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Ophiolites and Earth's mantle ophiolites, podiform chromitites and deep mantle recycling

PREFACE

This Special Issue brings together a variety of recent studies on mostly Tethyan ophiolites in China, Pakistan, Turkey, Albania, Cyprus, and Iran, as well as two papers dealing with ophiolites in Cuba and one reporting on chromitites in the Philippines. These papers cover a range of topics ranging from magmatic processes in mantle peridotites, to hydrothermal alteration and associated mineralization in ophiolites as well as continuing attempts to understand the origin and evolution of the enigmatic Xigaze ophiolite of Tibet, which has puzzled multiple authors for decades.

With the recognition that most ophiolites were either formed in, or modified by suprasubduction zones, the focus of ophiolite studies has shifted from discoveries and descriptions of new bodies to specific, detailed investigations of magmatic processes to better understand the roles played by mantle mineralogy, geochemistry, partial melting, magma mixing, and SSZ fluids in the mantle and crustal sequences. Thus, nearly half of the papers in this Issue are based on these topics. And a key question addressed by several of the studies is the extent to which the records of these processes have been overprinted or even obliterated by mantle processes.

1. Subduction initiation, slab rollback and fore-arc magmatism

1.1. Plate subduction

Subduction of oceanic lithosphere is considered to be the major driving force of plate tectonics, with mid-ocean ridge spreading and igneous activity being a consequence of slab consumption. The specific causes of subduction initiation are not clear but are thought to reflect changes in the tectonic regime, particularly plate collisions, irregularities on the sea floor such as those produced by transform faults, or variations in composition, thickness, or density within plates.

There are two extant models for subduction initiation - spontaneous and induced - but these are somewhat misleading terms because they describe the onset of tectonic and magmatic processes in the overlying mantle wedge, not the initial foundering of the downgoing slab. Thus, the term 'spontaneous' subduction is currently applied when extension and magmatism in the upper plate coincides with the initial sinking of the downgoing slab whereas 'induced' subduction occurs when there is a considerable delay between the two events.

(1 Guang-Yao Xin et al., 2022) used this concept to investigate subduction initiation in the Neo-Tethys Ocean of Turkey. Using the Bursa ophiolite as a representative massif of the region, they found a difference of approximately 9.4 to 3.8 Myr between unmodified MORB-like dikes of the upper plate and *E*-MORB-like amphibolites representing metamorphism of the downgoing slab. From this information, they deduced that the Bursa ophiolite formed by induced subduction and inferred a similar model for other bodies the region.

What happens after subduction is initiated depends on many factors, but generally involves heating and dewatering the downgoing slab, releasing fluids into the overlying mantle wedge leading to partial melting, and production of a magmas of variable composition. Continued sinking and rollback of the slab leads to rifting in the fore-arc area, allowing the magmas to rise through wedge and build the crustal section. These on-going processes leave behind a complex record of melting, depletion, and refertilization of the mantle peridotites that requires careful interpretation.

1.2. Mantle melting

In an excellent paper, (2 Chen et al., 2021) report that variations in composition of the crustal section of the Kizildag ophiolite of Southern Turkey most likely reflect different melting models of the mantle. Both the sheeted dikes and gabbros have Pb isotope values that plot between Indian Ocean MORB and modern ocean sediments. Most of the sheeted dikes, which have low REE values and trace element ratios similar to those of boninites, but enriched in LILE, which are attributed to slab-derived fluids in a protoarc-forearc setting. Modeling suggests a mixing of polybaric, continuous melting and flux melting of the mantle wedge produced the sheeted dikes, whereas both the layered and isotropic gabbros have boninitic compositions. The authors propose that the sheeted dikes were formed from two types of melting, whereas the gabbros formed from a crystal mush flushed by interstitial liquids. They further suggest that such a model may be widely applicable to other Turkish ophiolites.

