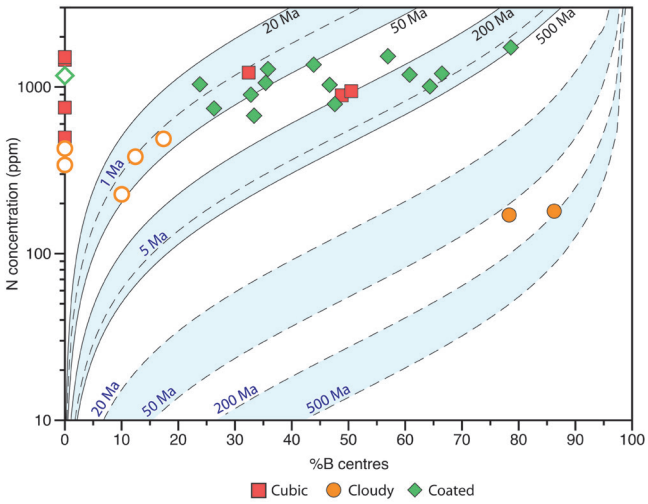

Figure 4 Total nitrogen concentrations *vs.* the percentage of nitrogen in the B aggregated state. Each point is from the analysis of a single diamond, full symbols are from the bulk measurement, whilst open symbols are from the fibrous coat or cloudy interior of the coated and cloudy diamonds respectively. Isotherms are calculated assuming a temperature range between 1200 °C (solid lines) and 1300 °C (dashed lines) as reported for Udachnaya xenolith (Boyd *et al.*, 1997) and assumed residence times between 1 Ma and 200 Ma. All diamonds indicate a residence time of less than 200 Ma at the temperature estimated for the Siberian SCLM at 360Ma (eruption age of Nyurbinskaya and Udachnaya kimberlites).

from supersaturated fluids (Sunagawa, 1984), either during the progressive cooling of the C-O-H metasomatic fluids or from a change in the oxidation state where upon dissolved carbon can be precipitated as diamond (Klein-BenDavid *et al.,* 2010). Cooling of C-O-H fluids as they interact with the surrounding lithosphere causes a decrease in the solubility of carbon leading to the supersaturation of the fluid and precipitation of diamond (Stachel and Luth, 2015).

Carbon isotopes in the cores of fibrous diamonds from the Sytykanskaya kimberlite in Yukutia extend from mantle-like to light $\delta^{13}C$ values (–3.8 to –19.7 ‰) indicating that the Siberian craton contains a subducted carbon component (Skuzovatov *et al.,* 2012). Fibrous diamonds often appear to be genetically linked to the last episode of metasomatism within the SCLM, possibly associated with kimberlite magmatism (Burgess *et al.,* 2002), although there is evidence for the formation of fibrous diamond in older metasomatic events (Zedgenizov *et al.,* 2006). The input of plume mantle material to the Siberian SCLM (Sumino *et al.,* 2006) may therefore have re-mobilised subducted halogen (this study) and carbon-rich material (Jacob *et al.,* 2000) already present within the lithosphere, leading to the precipitation of fibrous diamonds, and fibrous coats around a previous generation of diamonds within the Siberian SCLM.

Acknowledgements

This work was financially supported though a JSPS international research fellowship PE 14721 (to MWB) and JSPS KAKENHI grant numbers JP 26287139 and JP15KK0150 (to HS). The work of DAZ and ALR was supported by Russian science foundation (16-17-10067). RB acknowledges funding from the NERC (NE/M000427/1). SM acknowledges funding from the NERC (NE/PO12167/1). We also appreciate the constructive comments from Yaakov Weiss and an anonymous reviewer, which contributed greatly to our manuscript.

Editor: Helen Williams

Additional Information

Supplementary Information accompanies this letter at http://www.geochemicalperspectivesletters.org/article1825.

Cite this letter as: Broadley, M.W., Kagi, H., Burgess, R., Zedgenizov, D., Mikhail, S., Almayrac, M., Ragozin, A., Pomazansky, B., Sumino, H. (2018) Plume-lithosphere interaction, and the formation of fibrous diamonds. *Geochem. Persp. Let.* 8, 26–30.

