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# Ophiolite-Hosted Diamond: A New Window for Probing Carbon Cycling in the Deep Mantle

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## ABSTRACT

As reported in our prior work, we have recovered microdiamonds and other unusual minerals, including pseudomorph stishovite, moissanite, qingsongite, native elements, metallic alloys, and some crustal minerals (i.e., zircon, quartz, amphibole, and rutile) from ophiolitic peridotites and chromitites. These ophiolite-hosted microdiamonds display different features than kimberlitic, metamorphic, and meteoritic diamonds in terms of isotopic values and mineral inclusions. The characteristic of their light carbon isotopic composition implies that the material source of ophiolite-hosted diamonds is surface-derived organic matter. Coesite inclusions coexisting with kyanite rimming an FeTi alloy from the Luobusa ophiolite show a polycrystalline nature and a prismatic habit, indicating their origin as a replacement of stishovite. The occurrence in kyanite and coesite with inclusions of qingsongite, a cubic boron nitride mineral, and a high-pressure polymorph of rutile (TiO<sub>2</sub> II) point to formation pressures of 10–15 GPa at temperatures ~1300 °C, consistent with depths greater than 380 km, near the mantle transition zone (MTZ). Minerals such as moissanite, native elements, and metallic alloys in chromite grains indicate a highly reduced environment for ophiolitic peridotites and chromitites. Widespread occurrence of diamonds in ophiolitic peridotites and chromitites suggests that the oceanic mantle may be a more significant carbon reservoir than previously thought. These ophiolite-hosted diamonds have proved that surface carbon can be subducted into the deep mantle, and have provided us with a new window for probing deep carbon cycling.

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## 1. Introduction

Carbon is the fourth most abundant element in the solar system, after hydrogen, helium, and oxygen [1,2]. It is a crucial element for life on Earth, and its chemical compounds are the main energy sources for human beings. Earth's carbon is mostly stored in mantle and sedimentary reservoirs, with a present-day mass of about  $3 \times 10^{19}$ – $2.4 \times 10^{20}$  kg of carbon stored in the mantle and a mass of about  $5.4 \times 10^{19}$ – $8.7 \times 10^{19}$  kg surficial carbon [3,4]. Research on Earth's carbon cycle processes mainly focuses on cycles of two different timescales: ① the short-term carbon cycle, which involves years to tens of thousands of years of carbon transfer among surficial reservoirs including the atmosphere, oceans, soils, and biosphere; and ② the long-term carbon cycle, which involves many millions to billions of years of carbon transfer

between rocks and surficial reservoirs [4–7]. Both the short-term and long-term carbon cycles play important roles in global climate change, which is a life-and-death factor for life on Earth. The short-term carbon cycle has been studied relatively extensively, whereas the long-term carbon cycle—and especially the deep carbon cycle—is still a very open question due to the rarity of research objects from the Earth's deep mantle. Mantle peridotites are commonly found in various orogenic belts in the world and preserve important information about the mantle carbon reservoir [8]. However, due to the extremely low solubility of carbon in mantle minerals such as olivine, diopside, and pyrope, the carbon budget of the mantle is dominated by carbonates and diamond [9,10], making them important candidates for investigating the carbon cycle in the Earth's mantle [11–13].

Diamond is well known to have been found in kimberlites, lamprophyres, and related placer deposits, which are sources of gem-quality diamonds [14]. Diamonds also occur in lamprophyres [15], ultrahigh-pressure (UHP) metamorphic rocks [16–18], and

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meteorites [19–21]; however, due to their small size and poor abundance, these diamonds have little commercial value but are of great scientific interest. Since the first microdiamond was recovered from the Luobusa ophiolite in the Tibet Autonomous Region (Tibet) [22], diamonds have been successively discovered in a series of ophiolites of different orogenic belts [23–26]. With increasing evidence for the existence of diamond in ophiolitic peridotites and chromitites [27,28], a new occurrence of diamond was proposed: namely, ophiolite-hosted diamond (also known as ophiolitic diamond) [29].

Subducted slabs may reach the mantle transition zone (MTZ) at 410–670 km [30], and even the core-mantle boundary (CMB) at a depth of 2900 km [31–33]. Most hydrous minerals in subducted slabs become unstable with increasing depth and are replaced by high-pressure minerals, while the water in their crystalline structure is released into surrounding fluids or melts. This process has been widely recognized based on evidence from surface geology, geophysical data, and high-temperature/high-pressure experiments [34]. Current knowledge of the fate of these deeply subducted materials within and near the MTZ or the CMB is still in its infancy. Mineral inclusions in diamonds provide a glimpse of mantle processes and the fate of recycled crustal material at various mantle depths [35,36]. At present, most knowledge related to the recycling of subducted material comes from diamonds and their mineral inclusions in kimberlites and related rocks from old cratons [1,13,37–40]. However, diamonds and recycled crustal minerals newly discovered in peridotites and chromitites from different ophiolites (Fig. 1) [22,24,26,28,41–45] have provided a new window for probing carbon and other crustal material cycling in the deep mantle.

Although we provide a brief description of different occurrences of diamonds in this paper, our emphasis is on the occurrence of natural and *in situ* diamonds in ophiolitic peridotites and chromitites, the significance of these occurrences for the petrogenesis of

the oceanic upper mantle, and the processes by which diamonds and high-pressure/high-temperature equivalents of subducted crustal material are integrated into chromitites–peridotites at MTZ depths. We summarize the geochemical characteristics and possible carbon sources of these unusual diamond occurrences in ophiolites and present a revised geodynamic model for their generation and transportation to shallow mantle depths in the oceanic lithosphere. Our results and interpretations have strong implications for the origin of ophiolite and related chromitites, and for revealing the carbon cycle on Earth.

## 2. Occurrences of diamond on Earth

Diamonds of different occurrences generally vary in terms of color, crystal size, crystal form, isotopic composition, and so forth.

### 2.1. Diamonds in kimberlite and related igneous rocks

Diamonds form at depths of over 150 km in the Earth's mantle [1], and are carried to the Earth's surface by three main types of rocks: kimberlite, lamproite, and lamprophyre [14,37,46]. Kimberlite and lamproite are the main sources of gem-quality diamonds in the world, and are distributed in ancient cratons in Australia, South Africa, Siberia, the North Atlantic, and North China [47–51]. The lamprophyre rocks in the Wawa and Abitibi subprovinces of Canada host the world's oldest diamond deposits (~2.67 Ga) [52].

Diamonds in kimberlite and related rocks mainly occur in three forms—namely, monocrystalline, polycrystalline, and fibrous/coated forms [14]. Monocrystalline diamonds generally show an octahedral, cubic, or cubo-octahedral crystal shape, and are often cut and polished to make gems (Fig. 2(a)) [46]. Polycrystalline diamonds can be classified into different subtypes including frame-site, bort, ballas, and carbonado [53]. Due to the high densities of

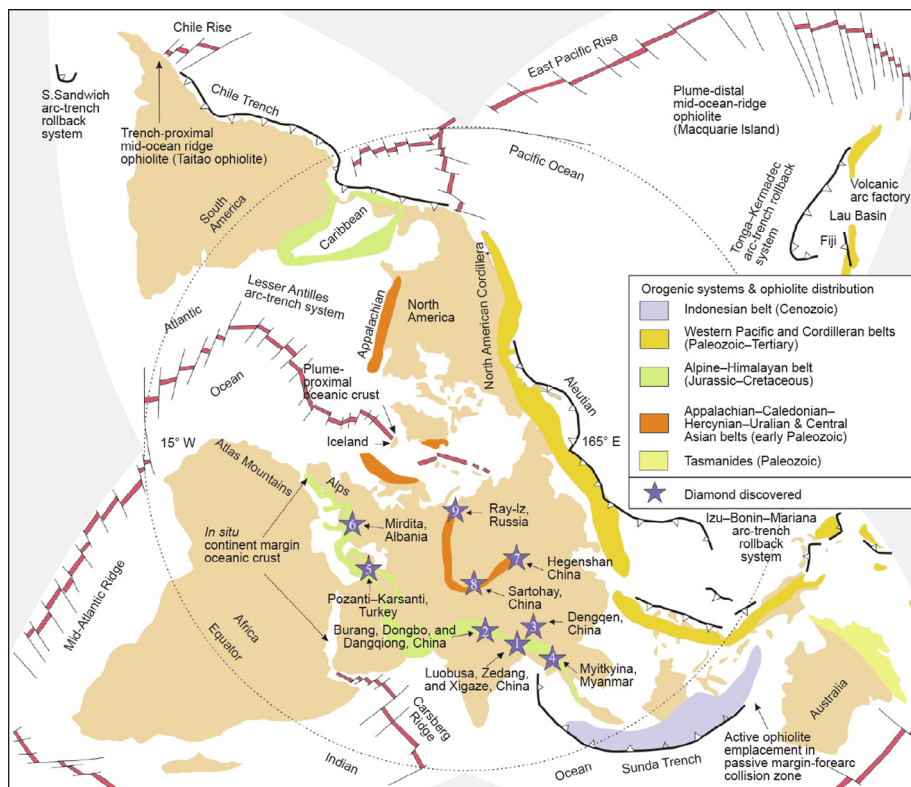
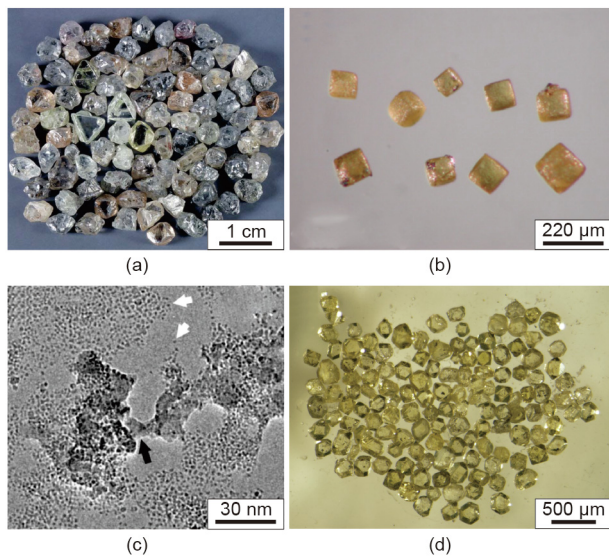


Fig. 1. Global distribution of diamond-bearing ophiolites; purple stars represent diamond-bearing ophiolites. Reproduced from Ref. [45] with permission of GeoScienceWorld.



