

Ophiolites, diamonds, and ultrahigh-pressure minerals: New discoveries and concepts on upper mantle petrogenesis

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ABSTRACT

Ophiolitic peridotites represent variously depleted residues of the primitive mantle after multiple episodes of partial melting, melt extraction, and melt-rock interactions. They display a wide range of compositional and geochemical heterogeneities at different scales, and their incompatible bulk-rock compositions and mineral chemistries are commonly inconsistent with their evolution through simple partial melting processes at shallow mantle depths. Approaching these issues from different perspectives, the papers in this volume concentrate on (1) melt evolution and magmatic construction of ophiolites in various tectonic settings, and (2) the occurrence of microdiamonds, ultrahigh-pressure (UHP) minerals, and crustal material as inclusions in ophiolitic chromitites and peridotites. Crustal and mantle rock units exposed in different ophiolites show that the mantle melt sources of ophiolitic magmas undergo progressive melting, depletion, and enrichment events, constantly modifying the melt compositions and the mineralogical and chemical makeup of residual peridotites. Formation and incorporation of microdiamonds and UHP minerals into chromite grains occurs at depths of 350–660 km in highly reducing conditions of the mantle transition zone. Carbon for microdiamonds and crustal minerals are derived from subduction-driven recycling of surface material. Host peridotites with their UHP mineral and diamond inclusions are transported into shallow mantle depths by asthenospheric upwelling, associated with either slab rollback-induced channel flow or superplumes. Decompression melting of transported mantle rocks beneath oceanic spreading centers and their subsequent flux melting in mantle wedges result in late-stage formation of podiform chromitites during the upper mantle petrogenesis of ophiolites. Future studies should demonstrate whether diamonds and UHP minerals also occur in peridotites and chromitites of nonsubduction-related ophiolites.

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OPHIOLITES, DIAMONDS, AND ULTRAHIGH PRESSURE MINERALS

Recent geochemical and geochronological data from many ophiolites in different orogenic belts have shown strong evidence for structural and compositional heterogeneity in their crustal and mantle units, and for multiple episodes of melt extraction, melt-rock reactions, and melt migration in their mantle evolution history (Batanova et al., 1998; Morishita et al., 2006; Aldanmaz et al., 2009; Caran et al., 2010; Jean et al., 2010; Dilek and Furnes, 2014; Piccardo et al., 2014; O'Driscoll et al., 2015). These observations are not consistent with a concept of a simple steady-state magmatic accretion at an oceanic spreading center. High silica contents and high ratios of light/heavy rare earth elements (LREE/HREE) in most ophiolitic peridotites are incompatible, for example, with their origin as the residuum of partial melting of primitive mantle. Peridotites that underwent high degrees of melting are generally strongly depleted in incompatible elements in contrast to those that underwent low degrees of melting. Systematic covariations of major and trace element distributions in ophiolitic peridotites are commonly interpreted as artifacts of

partial melting processes (Walter, 2003). However, the incompatibilities between the bulk composition and mineral chemistry of peridotites in many ophiolites are inconsistent with simple crystal line of descent in concert with the liquid line of descent for a parental melt that evolved via fractional crystallization.

These geochemical characteristics are the manifestations of metasomatic processes between the mantle lithosphere and ascending melts and fluids beneath spreading centers in various tectonic settings (Dilek and Thy, 1998; Parkinson and Pearce, 1998; Braun and Kelemen, 2002; Ohara et al., 2003; Drouin et al., 2009; Dick et al., 2010; Ulrich et al., 2010; Wanless and Shaw, 2012; Dilek and Furnes, 2011; Furnes et al., 2014). They may have resulted, for example, from postcumulus infiltration of melts, which reacted and reequilibrated with the host peridotites, causing refertilization of an already depleted mantle by crystallization of interstitial mineral phases (mainly plagioclase and clinopyroxene) (e.g., Dijkstra et al., 2001). Therefore, the observed mineralogy, textures, and compositions in the upper mantle peridotites of some ophiolites do not reflect their primary features. Likewise, similar melt-peridotite reactions may have affected the lower crustal accretion by producing ultramafic intrusions (i.e., dunite, wehrlite, troctolite) in the layered gabbros (Shallo and Dilek, 2003; Lissenberg and Dick, 2008). Reaction of residual

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peridotites with slab-derived fluids in a mantle wedge, mixing with subducted sediments in the deep mantle, and interaction with asthenospheric melts at shallow depths are some of the processes that result in the modification or total obliteration of the primary structures, whole-rock chemistry, and mineralogical compositions of oceanic peridotites (O'Driscoll et al., 2012). Therefore, the mineralogy and geochemical compositions of crustal and mantle sequences in most ophiolites do not represent a simple melt-residua relationship.

Occurrences of diamonds, ultrahigh-pressure (UHP) minerals, highly reduced native elements, and crustal minerals as inclusions in ophiolitic peridotites and associated chromitites and platinum group metals also indicate deep recycling of crustal and mantle material during the formation of oceanic lithosphere (Liou et al., 2014). Recent findings and related data strongly suggest that diamonds and UHP minerals in ophiolitic peridotites and chromitites must have formed at mantle depths of 150–300 km or perhaps near the mantle transition zone (MTZ) (Bai et al., 1993; Yang et al., 2014, 2015a). Although investigated diamonds come from ophiolites with different ages and geographic locations, they show many similarities in their morphology, carbon isotopes, and mineral inclusions; however, they are distinctly different in all these respects from diamonds obtained from kimberlites and UHP metamorphic belts. These findings also indicate a completely new geological environment for diamond formation.

All these new findings and interpretations pose major questions about the validity of some of the widely accepted models for the formation of ancient oceanic lithosphere, which ultimately became ophiolites on land, and have significant implications about the global carbon cycle, mantle convection models, scales of mantle heterogeneities, role and nature of fluid phases at different levels of the mantle, and mantle dynamics in general. In light of these new advancements in the broad field of ophiolite science, we convened several scientific sessions and field-based workshops during the past two years to provide a forum for the international earth science community to exchange new analytical data and observations, modeling results and interpretations, and perceived new ideas on some of the outstanding questions about the role of mantle makeup and dynamics on the origin of ophiolites. The first one of these sessions, entitled Bridging Two Continents: Diamonds, Zircons and Native Elements in the Mantle: New Discoveries and Models on the Properties and Petrogenesis of Oceanic Mantle Lithosphere (T4), was held at the Joint Geological Society of America (GSA)–Geological Society of China (GSC) meeting in Baltimore (Maryland, USA) in November 2015. The second one was organized in Argos, Cyprus, in May 2016 and included a 4-day field workshop in and around the Troodos ophiolite. The third one was held in Havana, Cuba, in April 2017 and also included a 6-day field workshop in the Mayari-Baraco ophiolite on the island. The last two field-based workshops on Cyprus and Cuba were organized as part of International Geoscience Programme (IGCP) Project 649, Diamonds and Recycled Mantle, and were locally supported by the Geological Survey of Cyprus and the Cuban Geological Society, respectively. This Themed Issue of *Lithosphere* is largely based on presentations made at these three scientific meetings.

