Overview of the Special Issue “The Forefront of Mantle Material Research”

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I. Introduction

The Special Issue “The Forefront of Mantle Material Research” contains 10 review articles on petrologic and related studies of mantle materials, in which the authors describe various aspects of mantle materials and refer to future perspectives in individual research fields. The main target of the papers in this special issue is the upper mantle, from which materials can be obtained on the surface through the Earth’s dynamic activities. We know that as we go deeper into the Earth’s interior, its constituents become more uncertain; the upper mantle, which can barely be examined by us in terms of its constituents, places constraints on the compositions of deeper parts of the Earth. The upper mantle is in direct contact with the overlying crust via the Mohorovičić discontinuity (= Moho), suggesting its importance as a key to our understanding of the chemical evolution of the Earth as it formed the crust. We hope this special issue will provide readers with a better understanding of the Earth.

II. Our search for the mantle materials

The mantle occupies about 70 wt% of the entire Earth, and is the layer that surrounds the central core, so it needs to be examined in detail to unravel the Earth’s structure and evolution. Although the crust is thin, 6–7 km under the sea and up to 40 km on a continent, compared to the diameter of the Earth, around 6300 km, we have not been successful in extracting mantle materials from beneath the crust at any points desired on the Earth. Instead, we have tried to find mantle-derived rocks supplied to the surface by the

Earth’s dynamics, in order to understand what constitutes the mantle. The mantle-derived rocks thus obtained are mainly peridotites, and can be classified into two groups: one forms so-called solid-intrusive massifs (Pictorial 1), and the other occurs as mantle-derived xenoliths in magmas (Pictorial 2).

The solid-intrusive peridotite massifs are mainly formed through the emplacement of deep-seated rocks of one plate into or on the crustal rocks of another plate at convergent plate boundaries. They are also called orogenic peridotites or Alpine-type (or alpine) peridotites. Ophiolites are thrust-bounded slices of a kind of oceanic lithosphere, and their mantle section provides us with important information on mantle materials. One of the advantages of these mantle materials obtained as tectonic slices is the vast area of exposition, which is up to 500 km long and 50 km wide for the Oman ophiolite of the Arabian Peninsula (Pictorial 1). Good exposures of the boundary between gabbroic rocks and peridotites are another merit, where we can clearly observe the crust-mantle boundary to understand the petrologic nature of the Moho (Pictorial 1). A distinct disadvantage of such mantle-derived materials is low-temperature and low-pressure alterations to various degrees under hydrous conditions during and after emplacement. Peridotites formed in the mantle are readily converted into serpentinite under crustal conditions, losing the initial characteristics obtained in the mantle (Pictorials 1 and 3). Old ophiolites have, therefore, a lower probability of giving us information on mantle conditions than young ophiolites (Pictorial 1). Mantle-derived rocks are also exposed as a tectonic high,

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called oceanic core complexes, along oceanic fracture zones around mid-ocean ridges of the current ocean floor (described below), and are also solid-intrusive materials (Pictorial 1). They also occur as seamounts or form landward slopes on the forearc sea floor.

Serpentinization has thus presented a problem for us in extracting information on the mantle from mantle-derived rocks exposed on the surface. Many geoscientists are, however, now interested in serpentinites and serpentinization because of their unique and important properties (e.g., Kasahara *et al.*, 2003). They seem to be saviors, answering various unsolved questions in Earth sciences. As stated above, olivine, the main constituent of the upper mantle, is easily converted into serpentines and other minerals under low-temperature, low-pressure, hydrous conditions; peridotites are readily converted into serpentinites over time if emplaced in the crust (Pictorial 3). Conversely, the serpentinites return to peridotites with the release of water when heated and/or compressed. These changes between peridotites and serpentinites are expected to occur in the crust and mantle beneath the ocean floor and island arcs, and are closely involved with changes in the physical properties of peridotites, transportation of water and other elements, and construction of a sub-seafloor ecosystem (e.g., Ohara *et al.*, 2012). It is well known that serpentinization dramatically changes the physical properties of peridotite. For example, serpentinite is equivalent to the lower crust in physical properties, and serpentinization may play a role in the formation of a kind of Moho (= Hess model; Hess, 1962).

