minerals

Review

Inclusions, Nitrogen Occurrence Modes, and C-N Isotopic Compositions of Diamonds as Indicators for Exploring the Genesis Mechanism of Diamond: A Review

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Abstract

Diamond, a crucial carbon phase in the deep Earth, forms under ultrahigh-pressure (UHP, P > 4 GPa) conditions and serves as an important indicator mineral for the UHP environment. Based on their host rocks, diamonds are classified into mantle-derived diamonds, UHP metamorphic diamonds, impact diamonds, etc. While carbon constitutes the primary component of diamonds, nitrogen represents one of the most significant impurity elements. The study of the occurrence mode of nitrogen and the C-N isotope composition is essential for exploring the formation mechanism of diamond. Nitrogen primarily exists in diamonds as either isolated atoms (N) or aggregated forms (N2 or N4), with the dominant mode being controlled by temperature and residence time in the mantle. As temperature and residence time increase, isolated nitrogen progressively transforms into aggregated forms. As a result, mantle-derived diamonds typically contain nitrogen predominantly as N2 or N4, whereas metamorphic diamonds and impact diamonds mainly retain isolated N. Global C-N isotopic composition of over 4400 diamonds reveals a wide compositional range, with $\delta^{13}C$ ranging from −38.5‰ to +5.0‰, and $\delta^{15}N$ from −39.4‰ to +15.0‰. These values significantly exceed the typical mantle $\delta^{13}C$ and $\delta^{15}N$ values of −5‰ ± 3‰, indicating that the diamond formation may be influenced by subducted crustal materials. During crystallization, diamonds can encapsulate surrounding materials as inclusions, which are divided into three types based on their formation sequence relative to the host diamond: preformed, syngenetic, and epigenetic. Syngenetic inclusions are particularly valuable for constraining crystallization conditions and the genesis of diamonds. Furthermore, geochronology studies of radioactive isotope-bearing syngenetic inclusions are helpful to clarify the age of diamond formation. Usually, mantle-derived diamonds exhibit Archean age, whereas metamorphic diamonds are associated with subduction, showing younger ages that could be associated with metamorphic events. Therefore, the formation conditions and genesis of diamonds can be clearly constrained through integrating investigations of inclusions, nitrogen occurrence modes, and C-N isotopic compositions. The characteristics of occurrence modes, inclusions, and C-N isotope compositions of different types of diamonds are systematically reviewed in this paper, providing critical insights into their genesis and contributing to a deeper understanding of diamond formation processes in Earth's interior.

Keywords: diamond; Earth's interior; C-N isotope; inclusions; the occurrence mode of nitrogen

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1. Introduction

Carbon (C), the fourth most abundant element in the universe, is ubiquitously distributed across Earth's reservoirs. It is mainly stored in Earth systems in the form of organic carbon (C-H-O compounds) and inorganic carbon (carbonates, diamond, etc.) [1–8]. Specifically, in the atmosphere and biosphere, carbon primarily exists as CO_2, CH_4, and organic carbohydrates, whereas in the lithosphere, carbonate is the dominant species. In the deep Earth (the mantle and core), carbon predominantly occurs as high-pressure to ultrahigh-pressure (HP-UHP) carbon phases, including diamond, Fe-C alloy, and so on. The global carbon cycle is facilitated by processes such as photosynthesis, sedimentation, subduction, and magma degassing. Among these, subduction and magma degassing/eruption serve as the primary processes that connect surface carbon with the deep carbon of the Earth, facilitating the deep carbon cycle. Unlike surface carbon cycles, which operate on relatively short timescales, deep carbon cycling occurs over geological timescales. Understanding deep carbon dynamics is of great significance for deciphering Earth's evolution and global carbon balance. It is estimated that millions of tons of carbon are subducted annually, significantly influencing atmospheric carbon budgets and long-term climate regulation [9–12].