1.3. Alteration and refertilization

One of the major problems involved in quantifying the degrees of mantle melting in ophiolites is determining the extent to which the minerals of typical depleted mantle peridotites of ophiolites have been modified by later magmatic and fluid processes. (3 Qi-qi Pan et al., 2022) dealt directly with this problem in their study of the peridotites of the Lycian ophiolite of Turkey. They found that an abundance of clinopyroxene in these rocks, along with strong zoning in chromite and

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silicate grains, and the presence of amphibole, all indicate significant overprinting by high-Cr, high-Mg, hydrous melts/fluids and enrichment of fluid-mobile elements in both clinopyroxene and amphibole. Thus, the peridotites are not simple melt residues, and they cannot be used to reliably identify the original compositions of the oceanic lithosphere from which they originally formed. An abundance of fluids is considered to be a characteristic feature of suprasubduction zones and they are thought to have several potential sources, including dewatering of the metamorphic sole, thermal dehydration of the mantle wedge, and inputs of hydrous melts.

Unlike many mantle peridotites that have undergone extensive refertilization and enrichment, harzburgites of the Ladong ophiolite of the North Qilian Orogenic Belt of Tibet retain most of their highly depleted features (4 Xiang Zhou et al., 2023) The highly depleted rocks host podiform chromitites with Cr# values of 65–70 and have depleted LREE patterns, consistent with a residual body that has undergone ~20% partial melting. Less-depleted olivine websterite and wehrlite form numerous lenses in the depleted harzburgites, indicating localized refertilization like many other ophiolitic peridotites.

The Yushigou ophiolite also in the North Qilian Orogenic Belt consists of moderately depleted harzburgite whose major and trace element contents show that it cannot have formed only by partial melting of more enriched peridotites. The harzburgites contain high-Mg olivine and orthopyroxene accompanied by low-Al_2O_3 and low-TiO_2 clinopyroxene (5 Guangying Feng et al., 2021). Most whole-rock samples have depleted, chondrite-normalized, U-shaped REE patterns. The authors propose a two-stage melting and refertilization process similar to that described above. The first-stage involved 20%–25% melting at a mid-ocean ridge, followed by an additional 5%–10% melting that produced LREE-enriched, boninitic magmas in a forearc environment. Reaction between these magmas and the depleted harzburgites is thought to have produced the U-shaped REE patterns.

The Guleman ophiolite of Turkey provides another example in which the mantle section consists chiefly of depleted harzburgite and dunite with some less-depleted varieties, all of which contain moderately high Cr# values of 54–68 (6 Mustafa Eren Rizeli et al., 2023). The less depleted peridotites have significantly higher Al_2O_3 and CaO than the depleted harzburgite and are classified as abyssal in origin, whereas the others are thought to have formed in a SSZ forearc environment. The authors conclude that the mantle section underwent multi-stage melting and refertilization, initially with ~15% anhydrous melting of MORB-like peridotites. During the second stage, the peridotites underwent an additional ~10–28% melting and were then refertilized by hydrous melts in the forearc.

A study of peridotites of the RasKoh ophiolite in western Pakistan by (7 Inayat Ullah, et al., 2022a) revealed three types of peridotite; lherzolite, harzburgite, and dunite, which are thought to be refractory residues after 12–25% partial melting based on the mineral and bulk-rock, major and trace element compositions. Enrichment of LREE and water-soluble elements, such as Rb, Ba and Sr, are thought to reflect late-stage refertilization of the mantle wedge above an intra-ocean subduction zone.

A similar situation was observed in the Dargai Ophiolite Complex of the Indus Suture Zone of Northern Pakistan by (8 Zaheen Ullah, et al., 2022b). They report an upper mantle section composed of Cpx-bearing harzburgites, harzburgites, and dunites. The Cpx-bearing rocks have relatively high Al_2O_3 contents (~20 wt%) and low-Cr chromite (Cr# values of 15–21). In contrast, the depleted harzburgites and dunites are significantly more depleted than the Cpx-bearing varieties. In this case, the authors suggest that the Cpx-bearing peridotites formed by relatively low degrees of partial melting at a mid-ocean ridge, or distant fore-arc setting, whereas the more depleted peridotites and dunites are thought to have formed by a higher, second stage of partial melting.

1.4. Parental magma compositions

One of the major goals of most ophiolite studies is to determine the composition of the parental magma from which the body was formed. As demonstrated above, however, many ophiolites have experienced several episodes of magmatism, during which the compositions of both the melts and the residual mantle peridotites are changed, making it difficult to identify parental melt compositions. Parental melts can also be modified by reaction with crustal sections of ophiolites, particularly when the magmas are distinctly different in composition.