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Supplementary Information

The Supplementary Information includes:

- Samples and Geological Background
- Diamond FTIR and Nitrogen Aggregation
- Noble Gas Analysis
- Halogen Analysis
- Figures S-1 to S-5
- Tables S-1 and S-2
- Supplementary Information References

Sample and Geological Background

The Nyurbinskaya kimberlite pipe was discovered in 1994 in the Nakynsky kimberlite field, Yakutia (Spetsius *et al*., 2008). The kimberlite is one of the richest high-grade diamond deposit in Yakutia. The kimberlite was erupted 364 Ma and is similar in age to other Siberian diamond bearing kimberlites including: Mir, Internatsional'naya and Udachnaya (Davies *et al*., 1980; Kinny *et al*., 1997). Nyurbinskaya differs from other Yakutian kimberlites in its low Light Rare Earth Elements (LREE), Nb, Ta, U and Th contents (Agashev *et al*., 2001), it has therefore been classified as having a transitional composition between group I and II kimberlite types.

Mantle xenoliths from Nyurbinskaya are predominantly eclogitic, with only minor amounts of peridotites (Riches *et al*., 2010). The majority of diamonds originating from Nyurbinskaya can be classified into either those containing inclusions of eclogite minerals, or fibrous diamonds (Spetsius *et al*., 2017). The fibrous diamonds can be further subdivided in to three groups: coated, cloudy and cubic (Figure S-1). Coated diamonds, with green or yellow fibrous coats make up the majority of the fibrous diamonds, with cubic and cloudy diamonds being rarer (Spetsius *et al*., 2017).