Diamond, primarily composed of carbon, is a classic UHP mineral in the deep Earth. The first documented diamond discovery occurred in a kimberlite pipe, and subsequent development of diamond extraction techniques from kimberlite enabled both commercial mining and scientific research [13]. Advances in whole-rock geochemistry, geochronology, inclusion studies in diamonds, and high-pressure–high-temperature experimental petrology have significantly refined our understanding of diamond formation conditions. Generally, diamond formation requires temperatures and pressure exceeding 1150 °C and 4–7 GPa, respectively, corresponding to mantle depths greater than 120 km [14–23]. As such, diamonds serve as critical probes into Earth's interior, providing key insights into mantle and deep carbon cycling [24,25]. Systematic mineralogical and geochemical studies of diamonds provide critical information about Earth's interior. Based on the properties of their host rocks, diamonds could be classified into (1) Mantle-derived diamond: This mainly occurs in some kimberlite, lamprophyre, and alkaline mafic–ultramafic rocks that are derived from the mantle [22,24,26–30]. It is the most economically valuable type [30,31]. (2) Metamorphic diamond: Also known as UHP metamorphic diamond, it usually forms in subduction zones and is associated with UHP metamorphism [3,22,32–35]. Recently, the genesis of UHP metamorphic diamonds has gained much attention. (3) Impact diamond: This is generated due to meteorite impacts and crystallizes instantaneously under extreme pressures induced that transform carbon phases into diamond [36–39]. NASA scientists have discovered nanodiamonds in cold molecular clouds formed at low P-T conditions in space and speculated that 10%–20% of interstellar carbon exists in the form of diamond. This finding opens new possibilities for extraterrestrial diamond resources and provides insights into carbon phase transformations under diverse cosmic environments.

Therefore, clarifying the genesis of different types of diamonds plays a significant role in understanding the carbon cycling and searching for diamond mines. As we all know, each diamond type exhibits distinct formation mechanisms, necessitating tailored research approaches. Comprehensive studies on the occurrence mode of impurity nitrogen, C-N isotopic signatures, and the genesis of inclusions in diamonds are essential.

2. Reconstruction of Diamond Genesis

2.1. The Occurrence Mode of Nitrogen Impurity in Diamonds

While carbon constitutes the primary component of diamond, nitrogen represents its most significant impurity element due to its ability to substitute carbon atom in the diamond lattice. Nitrogen (N) can easily enter the crystal structure through various means:

(1) along with lattice defects, (2) through the replacement of carbon atoms with nitrogen atoms, and (3) by being captured during diamond formation. Based on nitrogen content, diamonds are divided into Type I diamonds (N content > 0.1%) and Type II diamonds (N content < 0.1%). Type I diamonds are further subdivided into Ia and Ib subtypes according to the structural configuration of N. N occurs as isolated (N) and aggregated (N2 and N4) in Ib and Ia diamonds, respectively. The transformation between these nitrogen configurations is principally governed by temperature and residence time in the mantle [24,40–43]. The isolated N could transform to aggregate N2/N4 when the temperature rises to 2200 °C, and the pressure is constant (9.3 Gpa) [41]. It is worth noting that the higher the temperature, the shorter the time required for the transformation of isolated N to aggregate N2/N4.

Stachel and Harris [31] proposed that most mantle-derived single-crystal diamonds crystallized at mantle depth or deeper to 600 km are usually associated with ancient cratons [30]. These diamonds reside in the mantle for extended geological periods following their formation before being transported to shallower depths or the surface via diamond-bearing kimberlite eruption. Previous studies show that Type Ia diamonds can persist in the mantle for 200 to 2000 Ma at temperatures between 1000 and 1400 °C, whereas Type Ib diamonds exhibit shorter preservation times under similar conditions [43]. Consequently, the long-term residence of N in the HP-HT mantle environment facilitates the transformation of Type Ib to Ia diamonds, explaining why nitrogen in the majority of mantle-derived diamonds predominantly exists in aggregated form.