In this introductory paper we first provide a synoptic overview of the data, observations, and interpretations presented in each paper, and relate them to the findings of the other papers in the issue. We then discuss some new concepts on upper mantle petrogenesis of oceanic lithosphere (as investigated in ophiolites) in light of the results of the studies documented in this issue. We then present a working hypothesis for the formation and exhumation of microdiamonds, UHP minerals, and crustal material that are embedded in chromite grains of ophiolitic peridotites from the MTZ depths, and evaluate several alternative models that are currently available in the literature. In the last part of the paper, we highlight some of the outstanding questions on the occurrence of microdiamonds and UHP

minerals in ophiolite-hosted chromitites, and present a focused discussion on the significance of rifts, plumes, and subducted slabs in oceanic lithosphere production within a global tectonic framework. We hope that this introduction and the findings of the case studies in the themed issue stimulate further discussions and systematic studies on ophiolites, which constitute one of the best archives of Earth's recycling processes.

SCOPE OF THE THEMED ISSUE

The contributions in this themed issue concentrate on two specific aspects of ophiolites: the first part, which includes six papers, involves mineralogical, petrological, geochemical, geochronological, and/or structural studies of different ophiolites in order to constrain their magmatic construction and melt evolution in various tectonic settings (Dilek and Furnes, 2011; Furnes et al., 2014). The second part, which includes three papers, demonstrates the occurrence of microdiamonds and UHP minerals in ophiolitic chromitites and peridotites exposed along several different suture zones. Collectively, the data and interpretations reported in these papers show that peridotites in most ophiolites underwent multiple partial melting, depletion, metasomatism, and refertilization processes, which strongly controlled their compositions and geochemical characteristics as well as those of their crustal derivatives. Microdiamonds, highly unusual UHP minerals and native elements encapsulated in chromite grains indicate that the temperature–pressure conditions of their formation and incorporation into the host chromites might have taken place at depths near or within the MTZ. This inference has, in turn, significant implications for (1) the development of chromitite deposits in ophiolitic peridotites, and (2) the transport mechanisms of chromite grains with inclusions of microdiamonds, crustal minerals, and other unusual native elements from the MTZ depths to shallow mantle levels beneath oceanic spreading centers.

Magmatic Construction and Melt Evolution of Ophiolites: Case Studies

Alparslan and Dilek (2018) report on the occurrence of a Penrose-type complete ophiolite sequence (Küre ophiolite) within the Central Pontide tectonic belt in northern Anatolia (Turkey) and document its seafloor spreading generated architecture, crystallization age, and regional geology. The Küre ophiolite displays three peculiar features that are highly atypical of other Mesozoic Tethyan ophiolites within the Anatolian-Iranian segment of the Alpine-Tibetan orogenic system. (1) It does not occur along a major suture zone between two different plates or crustal blocks, and it is limited in its north-south width and east-west lateral length. (2) It is tectonically imbricated within Paleozoic–Mesozoic crystalline basement rock units belonging to the Eurasian continent, there are no rift-drift volcanic-sedimentary sequences that are spatially and temporally associated with the ophiolite, and it is not tectonically overlying any passive margin assemblages of a continental block. (3) The ophiolite is stratigraphically overlain by a thick sedimentary sequence (~3 km in thickness) composed of black shale and turbiditic rocks, rather than pelagic limestone or chert as is typical of most Neotethyan ophiolites (Dilek and Eddy, 1992; Dilek et al., 1999). Brittle and ductile shear zones and normal faults in the sheeted dike complex, in the extrusive sequence and in the plutonic rocks (isotropic and layered gabbros) and the sheeted dikes all have a consistent west-northwest–east-southeast orientation in the field. This steady orientation of all seafloor spreading–generated structures in the Küre ophiolite indicates north-northeast–south-southwest–directed extension during its magmatic construction. The authors report the first U-Pb zircon age of 168 ± 2 Ma from a gabbro unit within the ophiolite, suggesting that the Küre oceanic crust formed in the Middle Jurassic (Bajocian–Bathonian). Detrital zircon

grains obtained from a turbiditic sandstone cover of the ophiolite display Paleoproterozoic, Neoproterozoic, and Paleozoic–early Mesozoic ages pointing to their likely provenance in the Ukraine shield and the Eastern European Platform within Eurasia to the north. The Küre ophiolite is interpreted as a Middle Jurassic continental backarc basin oceanic lithosphere, developed above a north-dipping subduction zone, behind a Late Triassic–Jurassic continental magmatic arc along the southern edge of Eurasia. Continental backarc basin ophiolites may be more common in the geological record than reported in the extant literature. Another example of a well-preserved continental backarc basin oceanic lithosphere occurs in the Early Cretaceous Rocas Verdes ophiolites, exposed in the southernmost Andes of South America (Stern and de Witt, 2003).

Saccani et al. (2018) examine the time-progressive melt evolution of the Jurassic Tethyan ophiolites in the Balkan Peninsula in eastern Europe, based on their new geochemical data from representative upper mantle peridotites and basaltic extrusive rocks, as well as on their previously published data (Dilek et al., 2008; Saccani et al., 2011) and those of other researchers. The authors identified four different magmatic suites in the extrusive sequences of the ophiolites exposed in the Albanides (Albania) and Western Hellenides (Greece), using the volcanic stratigraphy, mineral assemblages, and textural relationships displayed by relatively primitive basaltic rocks ($\text{MgO} > 7\%$ on anhydrous base). This selection was made in order to make sure that the compositions of the analyzed extrusive rocks would most likely represent liquid compositions of different primitive melts generated from partial melting of the upper mantle peridotites studied and sampled in the ophiolites. This approach was important because Saccani et al. (2018) used trace element modeling to define the melt, mantle residua, and melt-mantle source relationships for each identified magma type and its extrusive product found in the ophiolites. This is the first paper in the literature that reports a systematic geochemical characterization and correlation of ophiolitic peridotites and their crustal derivatives using carefully constructed, field-based volcanic stratigraphy. The peridotites in these Jurassic ophiolites are represented, based on their modal compositions, by lherzolites, clinopyroxene (cpx) poor lherzolites, and harzburgites that exhibit increasing LREE enrichment with increasing whole-rock depletion. The mafic volcanic rock types include, from the oldest to the youngest, (1) normal mid-oceanic ridge basalts (N-MORB), (2) medium-Ti basalts (MTB), (3) island arc tholeiitic basalts (IATB), and (4) boninitic lavas. The authors discuss the development of these different lava types from variously depleted peridotite types, which underwent different degrees of partial melting through time in continually evolved fluid-flux and slab dynamics conditions during subduction initiation. This study establishes a well-constrained spatial-temporal evolution of ophiolitic magmas beneath a forearc spreading center, and provides a realistic petrogenetic template for suprasubduction zone (SSZ) oceanic crust formation in a forearc setting that was driven by slab-rollback processes (Dilek and Thy, 2009). One of the most significant implications of the results of this study is that extrusive rocks ranging in compositions and age from N-MORB to IATB and boninites, which are commonly found in many ophiolites around the world (Furnes and Dilek, 2017), can be genetically related through subduction-related, time-progressive melting, depletion, and enrichment events in the upper mantle within the same SSZ tectonic setting. Therefore, they do not necessarily represent the melt products evolved in different tectonic environments at different times.

