

1 **Revision 2**

2 **A petrological assessment of diamond as a recorder of the mantle nitrogen cycle**

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7 **Abstract:**

8 **Nitrogen is fundamental to the evolution of Earth and the life it supports, but for reasons poorly**
9 **understood, it is cosmochemically the most depleted of the volatile elements. The largest reservoir in the**
10 **bulk silicate Earth is the mantle, and knowledge of its nitrogen geochemistry is biased, because $\geq 90\%$ of the**
11 **mantle nitrogen database comes from diamonds. However, it is not clear to what extent diamonds record the**
12 **nitrogen characteristics of the fluids/melts from which they precipitate. There is ongoing debate regarding**
13 **the fundamental concept of nitrogen compatibility in diamond, and empirical global datasets reveal trends**
14 **indicative of nitrogen being both compatible (fibrous diamonds) and incompatible (non-fibrous**
15 **monocrystalline diamonds). A more significant and widely overlooked aspect of this assessment is that**
16 **nitrogen is initially incorporated into the diamond lattice as single nitrogen atoms. However, this form of**
17 **nitrogen is highly unstable in the mantle, where nitrogen occurs as molecular forms like N_2 , or NH_4^+ , both of**
18 **which are incompatible in the diamond lattice. A review of the available data shows that in classic terms,**
19 **nitrogen is the most common substitutional impurity found in natural diamonds because it is of very similar**
20 **atomic size and charge to carbon. However, the speciation of nitrogen, and how these different species**
21 **disassociate during diamond formation to create transient monatomic nitrogen, are the factors governing**
22 **nitrogen abundance in diamonds. This suggests the counter-intuitive notion that a nitrogen-free (Type II)**
23 **diamond could grow from a N-rich media that is simply not undergoing reactions that liberate monatomic N.**
24 **In contrast, a nitrogen-bearing (Type I) diamond could grow from a fluid with a lower N abundance, in which**
25 **reactions are occurring to generate (unstable) N atoms during diamond formation. This implies that**
26 **diamond's relevance to nitrogen abundance in the mantle is far more complicated than currently**

27 **understood. Therefore, further petrological investigations are required to enable accurate interpretations of**
28 **what nitrogen data from mantle diamonds can tell us about the deep nitrogen budget and cycle.**

29

30 **1. Introduction**

31 The importance of the geodynamic nitrogen cycle should not be understated. Nitrogen is fundamental to the
32 evolution of Earth and the life it supports. This is demonstrated by the Earth's atmosphere being made up of roughly
33 78 % nitrogen (Porcelli and Pepin, 2003), and nitrogen is a key element in the structure of molecules vital to life,
34 including amino acids, proteins, and nucleic acids (Busigny and Bebout, 2013; references therein). It has also been
35 suggested that oxidation of ammoniacal nitrogen in the mantle can generate water on the surface (Li and Keppler,
36 2014), and that nitrogen may have played an important role in heating Earth's surface above the freezing point of
37 water despite a faint young sun (Sagan and Chyba, 1997; Goldblatt et al., 2009). Therefore, an understanding of the
38 geodynamic nitrogen cycle is fundamental to understanding the development of the habitable Earth (Canfield et al.,
39 2010).

40 Placing firm constraints on the flux of nitrogen between the Earth's reservoirs is fundamental for quantitative
41 models, but also very challenging. Empirical data used to trace the behavior of nitrogen in Earth's mantle across deep
42 time (Ga timescales) come from geochemical studies of nitrogen-bearing mantle xenoliths and xenocrysts. The
43 mantle mineral most widely used for this purpose is diamond (>90% of the mantle nitrogen database), in which
44 nitrogen is the most common and abundant lattice-bound impurity, with concentrations ranging from below
45 detection to >5000 ppm (**Fig.1a-c**). However, there are distinctions between mantle diamond-types. The
46 monocrystalline diamonds typically contain less nitrogen than coated diamonds (average = 200-300 ppm),
47 polycrystalline, garnet-bearing diamondites are also known to contain higher nitrogen abundances than
48 monocrystalline diamonds (average = 600 ppm; see Mikhail et al., 2013), and sublithospheric diamonds are typically
49 found to contain nitrogen below detection limits (average <20 ppm; Harte, 2010). The analysis of nitrogen in
50 diamond by non-destructive FTIR is relatively simple, which has led to the nitrogen-abundance classification system
51 (see Howell et al., 2012; references therein). Diamonds containing nitrogen are termed Type I, while Type II
52 diamonds contain no detectable nitrogen (the lower limit depends upon the technique used; see Mikhail et al.,
53 2014a). Kaiser and Bond (1959) were the first to show that differences in the FTIR spectra correlated with the
54 detection of nitrogen by mass spectrometry, leading to the concept that nitrogen is a lattice-bound substitutional