By contrast, nitrogen in metamorphic diamond mainly exists in the form of isolated N. An important observation by Barron et al. [44] suggests that thinner subducting plates experience more rapid temperature increases, resulting in the coexistence of graphite in the diamond stability domain. Due to their short residence time, Type Ib diamonds are common in metamorphic diamonds [44]. This characteristic is exemplified by UHP metamorphic diamonds from New South Wales, where the Ar-Ar dating of syngenetic inclusions yields an age of 320 Ma, significantly younger than the ancient Type Ia diamonds formed with the metamorphic age of the host rock, suggesting rapid exhumation following the formation of this metamorphic diamond.

Similar to metamorphic diamonds, impact diamonds are diamond particles formed in metamorphic rocks that are related to meteorite impacts [36,37,45]. Microstructural features of the graphite-diamond transition in the impact diamonds are distinguished [45], suggesting that these unique diamonds crystallize almost instantaneously when the extreme pressures generated by planetary collisions convert carbon-bearing phase (e.g., carbonates or graphite) into diamond through solid-state transformation. In addition, spectroscopic and CL images show that nitrogen defects, which were common in mantle-derived diamonds, are absent in impact diamonds [45]; thus, the occurrence mode of nitrogen in impact diamonds has not been distinguished.

Therefore, the study of the occurrence mode and contents of nitrogen in diamond could provide an important indicator for exploring the genesis mechanism of diamond.

2.2. Carbon–Nitrogen Isotope Composition of Diamonds

As the primary impurity substituting for carbon in the diamond lattice, nitrogen not only provides insights into diamond genesis through its occurrence modes but also serves as a key tracer for exploring its origin and source via C-N isotopic analyses [15,46–54]. As a consequence, the isotopic signatures of carbon and nitrogen in diamonds have become powerful tools for understanding diamond genesis and mantle processes [15,46–55]. Global compilation of C-N isotope from more than 4400 diamonds indicates that the carbon isotopic composition ($\delta^{13}C$) of diamond ranges from −38.5‰ to +5.0‰ (Figure 1), and the nitrogen isotopic composition ($\delta^{15}N$) ranges from −39.4‰ to +15‰ [15,48]. These values significantly exceed typical mantle values ($\delta^{13}C_{mantle}$: −5 ± 3‰; $\delta^{15}N_{mantle}$: −5 ± 3‰) [56].