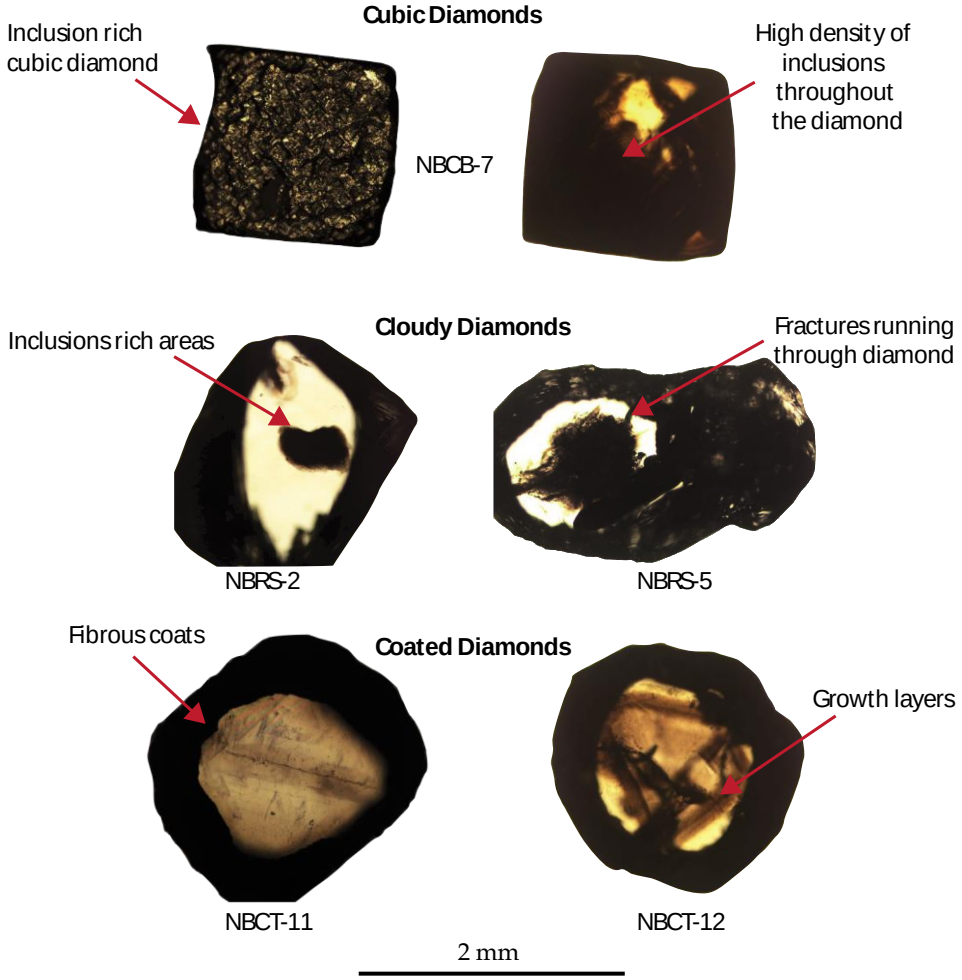

Figure S-1 Photomicrograph images of double cut and polished cubic, coated and cloudy diamonds from the Nyurbinskaya kimberlite. Cubic diamonds have a high density of fluid inclusions often rendering then completely opaque. The cloudy diamonds have internal areas rich in fluid inclusions whilst the majority of the fluid inclusions are within the fibrous coats of the coated diamonds. Note that diamond NBCT-12 was only analysed for nitrogen using FTIR and not for halogens and noble gases.

Diamond FTIR and Nitrogen Aggregation

Infrared absorption spectra were obtained for 29 diamonds using a Fourier transform infrared spectrometer (Spectrum 2000; Perkin Elmer Inc.) equipped with an IR microscope at Geochemical Research Center, The University of Tokyo. Samples were first mounted in indium and then analysed using a combination of a Globar light source, liquid nitrogen cooled MCT detector, and KBr beam splitter operating at a spectral resolution of 4 cm^{-1}. Spectral deconvolution was performed using the Diamap freeware (Howell *et al*., 2012). Seven H_2O-rich samples (Fig. S-2) were then chosen for halogen and noble gas analysis.

Nitrogen is the most common impurity in natural diamonds. It is a relatively mobile element within the diamond lattice at mantle pressure and temperatures and as a result nitrogen defects in diamonds can evolve through time, which can be determined by FTIR. Nitrogen defects begin as single nitrogen atoms (C centres, Type Ib), which then evolves to pairs of nitrogen atoms (A centres, Type IaA), and finally to 4 nitrogen atoms tetrahedrally arranged about a vacancy (B centres, Type IaB). This evolution of N defect distribution through time is referred to as nitrogen aggregation (Evans and Qi, 1982). The evolution from C to A centre aggregation occurs rapidly (<1 Ma), while the evolution from A to B centres occurs much more slowly (over Ga). A to B centre aggregation follows a second-order kinetics law (Chrenko *et al*., 1977), indicating it can be used to estimate either the mantle residence time of the diamond, or the average temperature at which it resided (assuming the other is known).