55 impurity in Type I diamonds. However, it was unknown if nitrogen was a primary or secondary impurity (Milledge
56 and Meyer, 1962). Our current understanding is that single N atoms substitute for single C atoms on a growth
57 interface, and become incorporated into the lattice as point defects. As diamond formation in the mantle spans a
58 large temporal and spatial range (from 0.6 to 3.5 Ga and <150 to >600 km depth; Gurney et al., 2010; Shirey et al.,
59 2013), the carbon and nitrogen geochemistry of diamonds have been used to place constraints on the nature of deep
60 volatile cycles through the mantle (see Cartigny et al. (2014) for a review).

61 To use the presence of nitrogen in diamond to constrain the extent and flux of the mantle's nitrogen reservoir(s)
62 requires an understanding of the partitioning behaviour of nitrogen into diamond as a function of P-T-X. The most
63 common method applied to constrain nitrogen uptake into diamond is reverse modeling of empirical data. This
64 method assigns a fluid-diamond partition coefficient for nitrogen by fitting the co-variations of carbon-isotope values
65 and nitrogen abundances to a curve for a given temperature (using theoretical equilibrium carbon-isotope
66 fractionation factors that assume the speciation of carbon as methane or carbonate: Javoy et al., 1984; Boyd et al.,
67 1987, 1992; Boyd and Pillinger, 1994; Bulanova et al., 2002, 2014; Cartigny et al., 1997, 1998a,b, 2001, 2003, 2004,
68 2009; Klein-BenDavid et al., 2010; Harte et al., 1999; Hauri et al., 2002; Howell et al., 2013, 2015a; Gautheron et al.,
69 2005; Hutchison et al., 1997; Mikhail et al., 2013, 2014a; Stachel and Harris, 2009; Palot et al., 2009, 2012, 2014;
70 Thomassot et al., 2007, 2009), where T is independently determined using the degree of nitrogen aggregation
71 and/or geothermometry on paired silicate inclusions (discussed by Stachel and Harris, 2008).

72 However, this approach has not explained how single atoms of nitrogen have been generated in the mantle for
73 incorporation into the diamond lattice. As monatomic N is highly unstable, nitrogen would be expected to occur in
74 other more stable forms (Mikhail and Sverjensky, 2014). Therefore, to interpret the meaning of the nitrogen data
75 recorded in diamonds, and to model any possible equilibrium stable-isotope fractionation of $^{15}\text{N}/^{14}\text{N}$ to explain the
76 large range of $\delta^{15}\text{N}$ data (Mikhail et al., 2014a) an understanding of the partitioning behaviour of nitrogen during
77 diamond formation is required (e.g. Howell et al., 2015a). In this paper we evaluate the behavior of nitrogen during
78 diamond formation, and show that the incorporation of nitrogen in to diamond is primarily controlled by diamond-
79 forming reactions involving nitrogen in the growth medium.

80

81 **2. Nitrogen compatibility in diamond**

82 Considering the rules of trace element partitioning, first laid down by Goldschmidt (1937), the presence of
83 nitrogen as a structural constituent in diamond is not unexpected, because carbon and nitrogen have similar charges
84 and ionic radii. The first rule states that atoms of the same charge and radius will enter a crystal lattice with equal
85 ease. This provides the basis for modern elemental substitution models, and in the simplest sense remains an
86 accurate assumption, e.g. Ni substituting for Fe in olivine (Blundy and Wood, 2003). Any resulting charge imbalance
87 will require balancing via a double substitution. For example, in diopside at 11.5 GPa and 750 °C, monovalent
88 ammonium can be incorporated (up to 1000 ppm) through a double-substitution mechanism, with a trivalent ion
89 balancing the charge: $(\text{Ca}^{2+})_{\text{M2}} + (\text{Mg}^{2+})_{\text{M1}} \rightleftharpoons (\text{NH}_4^+)_{\text{M2}} + (\text{Al}^{3+} \text{ or } \text{Cr}^{3+})_{\text{M1}}$ (Watenphul et al., 2010).