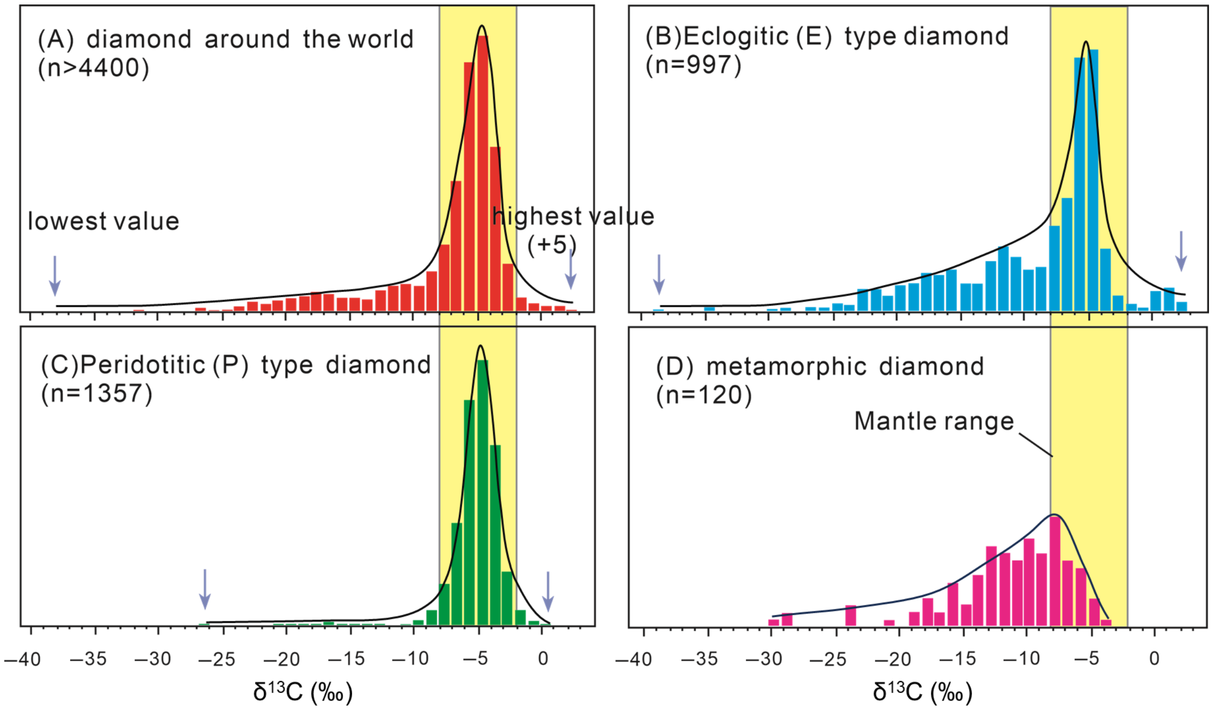

Figure 1. Carbon isotopic composition ($\delta^{13}C$) of diamond, data modified from [15]. Modified after Cartigny [15].

Carbon isotopic data reveal a broad compositional range for mantle-derived diamonds [15] (Figure 1B,C). Palot et al. [48] suggested that the large isotopic variations could be related to the heterogeneity of the mantle. Therefore, the C-N isotope composition of mantle-derived diamond can be used to infer the composition and properties of the mantle [57]. However, the pronounced negative drift of carbon isotope and positive drift of nitrogen isotope indicate substantial involvement of recycled organic-rich crustal materials in diamond formation [43,53,58–60]. Therefore, Thomassot et al. [51] further recognized that the subducted crustal carbon and mantle carbon are the main source of mantle diamond. It is worth noting that more than 72% of the C-N isotope compositions of mantle-derived diamonds are within the mantle range ($\delta^{13}C_{mantle}$: −5 ± 3‰; $\delta^{15}N_{mantle}$: −5 ± 3‰) (Figure 1), indicating that the majority of diamonds are of mantle origin [15].

In addition, recent analytical advances, particularly in situ secondary ion mass spectroscopy (SIMS) techniques, have enabled high-resolution isotopic mapping that reveals new complexities in diamond growth. Carbon isotope zoning pattern in the diamond has been recognized through high-spatial-resolution SIMS analysis [54]. The redox state of the diamond-forming medium affects the carbon isotope composition and the distribution of nitrogen between diamond and the medium. Diamonds crystallized under oxidizing mantle conditions tend to exhibit relatively higher N contents and $\delta^{13}C$ values compared to those formed in reducing environments [54]. Wiggers de Vries et al. [54] conducted in situ carbon isotope analyses on diamond core to rim, revealing significant $\delta^{13}C$ variations that indicate multi-stage crystallization processes. According to the carbon isotope fractionation mechanism, the $\delta^{13}C$ values of diamonds formed in reducing fluid vary from range from −7.3‰ to −4.6‰. However, diamonds formed in oxidizing fluid show values ranging from −5.8‰ to −1.8‰ and −3.8‰ to +0.2‰ when diamonds are crystallized from carbonate-rich and CO_2-dominant medium, respectively. Therefore, the zoning of carbon isotope is directly linked to changes in the redox states of the medium during diamond formation. Moreover, based on isotope fractionation principles, the redox states of the Archean mantle are constrained by the carbon isotope composition of mantle-derived diamond. Consequently, the in situ carbon isotopic composition of mantle-derived diamonds could be used as an important indicator that could reflect the Archean craton evolution that is affected by the heterogeneous fluid [51,54].

Compared with the mantle-derived diamond, the C-N isotopic composition of metamorphic diamond and impact diamond shows differences. Previous studies have revealed that the $\delta^{13}C$ of metamorphic diamonds shows a wide range of variation (−30‰ to −3‰), which is outside the mantle range (−5 ± 3‰) [15,61]. This indicates that crustal carbon plays a critical role in the formation of metamorphic diamonds. Additionally, crustal carbon is subducted to the mantle depth through dissolution, melting, and decarbonation processes. In addition, in situ SIMS analysis results show that there is a difference in carbon isotopic composition from core to rim [61], suggesting that the metamorphic diamonds from Kazakhstan experienced multiple growth stages.