The Troodos ophiolite of Cyprus is one such massif in which the earliest stage of arc tholeiite magma was replaced by younger boninitic melts. (9 Wen-Jun Hu et al., 2022) carried out an interesting study of one of the earliest tholeiitic olivine gabbros in the massif and demonstrated significant reaction between the host gabbro and the later boninitic melts that passed through it when it was a crystal mush. Embayed margins of the original olivine crystals and irregular boundaries of the clinopyroxene attest to dissolution of the olivine and growth of secondary clinopyroxene. The very low TiO_2 concentrations in the secondary pyroxene confirm that the intruding magma was boninitic, similar in composition to the upper pillow lavas of Troodos. The authors emphasize that both the host gabbro and the later melt have been significantly altered by melt/rock reaction, thus the end products are not representative of the parental magmas. Specifically, they suggest that care must be exercised when trying to constrain the parental compositions of the boninite lavas in Troodos.

2. Mineralization in ophiolites

Although chromitites and their PGE minerals are the most characteristic ore deposits in ophiolites, copper, iron, manganese and even REE mineralization is locally present. For example, the Troodos ophiolite of Cyprus is famous for its hydrothermal copper deposits and associated umbers (manganese-rich sediments) both of which have been mined since Roman times.

2.1. Chromite mineral deposits

Despite having been studied for many years, chromitites are still enigmatic features in ophiolites. For example, the ultimate source of the chrome in these bodies is still uncertain, as are the processes that control the size, distribution, and composition of the chromite ore bodies. Of particular interest is what specifically determines the formation of high Al- and high Cr varieties.

2.2. Zambales ophiolite

In an attempt to resolve this question, (10 Peng-Fei Zhang et al., 2021 undertook a new study of the chromitites of Zambales ophiolite in the western Philippines, where high-Cr and high-Al bodies occur as separate blocks in close proximity. The Acoje block is a remnant of Eocene forearc lithosphere that hosts abundant high-Cr chromitites in both the uppermost peridotites of the mantle and the overlying dunite of the Moho transition zone. The uppermost mantle harzburgites vary from Cpx-rich at depth to Cpx-poor varieties at the base of the transition zone, reflecting earlier melt impregnation. Significantly, whole-rock samples of the harzburgites and dunites also become increasingly depleted upward in major and trace element compositions (e.g., Al_2O_3 contents drop from 5.15 wt% to 0.84 wt%), changes that are compatible with a transition from MORB to boninitic melt affinity. Olivine grains in the dunites and chromitites vary widely in their δ7Li values, (primarily from ~ +1 to +10), suggesting that the mantle source of the high-Cr chromitites had been modified by slab fluids with high Li isotopic signatures. The authors suggest that upwelling of hot asthenosphere triggered partial melting of the modified harzburgites during slab rollback to form high-Ca boninitic magmas from which the high-Cr chromitites crystallized.

Thus the hi-grade chromitites in this case were formed by a combination of asthenospheric rise, partial melting and melt-rock reaction, with the chrome being derived from the asthenosphere.

2.3. Bulqiza ophiolite

The Bulqiza ophiolite of Albania also hosts a large deposit of high-Cr chromite that is characterized by having numerous inclusions of diamond, mafic silicates, PGE minerals and sulfides. As described by (11Fahui Xiong et al., 2021), some of the chromite grains contain acicular silicate inclusions aligned with crystallographic planes of the host mineral suggesting formation by exsolution. Many positive and negative crystal faces of cubic silicates also suggest a high-temperature origin. In addition, there are also abundant zircon grains in the chromitites with U/Pb ages ranging from164 to 3354 Ma, all older than the ophiolite. The high Cr# values of the chromite grains suggest crystallization in a suprasubduction zone but the diamonds, sulfides, and PGE minerals suggest formation under reducing conditions, but it is difficult to constrain the formation temperatures, pressures, and redox states of such a complex group of minerals. The old zircon grains were probably sourced from continental crust and carried into the mantle by previous subduction.

2.4. Fe—Ti mineralization

(12 Majid Gasemi Siani et al., 2022) report a well-developed occurrence of economic- grade Fe—Ti oxide mineralization (up to 25 wt% FeO + TiO_2 in the Cretaceous Kaanouj ophiolite of the Makran complex, Southwestern Iran. The oxides are hosted in the crustal section of the ophiolite, which consists mainly of layered gabbro with some sill-like ultramafic bodies. Most of the gabbros contain abundant hornblende and are associated with diabase dikes and sparse granitoids. The mineralization consists chiefly of intergrown titanomagnetite and ilmenite, ilmenite lamella in titanomagnetite and sparse discrete oxide minerals. Microtextures in the gabbros and the abundance of amphibole suggest formation in a water-rich environment fluxed by hydrothermal fluids.