Wu et al. (2018) document the nature of melting, depletion, and enrichment processes experienced by the upper mantle peridotites of the Skenderbeu ophiolite in northern Albania. The massif consists of, from bottom to top, harzburgites with lenses of dunite and podiform and disseminated chromitites, lherzolite, and plagioclase lherzolite representing the upper mantle peridotites. These ultramafic rocks are overlain by

layered dunite-gabbro and troctolite making up the cumulate sequences. Mafic pillow lavas directly overlie the peridotites along primary normal faults. Situated within the western part of the northwest-southeast-trending ophiolite belt in north-central Albania, the Skenderbeu massif differs significantly in terms of its internal structure and igneous stratigraphy from the coeval Mirdita ophiolite to the north (discussed in Saccani et al., 2018). The Skenderbeu ophiolite is lacking a sheeted dike complex and plutonic rocks, and its extrusive rocks are unconformably overlain by a supraophiolitic mélange (Shallo and Dilek, 2003). Using new mineral chemistry, whole-rock, trace element, and platinum group element (PGE) geochemistry data from the harzburgites, dunites, and chromitites, Wu et al. (2018) show that these upper mantle units record significantly different degrees of partial melting and rock-melt interactions during the evolution of the Skenderbeu massif. Trace element modeling indicates that harzburgites formed as a result of $\sim 10\%$ – 15% low-degree partial melting of an already depleted MORB mantle. LREEs and high field strength element (HFSE) enrichment of these peridotites was a result of interactions of asthenospheric decompressional melts with the residual MORB mantle. Trace element modeling of dunites suggests that they may have formed as a result of $\sim 20\%$ – 25% high-degree partial melting of refractory harzburgites under high temperatures and low pressures at shallow mantle depths. The resulting melts were boninitic in composition with high olivine and SiO_2 contents, and were enriched in incompatible PGEs and Cu-Ni sulfides. The authors propose that partial melting of subducted pelagic sediments may have also provided high concentrations of Cu, Mo, and PGEs into boninitic melts. Reactions of these boninitic melts with ultrarefractory harzburgites produced podiform chromitites and precipitated Cu-Ni sulfides and dunitic melt channels. Both harzburgites and dunites and chromitites formed during subduction initiation and related melt evolution beneath a forearc tectonic setting. Harzburgites represent the earlier stages of partial melting products of an already depleted mid-oceanic ridge mantle in anhydrous conditions and in the presence of decompressional melts. Dunites and chromitites are, however, the products of partial melting of subduction metasomatized, highly depleted harzburgites and their reactions with boninitic melts in later stages of subduction initiation magmatism. These findings reported by Wu et al. (2018) are consistent with the time-progressive melt evolution patterns of the upper mantle peridotites in the Mirdita ophiolite farther north (as presented by Saccani et al., 2018), and in some other Tethyan ophiolites (Dilek and Furnes, 2009).

The next three papers examine the mineralogy, geochemistry, and melt evolution of upper mantle peridotites in different but nearly coeval Tethyan ophiolites around the periphery of the India plate. The results of these studies clearly show that the Tethyan mantle rocks exposed along the eastern periphery of the India subcontinent had a very different partial melting, melt extraction, and enrichment history than those peridotite assemblages exposed within the Yarlung-Zangbo suture zone (YZSZ) along the northern periphery of India. Emplacement mechanisms of the Tethyan ophiolites along the eastern versus northern India periphery were also different; the ophiolites that are discontinuously exposed along the eastern edge of India originated from a downgoing Tethyan oceanic plate at a subduction zone, whereas those occurring along its northern edge originated from the upper plate of a subduction zone within a Neotethyan seaway. The crustal and upper mantle rock units in these northern periphery ophiolites therefore display a clear mineralogical, compositional, geochemical, and tectonic record of subduction influence in their magmatic construction.

Niu et al. (2018) present whole-rock major, trace, and PGE and mineral chemistry data from the Kalymyo peridotite massif, exposed in the central Indo-Myanmar Ranges of western Myanmar, and discuss its melt evolution and tectonic origin. This massif includes mainly serpentized peridotites, intruded by gabbro dikes and stocks and faulted against mafic lava flows,

radiolarian chert, shale, ocean island basalt, and tuffaceous rocks within an accretionary prism complex. A U-Pb zircon age of 127 Ma from a gabbro intrusion in the peridotites shows that the Kalaymyo massif is coeval with the Manipur-Nagaland ophiolites farther north in the Indo-Myanmar Ranges (Fareeduddin and Dilek, 2015) and with the YZSZ ophiolites to the north of India (Xu et al., 2015; Liu et al., 2018, and references therein). The Kalaymyo peridotites consist mainly of harzburgites with homogeneous whole-rock compositions. Their PGE patterns are comparable to those of sulfide-rich abyssal harzburgites. These geochemical features, combined with their mineralogical and textural characteristics, indicate that the Kalaymyo peridotites represent residual peridotites after 5%–15% partial melting beneath a mid-ocean ridge spreading axis. However, the Kalaymyo harzburgites also display LREE contents that are higher than the calculated LREE contents, and show relative enrichment in HFSEs and relatively high oxygen fugacities. All these geochemical attributes point out that the residual harzburgites underwent melt-rock interactions after partial melting. The inferred melts were enriched MORB in character, rather than subduction-derived island arc tholeiitic or boninitic melts. Therefore, the Kalaymyo harzburgites, like the other ophiolites in the Indo-Myanmar Ranges, are the residues of upper mantle peridotites that underwent low to moderate degrees of partial melting and variable degrees of basaltic melt extraction at a mid-ocean ridge setting, and they show no subduction influence in their melt evolution. This finding has significant implications for the mode of oceanic lithosphere formation in the Mesozoic Neotethys.