In addition, the $\delta^{13}C$ of impact diamonds ranged from −30‰ to −8‰ [15,45,62], which is similar with metamorphic diamonds but outside the mantle range (−5 ± 3‰), suggesting that the carbon source of impact diamonds is a mixture of carbon sources in which a meteoritic component is at most very minor along a mixing trend with carbon from target lithologies.

Above all, the C-N isotopic compositions of different types of diamonds exhibit differences; metamorphic and impact diamonds usually demonstrate a combination of different carbon sources. The carbon isotopic composition of mantle-derived diamonds not only records the carbon source but also reflects the redox environment of the mantle. In summary, the C-N isotopic framework of diamond provides fundamental insights into the mechanism of different types of diamonds, and the in situ carbon isotopic composition of mantle-derived diamond could also reverse the chemical evolution of Earth's interior through geologic time.

2.3. Inclusions in Diamonds

Diamonds usually encapsulate minerals or fluids as inclusions during their crystallization, preserving valuable records of the composition and physicochemical properties of their formation medium. These inclusions serve as critical tracers for studying the deep Earth's composition. With advancements in analytical techniques such as EPMA, Raman, LA-ICP-MS, and SMIS analysis, inclusions are divided into three types: preformed, syngenetic, and epigenetic inclusions. As for preformed and epigenetic inclusions, these are mineral or fluid/melt that existed prior to and after diamond crystallization and were subsequently trapped by the diamond; therefore, they have little or no effect in tracing the medium from which the diamond crystallized. However, syngenetic inclusions are trapped when diamond crystallizes. Typically, syngenetic inclusions are in the form of fluids, melt, or negative crystals, which can directly reflect the composition of the parental fluid or melt from which the diamond formed. Thus, they provide key insights into diamond formation [15,25,54,63,64]. Studies of syngenetic inclusions have revealed significant regional variations in the crystallization medium and formation P-T conditions of the diamond [25,65,66]. For example, sulfide–sulfate and Fe-Cr metals could act as oxidation-reduction buffers during diamond formation [11,43,67]. The presence of reduced phases such as Ni-Mn-Co alloy, H_2, and CH_4 indicates formation of diamond under a highly reducing environment, whereas oxidized carbonate inclusions suggest diamond growth through carbonate reduction [68]. However, recent studies suggest that reduced and oxidized carbon phases coexist during diamond formation [33,68], thus constituting the oxidation–reduction environment of diamond formation complex.

In particular, inclusions containing redox-sensitive elements help constrain the redox environment during diamond crystallization [67,69]. Syngenetic inclusions of sulfide, garnet, clinopyroxene, etc., which contain radioactive isotopes that are suitable for dating, have been distinguished in mantle-derived diamond. Therefore, this makes the geochronological study of diamond possible. Two indirect approaches have been employed for determining the age of diamond: (1) estimating the age of diamond by the aggregate form of nitrogen, and (2) dating syngenetic mineral inclusions containing radioactive isotopes [44,70]. For example, the syngenetic inclusions of sulfide can be dated using the Re-Os, U-Pb systems, while garnet–clinopyroxene inclusions can be analyzed via Sm-Nd and Ar-Ar systems. In general, mantle-derived diamonds exhibit Archean age, whereas metamorphic diamonds are associated with subduction, showing younger ages that could be associated with metamorphic events [44]. The age of UHP metamorphic diamond either coincides with or slightly predates the metamorphic event. A notable exception is Jack Hills zircons, where diamond inclusions in the oldest zircon with a high Th/U ratio and U-Pb age of 4140 Ma were identified by Menneken et al. [71]. This discovery presents a paradox: if these diamonds formed before or at the same time as the oldest zircon, it would imply the existence of UHP metamorphic conditions and possibly plate subduction at 4140 Ma. Thus, determining the diamond age is of great significance for unraveling diamond genesis. Therefore, the identification and genetic analysis of inclusions in diamond are not only of great significance for understanding the mechanism of diamond formation but also serve as powerful tools for reconstructing the redox environment of the deep Earth and the composition of Earth's interior.