90 The compatibility of an element is most commonly expressed in one of two ways (for a more detailed discussions
91 see Blundy and Wood, 2003). Assuming a two-phase system (diamond + fluid) the relative partitioning of N and C
92 can be represented by a partition coefficient (D), which reflects the compatibility of N/C relative to fluids/melts
93 (Eq.1). However, due to the crystal symmetry of diamond, N can be incorporated on any crystallographic site. In
94 addition, C + N mix on the same sites, meaning a chemical control (i.e., stoichiometric constraint) will drive the
95 partitioning behavior (K_d - Eq.2). Therefore, the partitioning behavior could be considered as the ratio of partition
96 coefficients (K_d - Eq.2). This approach is similar to what is typically implemented for describing e.g. Fe-Mg exchange
97 equilibrium between e.g. olivine and silicate melts (Toplis, 2005). Note that if D_N or $K_N \geq 1$, the element is described
98 as compatible.

99 Eq.1
$$D_N^{\text{Diamond-Fluid}} = \frac{N^{\text{Diamond}}}{N^{\text{Fluid}}}$$

100 Eq.2
$$K_{N-C}^{\text{Diamond-Fluid}} = \frac{N^{\text{Fluid}} \div N^{\text{Diamond}}}{C^{\text{Fluid}} \div C^{\text{Diamond}}}$$

101

102 2.1. Previous models

103 There is no consensus in the literature regarding the overall compatibility of nitrogen in diamond. Instead, there
104 are three contradictory arguments that are (confusingly) all supported by empirical datasets. These contradictory
105 arguments are as follows: [1] nitrogen is incompatible in diamond (Boyd et al., 1994; Cartigny et al., 2001), [2],
106 nitrogen is compatible in diamond (Stachel and Harris, 2009), and finally, [3] the compatibility of nitrogen in
107 diamond is redox-sensitive (Deines et al., 1989; Thomassot et al., 2007; Smith and Kopylova, 2014).

108 The evidence for nitrogen being incompatible: The global dataset for the abundance of nitrogen in diamond shows a
109 distribution skewed towards zero for non-coated monocrystalline mantle diamonds (**Fig.1a-b**), and this pattern is
110 characteristic of an incompatible element (Ahrens, 1954). If N is incompatible, the incorporation of nitrogen in
111 diamond must be governed by a kinetic process rather than by equilibrium distribution, despite the similarity in
112 charge and ionic radius between atomic N and C. This would mean that nitrogen-rich diamonds occur as a
113 consequence of rapid disequilibrium growth and the N/C ratio of diamond approaches that of the precipitating fluid
114 or melt. In contrast, Type II diamonds would be produced by slow growth under near-equilibrium conditions,
115 regardless of the nitrogen content of the growth medium (Cartigny et al 2001). In addition, a recent study by Palot et
116 al. (2013) that determined the co-variations for $\delta^{13}\text{C}$ values and N-abundances in situ using SIMS, argued that these
117 data are consistent with bulk-sample data (e.g. Cartigny et al., 2001), and concluded that nitrogen behaved
118 incompatibly during diamond formation.

119 The evidence for nitrogen being compatible: Stachel and Harris (2009) argue that nitrogen is compatible in diamond
120 irrespective of $f\text{O}_2$, citing the decreasing nitrogen contents from core to rim observed in high-pressure high-
121 temperature (HPHT) synthetic diamonds grown under reducing conditions in Fe-Ni solvent catalysts (e.g. Reutsky et
122 al 2008) and under more oxidizing conditions (de-carbonation of carbonate) in the presence of silicates (Pal'yanov et
123 al 2002). The concept of nitrogen being compatible is also consistent with recent data from single populations of
124 diamonds (e.g. Thomassot et al., 2007), and within single (zoned) diamonds (Smart et al., 2011; Palot et al., 2014;
125 Petts et al., 2015). Thomassot et al. (2007) analyzed a suite of diamonds from a single peridotite xenolith (assumed
126 to have formed in a single event) and found co-variations between the carbon-isotope values and nitrogen
127 abundances that fit the equilibrium Rayleigh fractionation model outlined by Cartigny et al. (2001). These data result
128 in a calculated K_{N} of 2 between diamond and a hypothetical methanogenic fluid; meaning nitrogen is twice as
129 compatible in the diamond relative to the fluid. Similar studies used high spatial-resolution SIMS profiles within
130 individual diamonds that showed pronounced oscillatory zoning and recorded co-variations of N contents vs. $\delta^{13}\text{C}$
131 (Smart et al., 2011; Palot et al., 2014; Petts et al., 2015). By applying the same reverse-modeling approach as Cartigny
132 et al. (2001) and Thomassot et al. (2007) a K_{N} value of 5 was calculated for diamond precipitation from a carbonatitic
133 fluid (Smart et al., 2011). Collectively, these two datasets suggest that nitrogen is compatible under both oxidizing
134 and reducing conditions conducive to diamond-formation, assuming a simple two-phase relationship between
135 diamond and fluid (i.e. not accounting for the possibility of ammonium partitioning into silicates or other phases).