Feng et al. (2018) present new mineralogy-mineral chemistry, whole-rock major and trace element geochemistry, and Re-Os isotope data from the Cuobuzha peridotites exposed in the northern ophiolite subbelt near the western end of the YZSZ in southern Tibet. The nearly east-west-trending YZSZ along the northern edge of the India subcontinent splits into two subbelts of ophiolites and ophiolitic mélanges by a sliver of a continental block, the Zhongba terrane (Liu et al., 2015, 2018; Xie et al., 2017). A more detailed regional geology of these two subbelts is provided in the paper by Liu et al. (2018). The northern subbelt of ophiolites along the northern edge of the Zhongba terrane includes a series of peridotite massifs and spatially associated crustal rocks as kilometer-scale blocks in a serpentinite matrix mélange. The Cuobuzha peridotites consist mainly of cpx-rich and depleted harzburgites with lensoidal bodies and veins of dunite and massive to disseminated chromitites. All these upper mantle rock units are intruded by dolerite and microgabbro dikes. Depleted harzburgites have lower concentrations of Al_2O_3 and CaO, but higher MgO concentrations than cpx-rich harzburgites. Total REE concentrations in both peridotite types are well below the primitive mantle concentrations, indicating high degrees of depletion. However, spinels in the cpx harzburgites have lower Cr# values than the spinels in the depleted harzburgites, and the cpx harzburgites show higher HREE concentrations than the depleted harzburgites. Os isotopic compositions of the two peridotite types are significantly different: the depleted harzburgites have subchondritic Os isotopic ratios, whereas the cpx harzburgites have suprachondritic ratios and higher Re concentrations. These geochemical and Os isotopic features indicate different partial melting and melt extraction histories for both peridotite types in the Cuobuzha massif. The cpx harzburgites formed as a result of low-degree (~5%) partial melting of a primitive mantle source. Higher degree (~10%–17%) partial melting of these cpx harzburgites in the presence of percolating melts produced the residual depleted harzburgites. Elevated Re concentrations in the cpx harzburgites suggest late-stage addition of Re into these peridotites as a result of their reaction with fluids, a process that removed sulfides while giving the residual cpx harzburgites their melt-like $^{187}\text{Os}/^{186}\text{Os}$ signatures. The authors suggest that all these melting, melt extraction, and fluid-rock interaction processes may have taken place beneath a single mid-ocean ridge spreading center, although

they do not rule out a possible subduction initiation origin of the inferred fluids percolated through the cpx harzburgites.

Liu et al. (2018) report new geochemical, geochronological, and Sr-Nd-Pb isotope data from dolerite and microgabbros dikes intruded into the Cuobuzha and Baer peridotite massifs in the northern subbelt of the western YZSZ. These intrusions occur as individual dikes crosscutting the peridotites, are mainly basaltic and basaltic-andesitic in composition, and have tightly constrained U-Pb zircon ages of 128–122 Ma. The authors have investigated these dikes in order to constrain their possible melt-residual genetic relationships with the host peridotites, and to document the melt evolution history of the upper mantle peridotites. The results presented here provide, therefore, additional insights for the petrogenesis and geochemical makeup of those ultramafic rock assemblages exposed along the western end of the YZSZ. The Cuobuzha peridotites are composed of cpx harzburgite and harzburgites, whereas the Baer peridotites farther west within the YZSZ consist of spinel lherzolite, cpx harzburgite, and harzburgite. Dike rocks show N-MORB-like whole-rock and REE patterns with significant enrichment in large ion lithophile elements (LILE) and LREEs in comparison to HFSEs, and exhibit negative Nb, Ta, and Ti anomalies. They also display high $\epsilon_{\text{Nd}(t)}$ values and high age-corrected ($t = 128 \text{ Ma}$) $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. The authors infer that these geochemical features of the dike rocks were manifested by an ~7%–12% partial melting of an N-MORB-type mantle source, which was metasomatized by subduction-derived fluids. They point out that there are no boninitic dikes or lavas associated with the Cuobuzha and Baer massif peridotites, as reported in the literature by other researchers from different parts of the YZSZ. This observation is significant because boninitic dikes and lavas are generally interpreted as important components of subduction initiation magmatism in SSZ ophiolite formation globally (Ishikawa et al., 2002; Dilek and Furnes, 2009, 2014; Pearce and Robinson, 2010; Reagan et al., 2010; Ishizuka et al., 2014; Pearce, 2014). Given the close spatial and temporal association of the Cuobuzha and Baer peridotites and their dike intrusions with an accretionary prism complex and Gangdese magmatic belt of the Eurasian continental margin, Liu et al. (2018) conclude that the ultramafic-mafic rock assemblages within the northern ophiolite subbelt in the western end of the YZSZ likely represent remnants of a forearc oceanic lithosphere developed above a north-dipping subduction zone adjacent to the Eurasia continental margin.

Diamonds, UHP Minerals, and Crustal Material in Ophiolitic Chromitites: Characteristics and Origin

The occurrence of diamonds in ophiolitic peridotites and chromitites poses a scientific conundrum. The widely accepted models envision the formation of podiform chromitites in highly depleted peridotites and the production of oceanic crustal rocks as partial melting derivatives of upper mantle peridotites at shallow mantle depths (60–80 km) beneath a seafloor spreading center (Zhou et al., 1996; Arai, 1997; Edwards et al., 2000). This view is incompatible with the well-established pressure-temperature conditions of diamond formation at great mantle depths. It is therefore not surprising that the first reports on the discoveries of microdiamonds in ophiolitic chromitites were received with much skepticism. However, subsequent findings of microdiamonds in chromitites of different ophiolites with different ages around the world (Tibet, Russian Urals, Burma-Myanmar, Albanides-Albania, Taurides-Turkey; Yang et al., 2014, 2015a; Lian et al., 2017; Xiong et al., 2017) have shown that (1) these microdiamonds widely exist in ophiolitic peridotites and chromitites of different ages; (2) they may be much more widespread in the mantle than previously thought; and (3) they display many similarities in their morphology, carbon isotopes, and mineral inclusions, while

they are distinctly different from diamonds occurring in kimberlites and UHP metamorphic belts. What we still do not know, however, is whether these microdiamonds and UHP minerals exist in ophiolites that formed in nonsubduction-related tectonic environments (i.e., mid-ocean ridges, ocean-continent transition zones, and plume-proximal spreading centers) other than forearc spreading centers of SSZ settings.

The next three papers in the second part of this special issue provide new analytical results on the crystallographic, textural, compositional, and isotopic characteristics of chromitite-hosted microdiamonds that help us further differentiate these diamond occurrences from their kimberlitic counterparts. Moe et al. (2018) present Fourier transform infrared (FTIR) and Raman microscopy results of their investigation of microdiamonds from chromitites and peridotites in the Luobusa ophiolite (eastern YZSZ, Tibet) and from the chromitites in the Ray-Iz ophiolite in the Polar Urals (Russia). They report that these microdiamonds occur in a cubo-octahedral polycrystalline or single crystal with partial cubo-octahedral form, and that they contain fluid inclusions composed of water, carbonates, silicates, hydrocarbons, and solid CO₂, all of which are exclusively unique to natural diamonds and not reported from high-pressure–high-temperature synthetic diamonds. Microinclusions of chromite, magnetite, albite, moissanite, hematite, and magnesiochromite in these microdiamonds are also unique to natural diamonds and do not form as high-pressure–high-temperature diamonds. All of these features collectively indicate that microdiamonds obtained from ophiolitic peridotites and chromitites are unusual natural diamond occurrences, which point to a new diamond genesis in a very different geological environment.