**Fig. 2.** (a) Mantle-derived diamonds from the Argyle lamproite, Australia. Reproduced from Ref. [46] with permission of Gemological Institute of America Inc., © 2001. (b) Metamorphic diamonds from the Kokchetav Massif, Kazakhstan. Reproduced from Ref. [65] with permission of Elsevier Ltd., © 2012. (c) A bright-field transmission electron microscope (TEM) image of nanometer-sized meteoritic diamonds from the Murchison meteorite with white arrows indicating nanodiamonds and the black arrow indicating amorphous carbon [82]. (d) Ophiolite-hosted diamonds from the Luobusa ophiolite in Tibet, China. Reproduced from Ref. [92] with permission of China University of Geosciences (Wuhan) and Springer-Verlag GmbH, © 2009.

the grain boundaries, polycrystalline diamonds are preferred over monocrystalline diamonds as super-hard abrasives [54,55]. Fibrous/coated diamonds are mixed polycrystalline-monocrystalline diamonds with a monocrystalline core mantled by a polycrystalline layer enclosing abundant fluid inclusions [14].

Only about 1% of these mantle-derived diamonds contain mineral inclusions such as olivine, pyroxene, chromite, garnet, sulfides, metal alloys, and fluid inclusions [56]. These mineral inclusions preserve information about the pressure–temperature ( $P$ – $T$ ) conditions of diamond formation, the formation ages, and the host rock types of diamonds [56–58].  $P$ – $T$  calculations of silicate mineral inclusions indicate that diamonds mainly form at a depth of 140–200 km in the lithospheric mantle of cratons [58,59]. However, an increasing number of observations show that diamonds may also form in the asthenosphere, MTZ, lower mantle, or even CMB [60–63]. These sublithospheric diamonds make up only about 1% of the world's diamond population, and contain mineral inclusions such as majorite, perovskite, stishovite, and periclase [57].

Based on mineralogy and chemical compositions, mineral inclusions in mantle-derived diamonds can be divided into three suites: ① the peridotitic/ultramafic suite (65%), ② the eclogitic suite (33%), and ③ the websteritic suite (2%) [56]. The peridotitic suite can be further subdivided into the lherzolitic (13%), harzburgitic (86%), and wehrlitic (1%) suites. Different suites of mineral inclusions reflect different rock types of mantle source rock during diamond formation. The chemical compositions of silicate minerals, such as  $\text{Cr}_2\text{O}_3$  in garnet and  $\text{Cr}\#$  ( $= \text{Cr}/(\text{Cr} + \text{Al}) \times 100$ ) of clinopyroxene, can be used to distinguish the different mineral suites in diamonds [56]. Diamonds with different mineral inclusion suites also vary in chemical composition.

According to the review by Cartigny [37], worldwide diamonds have a carbon isotopic composition with  $\delta^{13}\text{C}$  ( $= [({}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}})/({}^{13}\text{C}/{}^{12}\text{C}_{\text{RM}} - 1)] \times 1000$ ) values ranging between  $-38.5\%$  and  $+5.0\%$ . Peridotitic and eclogitic diamonds both have a peak  $\delta^{13}\text{C}$  value of about  $-5.0\%$ , which is consistent with that of the normal

mantle carbon reservoir [14,37]. However, eclogitic diamonds have a larger  $\delta^{13}\text{C}$  range (from  $-38.5\%$  to  $+2.7\%$ ) than that of peridotitic diamonds (from  $-26.4\%$  to  $+0.2\%$ ). About 34% of eclogitic diamonds have quite light carbon isotopic composition with  $\delta^{13}\text{C}$  values  $< -10.0\%$ , while this percentage is only about 2% for peridotitic diamonds. The difference in the carbon isotopic composition of peridotitic and eclogitic diamonds indicates a varied carbon source.

## 2.2. Diamonds in ultrahigh-pressure metamorphic rocks

Microdiamonds also occur in crustal rocks that have experienced UHP metamorphism ( $> \sim 4$  GPa) due to deep subduction ( $> \sim 140$  km) [17,64]. It is amazing that these UHP rocks can be brought back to the surface again after subducting to such extreme depth. Metamorphic diamonds were first discovered by Rozen et al. [18] in eclogites of the Precambrian Kokchetav Massif (Fig. 2(b)); however, their metamorphic origin was not accepted until the discovery of *in situ* diamonds as inclusions in zircons [65]. Since then, metamorphic diamonds were consecutively recovered in the Dabie Mountains and North Qaidam, China [16,66]; the Western Gneiss Region, Norway [67,68]; the Erzgebirge Massif, Germany [69,70]; the Rhodope Massif, Greece [71]; the Bohemian Massif, Czech Republic [72,73]; and the Pohorje region, Austria [74].

Metamorphic diamonds mainly occur as mineral inclusions in garnet, clinopyroxene, zircon, kyanite, zoisite, dolomite, and Mg-calcite from UHP metamorphic rocks [16,65,66,75]. These diamonds may have a cuboid, cube-octahedral, or octahedral shape. Unlike mantle-derived diamonds, metamorphic diamonds are usually quite small, at about 1–60  $\mu\text{m}$  in diameter [17]. In rare cases, these diamonds can reach several hundred micrometers in diameter [65,66].

Diamonds formed in metamorphic rocks have  $\delta^{13}\text{C}$  values ranging from  $-30\%$  to  $-3\%$  [37]. Most metamorphic diamonds have a much lighter carbon isotopic composition than those of the mantle carbon reservoir ( $\delta^{13}\text{C} = -5\% \pm 3\%$ ) [14,65]. According to the statistical work by Cartigny [37], metamorphic diamonds have exclusively positive  $\delta^{15}\text{N}$  values. Carbon and nitrogen isotopic compositions suggest that the material source for metamorphic diamonds is subducted metasediments [76]. The noble gas contents of metamorphic diamonds in the Kokchetav Massif have been analyzed by Verchovsky et al. [77]. The results showed that the saturation concentration of  ${}^4\text{He}$  ( $5.6 \times 10^{-4} \text{ cm}^3 \cdot \text{g}^{-1}$ , STP) is among the very highest observed in any terrestrial diamonds [77]. Sumino et al. [78] reanalyzed the noble gas composition of Kokchetav diamonds by crushing the diamonds *in vacuo*. The results showed that the inclusion-hosted  ${}^3\text{He}/{}^4\text{He}$  ratio is about  $(3.3\text{--}6.5) \times 10^{-5}$ , which is higher than that of the mid-ocean ridge basalt (MORB)-source mantle, but consistent with the maximum value of ocean island basalts (OIBs) [78]. Thus, it has been suggested that a plume-like component was involved in the formation of the Kokchetav diamonds [78].

## 2.3. Diamonds in meteorites and related impact craters

Diamonds related to meteorites can be classified into two groups: ① meteoritic diamonds, which occur as presolar grains in meteorites (Fig. 2(c)) [19,20,79–82]; and ② impact diamonds, which form under the high-pressure and high-temperature conditions produced when meteorites impact the Earth's surface [83–85].

Meteoritic diamonds are usually only a few nanometers in diameter and are thus also known as “nanodiamonds” [20]. The anomalous noble gas isotopic compositions in meteorites led to the discovery of nanodiamonds [79,86]. Diamonds in meteorites were first recognized by Lewis et al. [19] when checking the

residue carbonaceous material from the Allende, Murchison, and Indarch meteorites after acid treatment [19]. Meteoritic diamonds mainly have a cubic crystal structure, although rare cases show a hexagonal symmetry. Russell et al. [87] analyzed the isotopic composition of diamonds from primitive chondrites. These diamonds have  $\delta^{13}\text{C}$  values ranging from  $-38\%$  to  $-32\%$ , a  $\delta^{15}\text{N}$  of  $-348\% \pm 7\%$ , and nitrogen contents of 7–13000 ppm, which are obviously distinct from those of terrestrial diamonds [37,87]. By comparison, transmission electron microscope (TEM) studies of meteoritic diamonds with synthesized nanodiamonds produced by high-pressure shock waves and vapor-deposition processes suggest that these presolar diamonds in meteorites have a circumstellar condensation origin and form through low-pressure deposition processes [20,21].