The peridotite xenoliths, on the other hand, have the great advantage of preserving information on the mantle because of their rapid transportation from the upper mantle to the surface by magmas. Individual xenoliths are small, usually less than several tens of centimeters across compared to the solid-intrusive massif above. It is generally difficult to infer relationships between rock species due to their occurrence as small rock pieces (Pictorial 2). In addition, peridotite xenoliths are more or less altered by reactions with the host magma under low-pressure and high-

temperature conditions en route to the surface.

We have tried to overcome the various problems above (e.g., secondary alterations and small size) in our research on mantle materials. Our acquisition of them totally depends on the Earth's dynamics, and is inevitably a passive approach to sampling. This means that the mantle materials obtained are representative of limited conditions. If we could carry out active sampling of the mantle, i.e., if we obtained mantle materials from any desired points on the Earth, we could reach new horizons in our understanding of the mantle and, in turn, of the whole of the solid Earth. An example of actively sampling mantle materials is Mohole (or oceanic mantle drilling) using the famous research vessel Chikyu. Although mantle drilling can now be done at very limited areas of the ocean floor due to current technological restrictions, sampling of mantle materials from an area of a known geological and geophysical context is revolutionary for Earth sciences. Some papers in this special issue, e.g., Michibayashi (2015), Takano and Ohkouchi (2015) and Morishita (2015), refer to the Mohole as active mantle sampling.

The mantle research methods stated above aim to find mantle-derived materials and touch them for direct observations and analyses, and are called petrologic (or geologic) research approaches. This enables us to directly know the physical and chemical properties of the upper mantle, although in a very limited tectonic setting. In contrast, we can grasp geophysical properties, e.g., seismic and geomagnetic properties, of the upper mantle on a global scale. This geophysical research approach is, however, indirect, and is contrastive to the petrologic approach in many aspects. We can estimate the bulk chemical composition of the mantle from chondrite, assuming the layered structure of the Earth (e.g., Ringwood, 1975). If we subtract 30 wt% of iron and other elements equivalent to the Earth's core composition from the bulk composition of carbonaceous chondrite, which is almost equivalent to the Earth in the abundance of non-volatile elements, we obtain the mantle composition. This is the so-called cosmo-geochemical approach to

mantle research, and is also contrastive to the petrologic approach. This is especially important to constrain the materials constituting lower parts of the mantle, which are invisible using the petrologic method. Primitive chondrites are rich in olivine, and somewhat resemble peridotites in composition (Pictorial 4). Both geophysical and cosmo-geochemical approaches agree with the petrologic approach for peridotitic compositions of the mantle.

III. Overview of the contents of this special issue

Kodaira and Fujie (2015) review recent results of their own studies on the seismological properties of the oceanic lithosphere, which refer to what drives the oceanic plate. As stated above, direct information from mantle-derived rocks is available only for limited settings of the mantle, and is required to be generalized globally using its physical properties, especially seismic ones, which can be broadly obtained on the Earth. Their importance is clearly shown by the fact that the Moho and other discontinuities within the Earth's interior are defined only seismically.

Morishita (2015) proposes that we re-examine the oceanic mantle in terms of the inhomogeneity of the mantle, which has been a fundamental problem. The Earth's mantle has a complicated composition by nature; it is depleted in magma components via partial melting/melt extraction, and becomes complicated with the addition of melt components (crustal materials) and refractory mantle (the uppermost mantle) via subduction of the oceanic plate. Mid-ocean ridges mark the output of a material flow from the mantle, which possibly causes the exposure of various kinds of peridotite, including MORB residues related to modern and ancient melting events. Morishita (2015) attempts to find this heterogeneity of the mantle directly from mantle peridotite exposed on the ocean floor.