Xiong et al. (2018) document the occurrence of microdiamonds and other UHP and highly reduced minerals in the peridotites of the Late Triassic Dingqing ophiolite exposed along the Bangong–Nujiang suture zone in south-central Tibet, north of the YZSZ. Findings of this study are unique because microdiamonds and other unusual UHP minerals analyzed in this work were extracted solely from peridotites, not from chromitites, as in many other recoveries from other ophiolites around the world. Thus, the question is not just about where and how chromitites encapsulated and carried diamonds as inclusions, but how the peridotites acquired these extremely high temperature and high-pressure minerals at great mantle depths. The Dingqing ophiolite consists mainly of a large peridotite massif, overlain by gabbros with dolerite dikes and locally directly overlain by Norian chert deposits. Peridotites comprise harzburgite with minor dunite lenses and bodies. Gabbro and pyroxenite dikes intrude these peridotites. Orthopyroxene and clinopyroxene compositions in the harzburgite and dunite samples reflect high degrees of partial melting and melt extraction history, and resemble the compositional features of their counterparts in forearc ophiolites (Bédard et al., 1998; Ishikawa et al., 2002). These observations are also consistent with the enrichment of the Dingqing gabbro and dike rocks in Si, Mg, and LILEs and their depletion in HFSEs, characteristic of boninitic crustal rocks in forearc ophiolites (Meffre et al., 1996; Bédard et al., 1998; Dilek and Thy, 2009; Saccani et al., 2018). Thus, the Dingqing ophiolite is another ancient SSZ oceanic lithosphere, as the other ophiolites from which all reported microdiamonds and UHP minerals have been obtained. Xiong et al. (2018) infer that highly reduced minerals recovered from the Dingqing peridotites were incorporated into chromian spinel grains in peridotites near the MTZ. These chromian spinel grains and their host peridotites were brought up by asthenospheric upwelling processes into shallow mantle depths, where subsequent partial melting episodes beneath a forearc spreading center produced dunite bodies in ultradepleted harzburgites and boninitic crustal units of the ophiolite. The widespread occurrence in the Dingqing peridotites of quartz, rutile, titanite, corundum, almandine garnet, kyanite, and andalusite also shows deep, subduction-driven recycling of crustal material in the mantle.

Xu et al. (2018) report new $\delta^{13}\text{C}$ data and nitrogen content and aggregation state values for microdiamonds obtained from peridotites and chromitites of the Cretaceous Luobusa ophiolite in southern Tibet and from chromitites of the Early Devonian Ray-Iz ophiolite in the Polar Urals of Russia (Yang et al., 2015b). The authors chose to do this work because nitrogen is the most abundant impurity in natural diamonds and nitrogen aggregation characteristics in diamonds help to constrain diamond residence time and mantle temperatures during their formation. Nitrogen contents and aggregation states of representative diamonds were determined by FTIR. The authors report that all analyzed microdiamonds from both Luobusa and Ray-Iz ophiolites have significant nitrogen contents with a low aggregation state and identical infrared spectra, characterizing them as Type Ib natural diamond. The analyzed samples are distinctly different from other metamorphic diamonds. These diamond samples display enhanced $\delta^{13}\text{C}$ variability and less advanced state of N aggregation than synthetic diamonds. Thus, the findings of this study confirm that ophiolite-hosted microdiamonds are natural, and that their occurrence does not involve contamination of any synthetic diamonds during sample preparation. The combined $\delta^{13}\text{C}$ and nitrogen data point to the formation of microdiamonds over a narrow and cold temperature range (i.e., <950 °C), and in a short residence time (i.e., within several million years) at high temperatures in the deep mantle. This inference implies that those microdiamonds incorporated into the chromitites and peridotites near the MTZ must have been transported, with their host rocks, to the shallow mantle depths at very fast rates.

NEW CONCEPTS ON UPPER MANTLE PETROGENESIS

Results of the studies presented in this issue clearly demonstrate that subduction-driven mantle dynamics play a significant role in the melt evolution of peridotites and ophiolitic magmas, and in the incorporation of crustal materials, UHP minerals, and diamonds into ophiolitic peridotites and chromitites. MTZ depths of the origin of ophiolite-hosted microdiamonds and UHP minerals are now well established. However, the mechanisms of relatively rapid transportation of such earth materials from these depths to shallow mantle levels, where partial melting processes take place to form depleted upper mantle peridotites and podiform and disseminated chromitites are still a challenging question. Large-scale mantle upwelling processes induced by subduction slab rollback and plume and superplume events appear to be the most likely drivers.

In light of the new discoveries and interpretations for the occurrence and origin of microdiamonds, UHP and other crustal minerals in their host chromitite deposits and peridotites reported in this themed issue and elsewhere in the literature, we propose a new working hypothesis for their formation and incorporation into ophiolitic upper mantle rocks (Fig. 1). We note several important constraints in the development of this new hypothesis. (1) All analyzed chromitites and peridotites containing microdiamonds also contain mixtures of UHP, highly reduced minerals and crustal material (Zhou et al., 2014; Yang et al., 2014, 2015a, 2015b). These minerals do not represent any type of equilibrium assemblage, and they coexist far outside their normal stability fields in their ophiolitic host rocks. They represent a mixture of minerals from different sources that formed under various pressure-temperature conditions (Liou et al., 2014), indicating multistage mechanisms and timing of their formation and their incorporation into peridotites and chromitites. (2) The abundance of native elements and metallic alloys, such as SiC, suggests derivation from a highly reduced section of the mantle. (3) The carbon sources of microdiamond and highly reduced minerals in the ophiolitic peridotites and chromitites are most likely previously subducted continental and oceanic crustal material. Fluid inclusions in the analyzed microdiamonds