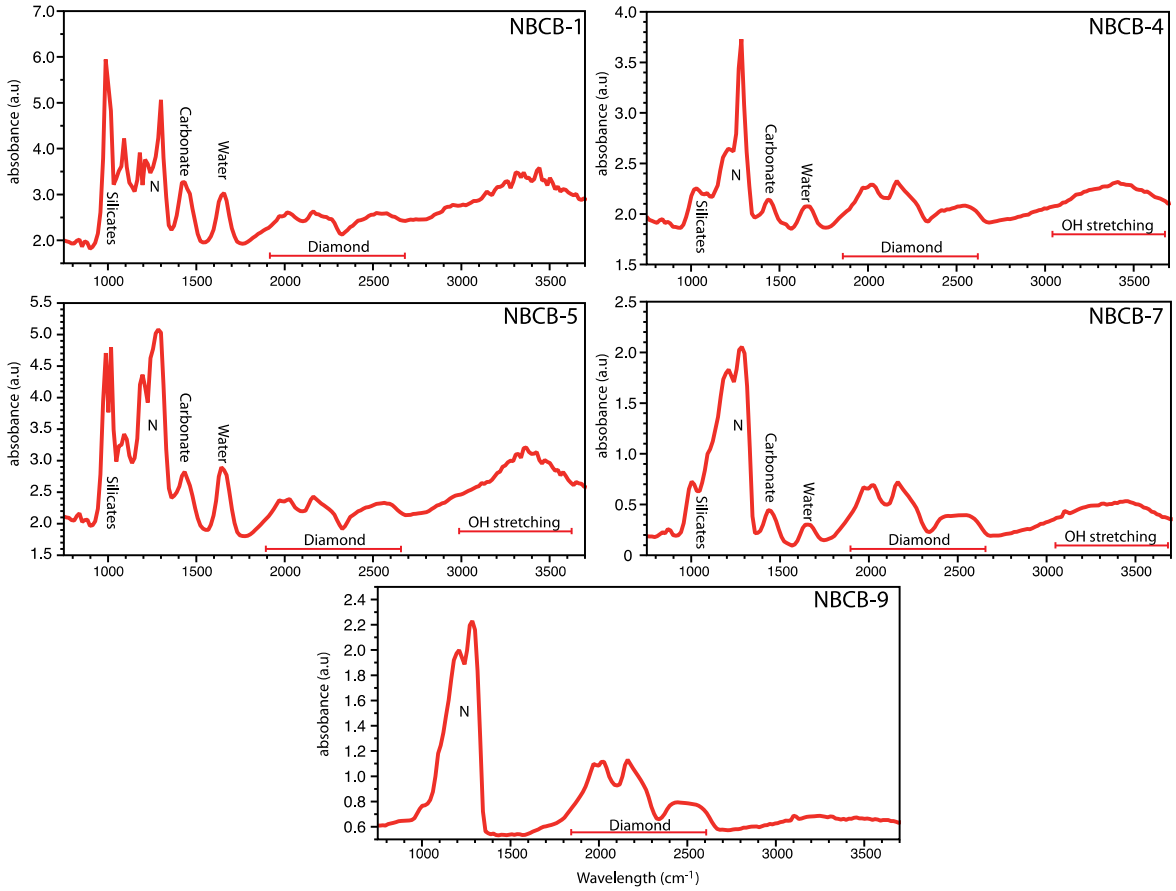

Figure S-2 FTIR spectra for all the cubic diamonds (NBCB) selected for noble gases and halogen analysis. Peaks representing hydrogen, water, silicates, carbonate and the range of OH stretching are all highlighted. All diamonds show evidence of being rich in a fluid component. Diamonds NBCB-1 and NBCB-5 have a poorly defined spectra due to the high density of fluid inclusions and opaque nature.

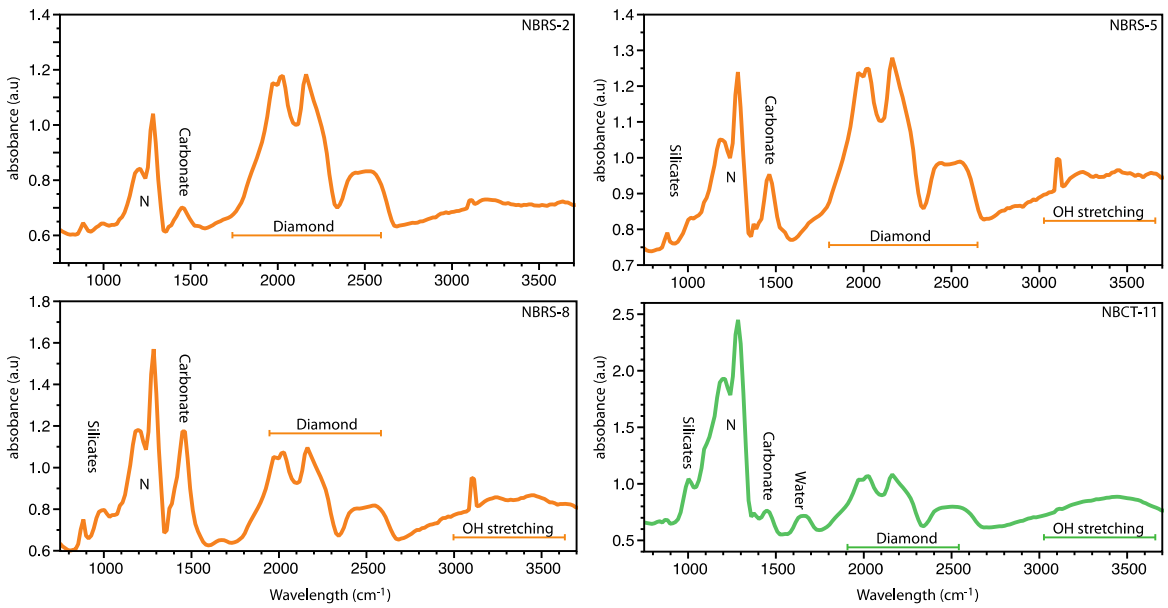

Figure S-3 FTIR spectra for all the cloudy (NBRS) and coated (NBCT) diamond selected for noble gases and halogen analysis. Peaks representing hydrogen, water, silicates, carbonate and the range of OH stretching are all highlighted. All diamonds show evidence of being rich in a fluid component.