136 The evidence for nitrogen compatibility being redox sensitive: Several studies have proposed that the compatibility
137 of nitrogen in diamond is redox-sensitive (Deines et al., 1989; Thomassot et al., 2007). The most recent model argues
138 that nitrogen is compatible in diamond only in the absence of Fe⁰ or Fe-Ni alloys (Smith and Kopylova, 2014). This is
139 largely based on the observation that the decrease in average nitrogen abundance in diamonds with increasing
140 depth of origin can be correlated (crudely) with the predicted increasing mole fraction of Fe⁰ in peridotitic mantle
141 with depth (Frost et al., 2004; Rohrbach et al., 2007). Smith and Kopylova (2014) cite experimental data for diamond
142 synthesis in a sealed capsule with a strong redox gradient where one end contained Fe-metal and the other
143 contained carbonate (Palyanov et al. 2013). The diamonds in contact with Fe⁰ contained 100–200 ppm N, whereas
144 the diamonds in the carbonate-melt portion contained 1000–1500 ppm N. However, despite one potential exception
145 (Howell et al., 2015b), there is little evidence to justify modeling diamond-formation in the mantle in equilibrium
146 with a metallic solvent catalyst, especially considering that the theoretical metal saturation in the mantle is only 1wt
147 % Fe⁰ (Frost et al., 2004). Therefore, the application of the study by Smith and Kopylova (2014) to natural systems is
148 limited. The total nitrogen abundance of the charges used in all diamond-synthesis experiments is unknown (i.e.
149 never reported). Ergo, it is not possible to determine D_N or K_N values during experimental diamond formation using
150 the existing published datasets.

151

152 **3. A new petrological assessment of the incorporation of nitrogen in mantle diamonds**

153 The preceding review demonstrates, quite surprisingly, that the compatibility of nitrogen in diamond remains a
154 highly debated topic. Thomassot et al. (2007) and Smart et al. (2011) show convincing data that indicate nitrogen is
155 compatible in diamond, with K_N values of 2 and 5 during diamond precipitation from CH₄-rich and CO₃²⁻-rich fluids
156 respectively (at 1200°C). However, these conclusions do not explain why the global distribution of nitrogen
157 concentrations for in non-coated monocrystalline diamonds is skewed towards zero (akin to incompatible behavior;
158 **Fig.1a-b**), whereas the distribution for the fibrous growth of coated diamonds is Gaussian, peaking at *ca* 800 ppm
159 (akin to compatible behavior; **Fig.1c**). Equally perplexing are the low nitrogen concentrations observed in diamonds
160 from the deeper parts of the mantle (see Harte (2010) and references therein). Despite the question of nitrogen
161 compatibility in diamond being contested, we propose it to be a moot point for the following reasons. According to
162 Goldschmidt's (1937) rules for element compatibility, nitrogen is of the similar atomic size and charge to carbon,
163 making N compatible in the diamond lattice, as is borne out by nitrogen being the most common substitutional

164 impurity in diamond. However, nitrogen is incorporated into diamond in a monatomic state, even though it does not
165 occur in the mantle in this highly unstable form (Mikhail and Sverjensky, 2014; Li and Keppler, 2014). Nitrogen is
166 stable under equilibrium conditions as a variety of molecules, where each nitrogen complex exhibits radically
167 different chemical affinities. Therefore, the real focus of investigation should be into understanding how these
168 various nitrogen species behave, and which potential chemical reactions can disassociate these compounds to
169 produce (unstable) monatomic N during diamond formation.