Impact diamonds have been discovered in impact melt rocks and breccias in several terrestrial impact craters in Russia [84,88], Ukraine [89], and Germany [83,90]. Impact diamonds have a relatively large size, ranging from tens of nanometers to several hundred micrometers, or even millimeters, in diameter [83,84]. Diamonds from the Popigai impact crater in Russia have been analyzed for carbon and nitrogen composition. These diamonds have  $\delta^{13}\text{C}$  values of  $-20\%$  to  $-8\%$ ,  $\delta^{15}\text{N}$  values ( $= [^{15}\text{N}/^{14}\text{N}_{\text{sample}}]/(^{15}\text{N}/^{14}\text{N}_{\text{RM}}) - 1] \times 1000$ ) of  $-6\%$  to  $-2\%$ , and nitrogen contents of 5–50 ppm, all of which differ from those of presolar diamonds [84,87]. Similarities in mineralogical, isotopic, and crystallographic characteristics between impact diamonds and graphite in the Popigai impact crater indicate that these diamonds have transformed from associated graphite in the solid state [84]. A study on diamond and graphite from the Ries impact crater demonstrated a similar formation mechanism for impact diamonds [91].

#### 2.4. Diamonds in ophiolitic peridotites and chromitites

Diamonds were first recovered from podiform chromitites of the Luobusa and Dongqiao ophiolites in Tibet, China, in 1981. Since then, diamonds have been successively discovered in ophiolitic peridotites and chromitite of different orogenic belts (Fig. 1). These diamond-bearing ophiolites mainly include: ① the Luobusa, Xigaze, Dongbo, Burang, Dangqiong, and Dongqiao massifs in Tibet, China [22,28,41,92,93]; ② the Sartohay ophiolite in the Xinjiang Uygur Autonomous Region, China [94]; ③ the Hegenshan ophiolite in the Inner Mongolia Autonomous Region, China [95]; ④ the Ray-Iz ophiolite in Polar Urals, Russia [44]; ⑤ the Pozanti–Karsanti (also called Aladag) ophiolite in Turkey [24]; ⑥ the Mirdita ophiolite in Albania [26,96]; and ⑦ the Myitkyina ophiolite in Myanmar [25]. The abundance of diamonds varies considerably between different ophiolites. Xu et al. [92] discovered more than 1000 grains of diamonds in 1100 kg of chromitites from the Luobusa ophiolite (Fig. 2(d)), which is about 1 grain per kilogram. In the Hegenshan ophiolites, about 130 diamond grains were recovered from 2000 kg of chromitites, which is about 0.06 grain per kilogram [95]. Lian et al. [24] recovered more than 100 grains of diamond from 500 kg of chromitite from the Pozanti–Karsanti ophiolite, which is about 0.2 grain per kilogram. However, ophiolites such as the Mirdita [97], Sartohay [94], and Myitkyina [25] ophiolites have quite low abundances of diamonds. Chen et al. [25] only recovered 6 grains of diamond from 1540 kg of peridotites in the Myitkyina ophiolite.

Ophiolites are relics of the ancient oceanic lithosphere that were tectonically emplaced into continental margins [45]. An intact ophiolitic sequence includes the following units, from bottom to top: mantle peridotites, ultramafic and mafic cumulate rocks, sheeted dykes, pillow lavas, and sedimentary cover. Chromitites may occur in both mantle and crustal horizon in the ophiolitic sequence [24,98]. It is well accepted that peridotites, chromitites, and the oceanic crustal derivatives in ophiolitic sequence form at

shallow depths (60–80 km) beneath a spreading center in a mid-ocean ridge setting or above a suprasubduction zone [99–101]. However, diamonds form at depths greater than 150 km or at pressures greater than 5 GPa [37]; therefore, the formation conditions for diamond and ophiolite are incompatible with each other. The discovery of diamonds in ophiolitic chromitites and peridotites have received much skepticism. In the early stages of this research, when diamonds were being recovered from mineral concentrates rather than as *in situ* minerals, scholars questioned whether these diamonds to be contaminants during mineral separation processes. Therefore, conducting a comparison study between ophiolitic diamonds and synthetic diamonds and looking for *in situ* diamond grains in ophiolites are of great importance to prove the natural origin of these diamonds.

Howell et al. [28] reported an independent discovery of diamonds from several hand-specimens sampled from the Luobusa ophiolite. The diversity in diamond sizes ruled out the possibility of contamination from drill bits or saws [28]. Systematic comparison studies of isotopic and trace element compositions between the Luobusa diamonds and synthetic diamonds revealed a natural rather than anthropogenic contamination origin for these diamonds. Yang et al. [41] reported the first discovery of an *in situ* diamond as an inclusion enclosed by an OsIr alloy. However, this diamond grain is only 1–2  $\mu\text{m}$  in size, which is much smaller than the diamonds from mineral concentrates [29]. Due to the rarity of diamonds in peridotite and chromitite, it is extremely difficult to discover *in situ* diamonds. After extensive work checking polished chromitite pieces for more than a year, six *in situ* diamonds were finally discovered in the Luobusa and Ray-Iz chromitites [44]. These *in situ* diamonds are exclusively enclosed by chromite and associated with amorphous carbon [29]. The diamonds hosted by chromite are similar to the diamonds recovered from mineral concentrates.

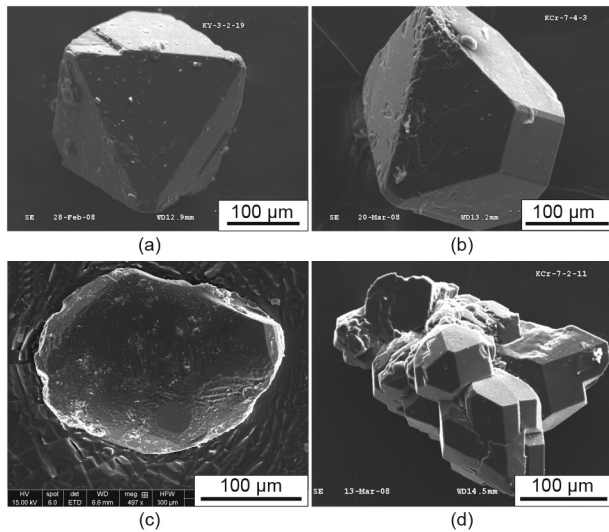
### 3. Characteristics of diamonds in ophiolitic peridotites and chromitites

Despite their occurrences in ophiolites of different age and tectonic setting, these diamonds share some common features in terms of morphology, internal structure, and chemical composition.

#### 3.1. Morphology and diamond type

Ophiolite-hosted diamonds mainly range from colorless to light yellow. Most of the recovered diamonds are 50–500  $\mu\text{m}$  in size, with a few as large as 700  $\mu\text{m}$  (Fig. 2(d)). These diamonds include both monocrystalline and polycrystalline crystals, and no coated crystals have ever been recovered. Most diamonds are euhedral minerals with sharp crystal edges, while some grains are rounded with eroded or pitted surfaces (Fig. 3) [24,92]. Ophiolite-hosted diamonds predominantly show a cubo-octahedral morphology, with a small portion having a perfect octahedral shape (Fig. 3(a, b)).

Nitrogen is the most common and important impurity in diamonds. Based on the nitrogen content, diamonds can be classified into Type I (nitrogen concentration  $> 20$  ppm) and Type II (nitrogen concentration  $< 20$  ppm) diamonds [102]. According to the aggregation form of the nitrogen atoms, Type I diamonds can be further subdivided into Ia and Ib subgroups [102]. Secondary ion mass spectrometry (SIMS) and Fourier transform infrared spectroscopy (FTIR) can both be used to measure the nitrogen concentration in diamonds, but only FTIR can obtain information about the nitrogen aggregation form. FTIR analyses of diamonds from the Ray-Iz and Luobusa ophiolites indicate that these diamonds are Type Ib with a single substitutional center, implying a relatively short mantle residence time [28,103].



**Fig. 3.** Scanning electron microscope (SEM) images of ophiolite-hosted diamonds. (a) Euhedral octahedral diamond; (b) euhedral cubo-octahedral diamond; (c) anhedral rounded diamond; (d) polycrystalline diamond. Reproduced from Ref. [92] with permission of China University of Geosciences (Wuhan) and Springer-Verlag GmbH, © 2009 and from Ref. [24] with permission of Mineralogical Society of America, © 2017.

### 3.2. Internal structure and mineral inclusions

Diamonds with both cuboid and octahedral growth habits are known as “mix-habit diamonds” [104,105]. Ophiolite-hosted diamonds show growth sectors with different brightness in cathodoluminescence (CL) images (Fig. 4(a, b)). A bright sector represents an octahedral growth sector with a layered-growth characteristic, and a dull sector represents a cuboid growth sector [28]. These ophiolite-hosted diamonds are mainly mix-habit diamonds.

Both nanometer-sized and micrometer-sized mineral inclusions have been observed in diamonds from the Luobusa, Ray-Iz, Hegen-shan, and Pozanti–Karsanti ophiolites [44,92,95,106,107]. These inclusions have been studied using scanning electron microscope (SEM), FTIR, Raman spectroscopy, focused ion beam (FIB), and TEM techniques. Recognized mineral inclusions include: ① metal alloys, including Ni–Mn–Si–Co, Ni–Mn–Co, Cr–Fe, and Fe–Si; ② silicate minerals, including albite, Mn-garnet, Mn-olivine, CaMn-wollastonite, and CaMn-perovskite; ③ oxides, including chromite, hematite, magnetite, and coesite; and ④ fluid inclusions (Fig. 4) [28,44,106]. Lian et al. [106] reported a mineral inclusion assemblage of  $(\text{Ca}_{0.81}\text{Mn}_{0.19})\text{SiO}_3$ , Ni–Mn–Co alloy, and a nanometer-sized quenched fluid phase in diamonds from the Pozanti–Karsanti chromitite (Fig. 4(d)). As such a mineral combination has never been reported in a synthetic diamond, the discovery of this mineral inclusion assemblage provides further evidence for the natural origin of ophiolite-hosted diamonds [106].