Previous studies have suggested that many inclusions are easily distinguished in large-grained mantle-derived diamonds [55]. Merey [72] and Tappert [73] classified inclusions into two types: (1) peridotitic (P-type) or ultramafic (U-type) inclusions, olivine (primarily forsterite, with an $Mg^{\#}$ value between 90.2 and 95.4), Cr-bearing garnet with a high pyrope component, Mg-rich orthopyroxene, clinopyroxenes with high diopside component, chromite, high-Ni sulfides (Ni > 12 wt%), Mg-Cr spinel, and Mg-Cr ilmenite; (2) eclogitic (E-type) inclusions, pyrope–almandine garnets, clinopyroxenes (omphacite), and low-Ni sulfides (Ni < 12 wt%) are common minerals; in addition, corundum, rutile, coesite ilmenite, and chromite occur less frequently as inclusions in eclogitic diamonds. Precisely, Stachel and Harris [74] and Cartigny [15] classified inclusions in mantle-derived diamond into three types: (1) peridotitic (P-type) inclusions, which account for 65% of the total inclusions; (2) eclogitic (E-type) inclusions, representing about 33% of the total inclusions; and (3) websteritic (W-type) inclusions, accounting for about 2% of the total inclusions. Peridotitic mineral inclusion assemblages are used to constrain the pressure and temperature conditions, e.g., Grt-Cpx or Grt-Opx for pressure and Opx-Cpx or Grt-Ol for temperature.

Since then, diamonds have been identified in more than 30 ultrahigh-pressure subduction zones worldwide, including the Alps [16], Dabie–Sulu [34,75], Kokchetav [76,77], and North Qaidam [78] orogenic belts. These findings have revolutionized our understanding of plate subduction dynamics [79]. The crystallization of UHP metamorphic diamonds in subduction zones experienced complex growth processes related to metamorphic fluid activities. Experimental studies and inclusion analyses show that diamonds could crystallize from C-saturated CHO fluids under reducing conditions [3,49,55,80–87]. The carbon in these fluids is released from the subducted plate through the decomposition, dissolution, and partial melting of carbonates [88]. In addition to carbonate, the predominant carbon-bearing species in these fluids include CH_4, CO_2, CO_3^{2-}, and COOH- [3,6,49,86,88–91].

The rapid growth of subduction-related diamond in metamorphic fluid is accompanied by the entrapment of various inclusions, such as carbonate, olivine, Fe-Cr-Ni metal alloys, Fe-C carbides, sulfides, high-salinity fluid inclusions, and multiphase inclusions (H_2, CH_4) [25,44,51,55,66,92]. These inclusions provide important information for the genesis and crystallization conditions of subduction-zone diamond. For instance, Frezzotti et al. [81] identified micro-diamond trapped within fluid inclusion in the Alps through Raman 2D scanning. Further analysis showed that the coexisting carbon phases mainly consisted of hydrocarbon groups (-COOH), methane, and amorphous carbon [3]. This led to the hypothesis that diamonds in the Alps formed via the dehydrogenation of hydrocarbon groups and methane (CH_4) in reduced CHO fluids. In contrast, Wang et al. [33] used Raman 3D imaging to document diamond–methane–magnesite multiphase inclusions in mantle-type peridotite in the Dabie orogenic belt (Figure 2), inferring diamond formation through the decarbonization of carbonate phase in metamorphic CHO fluids. Taken together, the crystallization of subduction-derived metamorphic diamond has been associated with carbon-saturated fluids, exhibiting a more complex genesis than mantle-derived diamonds.