170 Historically, nitrogen has been considered an atmophile element and accordingly grouped with the noble gases.
171 Atmophile elements are defined as 'those elements that remain mostly on or above the surface because they are, or
172 occur in, liquids and/or gases at temperatures and pressures found on the surface' (Goldschmidt, 1937). However,
173 under conditions of high P and T, nitrogen can behave like a noble gas (N₂), a siderophile element (Fe₃N, TiN, BN), an
174 alkali metal (NH₄⁺) or an organic reactant (e.g. nitrosyl; NO⁻). In fact, in samples from the lower crust and the upper
175 mantle, nitrogen has been found as molecular N₂ (Andersen et al., 1995; Smith et al., 2014), ammonium (implied by
176 Yokochi et al., 2009), metallic nitride (Fe₃N, TiN, BN; Dobrzhinetskaya *et al.* 2009), an impurity in carbide (Kaminsky
177 & Wirth, 2011) and as a lattice-bound component within diamond (NC₄; Kaiser & Bond, 1959). Recent experimental
178 and theoretical data have shown that pressure, temperature, redox state, pH, and the molar abundance of nitrogen
179 can have significant effects on the speciation of nitrogen, with redox being the most important (Li and Keppler, 2014;
180 Mysen et al., 2014; Mikhail and Sverjensky, 2014; Roskosz et al., 2006). For conditions relevant to most (by sample
181 mass) diamond formation (1000-1300°C and 4-7 GPa across a LOGfO₂ range of QFM +2 to -4), nitrogen will be stable
182 in diamond-forming fluids as ammoniac (NH₄⁺/NH₃⁰) or molecular (N₂) forms (**Fig.2 & 3**).

183 None of the nitrogen molecules listed above are compatible in diamond, because they are far too large to fit
184 within the diamond lattice (or neutrally charged and therefore inert, as is the case for N₂ and NH₃). Therefore, the
185 only state in which nitrogen can be partitioned into diamond is as monatomic N⁻³, which as noted above is not a
186 stable form of nitrogen. This requires that nitrogen is incorporated into diamond when monatomic N is produced by
187 coupled oxidation/reduction and acidity/basicity reactions involving N₂ or NH₄⁺ and CO₂ or CH₄. Three simplified
188 ideal reactions are shown in equations 3-5, where CO₂ is interchangeable with CO₃²⁻ (but would require a different
189 mass balance). Noteworthy, the "NC₄" molecule is not an independent species, but instead represent diamond
190 containing N as a point defect in the crystal structure:

191 Oxidation/reduction reactions:

220 carbide inclusions within a diamond from the Amazon craton (Juina, Brazil; Kaminsky and Wirth, 2011). The Fe-
221 carbide has a high N content (termed nitro-carbide; 73 000–91 000 ppm N) while the host diamond contains only
222 44ppm nitrogen. This would give a $K_{N \text{ diamond-carbide}}$ of only 0.0005. However, Mikhail et al., (2014c) also described
223 several Fe-carbide inclusions from two Southern African diamonds (from Jagersfontein, Kaapvaal craton, South
224 Africa) in which neither the diamond nor the syngenetic carbide inclusions contained detectable nitrogen.
225 Interestingly, a recent study by Tsuno and Dasgupta (2015), demonstrating the effect of S on the stability of diamond
226 in equilibrium with Fe-Ni alloys, undermines the argument for co-existing nitride formation. They found that the
227 presence of S results in the assemblage diamond + sulfide, whereas in the absence of S the assemblage is Fe-carbide
228 (cementite) + Fe-Ni alloy (Lord et al., 2009). As sulfides are the most common inclusion in diamond (Shirey et al.,
229 2013), it is likely that the formation of sulfide precludes the formation of nitrides, as it does for carbides. Although
230 this aspect is the subject of debate and ongoing study, it is important to note that the existence of lithospheric Type II
231 diamonds (i.e. those formed at more typical depths of 120-200 km) and the lack of metallic inclusions in almost all
232 sub-lithospheric diamonds demonstrate that the presence of native metals and exceedingly reduced conditions are
233 not required to explain the formation of Type II diamonds in the sub-lithospheric mantle. In addition, there is
234 evidence that sub-lithospheric diamond-formation occurs in equilibrium with relatively oxidizing subducted
235 carbonate melts in the sublithospheric mantle, ergo, inhibiting carbide or nitride stability during ‘deep’ diamond-
236 formation (Walter et al., 2008, 2011; Thompson et al., 2014).