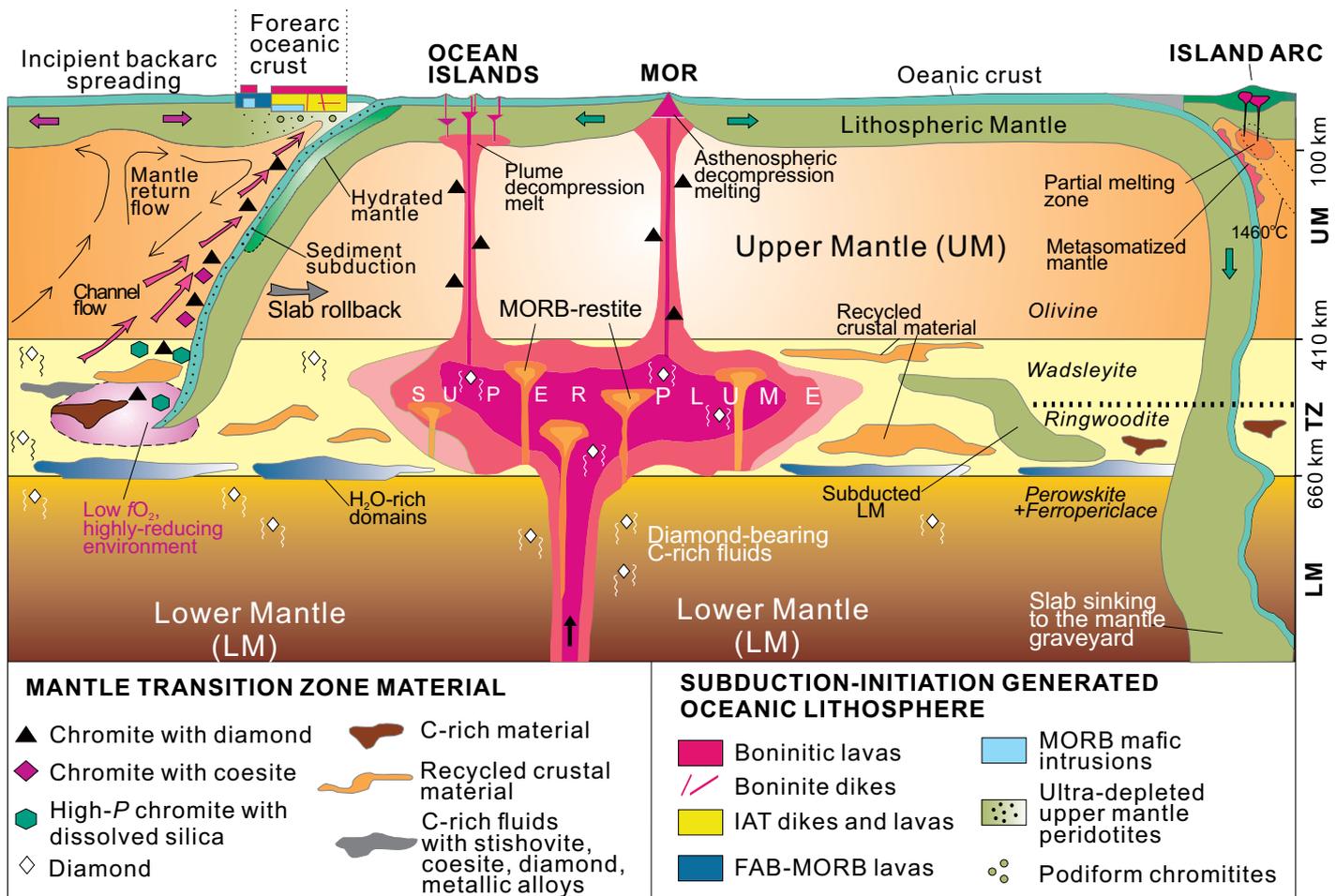


Figure 1. Interpretive model for the formation of microdiamonds and associated ultrahigh-pressure minerals in the oceanic mantle and for their incorporation into ophiolite-hosted chromites within the mantle transition zone (TZ). FAB—forearc basalts; IAT— island arc tholeiite; LM—lower mantle; MORB—mid-ocean ridge basalt; MOR—mid-ocean ridge; UM—upper mantle; *P*—pressure. See text for discussion. Data are from Liou et al. (2014) and Yang et al. (2014, 2015b).

and their surrounding amorphous carbon indicate that original fluids were rich in C, and that they contained Mn, Ni, Co, Si, Ti, REEs, and Cl, which occur abundantly in subducted oceanic slabs. Recycled oceanic crust with biogenic carbon (Furnes et al., 2006) and organic sediments also constitute important carbon supply to the deep mantle.

Working Hypothesis and Model

Subducting slabs recycle oceanic lithosphere and continental crustal material down to the MTZ or to the core-mantle boundary (Fig. 1). The ambient conditions within the MTZ are ~15–16 GPa and ~1600 °C, and under such conditions, slabs of oceanic lithosphere, including peridotites, chromitites, and dense eclogites undergo partial melting (Maruyama et al., 2007) in the presence of 1–1.5 wt% water (Pearson et al., 2014). H₂O, CO₂, and other fluids are released during this partial melting, and some minerals become reduced to single element material such as C and H in a highly reduced environment. Most crustal minerals reaching the MTZ would either break down or react with the highly reduced phases (e.g., coesite and kyanite rimming Ti-Fe alloy; Yang et al., 2007), whereas some others such as zircon may likely survive (Tange and Takahashi, 2004; Yamamoto et al., 2013).

Diamond, stishovite, qingsongite, and Ca-silicate perovskite that form from melts and recycled material become mixed with other UHP phases and highly reduced minerals, derived from zones with extremely low *f*O₂ within the MTZ, as required for the formation of moissanite and other numerous native elements (Bai et al., 1993; Xu et al., 2018). Near the top of the MTZ (>300 km depth) (Fig. 1), high-pressure chromite (with dissolved Si) begins to crystallize, as demonstrated by experimental studies of Wu et al. (2016), encapsulating diamond, moissanite, and other highly reduced phases (Yang et al., 2007; Trumbull et al., 2009). The association of in situ diamonds with spherical patches of amorphous carbon around them suggests that they grew in a carbon-rich fluid that also contained metallic alloys, stishovite and/or coesite, and Mn-rich phases, all of which occur as inclusions in the diamonds (Yang et al., 2014, 2015a). These patches of amorphous carbon that host moissanite and corundum had to form at the same time as the in situ diamonds, but at faster cooling rates, as the study by Xu et al. (2018) demonstrates.

Exhumation of MTZ Diamonds and UHP Minerals in Slab Rollback-Driven Channel Flows

Chromites containing inclusions of microdiamond, moissanite, other UHP minerals, and crustal material (e.g., zircon, tourmaline) and their

host peridotites are transported from the MTZ depths to shallow mantle levels beneath oceanic spreading centers by asthenospheric upwelling (Fig. 1), associated either with slab rollback–induced return-channel flow in the upper plate of a newly initiated subduction zone (Husson et al., 2009; Alfonso and Zlotnik, 2011; Rollinson, 2016) or with a superplume event (Brunet and Yuen, 2000; Maruyama et al., 2007). As an old and dense oceanic lithosphere plunges into the mantle during the establishment of a new subduction zone, gravitational pull of this descending slab causes it to roll back, a process that triggers asthenospheric mantle flow and upper plate extension beneath a forearc setting (Brun and Faccenna, 2008; Schellart, 2008; Husson et al., 2009). Relatively fast channel flow velocities (6–8 cm/yr; McGowan et al., 2015), resulting in short residence time in the upper mantle of diamond-bearing chromite and their host harzburgites, and rapid cooling in the shallow mantle depths collectively facilitate the preservation of diamonds and UHP and highly reducing minerals. However, during the upwelling coesite exsolution lamellae may form in the chromite grains (Fig. 1), and stishovite may become replaced by coesite (Yamamoto et al., 2009).

Harzburgitic peridotites brought up to shallow mantle depths beneath forearc spreading centers first undergo decompression melting, followed by flux melting, producing magmas with forearc basalt, arc tholeiitic, and boninitic chemical affinities (Fig. 1; Dilek et al., 2008; Dilek and Furnes, 2009, 2014; Saccani et al., 2018) and causing the redistribution of chromite grains and the formation of small chromitite pods. Migrating, slab-influenced fluids and melts interact with harzburgites in the mantle wedge, forming dunite channels and lenses (Dilek et al., 2008; Morishita et al., 2011), and redistributing, chemically modifying, and redepositing chromite grains with microdiamond and UHP mineral inclusions into podiform chromitites (Xiong et al., 2018). This model is compatible with the earlier interpretations of the formation of podiform chromitites in many ophiolites within SSZ environments (i.e., Edwards et al., 2000; Rollinson and Adetunji, 2013), and it also provides a viable explanation for the need for deep crystallization of chromite grains to entrain the well-documented occurrence of diamonds and UHP and highly reduced minerals in them near the MTZ depths.