Of the mineral inclusions found in ophiolite-hosted diamonds, CaMn-perovskite is of great importance. Perovskite (Ca-perovskite,  $\text{CaSiO}_3$ ) is an important mineral in both the MTZ and the lower mantle [108]. Its modal mineral proportions are inferred to be about 5 vol% and 25 vol% in the pyrolitic mantle and subducted MORB materials, respectively, under lower mantle conditions [108,109]. Ca-silicate perovskite was discovered as mineral inclusions in diamonds from podiform chromitite of the Hegen-shan and Sartohay ophiolites in China. The mineral inclusions were identified by FIB and TEM analyses. The calculated mineral formula of the mineral is  $\text{Ca}_{0.8}\text{Mn}_{0.2}\text{SiO}_3$ —that is, Mn-bearing Ca-silicate perovskite. TEM diffraction data reveal that the Hegen-shan inclusion has *d*-spacings and angles between adjacent lattice planes

consistent with those of Ca-silicate perovskite with an orthorhombic structure [110]. In comparison with other research results [111], the *P*–*T* formation conditions of these inclusions in Hegen-shan diamonds are estimated to be  $P > 20$  GPa and  $T > 1600$  °C. Different from the Ca-silicate minerals in Hegen-shan and Sartohay ophiolite-hosted diamonds, the  $(\text{Ca}_{0.81}\text{Mn}_{0.19})\text{SiO}_3$  mineral inclusions in the Pozanti–Karsanti diamonds have a crystal structure of wollastonite rather than UHP perovskite, indicating that this inclusion may be a retrograde phase of UHP perovskite [106].

### 3.3. Isotopic and trace element compositions

Cartigny [37] and Shirey et al. [14] have reviewed the carbon and nitrogen isotopic composition and nitrogen concentration of diamonds of different occurrences (Fig. 5) [14,37,106]. However, in comparison with mantle-derived and metamorphic diamonds, the chemical compositions of ophiolite-hosted diamonds have not been well studied. Thus far, only diamonds from the Luobusa [28,29,103], Ray-Iz [44], and Pozanti–Karsanti [106] ophiolites have been analyzed by SIMS for carbon and nitrogen compositions. We have compiled the available chemical composition data for the ophiolite-hosted diamonds, and compared these data with those of other types of diamonds (Fig. 5).

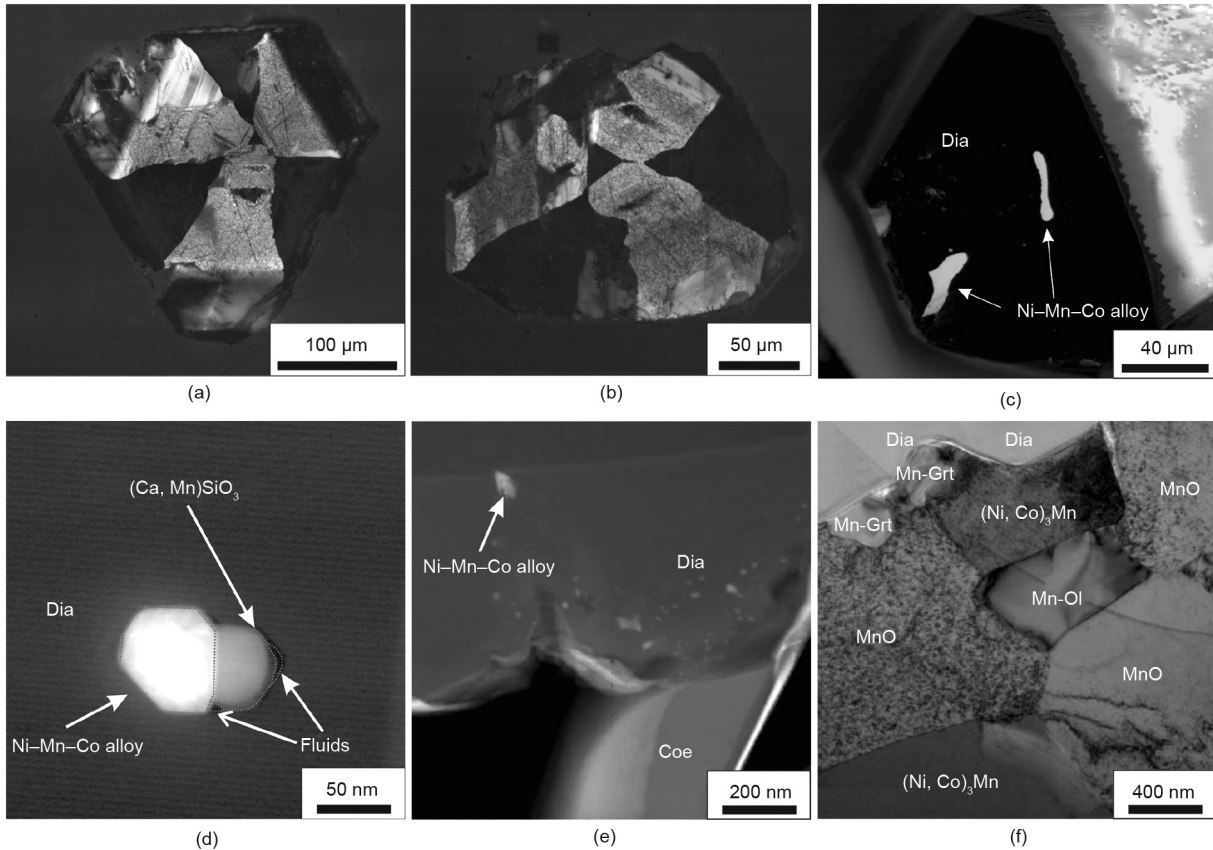
Ophiolite-hosted diamonds are characterized by quite light carbon isotopic composition, with  $\delta^{13}\text{C}$  values ranging from  $-29\%$  to  $-18\%$  and a primary  $\delta^{13}\text{C}$  mode at  $-25\%$ . These values are much lower than those of diamonds from either kimberlites/lamproite (mainly from  $-2\%$  to  $-8\%$ ) or UHP metamorphic belts (mainly from  $-5\%$  to  $-18\%$ ). The nitrogen isotopic composition and nitrogen concentration of ophiolite-hosted diamonds are quite different from those of UHP metamorphic diamonds, but are consistent with those of peridotitic and eclogitic diamonds (Fig. 5). Different models such as ① the primordial inhomogeneity model [1,112], ② the isotopic fractionation model [113,114], and ③ the subduction model [35,115] have been proposed to explain the origin of low  $\delta^{13}\text{C}$  values in diamonds. Considering the characteristics of ophiolite-hosted diamond, Lian et al. [106] proposed that the  $^{13}\text{C}$ -depleted carbon signature of ophiolite diamonds was inherited from previously subducted crustal matter.

Trace element concentration has been analyzed by Howell et al. [28] for the Luobusa diamonds, which have light rare earth element (LREE)-enriched trace element patterns similar to those of some kimberlitic fibrous diamonds, but are characterized by strong negative anomalies in strontium (Sr), samarium (Sm), europium (Eu), and ytterbium (Yb). The trace element patterns are clearly distinct from those of synthetic diamonds [28].

### 3.4. In situ diamonds

*In situ* diamond grains have been found in polished sections of chromitite ore from both the Luobusa and Ray-Iz ophiolites [44]. Carbon element mapping and laser Raman studies on these *in situ* microdiamonds show that they are enclosed in spherical or irregular patches of amorphous carbon hosted in chromite grains (Fig. 6).

Diamonds and amorphous carbon collectively form round inclusions. Such an inclusion usually contains a diamond in the center of about 0.2 mm in size and a few small pieces of chromite, along with numerous tiny silicate minerals (Fig. 6). The small angular pieces of chromite (Fig. 6(e)) in the inclusion are compositionally similar to the chromite grains surrounding the inclusions. The diamond in this inclusion is euhedral in shape, with a sharp edge within the surrounding amorphous carbon (Fig. 6). The spatial relationship clearly indicates that the diamond formed first, and the amorphous carbon subsequently cooled rapidly under decreasing temperatures. These textures likely formed when relatively



**Fig. 4.** (a, b) Diamond from the Pozanti–Karsanti ophiolite showing different growth sectors with different brightness in CL images; (c) backscattered electron (BSE) image of Luobusa diamond with bulbous Ni–Mn–Co-alloy inclusions. Reproduced from Ref. [28] with permission of Elsevier B.V., © 2015. (d) Inclusion assemblage of  $(\text{Ca}_{0.81}\text{Mn}_{0.19})\text{SiO}_3$ , Ni–Mn–Co alloy, and quenched fluids in the Pozanti–Karsanti diamond. Reproduced from Ref. [106] with permission of Springer-Verlag GmbH Germany, © 2018. (e) High-angle annular dark field (HAADF) image of Ni–Mn–Co alloy and coesite inclusions. Reproduced from Ref. [44] with permission of International Association for Gondwana Research, © 2014. (f) HAADF image of Mn-rich mineral inclusion in diamond. Dia: diamond; Coe: coesite; Mn-Grt: manganese garnet; Mn-Ol: manganese olivine.

hotter carbon fluids with diamond crystals entered cooler chromite grains. Highly pressurized fluids moving at high velocities appear to have shattered the host into smaller pieces.