Another example of low-temperature hydrothermal alteration and weak Fe - mineralization in chromitites of the Bursa ophiolite of Turkey is described by (13 Xia Liu et al., 2023). The ore bodies consist chiefly of chromite in a matrix of magnesite and quartz. Many of the chromite grains contain both monophase and multiphase inclusions of magnetite and quartz +/− chlorite, some of which also contain ferrian chromite characterized by higher Cr# values but lower MgO contents and Fe^{3+}/Fe^{2+} ratios than the fresh chromite. The authors suggest that fluxing with carbonated fluids broke down the primary chromite grains, causing redistribution of MgO, reduction of the Fe_2O_3 and growth of ferrian chromite. Trails of small quartz inclusions in the chromite grains indicate healing of the fractures in the chromites.

3. Yarlung-Zangbo suture zone of Tibet and its associated ophiolites

The Yarlung-Zangbo suture zone extends nearly 2500 km from the Namcha Barwa syntaxis in the east to the high Himalaya in the west. It is generally thought to mark the collision between the Eurasian plate and the India Block between ca. 145 and 125 Ma, and the many ophiolite blocks in the suture are interpreted as fragments of Neotethyan oceanic lithosphere. Many studies of the ophiolites have been carried out, particularly in the last 50 years and a broad consensus has developed over the origin and significance of the various ophiolites. However, one large massif in the central part of the belt, the Xigaze ophiolite, remains enigmatic, with each new study reaching different conclusions. Two papers in this Special Issue address the origin of this ophiolite and, as in the past, the authors propose significantly different models of formation.

3.1. Xigaze ophiolite

This ophiolite differs from most of the others in the YZSZ in having a very thin crustal section composed mostly of gabbro lenses, amphibolite dikes, and sills, with very few lavas. Crystallization ages of zircon in the crustal rocks cluster in a narrow range between ca. 124 and 125 Ma. Most of the rocks have MORB-like affinities and the body has generally been assigned to a slow-spreading, mid-ocean ridge, whereas most of the other ophiolites in this belt probably formed in a SSZ environment. Citing the absence of boninites, hi-Mg andesites, island arc tholeiites, and calc-alkaline lavas,(14 Shengbiao Yang et al., 2022) speculate that the massif is a fragment of SSZ-type oceanic lithosphere formed in the Gangdese fore-arc during upper plate extension and rollback of the Neotethyan slab.

In contrast,(15 Yuan Li et al., 2022) suggest that the complex represents an oceanic core complex from which the upper crustal rocks have been stripped off by detachment faulting. This interpretation is supported by the discovery of a serpentinized, low-angle fault zone and by the observation that the mantle rocks in the complex are depositionally overlain by radiolarian cherts similar to those in the broad fore-arc basin south of the suture zone. They recognize three stages of magmatism, all derived from a common source at different times based on cross-cutting relationships between the dikes and sills. The geochemical anomalies in the ophiolite are attributed to magma-fluid interaction enhanced by the observed serpentinized fault zones. In summary, both groups of authors argue for formation at a slow-spreading ridge in a distal fore-arc environment.

3.2. Luobusa ophiolite

The Luobusa ophiolite of Tibet, in the eastern part of the Yarlung-Zangbo suture has been the main target of ophiolite studies in China due to its large, high-Cr chromite deposits. Recent studies by (16 Xiangzhen Xu et al., 2023) have focused on understanding the origin of this ophiolite and its mineralization. As part of this study, two boreholes were drilled to explore the subsurface distribution of the chromitite ores and their relationship to the host rocks.

One hole (LSD-1) reached a depth of nearly 1500 m with a core recovery of 94%, and the other (LSD-2) sampled a 1854-m section with nearly 100% recovery. The drilled section in both boreholes consists of three main units; tectonized mantle peridotites, a crust-mantle transition zone of dunite, and crustal cumulates. The crustal rocks and the tectonites have been transposed by thrust faulting. The mantle sequence has undergone variable degrees of partial melting and records a transition from a MORB-like to an SSZ tectonic environment. The cumulate section contains many repetitive layers that appear to have formed by mineral accumulation rather than tectonic emplacement.