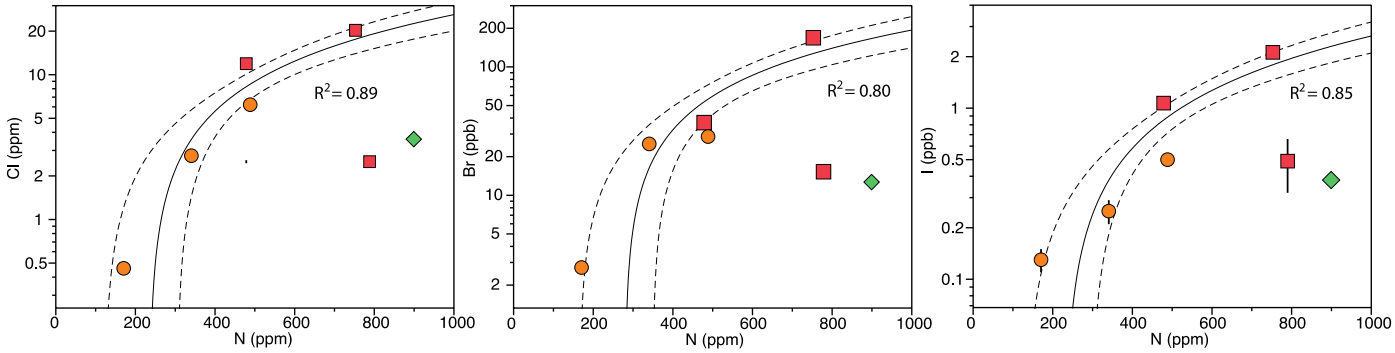

Figure S-4 Halogen concentrations *vs*. bulk nitrogen concentration. The concentration of Cl, Br and I of the cubic and cloudy diamonds are correlated with N concentrations. Black line represents a best fit of the cubic and cloudy diamonds data (excluding NBCB-4), with a 1σ uncertainty prediction (dashed lines). Coated diamond NBCT-11 and one cubic diamond (NBCB-4) do not fit along the same correlation line, suggesting that the halogens and N within the these diamonds may be related to another source, in agreement with the potentially higher mantle residence times (Fig. 4, main text). No evidence of correlation between N and noble gas concentrations exists suggesting that N and halogens may be more closely related to the trapped fluid inclusions, than the noble gases. All uncertainties are shown to 1σ. This correlation could be explained by nitrogen being present in the fluid as ammonic nitrogen, and so could form salt complexes with halogens, and therefore follow similar geochemical pathways. This inference is consistent with the predicted speciation of aqueous nitrogen at 5 GPa and up to 1000 °C in equilibrium with peridotitic and/or metasedimentary (eclogitic) mineral phases (Mikhail *et al*., 2017).

Noble Gas Analysis

Noble gases were first extracted from the diamonds *via* crushing. Individual diamonds were placed into a stainless steel crushing chamber, a steel ram attached to a bellows was then placed on top and the whole crusher was baked at 200 °C overnight under vacuum. The diamonds were then fractured by applying a hydraulic pressure (up to 70 MPa) to the steel ram using an external hydraulic hand pump. Extracted gases were purified by a series of Ti-Zr getters and then separated according to mass using a cryogenically cooled trap containing sintered-stainless steel. Helium, neon and argon were then released individually into the modified VG5400 mass spectrometer at the University of Tokyo for analysis following the procedure described in Sumino *et al*. (2001).

Roughly half of the crushed diamond chips were then analysed for He and Ne by bulk heating at the noble gas laboratory at CRPG, Nancy (France), using the Thermo Fischer Helix MC Plus. Samples weighing ~1-6 mg were loaded in an infrared laser chamber. The samples were pumped under high vacuum and baked at 110°C overnight to release any adsorbed atmospheric gases. Prior to analysis, blanks were measured to ensure the background of noble gases was low. Average blank values were 1.4 x 10^{-17} cm^3 STP ^4He and 1.5 x 10^{-15} cm^3 STP ^{20}Ne. The sensitivity and mass discrimination of the mass spectrometer was calibrated by the analysis of daily standards consisting of an atmospheric Ne standard and the HESJ standard for He, with has a $^3He/^4He$ ratio of 20.63 ± 0.10 R_A, where R_A is the ratio of atmosphere (Matsuda *et al*., 2002).