237

238 **4. Implications for diamond-formation**

239 Despite the similarity in charge and ionic radius between N and C, data from extensive studies of natural
240 diamonds and HPHT experiments provide conflicting evidence regarding the compatibility of nitrogen in diamond
241 (e.g. Deines et al., 1989; Cartigny et al., 2001; Thomassot et al., 2007; Stachel and Harris, 2009; Smart et al., 2011;
242 Smith and Kopylova, 2014). It is clear that when the matter is considered from a petrological standpoint, the
243 behavior of nitrogen during diamond formation is complex. For nitrogen to be in an atomic form, capable of
244 incorporation into the diamond lattice during growth, requires coupled oxidation/reduction (Eq.3-4) or acid/base
245 (Eq.5) reactions during diamond formation to liberate N in the monatomic state. This fundamental concept
246 undermines our entire thinking about diamond as a recorder of mantle nitrogen. For example, it is possible to argue
247 that a Type II diamond could have grown from a fluid with a high nitrogen concentration, where conversely a Type I

248 diamond can precipitate from a fluid with a much lower N content - a counter-intuitive notion. Ergo, the nitrogen
249 abundance of mantle diamonds is potentially controlled by the fO_2 conditions during diamond formation, and not
250 just the nitrogen concentration of the diamond-forming fluid. By inference, using the global datasets (**Fig. 1a-c**) we
251 predict that the formation of the fibrous overgrowths of coated diamonds may require a large redox gradient that
252 transitions across the stability of ammonium and molecular nitrogen (which is dependent upon P, T, and X),
253 generating abundant monatomic nitrogen that is readily incorporated into the fibrous diamond. Conversely, the
254 formation of non-fibrous monocrystalline diamond occurs across a large range of redox states, that do not
255 necessarily cross the boundary between nitrogen species, meaning many samples may grow under conditions where
256 ammonium or molecular nitrogen are completely stable species during diamond formation (and are dissolved in the
257 fluid). This model explains why the distribution of nitrogen concentrations in non-fibrous monocrystalline diamonds
258 is skewed towards zero (akin to an incompatible element; **Fig.1a-b**) and the distribution for the fibrous overgrowths
259 of coated diamonds is Gaussian (akin to a compatible element; **Fig.1c**).

260 It is important to reiterate the point that broad statements regarding the compatibility of nitrogen in diamond
261 are too simplistic. Atomic nitrogen is compatible, whereas molecular nitrogen, ammonium/ammonia and metallic
262 nitrides are not. Therefore, we need to understand the effects of the mantle P-T-X- fO_2 conditions on the speciation of
263 nitrogen over the range relevant to diamond formation. The diversity of stable nitrogen molecules under this range
264 of mantle conditions can exhibit radically different solubility, stability, and partitioning behavior in fluids and melts,
265 meaning a general view on nitrogen compatibility in diamond is irrelevant and it needs to be considered on a case-
266 by-case basis. Therefore, a much more pertinent question is 'what is the behavior of nitrogen in the mantle, and how
267 is diamond formation recording it?'

268 **4.1 N in HPHT Synthetic Diamonds**

269 This review of N behavior during natural diamond growth raises obvious questions when it comes to synthetic
270 diamond growth. When diamonds are synthesized under HPHT conditions from metal solvents (e.g. FeNi alloy), they
271 commonly contain substitutional N unless special steps are taken (i.e. the addition of N getters such as Ti⁰). The
272 source of the N is assumed to be atmospheric contamination (i.e. N₂; Boyd et al., 1988). If we consider the redox
273 reactions above (eq. 3-5) which affect N speciation, then it is likely that the N₂ will be subjected to very reducing
274 conditions within the HPHT capsule (in equilibrium with C⁰ and a Fe-Ni alloy). This means that N₂ will be converted

275 to iron nitride or NH_4 , during which time monatomic N will be generated, which can be incorporated into the
276 diamond lattice.