Matsukage (2015) summarizes recent experimental studies on the petrologic properties of the mantle deeper than the upper mantle, based on the petrologic framework of the upper mantle we have constructed. The procedure of Matsukage

(2015) for synthetic mantle materials is convincing because the author is familiar with the upper mantle materials through her own work. Matsukage (2015) also refers to limitations of the petrologic approach for researching the mantle.

Hirauchi and Katayama (2015) summarize the importance of serpentinites and serpentinization of mantle peridotites. Serpentinites are common as alteration products of mantle peridotites uplifted in the crust as described above. They are also formed widely through in-situ hydration of the mantle peridotite within the mantle wedge, especially around its tip. Hirauchi and Katayama (2015) state the important roles of serpentinites in dynamic processes both in the crust and in the upper mantle.

Michibayashi (2015) reviews recent advances in studies on petrofabrics, especially crystallographic fabrics, of peridotites and their bearing on the seismic (P-wave) velocity structure of the upper mantle. Peridotites flow along with recrystallization in a solid stage, as do glaciers. A fabric analysis of mantle-derived peridotites enables us to unravel not only mantle dynamics but also the emplacement processes of a solid-intrusive peridotite massif. The method described in Michibayashi (2015) is interdisciplinary, bringing together the physics and chemistry of the mantle, and is becoming more important for future mantle studies.

Obata (2015) summarizes the petrologic properties of pseudotachylytes produced by local melting and extreme comminuting of mantle peridotite. It also contains short reminiscences of the author, a pioneer of pseudotachylyte studies. Obata (2015) suggests that analyzing this apparently strange and rare kind of rock will be useful for our understanding of earthquakes and related phenomena within the mantle.

Yamamoto *et al.* (2015) review analyses of CO₂-rich fluid micro-inclusions in mantle minerals. Carbon dioxide is the most common species of carbon, which is important as a redox state indicator, in the upper mantle condition. A series of studies by Yamamoto and his co-workers indicates the importance of CO₂-rich inclusions as sources of information on the upper mantle.

Kobayashi *et al.* (2015) start with the fundamentals of halogens and fluid inclusions, and subsequently review the behaviors of halogens in the mantle. The key phenomenon of halogen behavior in the mantle is the release of fluids from the oceanic slab beneath arcs such as the Japan archipelago. The authors' original research on traces of halogens derived from the slab deserves our attention.

Kawamoto (2015) describes fundamental behaviors of water-rich fluids supplied to the mantle wedge from the slab. Although their important role in arc magma genesis is well known, Kawamoto (2015) presents a new model of the genesis of arc magmas after discussing the formation and decomposition of supercritical fluids between melts and water-rich fluids.

Takano and Ohkouchi (2015) review the origin of organic matter in the mantle after summarizing the fundamentals of the origins and behaviors of carbon and nitrogen in the Earth system. This issue still remained unclear, although it emerged around 1990. It is closely related to the origins of the undersea extreme biosphere, to which we should pay attention.

IV. Concluding remarks

This special issue cannot cover all fields of mantle material research. Please refer to the literature listed by the authors of articles in this issue for related subjects. Special issues in other journals (e.g., Arai and Abe, 2005; Morishita *et al.*, 2012) and other review articles (e.g., Arai and Ishimaru, 2008) are also available to readers who are interested in mantle petrology. The upper mantle contains pyroxene-rich rocks, such as pyroxenites and eclogites, and chromitites that are rich in chromian spinel, as well the peridotites discussed by many authors in this issue. Many geoscientists are now interested in a particular rock, chromitite, as an indicator of peridotite-melt reaction and mantle recycling (e.g., Arai, 2010, 2012).

The publication plan of this special issue was initiated by a suggestion of the late Prof. N. Shikazono, a former Editor-in-Chief, to S. Arai upon his retirement from Kanazawa University.

It is unfortunate that he died shortly before he could see this issue. I acknowledge his contributions and pay my last respects to him again on this occasion. I am very grateful to the authors who submitted the articles contained in this issue, and to the reviewers of their manuscripts for their support. I thank K. Michibayashi, N. Abe, A. Tanaka, and Y. Kumaki for their efforts in editing this issue. M. Michibayashi kindly checked a draft of this preface.

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