Gases were extracted from the diamonds using a CO_2 infrared (λ = 10.3 μm) laser for 5 minutes or until the diamonds were visibly graphitised. Noble gases were then first passed through an in-line Ti-sponge getter heated at 600 °C and purified with two Ti-sponge getters at 550 °C for 5 min. Argon was separated from He and Ne using a charcoal cold finger held at N_2 liquid temperature for 10 minutes and wasn't analysed in this study. Helium and neon were trapped using a cryogenic trap at 15K for 15 min. Helium was released at 34 K before being admitted to and analysed on the mass spectrometer. Neon was subsequently released at 110K and purified with a further two Ti-sponge getters, one at 550 °C and the other at the room temperature (~ 20 °C), for 10 minutes before analysis. The mass resolution of the MC Plus (~ 1800) enables the discrimination of the ^{20}Ne peak from $^{40}Ar^{++}$. Neon isotopes ratios were corrected for interference from CO_2^{++} with ^{22}Ne.

Differences between crushing and laser noble gas extraction

The maximum $^{40}Ar/^{36}Ar$ released from the cloudy and coated diamonds during crushing (461 ± 24) are closer to the atmospheric value of 298.6 (Lee *et al*., 2006), compared to cubic diamonds showing an average $^{40}Ar/^{36}Ar$ =1479 (Table S-2). The higher proportion of microinclusions in the cubic diamonds resulted in higher quantities of trapped noble gases released during crushing. The $^{40}Ar/^{36}Ar$ values of Ar released by laser heating of coated and cloudy diamonds (halogen analysis) are consistently higher (>1000) than the crushing release, whilst the cubic diamonds show little variation between crushing and heating. The difference in noble gas composition is considered to reflect the much higher abundance of microinclusions in cubic diamond coats and potential

release from the clear diamond sections of the cloudy and cubic diamonds during laser heating.

Concentrations of He are significantly lower during laser extraction compared to crushing, whilst Ne concentrations are similar during both extraction methods. Helium therefore appears to be more concentrated within the fluid inclusions relative to the diamond matrix. During graphitisation the majority of noble gases in the remaining fluid inclusion and the diamond matrix should be released. The low He and Ne concentrations during laser extraction suggest that the noble gas extraction was not completely efficient, possibly because of the build-up graphite on the sample surface impeding further release from deeper within the diamond. Despite the differences in He and Ne concentrations between the crushing and laser extraction the isotopic ratios are similar between the different extraction methods indicating the same volatile component is present in both the fluid and matrix phase of the diamonds.