277 **5. Broader implications and future directions**

278 **5.1 Stable isotope fractionation**

279 The use of stable isotopes to trace subducted material through the mantle is widespread, and based on the
280 thermodynamic principle that equilibrium stable isotope fractionation is large at low temperatures and decreases
281 greatly as a function of T (Urey, 1947). Therefore, the light element stable isotope ratios (e.g. carbon and nitrogen)
282 are fractionated in Earth's surficial reservoirs, primarily the atmosphere and hydrosphere, by much larger factors
283 than are possible in the mantle. This makes the stable isotopes of light atmophile elements powerful tracers of
284 material subducted through the mantle (Hilton et al., 2002). However, because carbon isotopes can be significantly
285 fractionated in the mantle under open-system Rayleigh conditions (Cartigny et al., 2001), or reducing conditions
286 involving Fe-carbides (Mikhail et al., 2014c), the use of diamonds' carbon isotopes alone cannot conclusively ascribe
287 a mantle origin to the diamond-forming carbon (Cartigny et al., 1997). As nitrogen is present in most diamonds, the
288 $^{15}\text{N}/^{14}\text{N}$ ratios in diamond have been coupled with the $^{13}\text{C}/^{12}\text{C}$ ratios to verify or challenge the conclusions based
289 solely on carbon-isotope data (Javoy et al., 1984; Boyd et al., 1987, 1992; Boyd and Pillinger, 1994; Cartigny et al.,
290 1997, 1998a,b, 2001, 2003, 2004, 2009; Harte et al., 1999; Bulanova et al., 2002, 2014; Hauri et al., 2002; Howell et
291 al., 2015a; Gautheron et al., 2005; Hutchison et al., 1997; Thomassot et al., 2007, 2009; Petts et al., 2015; Palot et al.,
292 2009, 2012; 2014; Klein-BenDavid et al., 2010; Mikhail et al., 2013, 2014a). However, it is unclear whether the
293 $^{15}\text{N}/^{14}\text{N}$ ratio in diamond records the $^{15}\text{N}/^{14}\text{N}$ ratio of the diamond-forming fluids. The model presented here implies
294 that partitioning of nitrogen into diamond can occur *via* three main reactions, involving either N_2 or NH_4 (Eq.3-5).
295 Due to significant differences in the vibrational frequencies for nitrogen bonds in reduced and oxidised species (e.g.
296 C-N, bonds, N-H bonds, and N-N bonds; Richet et al., 1977), deviations from the typical $^{15}\text{N}/^{14}\text{N}$ ratios in mantle-
297 derived rocks and within single minerals (e.g. diamond) may be a consequence of redox and pH changes in upper-
298 mantle fluids (Petts et al., 2015). Instead of requiring special mechanisms such as tectonic injection of isotopically
299 heterogeneous crustal sources (Boyd and Pillinger, 1994; Mikhail et al., 2014a) or primordial heterogeneities (Javoy
300 et al., 1986; Cartigny et al., 1997; Palot et al., 2012), the observed variations in the nitrogen isotopic compositions of
301 diamonds and other mantle materials might be the result of intra-mantle equilibrium (Petts et al., 2015) or kinetic
302 (Yokochi et al., 2009; Li et al., 2009) stable-isotope fractionation associated with changes in fluid chemistry during

303 metasomatic reactions in the mantle. Therefore, qualitative understandings of equilibrium stable-isotope
304 fractionation factors for nitrogen isotopes during the reactions shown in Eq. 3-5 are required.

305 **5.2 The mantle nitrogen budget**

306 Mantle diamonds show a decrease in average nitrogen abundance with increasing depth of formation. This could
307 reflect a decrease in the nitrogen content of the silicate Earth with depth, as would be predicted if nitrogen were to
308 behave like a noble gas, or if nitrogen is more compatible in other phases with increasing depth. Several lines of
309 direct and indirect evidence show that nitrogen does not necessarily behave like a noble gas, and that the mantle is a
310 significant reservoir for nitrogen: [1] Nitrogen shows the largest depletion (relative to chondrites) in the bulk silicate
311 Earth + atmosphere compared with the enrichment levels of other volatile elements, including the noble gases (H, C,
312 N, Ne, Ar, Kr, and Xe; Marty, 2012; Halliday, 2013), [2] The calculated flux for nitrogen between the surface and
313 interior (subduction vs. volcanism) implies that more nitrogen is being out-gassed from the interior than is being
314 returned into the mantle (Busigny et al., 2011), and [3] the solubility of nitrogen in enstatite and forsterite
315 demonstrates that the reduced parts of the upper mantle can store >50 times more nitrogen than the surface
316 reservoirs (including the atmosphere; Li and Keppler, 2013; Watenphul et al., 2010). Collectively, these data strongly
317 imply the existence of a deep reservoir. Paradoxically, diamond is the mantle mineral with the highest average
318 nitrogen abundance, but may not be the largest reservoir of mantle nitrogen. By far the most important storage
319 mechanism for nitrogen in the mantle is probably through the exchange equilibria between positively charged
320 ammonium cations (NH_4^+) and positively charged alkali metals (e.g. Rb^+ & K^+). This implies that the mantle N-H cycle
321 could follow the same pathways as alkali metals. Thus, based on the stability of the known K-bearing phases (Harlow
322 and Davies, 2004) it is likely that ammonium-bearing mantle phases are stable throughout the entire silicate portion
323 of the Earth. The nature of the deep nitrogen reservoir therefore depends upon the stability of ammonium in the
324 mantle. The mole fraction of ammonic/total nitrogen is predicted to decrease with increasing temperature (e.g. **Fig.3**
325 **a & b**). However, there the mole fraction of ammonic/total nitrogen should increase with increasing pressure (e.g.
326 **Fig.3 b & d**), albeit this relationship is known with a limitation of only 4 GPa for ΔP and maximum T of only 1400°C
327 (Mikhail & Sverjensky, 2014; Li & Keppler, 2014). What is now required are data on the solubility and partitioning of
328 ammonic nitrogen between fluids, melts, and high-pressure K-bearing phases, to address the depletion of nitrogen
329 relative to the other volatile elements, and by inference to express (mechanically) why average nitrogen abundance
330 in diamonds decreases with increasing depth of formation. Addressing this question will provide a more robust