### 3.5. Associated UHP, super-reduced, and crustal minerals

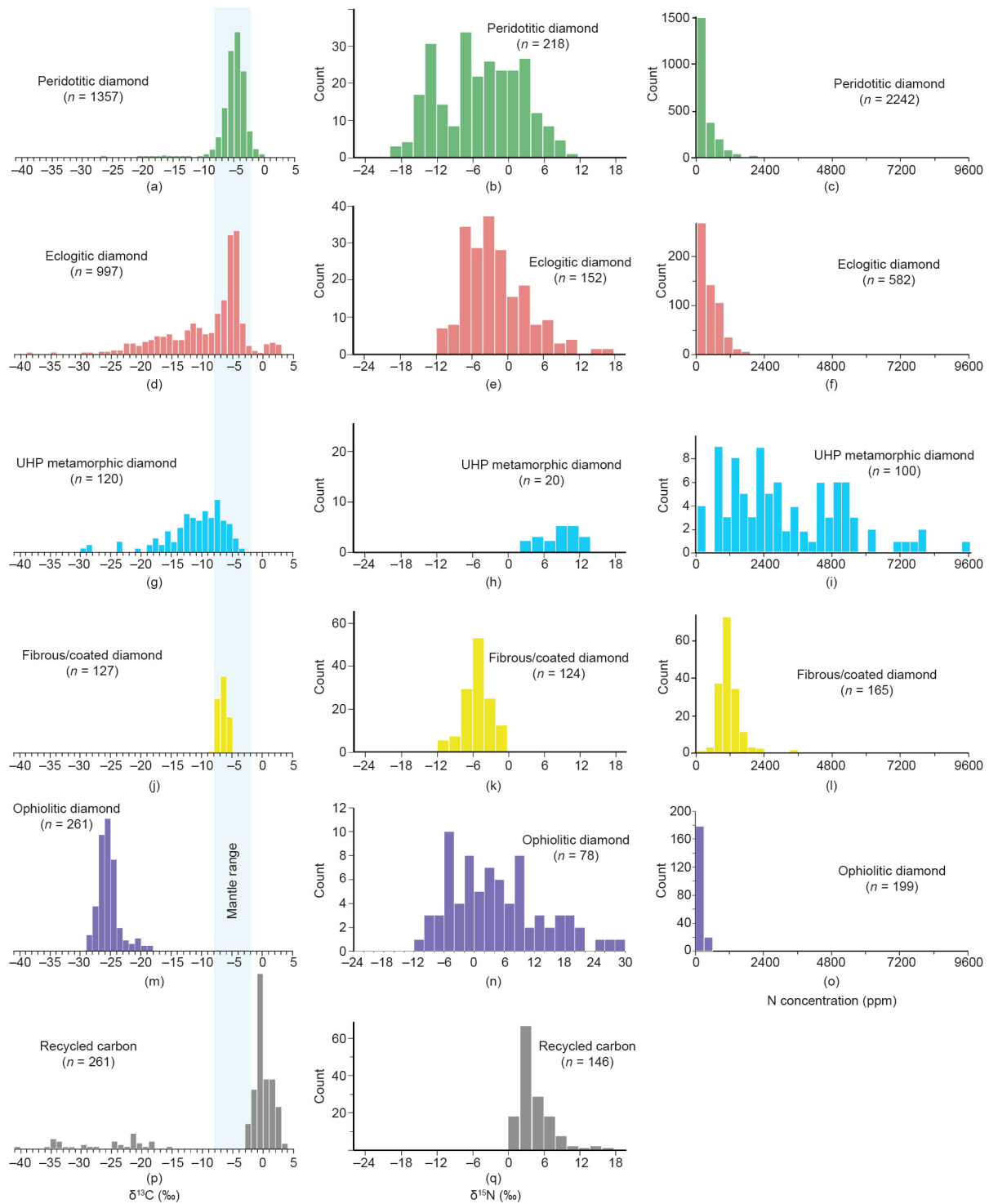
In addition to diamonds, other UHP minerals (e.g., pseudomorph stishovite, coesite, and qingsongite) and crustal minerals (e.g., zircons and quartz) have been discovered in different ophiolites, as summarized in Table 1 [22,24–26,29,41,43,44,92–95,116]. Yang et al. [41] have observed lath-like grains of coesite and kyanite rimming a Fe–Ti alloy grain. The morphologies of individual coesite “crystal,” which is actually a mineral aggregate, are unlike the morphologies of known coesite grains formed in UHP metamorphic belts in the continental crust, but are similar to those of stishovite [41,117]. The polycrystalline nature and prismatic habit of these coesite crystals (which are several tens of micrometers long) strongly suggest that the observed coesites are replacements of stishovite (Fig. 7) [24,41–43]. The presence of pseudomorph stishovites in our samples may imply pressures of greater than 9 GPa (~300 km) and temperatures of 1000 °C for their formation conditions [41].

Qingsongite, a natural analogue of cubic boron nitride (c-BN), has been found enclosed in lath-like kyanite and coesite from the Luobusa ophiolite (Fig. 7(b)). Other phases spatially associated with qingsongite include native iron,  $\text{TiO}_2$  II (a high-pressure polymorph of rutile with a  $\text{PbO}_2$  structure), amorphous carbon, and boron carbide of unknown stoichiometry [41]. The accompanying mineral assemblages suggest qingsongite formation pressures of

10–15 GPa, assuming temperatures of about 1300 °C [42]. Qingsongite is thus a typical UHP mineral, and its boron content is likely to have originated from the Earth’s surface via subduction.

Yamamoto et al. [43] discovered numerous exsolution lamellae of diopside and coesite in chromites of the Luobusa podiform chromitites (Fig. 7(c)). This occurrence requires high solubility of  $\text{SiO}_2$  and CaO in the host chromite. Chromite with diopside and coesite inclusions was interpreted to retrograde from a UHP  $\text{CaFe}_2\text{O}_4$  (CF)-type structured polymorph, which is stable at pressures over 12.5 GPa (> 380 km) [43]. These observations suggest that the source peridotites exposed along the Yarlung Zangbo Suture Zone (YZSZ) in southern Tibet may have originally been transported from the deep mantle (probably more than 380 km deep) to shallow depths beneath the Tethyan seafloor spreading system that produced these ophiolites. Recent experimental work has shown that chromite can form as deep as 410 km in the mantle, close to the MTZ [118]. Thus, it appears that some ophiolitic chromitites have preserved the mineralogical evidence for their UHP origins and records [29].

Super-reduced SiC minerals, which accompany diamonds, have been recovered from all the diamond-bearing ophiolites (Fig. 7(d)) [24,44,92,116]. The maximum oxygen fugacity ( $f_{\text{O}_2}$ ) of SiC stability throughout the upper mantle is around five to six orders of magnitude below iron-wüstite oxygen buffer at equivalent temperature and pressure [119,120]. SiC minerals from ophiolite are generally light blue to blue in color, and are 50–300 μm in diameter (Fig. 7(d)). The existence of SiC in ophiolitic peridotite and chromitite suggests that these rocks have experienced a super-reduced condition. However, it is still under

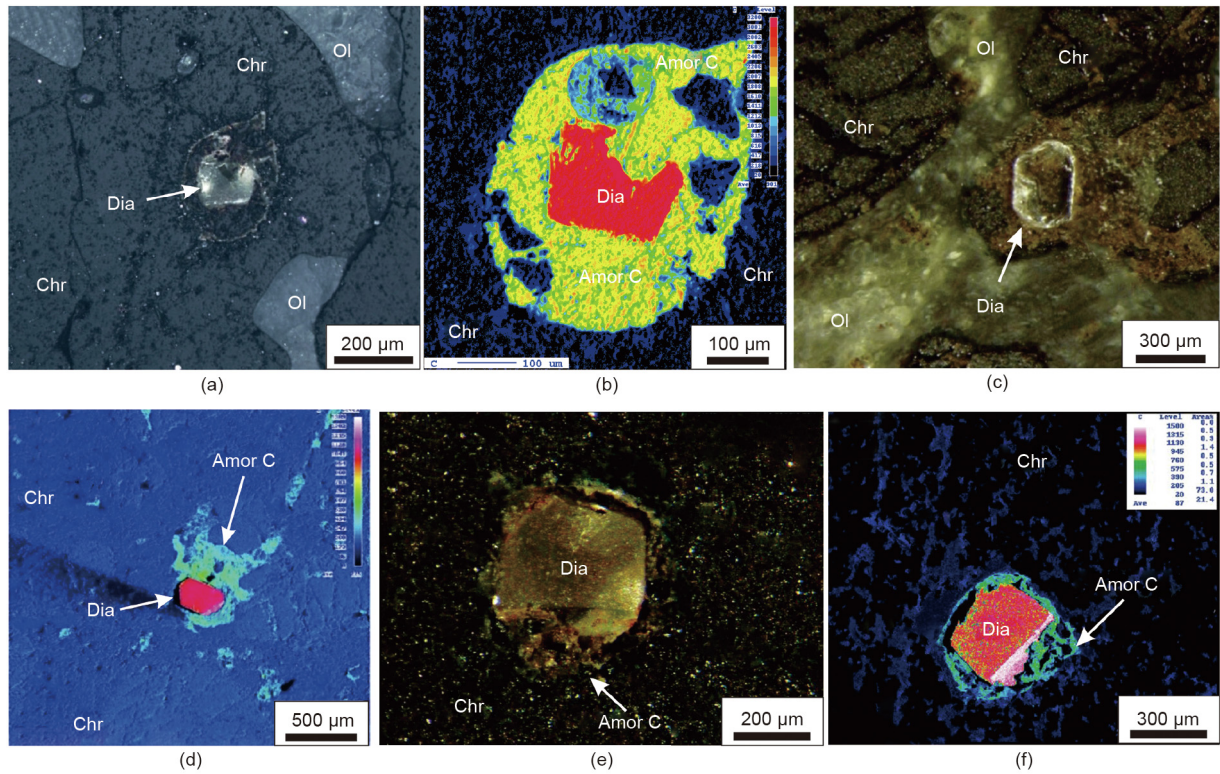


**Fig. 5.** Comparative frequency histograms of  $\delta^{13}\text{C}$  values,  $\delta^{15}\text{N}$  values, and nitrogen concentrations for (a–c) peridotitic diamonds, (d–f) eclogitic diamonds, (g–i) UHP metamorphic diamonds, (j–l) fibrous/coated diamonds, (m–o) ophiolitic diamonds, and (p, q) recycled carbon and metasediments. Reproduced from Ref. [14] with permission of International Association for Gondwana Research, © 2014, from Ref. [37] with permission of GeoScienceWorld, © 2013, and from Ref. [106] with permission of Springer-Verlag GmbH Germany, © 2018.

debate whether this super-reduced condition represents a grain-scale micro-environment [121,122] or is a common feature of Earth's deep mantle [44,116].