3.3. Amdo ophiolite

Although the Amdo ophiolite is located in the Bangong-Nujiang suture zone of Tibet, we group it here with the massifs described above because it is part of the Tibetan regional geological framework. (17 Ka ng Wu et al., 2021) provide a detailed discussion of the mineralogy geochemistry, and Os isotopic composition of the body and explain its enigmatic character. The ophiolite is a fragment of Neo-Tethyan lithosphere consisting of mantle peridotites, mafic and ultramafic cumulates, massive gabbros, diabases and pillow lavas. The peridotites are mostly refractory harzburgite with <4% clinopyroxene and have coarse-grained, protogranular textures. However small, interstitial olivine grains have low Fo values but extremely high MgO (up to ~17 wt%), which the authors suggest may be due to metasomatism by carbonate-bearing fluids. Also, some of the residual clinopyroxene grains have secondary rims rich in Na_2O suggesting melt metasomatism. Interestingly, the ophiolite is physically associated with high-grade metamorphic rocks and the authors propose that the mineralogy and Os isotopic compositions of the peridotites may represent a mixture of ancient subcontinental lithospheric mantle (SLCM) and Mesozoic oceanic lithosphere.

4. Cuban and Caribbean ophiolites

The origin of the Caribbean plate and its circumferential ophiolites has long been debated. The plate has been variously described as an oceanic plateau produced by a mantle plume or as a fragment of the Pacific plate that was detached by subduction along the western margin of Central America. It has generally been divided into a proto-Caribbean and a Caribbean plate, with the former being the older and denser than the younger.

Ophiolites along the northern margin of Cuba, such as those in the northeastern part of the island, are thought to mark a trench -arc system initiated by southward subduction of the proto-Caribbean plate. A detailed study of the Moa-Baracoa massif by (18 Hui-Chao Rui et al., 2022) shows that most of the crustal rocks can be divided into two parts - a sequence of gabbro sills and dikes with zircon U—Pb ages of 136.7 ±1.8 Ma to 122.3 +/− 0.5 Ma that are compositionally similar to mid-ocean ridge varieties, and a group of layered gabbros with zircon U/Pb ages ranging from 158 to 2556 Ma. Rocks of the former group have geochemical compositions similar to those of ocean-ridge gabbros whereas the layered gabbros have mineralogical and chemical characteristics indicating derivation from hydrous magmas in a supra-subduction zone. Low $^{87}Sr/^{86}Sr$ ratios suggest that all the gabbros were derived from a depleted source. The authors suggest that these crustal rocks were all formed during subduction of the proto-Caribbean plate, which was initiated prior to 137 Ma. If correct, all the older zircons in the layered gabbros are most likely subducted detrital grains.

A related study of an ophiolitic-volcanic arc complex in central Cuba by (19 Xiaolu Niu et al., 2022) supports this basic model. These authors suggest that a typical trench-arc-basin system was generated in the region at ca. 135 Ma, also by southward subduction of the proto-Caribbean plate that continued to ca. 81 Ma.

5. Ophiolites of the Central Asian orogenic belt (CAOB)

The CAOB is a vast expanse that extends E-W across North China. It contains many different lithologies, most of which occur as poorly exposed tectonic fragments. The discontinuous outcrops and tectonic disruption make it difficult to discern large-scale tectonic events. Even when outcrops are present, they typically consist of individual domains that may, or may not, be connected at depth (e.g., the Hegenshan ophiolite complex).

A long-standing debate regarding the regional geology of the CAOB has been whether or not it includes a Mid-Paleozoic collisional event.(20 Jianfeng Liu et al., 2022) report the discovery of ophiolitic fragments in the Late Devonian Diyanmiao Mélange in southeastern Inner Mongolia and compare them with previously reported ophiolites in the same region. On the basis of a strong similarity between the two, the authors argue for the existance of a mid-Paleozoic ocean basin. They support this argument with geochemical data from the mafic volcanic rocks that imply an evolutionary trend from ocean ridge to SSZ environments. Synthesizing the available data, they postulate the former presence of a trench-arc-basin system in the region, and further propose that the eastern section formed on oceanic basement, whereas the western part formed on continental basement in a manner analogous to the modern northwestern margin of the Pacific Ocean.

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