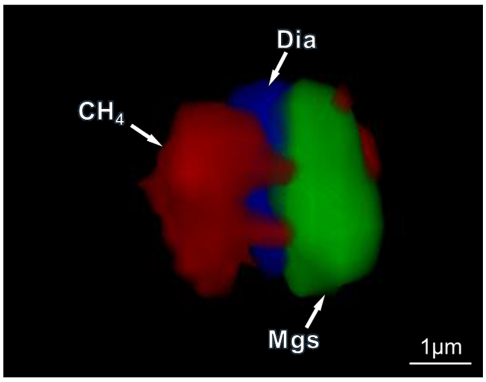

Figure 2. Three-dimensional multiphase inclusions of diamond (blue), CH_4 (red), and magnesite (green) in olivine from Dabie organic belt, data from Wang et al. [33]. Dia stands for diamond, CH_4 stands for methane, and Mgs stands for magnesite.

In addition, an important observation by Barron et al. [44] shows that sp^2-disordered carbon, characterized by a Raman peak at 1580 cm^{-1}, is distinguished in metamorphic diamond. Experimental petrological studies have further verified that hydrogen in diamond-forming medium is preferentially incorporated into cubic diamonds, donating an electron [49]. This process causes cubic diamonds containing both sp^3-ordered carbon and sp^2-disordered carbon, whereas octahedral diamond only has sp^3-ordered carbon. Thus, Raman spectroscopic analyses show that diamond inclusions trapped in olivine primarily consist of sp^3-ordered carbon (1332 cm^{-1} peak), with additional peaks at 1340 cm^{-1} and 1580 cm^{-1} for disordered carbon [3,84] (Figure 3). H- groups on the carbon surface serve as terminal bonds, promoting the transformation of sp^2 to sp^3 carbon during diamond growth, which is significantly different from mantle-derived diamond.

Although the genesis of metamorphic diamond in subduction zones has been studied systematically, key controversies persist regarding the relationship between metamorphic diamond and coexisting carbonaceous phases. Resolving these scientific issues could provide a crucial insight into carbon transfer mechanisms in subduction zones and deep carbon cycling processes. Such understanding could fundamentally advance our knowledge of Earth's early geodynamic evolution and the global carbon cycle through geological time. Therefore, resolving the carbon source of metamorphic diamond is of great significance to understand the genetic mechanism of diamond that is formed in subduction zones.

Unlike the multiplicity of inclusions in metamorphic and mantle-derived diamonds, the Raman analysis studies of inclusions in impact diamonds have revealed that quartz and iron oxide (magnetite and hematite) [93]. In addition, chromium is recognized in inclusions that have also been observed in mantle-derived and metamorphic diamonds [25,63], suggesting that it may play a significant role during impact diamond formation.

Inclusions trapped by different types of diamonds exhibit differences; metamorphic and impact diamonds usually show the mixed characteristics of the crustal source. By contrast, inclusions in mantle-derived diamonds have been associated with the type of inclusions. All inclusions in diamonds can record the medium of diamond crystallization. Some inclusions containing radioactive isotopes or valuable elements can also reflect the diamond formation age and redox environment. Therefore, it is helpful to study the inclusion in diamonds for determining the formation mechanism of diamonds.