Many typical crustal minerals, such as zircon, quartz, amphibole, and rutile, have also been recovered from podiform chromitites of the Luobusa and Dongqiao ophiolites in Tibet, the Oman ophiolite in the Southeast Arabian Peninsula, the Pozanti–Karsanti ophiolite in Turkey, and the Ray-Iz ophiolite in the Polar Urals,

Russia (Fig. 7(e, f)) [24,44,123,124]. Most of the recovered zircons are sub-rounded grains with complex internal structures indicating polyphase growth. Their trace element contents and low-pressure inclusion assemblages (i.e., quartz, muscovite, K-feldspar, apatite, ilmenite, and rutile) indicate a continental crustal origin. Zircon grains have SIMS U–Pb ages that are generally much older than the host body (total range: 90–2500 Ma) [123]. The presence of numerous crustal minerals, particularly zircons,



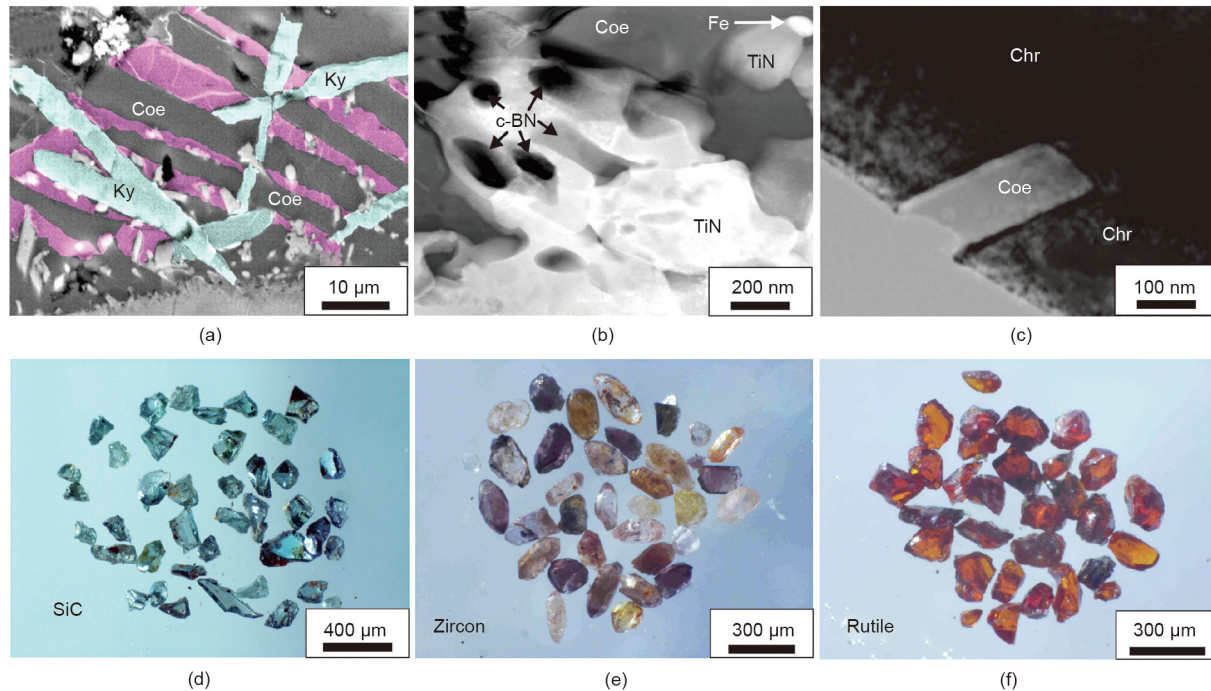
**Fig. 6.** (a, c, e) Photomicrographs and (b, d, f) carbon element mapping images of *in situ* ophiolite-hosted diamonds. Reproduced from Ref. [29] with permission of GeoScienceWorld, © 2014 and from Ref. [44] with permission of International Association for Gondwana Research, © 2014. Chr: chromite; Ol: olivine; Amor C: amorphous carbon.

**Table 1**  
Diamonds and other associated minerals recovered from different ophiolites.

Ophiolite	Location	Tectonic setting of ophiolite	Rock type	Minerals	Type	Ref.
Dongqiao ophiolite	Tibet, China	SSZ	Chromitite	Diamond, SiC, graphite, native chromium, Ni-Fe alloy, Cr <sup>2+</sup> -bearing chromite	Mineral concentrate	[22]
Luobusa ophiolite	Tibet, China	MOR + SSZ	Chromitite	Diamond inclusion, OsIr alloy, coesite, kyanite, Si-Ti oxide, Si-Al-Ti oxide, unknown silicate phase, native Ti, and Ti-Fe alloy	<i>In situ</i> mineral; mineral concentrate	[41]
Semail ophiolite	Oman, the United Arab Emirates	SSZ	Chromitite	Moissanite, native Si, and Si-Fe alloy	Mineral concentrate	[116]
Luobusa ophiolite	Tibet, China	MOR + SSZ	Peridotite, ore-body 11 chromitite in Kangjia district	Diamond, moissanite, native elements, alloys, oxides, sulphides, silicates, carbonates, and tungstates	Mineral concentrate	[92]
Luobusa ophiolite	Tibet, China	MOR + SSZ	Chromitite	Diopsidic clinopyroxene, coesite lamellae, MgSiO <sub>3</sub>	<i>In situ</i> mineral	[43]
Luobusa ophiolite	Tibet, China	MOR + SSZ	Chromitite	<i>In situ</i> diamond with amorphous carbon	<i>In situ</i> mineral	[29]
Ray-Iz ophiolite	Polar Urals, Russia	SSZ	Chromitite	<i>In situ</i> diamond with amorphous carbon, diamond, moissanite, native elements, oxides, and sulfides	<i>In situ</i> mineral; mineral concentrate	[44]
Hegenshan ophiolite	Inner Mongolia, China	SSZ	Chromitite	Diamond, moissanite, oxides, sulfides, silicates, alloys, and other minerals	Mineral concentrate	[95]
Sartohay ophiolite	Xinjiang Uygur, China	BAB	Chromitite	Diamond, moissanite, native elements, and alloy	Mineral concentrate	[94]
Mirdita ophiolite	Albania	MOR + SSZ	Chromitite	Diamond, moissanite, rutile, zircons, sphenes, and sulfides	Mineral concentrate	[26]
Dangqiong ophiolite	Tibet, China	MOR + SSZ	Peridotite	Diamond, moissanite, kyanite, rutile, zircon, and sulphides	Mineral concentrate	[93]
Pozanti-Karsanti ophiolite	Turkey	SSZ	Chromitite	Diamond, moissanite, rutile, zircon, monazite, and sulphides	Mineral concentrate	[24]
Myitkyina ophiolite	Myanmar	MOR + SSZ	Peridotite	Diamond, moissanite, native Si, rutile, and zircon	Mineral concentrate	[25]

SSZ: suprasubduction zone; MOR: mid-ocean ridge.





**Fig. 7.** (a) Image showing the detailed morphology of the silicate phases mainly composed of prismatic coesite and crosscutting kyanite (Ky), where prismatic crystals of coesite are shown in grey, crosscutting kyanite in blue, and unknown phases in pink. Reproduced from Ref. [41] with permission of GeoScienceWorld, © 2007. (b) Nanometer-sized cubic qingsongite (c-BN) inclusions in coesite. Reproduced from Ref. [42] with permission of JSTOR, © 2009. (c) TEM foil cut from the Luobusa chromitite showing coesite inclusion in chromite. Reproduced from Ref. [43] with permission of Elsevier B.V., © 2008. (d) Moissanite (SiC), (e) zircon, and (f) rutile recovered from the Pozanti-Karsanti ophiolite, Turkey. Reproduced from Ref. [24] with permission of GeoScienceWorld, © 2017.

suggests recycling of metasedimentary rocks on land into the deep mantle via subduction.

#### 4. Origin of ophiolite-hosted diamonds

The discovery of diamonds and other unusual minerals in ophiolitic peridotites and chromitites has led to wide interest and debates on the origin of these minerals. Different models have been successively proposed by various scientific groups to explain the formation process of the diamonds and the hosting peridotites and chromitites (Fig. 8) [44,125,126].