331 understanding of the fluxing of nitrogen during subduction, and the N-H storage capacity of planetary silicate
332 mantles as a whole.

333 **6 Summary**

334 Nitrogen is initially incorporated into the diamond lattice as single nitrogen atoms, a form of nitrogen which is
335 highly unstable. However, the stable forms of nitrogen in the mantle are dominated by N_2 , and NH_4^+ , both of which
336 are incompatible in the diamond lattice. A review of the available data shows that in classic terms, nitrogen is the
337 most common substitutional impurity found in natural diamonds because it is of very similar atomic size and charge
338 to carbon. However, the speciation of nitrogen, and how these different species disassociate during diamond
339 formation to create transient monatomic nitrogen, are the factors governing nitrogen abundance in diamonds. Our
340 model suggests a counter-intuitive notion; nitrogen-free diamond could grow from a N-rich media that is simply not
341 undergoing reactions to liberate monatomic N from N_2 , or NH_4^+ during coupled oxidation/reduction or acid/base
342 reactions during diamond-formation (Eqs.3-5). In contrast, a nitrogen-bearing diamond could grow from a fluid with
343 a lower N abundance, in which reactions are occurring to generate (unstable) N atoms during diamond formation are
344 occurring.

345 The most logical conclusion we can derive is that, at present, we do not understand how diamonds are recording
346 the mantle nitrogen cycle. However, we believe diamonds still represent our best tool for investigating numerous
347 aspects of the mantle C-N cycle, especially when considering carbon and nitrogen stable isotope data. However,
348 further investigations into the speciation, partitioning, and equilibrium stable-isotope fractionation of nitrogen will
349 enable a more accurate interpretation of the nitrogen data from mantle diamonds, and lead to a better
350 understanding of the Earth deep volatile cycles and fluxes.

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360

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562

563 **Figure 1.** Histogram showing the distribution of nitrogen contents (ppm) of mantle diamonds. Data from multiple
564 sources (Boyd et al., 1987, 1992; Bulanova et al., 2002, 2014; Cartigny et al., 1997, 1998a, 1998b, 2001, 2003, 2004;
565 2009; Gautheron et al., 2005; Harte et al., 1999; Howell et al., 2015a; Hauri et al., 2002; Javoy et al., 1984; Klein-
566 BenDavid et al., 2010; Mikhail et al., 2013, 2014a, 2014b; Palot et al., 2009; 2012, 2014; Smart et al., 2011;
567 Thomassot et al., 2007, 2009)

568

569 **Figure 2.** A schematic representation of the aqueous speciation of nitrogen and carbon and the solid state of carbon
570 as a function of redox state at 5 GPa and 1200 °C (*denotes calculations are in equilibrium with diamond). Data for
571 aqueous nitrogen speciation from Mikhail and Sverjensky (2014), Mysen et al., (2014), and Li and Keppler (2014),
572 data for aqueous carbon speciation from Sverjensky et al. (2014) and Frost and McCammon (2008), and the data for
573 solid carbon speciation are from Stagno et al. (2010) and Rohrbach and Schmidt (2011).

574

575 **Figure 3.** Diagrams showing the aqueous speciation of a fluid with 1 wt.% nitrogen as a function of the fluid P, T, fO_2 ,
576 and pH (a-d) using data from Mikhail and Sverjensky (2014).

Peridotitic

350

250

150

50

Eclogitic

120

80

40

Coated

12

8

4

200 600 1000 1400 1800

Nitrogen abundance (at.ppm)