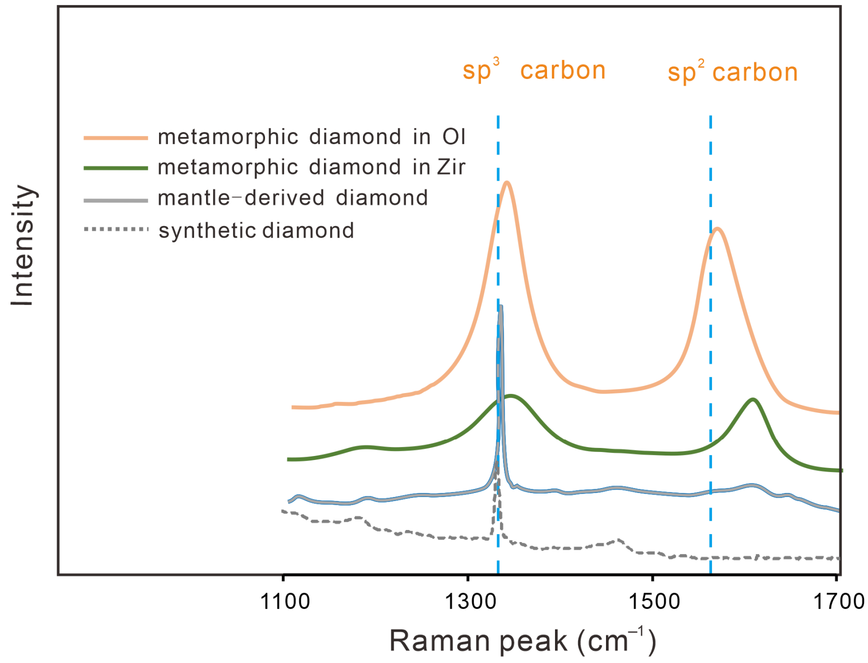

Figure 3. Raman spectrum diagram, data from Wang et al. [33].

3. Conclusions and Prospects

Diamond formed in the deep UHP environment can be transported to the surface through volcanic eruption (e.g., diamond-bearing kimberlite) and exhumation processes, serving as an important window for exploring the deep carbon cycling. Studies on the occurrence modes of nitrogen, the C-N isotope composition, and inclusions in diamond not only constrain the genesis of diamond but also provide important information for understanding the properties of the deep Earth and deep carbon cycling. Recent advances in HT-HP experimental techniques and in situ analysis methods (e.g., SIMS, Raman spectroscopy, etc.) have enabled the precise characterization of the internal structure and growth process of diamond.

(1) Mantle-derived diamonds are hosted in kimberlite, lamprophyre, and alkaline mafic-ultramafic rocks. These diamonds have been stored at mantle depths since their formation, with nitrogen mainly existing in aggregated form (N2/N4). The C-N isotopic composition of mantle-derived diamonds indicates that carbon predominantly comes from primordial mantle reservoirs, as evidenced by their characteristic isotopic signatures. However, negative carbon isotopic drift and positive nitrogen

isotopic drift have been distinguished, recording crustal carbon contributions. Based on the chemical composition of inclusions within the diamond, it can be classified into two or three types. Radioactive isotope-bearing syngenetic inclusions are ideal for determining the formation age of diamonds. Mantle-derived diamonds typically yield Archean crystallization ages, consistent with their prolonged residence in stable lithospheric roots. In the future, in situ analyses will be an important aspect, and statistical big data on global diamond research will provide an important scientific basis for the global deep carbon cycle.

(2) Metamorphic diamonds are usually formed in ultrahigh-pressure metamorphic belts. Nitrogen in metamorphic diamonds mainly exists in the isolated form due to the relatively short mantle residence. Additionally, crustal carbon plays a critical role in the formation of metamorphic diamonds. It crystallizes from carbon-saturated metamorphic fluids that were released from the subducted plate. As a result, the formation age of metamorphic diamonds is similar to that of the subduction events, which is much younger than mantle-derived diamonds. During this process, inclusions were trapped in diamonds, recording the medium from which the diamond crystallized. It is worth noting that the presence of H-groups in the crystallization medium (such as fluids, melts, or supercritical fluids) may catalyze the transformation of sp^2 to sp^3 carbon during diamond growth, resulting in significant differences with mantle-derived diamonds (only sp^3 carbon). Subduction-related diamond is one of the most important targets for studying the deep carbon cycling.

(3) Impact diamonds form through an instantaneous solid-state transformation of precursor carbon phases during hypervelocity meteorite collisions, and graphite coexists with diamond. Compared with the former two types of diamonds, there are no nitrogen defects in impact diamonds. The analysis of carbon isotopic composition and inclusions indicates a mixture of carbon sources. As humans continue to explore space, impact diamonds may become another important target for the exploration of future diamond deposits.

Interdisciplinary approaches in diamond research will significantly advance the theory of deep carbon cycling and also provide new directions for technological innovation. The advancement of analytical capabilities and cross-disciplinary approaches will further enhance diamonds' role as probes of Earth's deep interior and carbon transfer processes.

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