Overall, these models can be classified into three categories: ① the deep subduction-rapid exhumation model [125,127,128]; ② the plume-related model [44,129]; and ③ the lightning-strike model [130,131]. In the deep subduction model, low-pressure rocks are subducted into the deep mantle (e.g., the MTZ or even the lower mantle), resulting in the formation of UHP minerals in ophiolitic peridotites and chromitites; these UHP mineral-bearing rocks are later transported into the shallow mantle via mantle convection (Fig. 8(a)) [125], or rise up in response to slab rollback in a collisional zone [127]. Zhou et al. [126] have suggested that ophiolite-hosted diamonds are of UHP metamorphic origin, and form in the subducting slab (Fig. 8(b)). However, ophiolite-hosted diamonds are clearly distinct from diamonds in UHP metamorphic rocks in terms of grain size and chemical composition [106]. The plume-related model suggests that diamonds and other UHP minerals form in the transition zone and are carried up to the shallow mantle by plume upwelling (Fig. 8(c)) [44,129]. Yang et al. [23] reviewed the various observations and interpretations of these different models and developed a revised three-stage model, which includes: ① the generation of carbon-bearing fluids in the deep mantle; ② the formation of diamond-bearing chromites in the MTZ; and ③ the transport of chromites and other UHP minerals to shallow depths through plume upwelling (Fig. 9).

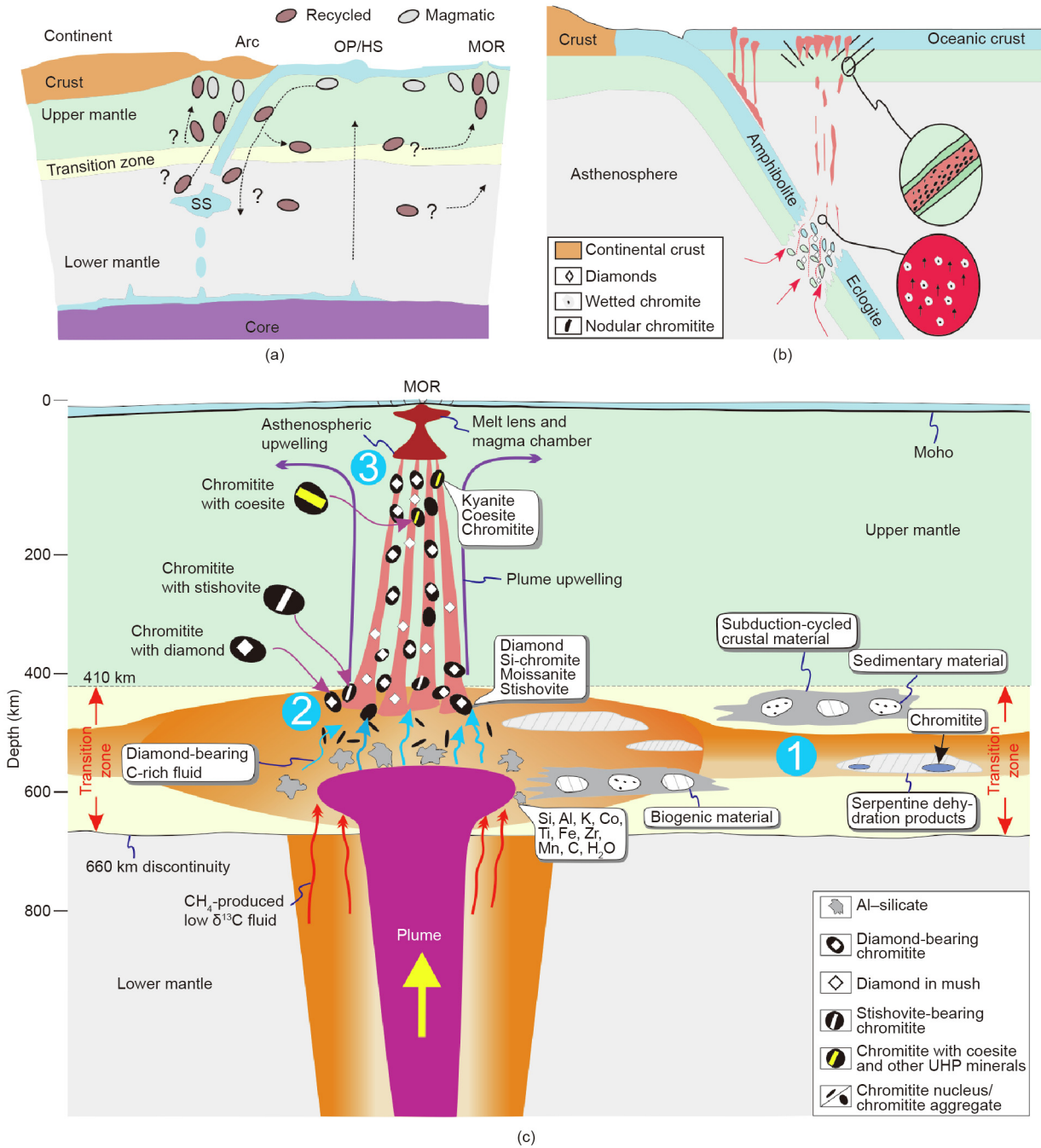
An interesting and innovative perspective on the origin of ophiolite-hosted diamonds and associated minerals was recently proposed by Ballhaus et al. [132]. These scholars argued that the unusual mineral association discovered in ophiolitic peridotites and chromitites may form through lightning strikes [132]. However, several lines of evidence do not support the lightning-strike model, as has been clarified by Griffin et al. [131] and Yang et al. [133]. These lines of evidence mainly include ① the common occurrence of UHP and super-reduced minerals in ophiolites of different elevations with little possibility of lightning strike [106,133]; ② the common existence of UHP minerals that are not likely to form through lightning strike [131,133]; ③ the abundant mineral inclusions in ophiolite-hosted diamonds, which were not produced in lightning-strike experiments [133]; and ④ the large size of ophiolite-hosted diamonds, which cannot be produced through the chemical vapor-deposition process in several seconds' time during a lightning strike [131].

In summary, the origin of ophiolite-hosted diamonds and associated minerals is still a conundrum. To solve this conundrum, many fundamental questions—such as how and where these minerals first crystallized, how they were incorporated into ophiolitic peridotites and chromitites, and how they were preserved during transportation to the shallow mantle—need to be answered. To answer these questions, continued research work must be conducted on these unusual minerals and hosting ophiolites through mineralogical and geochemical analyses, high-temperature and high-pressure experiments, and numerical modeling.

#### 5. A new window for probing deep carbon cycling

##### 5.1. Crustal material influx and efflux in the deep mantle

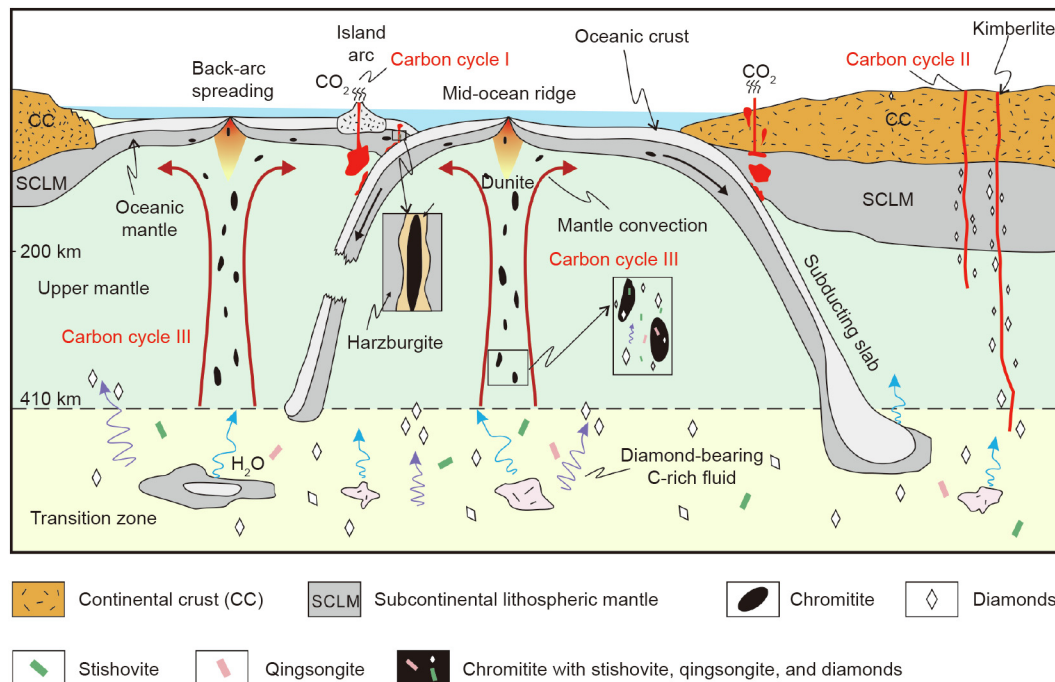
Seismic tomography has shown that the oceanic lithosphere and continental crust may subduct into the MTZ depths



**Fig. 8.** Different models for the origin of unusual minerals and podiform chromitite. (a) A deep subduction model. Reproduced from Ref. [125] with permission of Elsevier B. V., © 2013. (b) A deep subduction model. Reproduced from Ref. [126] with permission of International Association for Gondwana Research, © 2013. (c) A plume-related model. Reproduced from Ref. [44] with permission of International Association for Gondwana Research, © 2014. SS: stagnant slab; OP/HS: oceanic plateau/hotspot; MOR: mid-ocean ridge.