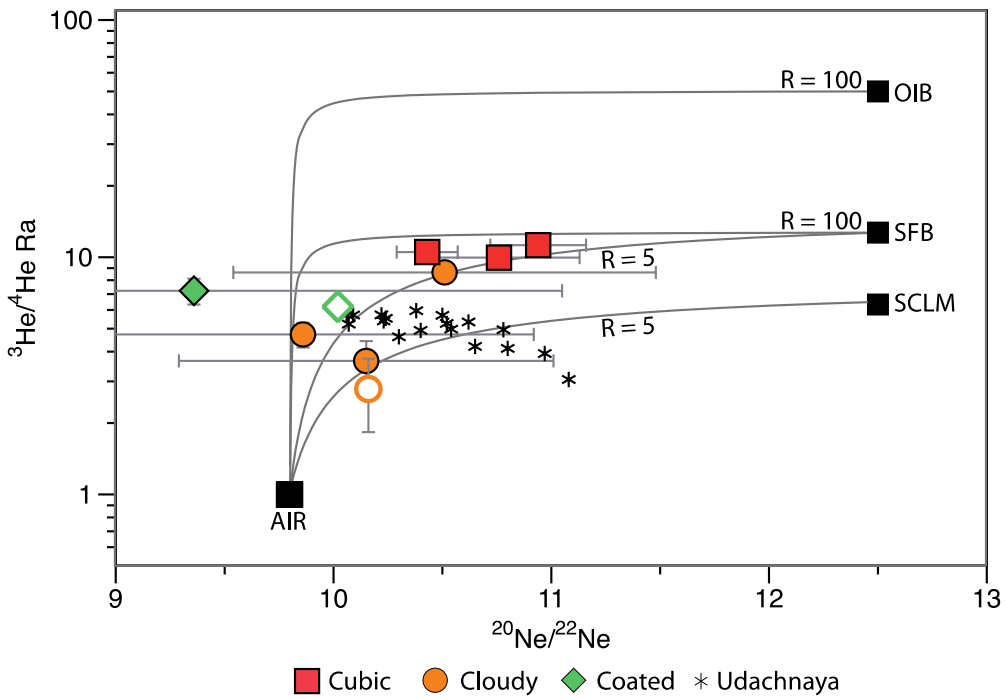

Figure S-5 ^{3}He/^{4}He *vs*. ^{20}Ne/^{22}Ne for Nyurbinskaya diamonds. The diamonds show a relationship between He and Ne and trend from air towards the value of the Siberian flood basalts (Basu *et al*., 1995). There is potentially a third component present from the SCLM (having lower ^{3}He/^{4}He composition) that causes the mixing line to be shallower (R = 5) than generally expected for mixing between air and mantle alone (R = 100). Data for Udachnaya xenoliths are shown for reference indicating they contain a greater proportion of radiogenic ^{4}He from the SCLM relative to the Nyurbinskaya diamonds (Sumino *et al*., 2006). Reference data for SCLM, MORB and OIB are from Gautheron and Moreira (2002); Graham (2002) and Stuart *et al*. (2003), respectively.

Halogen Analysis

The other half of the crushed diamond chips were analysed for their halogen abundance using Neutron-Irradiated Noble Gas Mass Spectrometry (NI-NGMS) at the University of Manchester following the methods outlined in Ruzié-Hamilton *et al*. (2016). Samples were weighed, wrapped in Al foil and vacuum encapsulated in a silica tube. Irradiation was carried out at for 24 hrs at the Safari-1 reactor, Pelindaba, South Africa (irradiation designated MN2017a). Noble gas proxy isotopes ($^{38}Ar_{Cl}$, $^{80}Kr_{Br}$, $^{128}Xe_{I}$ and $^{39}Ar_{K}$) formed during irradiation were measured on a Thermo Fisher Scientific ARGUS VI mass spectrometer. Prior to analysis, samples were baked at 150°C overnight to remove surficial adsorbed noble gases either from atmospheric contamination or from halogen producing noble gases during irradiation. Noble gases were released from the samples using a 10.6 µm wavelength CO2 laser. Halogens abundances were then calculated using well-defined conversion standards with known halogen concentrations (Hb3gr, scapolite and Shallowater meteorite), which monitor the efficiency of noble gas production through thermal and epithermal neutron reactions (Kendrick, 2012; Ruzié-Hamilton *et al*., 2016).

Supplementary Tables

Table S-1 Halogen and nitrogen (bulk FTIR) concentrations and molar ratios as well as $^{40}Ar/^{36}Ar$ of Nyurbinskaya fibrous diamonds measured during neutron irradiation mass spectrometry. Sample NBCB-7 was lost during the irradiation process and therefore halogens were not measured within this sample. All uncertainties are 1σ

Sample	Mass (mg)	Cl (ppm)	±	Br (ppb)	±	I (ppb)	±	Br/Cl x 10^{-4}	±	I/Cl x 10^{-6}	±	$^{40}Ar/^{36}Ar$	±	N (ppm)
NBCB-1	3.1	11.92	0.44	36.82	3.52	1.07	0.09	13.71	1.26	14.59	1.44	1080.7	39.7	478
NBCB-4	0.6	2.51	0.06	15.27	1.34	0.49	0.05	26.98	2.38	31.80	3.95	529.5	35.1	782
NBCB-5	0.4	20.26	0.61	168.58	6.77	2.12	0.17	36.92	1.38	16.99	1.61	1667.9	94	753
NBRS-2	2.9	0.46	0.01	2.74	0.20	0.13	0.01	26.24	2.03	43.86	4.62	456.8	71.1	171
NBRS-5	1.9	2.76	0.05	25.14	0.85	0.25	0.02	40.38	1.54	14.74	1.44	1316.4	154.6	341
NBRS-8	1.5	6.21	0.12	28.67	1.37	0.50	0.04	20.49	1.04	13.00	1.29	2633.3	159.3	488
NBCT-11	2.6	3.59	0.07	12.68	0.55	0.38	0.03	15.68	0.74	17.26	1.64	2211.8	97.5	899