Exhumation of MTZ Diamonds and UHP Minerals in Mantle Superplumes

Superplumes are vast plumes that form when thermal upwellings and mantle updrafts (Anderson et al., 2014), initially originating from or near the core-mantle boundary, are coalesced and reorganized within the MTZ as a result of phase transformations, accelerated partial melting due to the presence of abundant water, significant viscosity changes, and depth-dependent thermal expansivity (Brunet and Yuen, 2000; Condie et al., 2000; Maruyama et al., 2007). The South Pacific and the East Africa superplumes are two modern examples; at least one other superplume is inferred to have existed beneath the combined Gondwana-Laurasia supercontinent in the Late Cretaceous (ca. 100 Ma), in addition to the South Pacific superplume (Fig. 2). Formation of these superplumes may follow supercontinent assembly through multiple subduction-driven collision events and accumulation of thick piles of subducted slabs at the 660 km seismic discontinuity. Catastrophic collapsing of these stagnant slabs and their descent into the lower mantle likely trigger upwelling of hot and fertile material from the lower mantle via updrafts and plumes. Small-scale plumes collide and collapse together, forming a superplume and a series of small reservoirs of MORB restite within the MTZ (Fig. 1; Brunet and Yuen, 2000). Phase transformations near the thermal boundary layer at the ~410 km discontinuity facilitate the launching of new smaller plumes near the top of the superplume that feed into intraplate ocean island volcanism and/or asthenospheric upwelling zones associated

with mid-ocean ridge spreading. During mixing, melting, and amalgamation of plume melts within the MTZ, chromite grains with inclusions of microdiamonds, UHP and crustal minerals, and other metallic alloys may be incorporated into the resulting melts and may then be transported by plumes ascending rapidly through the upper mantle to the decompression melt zones beneath ocean islands and mid-ocean ridge spreading centers (Fig. 1).

Alternative Models?

We are aware of other alternative explanations for the origin of chromitites in ophiolites and the relative timing of the incorporation of UHP and highly reducing minerals into them. Models by Arai (2013) and McGowan et al. (2015) suggest that podiform chromitites in depleted harzburgites in some SSZ ophiolites might have initially formed in shallow mantle depths (<30 km), and that these chromitite deposits and their host peridotites were subsequently subducted into MTZ depths, where their reactions with reducing fluids might have formed the UHP mineral phases and highly reducing minerals. These interpretations envision >150 m.y. of residence time for the subducted chromitites and their host harzburgites to undergo these reactive phase changes in the MTZ. However, this kind of very long time span is not supported by the new $\delta^{13}\text{C}$ data and nitrogen content and aggregation state values for microdiamond inclusions, which indicate only several million years of residence time (Xu et al., 2018). Furthermore, these models do not provide a viable mechanism for the incorporation of microdiamond and crustal minerals into chromite grains and for the existence of exsolution lamellae textures observed in very high pressure chromite types. Therefore, we prefer an initially deep origin of chromites and their microdiamond and UHP mineral inclusions within the MTZ depths, followed by their rapid exhumation to shallow mantle depths, where podiform chromitites and their highly depleted harzburgite-dunite host peridotites formed as a result of repeated episodes of partial melting and melt-rock interactions.

OUTSTANDING QUESTIONS

Microdiamond and UHP mineral occurrences in chromitites and peridotites as reported in this themed issue and in the previously published literature are entirely limited to those ophiolites that formed in SSZ settings, specifically in forearc tectonic settings. Thus, the explanation of rapid exhumation of MTZ peridotites with diamond-bearing chromites in slab rollback–induced asthenospheric flow channels beneath forearc spreading centers is mechanistically favored. However, our knowledge of the occurrence of diamonds and UHP minerals in ophiolitic chromitites and peridotites is still limited because we do not know whether such minerals are also present in ophiolites that formed in nonsubduction-related tectonic environments, such as mid-ocean ridge, ocean-continent transition zone (or continental margin), and plume-related ophiolites (Dilek and Furnes, 2011, 2014). Future investigations of the upper mantle peridotites exposed in the mid-ocean ridge–type Taitao ophiolite in Chilean Patagonia (Shin et al., 2015), ocean-continent transition zone–type Jurassic ophiolites of the Western Alps (Festa et al., 2015), and the plume-type Colombian ophiolites in the northernmost Andes (Kerr et al., 1998; Dilek and Furnes, 2014) should help us answer this question.

Work is in progress on systematically collected upper mantle peridotites of the Chile Rise oceanic lithosphere, now exposed in the 5.9 Ma Taitao ophiolite in Chilean Patagonia, and on the Jurassic–Cretaceous lavas and peridotites of the plume-type Tethyan ophiolites in Anatolia (Turkey) and southern Tibet. Plume-type ophiolitic rocks occur extensively within the entire Alpine-Tibetan orogenic system and are interpreted to have formed from plume-metasomatized asthenospheric mantle sources during the early stages of the opening of Neotethyan seaways between