(410–660 km). Some slabs may even penetrate through the 660 km seismic discontinuity and reach the CMB (2900 km), providing evidence for wholesale mantle convection [31–33,134,135]. On the basis of plate reconstructions and tomographic images, it has been shown that the edges of the largest heterogeneities in the deepest mantle have controlled the eruption of most Phanerozoic kimberlites as well as large igneous provinces [136,137]. Researchers have proposed that the plume-generation zones of large low shear velocity provinces are on the CMB, and have inferred that diamonds may be sampled by plumes from the CMB [137].

Oceanic crust becomes integrated into the mantle in significant quantities as oceanic slabs plunge into the mantle in subduction zones. An experimental study demonstrated that the subducted upper continental crust could not exhume back to the surface once it reached a depth of 250 km, because at those pressures, the crustal material would be transformed into a jadeite-stishovite lithology, which facilitates further sinking into the MTZ depths [138]. Thermally equilibrated subducted MORB crust is denser than the average mantle at all depths [138–141]. Thus, subducted MORB slabs can readily penetrate the D'' region (the lowermost ~150 km of the mantle) at the CMB.



**Fig. 9.** A speculative model to explain the presence of ophiolite-hosted diamonds in chromitites and mantle peridotites of different ophiolites. Mantle plume upwelling and mantle convection bring UHP and super-reduced minerals into the shallow mantle, and previous subduction brings crustal minerals into the mantle. Carbon cycle I: subduction-related volcano eruption; Carbon cycle II: kimberlitic and related magmatic eruption in continent; Carbon cycle III: oceanic-spreading-ridge-related ophiolite-hosted diamond. Reproduced from Ref. [23] with permission of International Union of Geological Sciences, © 2015.

Large amounts of water can be transported into the Earth's deep mantle by hydrous minerals in subducted crust. At the CMB, the subducted water may react with iron, forming an extremely oxygen-rich layer composed of iron, iron dioxide, and iron hydride, which can be reflected by the seismic signature of the D'' layer [142–144]. Liu et al. [143] produced hydrogen-bearing iron peroxide ( $\text{FeO}_2\text{H}_x$ ) through a reaction between water and iron at 86 GPa and 2200 K. These  $\text{FeO}_2\text{H}_x$  phase minerals have sound velocities consistent with the ultralow-velocity zones (ULVZs) at the Earth's CMB. Liu et al. [143] pointed out that one-tenth the mass of the Earth's ocean water is needed to produce the ULVZs through the water–iron reaction, making Earth's CMB an important hydrogen and oxygen reservoir for life on Earth. Hu et al. [142] identified a highly stable pyrite-structured iron oxide ( $\text{FeO}_2$ ) at 76 GPa and 1800 K using first-principles calculations and experiments. Decomposition of the mineral goethite,  $\text{FeOOH}$ , under deep lower mantle conditions will produce  $\text{FeO}_2$  and  $\text{H}_2$  [142]. When  $\text{FeO}_2$  moves upward into the middle lower mantle, it decomposes to form  $\text{Fe}_2\text{O}_3$  and releases  $\text{O}_2$ , making  $\text{FeO}_2$  a sporadic source of extra  $\text{O}_2$  [142]. These critical experiments and theoretical calculations indicate the possibility that fluids formed in the deep Earth contain recycled hydrogen, oxygen, and—most likely—carbon as well, although no experimental work has been carried out for carbon yet.

### 5.2. Ophiolite-hosted diamond as a new window

Large amounts of organic and inorganic carbon have been carried by subducting slabs into the Earth's mantle, which plays an important role in balancing  $\text{CO}_2$  in the atmosphere. The average oceanic crust production rate from the Mesozoic to the present time is estimated to be about  $25 \text{ km}^3 \cdot \text{a}^{-1}$  [145]. Assuming that this production rate has been constant during the last 4 billion years, the total amount of oceanic crust that has been subducted corresponds to at least 11% of the Earth's mantle in volume, suggesting that large quantities of MORB resides in the mantle [145]. On the

basis of cosmochemical and geochemical arguments, the upper mantle is estimated to contain about 100 ppm carbon, while the undegassed lower mantle is estimated to have about 1000–3700 ppm carbon, making it a substantial carbon reservoir [1,146]. Carbon in the mantle has three main forms: ① oxidized species such as  $\text{CO}_2$  and carbonate; ② neutral species such as graphite and diamond; and ③ reduced species such as  $\text{CH}_4$ ,  $\text{CO}$ , and  $\text{SiC}$  [8]. Of these different carbon species, diamond has the most extensive distribution in the Earth's interior from the CMB to the upper mantle [38,57], and is thus of great significance in tracing the carbon cycle in the deep mantle.

It has long been known that current volcanoes in the world's island arcs can release tremendous amounts of  $\text{CO}_2$  from the mantle into the air and lavas [147,148]. Intrusions and lavas in this setting also contain large amounts of  $\text{CO}_2$  and have light carbon isotopic composition, with  $\delta^{13}\text{C}$  values between  $-25\%$  and  $-30\%$ , which are indicative of the recycling of subducted organic materials [147,148]. More recently, ultrapotassic mantle-derived lavas (lamproites) from Gausberg, Antarctica, have been interpreted as a product of the melting of deeply recycled (subducted) Archean-age metasediments in the MTZ [149]. However, it is not clear how deep these materials have recycled in the mantle. Subduction-related volcano eruption can be seen as representing Type I carbon recycling (Fig. 9).

As a messenger from the Earth's interior, diamonds preserve information on the fate of deep subducted material and the composition of the deep mantle. Most peridotitic, eclogitic, and fibrous/coated diamonds from around the world have carbon isotopic compositions within the normal mantle range, indicating that the mantle carbon reservoir is the main carbon source for diamond formation in the mantle. However, as stated before, a large proportion (~34%) of the world's eclogitic diamonds have  $\delta^{13}\text{C}$  values outside of the normal mantle range. This finding cannot simply be explained by the isotopic fractionation process, and may be indicative of a recycled crustal carbon source [14,37]. Mineral

inclusions in diamonds can provide information about the formation depths [13,56]. About 1% of mantle-derived diamonds worldwide are suggested to have formed beneath the lithospheric mantle [56,150]. Walter et al. [13] reported kimberlitic diamonds with lower mantle mineral inclusion assemblage and a light carbon isotopic composition (mainly  $\delta^{13}\text{C} < -15\%$ ), confirming the deep mantle cycling of oceanic crust. This kimberlite eruption in the continent can be seen as representing Type II carbon recycling (Fig. 9).

More importantly, ophiolite-hosted diamonds are all characterized by a quite unique carbon isotopic composition with low  $\delta^{13}\text{C}$  values ( $< -18\%$ ). These diamonds have a light carbon isotopic composition that is consistent with carbon sources of subducted organic matter [151,152]. A small portion of eclogitic diamonds also have positive  $\delta^{13}\text{C}$  values consistent with carbon sources of subducted inorganic matter, such as carbonate (Fig. 6) [37]. Collectively, the isotopic compositions of ophiolite-hosted diamonds and other mantle-derived diamonds have proved that surface-derived carbon can be subducted into the Earth's mantle at depths greater than 150 km. CaMn-perovskite/wollastonite inclusion exists in ophiolite-hosted diamonds, indicating a super-deep origin for this newly discovered occurrence of diamonds. However, the lower limit of the subduction depth needs to be further constrained. These oceanic-spreading-center-related ophiolite-hosted diamonds can be seen as representing Type III carbon recycling (Fig. 9).

In summary, systematic studies on traditional mantle-derived diamonds (e.g., peridotitic, eclogitic, and fibrous/coated types) have greatly contributed to our understanding of carbon in the Earth's interior. Present studies have shown that diamonds have common occurrences in ophiolitic peridotites and chromitites, making the ophiolite-hosted diamond a new window for probing carbon cycling in the deep mantle.

## 6. Conclusions

Diamonds have been recovered from ophiolitic peridotites and chromitites in different orogenic belts. Diamonds of this newly discovered occurrence have been named ophiolite-hosted diamonds. Ophiolite-hosted diamonds from different ophiolites show many similarities in their morphology, mineral inclusion associations, and chemical compositions. The discovery of ophiolite-hosted diamonds provides evidence of a completely new geological environment for diamond formation in the Earth's mantle. We posit that diamonds and associated UHP minerals have a common existence in the so-called suprasubduction zone (SSZ)-type or mid-ocean ridge (MOR)-type ophiolitic peridotites and chromitites. Whether such diamonds may also occur in ophiolites formed in different geodynamic settings (i.e., plume-proximal MOR or ocean-continent transition (OCT) zones) is a significant question that needs to be tested with further systematic field-based, structural, and geochemical studies.

The widespread occurrence of ophiolite-hosted diamonds and associated UHP minerals suggests that they may be a common feature of *in situ* oceanic mantle, since oceanic spreading centers are widely distributed on the seafloor and major igneous accretion of the oceanic lithosphere occurs along such spreading centers [153]. Ophiolites remain an important geological window that gives us a close look at mantle dynamics, and the newly recognized ophiolite-hosted diamonds have provided us with a new window for probing the Earth's deep carbon recycling processes and revealing the compositions and processes of the deep mantle.

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## Compliance with ethics guidelines

Dongyang Lian and Jingsui Yang declare that they have no conflict of interest or financial conflicts to disclose.

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