Table S-2 Helium and Neon concentration and isotopic ratios from crushing and laser extraction (italics) from the Nyurbinskaya diamonds. Diamond NBCB-9, was not successfully crushed and the complete diamond was analysed by laser extraction for noble gases. All uncertainties are reported to 1σ. n.d = not determined

Sample	Mass (mg)	^{4}He cm^3 STP/g	±	$^{3}He/^{4}He$ R_A	±	^{20}Ne cm^3 STP/g	±	$^{20}Ne/^{22}Ne$	±	$^{21}Ne/^{22}Ne$	±	$^{40}Ar/^{36}Ar$	±
NBCB-1	6.9	2.1×10^{-6}	8.5×10^{-8}	7.84	0.56	3.4×10^{-11}	3.7×10^{-12}	*n.d*	n.d	*n.d*	n.d	2755.7	198.1
	4.3	*n.d*	*n.d*	*n.d*	*n.d*	*1.6×10^{-10}*	*4.7×10^{-13}*	*10.04*	*0.04*	*0.0307*	*0.0014*	*n.d*	*n.d*
NBCB-4	3.8	1.6×10^{-5}	6.9×10^{-7}	10.5	0.69	1.3×10^{-11}	6.4×10^{-11}	10.43	0.14	0.0302	0.0011	862.5	61.8
NBCB-5	6	1.3×10^{-5}	5.9×10^{-7}	11.23	0.74	5.1×10^{-10}	2.7×10^{-11}	10.94	0.22	0.0368	0.0039	1956.9	122
NBCB-9	*5*	*n.d*	*n.d*	*n.d*	*n.d*	*3.4×10^{-10}*	*9.0×10^{-13}*	*9.99*	*0.03*	*0.0288*	*0.0006*	*n.d*	*n.d*
NBCB-7	5.8	2.3×10^{-6}	1.2×10^{-7}	9.95	0.77	3.6×10^{-10}	1.9×10^{-11}	10.76	0.37	0.0321	0.0032	352.1	25.2
NBRS-2	7.3	2.4×10^{-7}	1.3×10^{-8}	3.65	0.78	1.8×10^{-10}	9.6×10^{-12}	10.15	0.86	0.0288	0.0053	298.6	21.4
	3.8	*4.3×10^{-11}*	*9.3×10^{-12}*	*2.96*	*0.94*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*
NBRS-5	5.1	7.5×10^{-7}	3.8×10^{-8}	8.62	0.6	2.1×10^{-10}	1.2×10^{-11}	10.51	0.97	0.0294	0.007	437.6	31.4
	3	*3.9×10^{-9}*	*7.7×10^{-11}*	*2.78*	*0.95*	*3.2×10^{-11}*	*1.1×10^{-13}*	*10.16*	*0.04*	*0.0287*	*0.0013*	*n.d*	*n.d*
NBRS-8	7.1	1.7×10^{-6}	7.2×10^{-8}	4.72	0.56	1.7×10^{-10}	1.1×10^{-11}	9.86	1.06	0.0323	0.0077	461	24
	4.5	*9.8×10^{-10}*	*3.2×10^{-11}*	*5.62*	*0.37*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*
NBCT-11	6.3	4.0×10^{-7}	2.1×10^{-8}	7.21	0.9	5.8×10^{-11}	3.8×10^{-12}	9.36	1.69	0.0334	0.0139	339.1	24.2
	3.4	*3.9×10^{-9}*	*3.1×10^{-11}*	*6.18*	*0.22*	*4.0×10^{-11}*	*1.4×10^{-13}*	*10.02*	*0.03*	*0.0302*	*0.001*	*n.d*	*n.d*

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