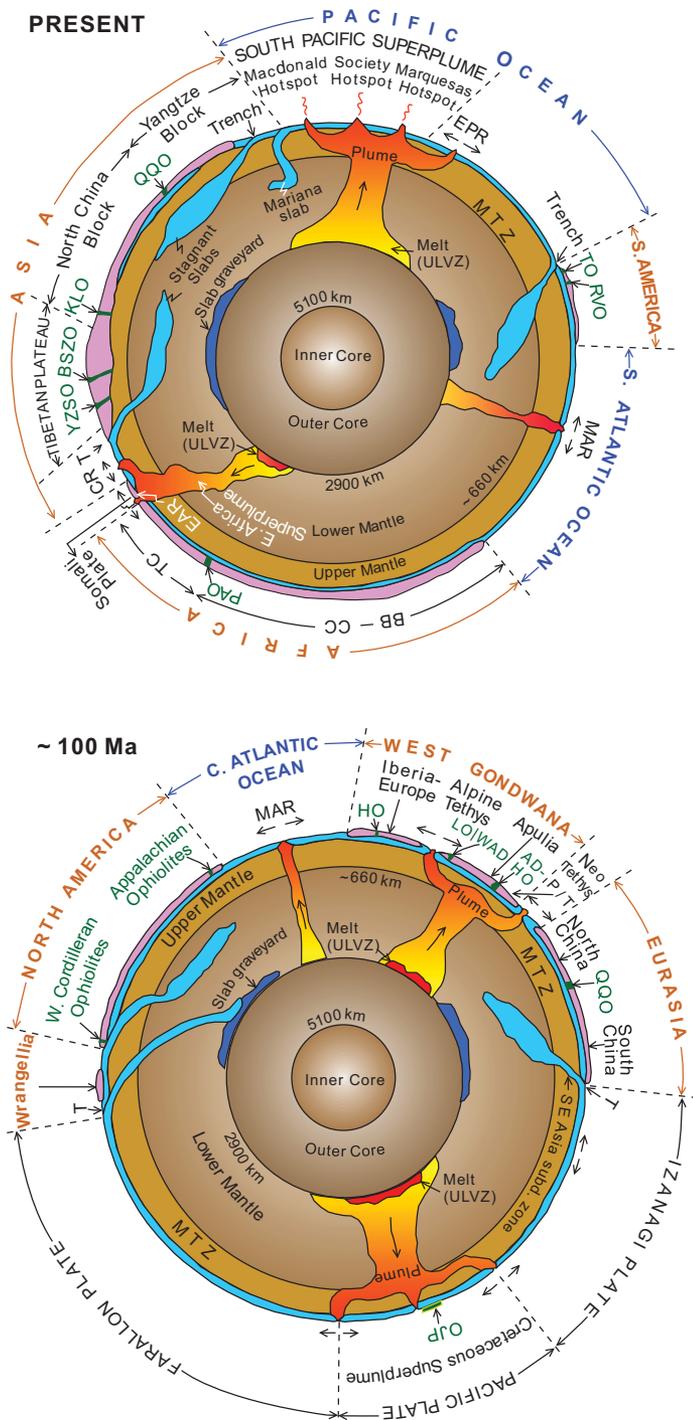


Figure 2. Earth sections (present and 100 Ma–Cretaceous) showing the distribution of the subduction (subd.) zones, slabs, superplumes, and mid-ocean ridges. ADHO—Albanide-Dinaride-Hellenide ophiolites; BB-CC—Bangweulu Block-Congo Craton; BSZO—Bangong-Nujiang suture zone ophiolites; CR—Carlsberg Ridge; EAR—East African Rift; EPR—East Pacific Rise; HO—Hercynian ophiolites; KLO—Kunlun ophiolites; LO—Ligurian ophiolites; MAR—Mid-Atlantic Ridge; MTZ—Mantle transition zone; OJP—Ontong Java Plateau; P—Pelagonia; PAO—Pan-African ophiolites; QQQ—Qilian-Qinling ophiolites; RVO—Rocas Verdes ophiolites (Chilean Andes), T—Tauride; TC—Tanzanian Craton; TO—Taitao ophiolite (Chile); ULVZ—ultralow-velocity zone; WAD—Western Alps domain; YZSO—Yarlung Zangbo suture zone ophiolites. See text for discussion. Data are from Maruyama et al. (2007) and Moores et al. (2000).

Laurasia and Gondwana-derived continental bodies (Fig. 2; Dilek et al., 1999; Dilek, 2003a; Saccani et al., 2015; Yang and Dilek, 2015). Recovery of microdiamonds and UHP and crustal minerals from mid-ocean ridge- and plume-type ophiolitic peridotites would show that superplumes play a significant role in effectively transporting MTZ material to shallow mantle partial melting factories beneath oceanic and continental rifts.

We also do not know whether diamond-bearing peridotites are restricted to ophiolites, or they may also be common in modern, in situ ocean lithosphere formed at mid-ocean spreading centers, trench-distal backarc spreading centers, and forearc extensional settings (e.g., the Izu-Bonin-Mariana forearc). If both modern oceanic lithosphere and ophiolites originated from diverse tectonic settings (not just SSZ tectonic environments) contain abundant diamond-bearing peridotites and chromitites, then diamonds and UHP minerals may be common features of oceanic mantle. In that case, the oceanic mantle might be a more significant carbon reservoir than ever thought.

The presence of the UHP, highly reduced, and crustal minerals in the MTZ provides us with additional information about the mantle composition, dynamics, and evolution besides what have been already learned from seismic tomographic studies over the past decade (Thomas and Billen, 2009; Karato, 2011; Kuritani et al., 2011; Schmandt et al., 2014). However, new geochemical and isotopic techniques are needed to fingerprint tectonic settings of chromitite formation, and to reliably decipher the timing of the genesis of chromitites with different compositions and different pressure-temperature conditions of formation.

GLOBAL TECTONICS: RIFTS, PLUMES, AND SLABS

The primary global tectonic features that affect the oceanic crust generation and ophiolite formation are continental and oceanic rifts (including mid-ocean ridges), plumes, and subducted slabs. The processes associated with these features are fundamental in driving plate tectonics, as well as producing compositional and geochemical heterogeneities in the mantle. Figure 2 shows cross sections of the modern and the 100 Ma Earth, depicting its internal structure and the inferred distribution of the continents, mid-ocean ridges, superplumes, and subducted slabs. The two modern superplumes in the western Pacific and in the Africa–Indian Ocean region are driven by the core heat supply and provide fertile and high-temperature materials into the upper mantle. The East African Rift Zone, East Pacific Rise, Carlsberg Ridge, and Mid-Atlantic Ridge are sites of different types of modern oceanic crust formation (future ophiolites?), variously affected by plume activities.

Mantle tomography studies and high-resolution seismic models have shown that subducted slabs may either stagnate in the MTZ between 410 km and 660 km or penetrate into the lower mantle, extending from ~1500 km depth to the core-mantle boundary (Moores et al., 2000; Maruyama et al., 2007, and references therein). Those subducted slabs in the MTZ constitute the main sources of water, crustal sediments, and surface carbon, contributing significantly to the water budget, fertility, and heterogeneity of the mantle. The water here plays a major role in lowering the viscosity and the solidus temperatures of the mantle rocks, triggering partial melting. A thick, high-velocity anomaly zone at 2900–2700 km depth near the core-mantle boundary represents slab graveyards (Fig. 2; Moores et al., 2000; Maruyama et al., 2007), which make up a major geochemical reservoir in the Earth and add to the heterogeneous isotopic signatures of the material derived from the core-mantle boundary.

The 100 Ma reconstruction of the Earth’s structure in Figure 2 shows the distribution of the two superplumes, the major active margins and associated subduction zones, stagnant slabs, and slab graveyards. This was the timing of some large-scale changes and events in the geological

record of the Earth. Increased seafloor spreading rates and oceanic crust generation, eruption of basaltic plateaus, intense deformation at continental margins due to widespread ophiolite emplacement, blueschist formation, and anomalously uniform and prolonged normal polarity of the Earth's magnetic field occurred in the middle Cretaceous and coincided with the superplume events (Dilek, 2003a; Vaughan and Scarrow, 2003). The superplume activities beneath Laurasia and Gondwana led to thermal weakening of the continental lithosphere and to the opening of different Neotethyan seaways (Fig. 2). The continental margin, MOR, SSZ, and plume-type ophiolites of the Alpine-Himalayan and the peri-Caribbean orogenic belts formed during the rift-drift and subduction zone evolution of these Neotethyan seaways (Dilek, 2003b). The western margin of the North American continent facing the large Pacific Ocean underwent long-lived subduction zone tectonics during the Jurassic–Cretaceous, developing into an accretionary-type orogenic belt (Dickinson, 2004). Oceanic plateaus (e.g., Wrangellia) and archipelagoes of intraoceanic island arcs (e.g., California ophiolites) were accreted into this orogenic belt through a combination of active margin and transform fault plate boundary processes (Saleeby, 1983; Dilek and Moores, 1993, 1999; Godfrey and Dilek, 2000; Ingersoll, 2000; Dickinson, 2004; Sigloch et al., 2013).

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