論文の内容の要旨

Thermal state of the upper mantle and the origin of the ophiolite pulse in the Cambrian-Ordovician time

（カンブリア-オルドビス紀における上部マントルの熱状態とオフィオライトパルスの成因）

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The Earth releases heat into the space, which drives internal and surface processes, such as magmatism, plate tectonics, and evolution of the surface environment. In this regard, the thermal history of the Earth is an essential part of its evolution. In order to better understand the past and future evolution of the Earth, it is important to reveal temporal changes of the thermal state of the mantle, which occupies 80 vol% of the solid Earth transferring heat to the Earth's surface by thermal convection. Ophiolites, suites of temporally and spatially associated ultramafic, mafic, and felsic magma-related rocks, were formed and exhumed at least since the Paleoproterozoic to the very recent past and may provide rich information on the thermal history of the Earth. Their age distributions show confined periods with high rates of occurrence in late Neoproterozoic, Cambrian-Ordovician, and Jurassic-Cretaceous times, which are called "ophiolite pulses".

The ophiolite pulses have been explained by highly active superplumes (superplume model). However, the Cambrian-Ordovician pulse has two critical geological features that cannot be explained by such superplume model: predominance of subduction-related ophiolites and scarcity of plume-related magma activities. We addressed this issue by quantitatively estimating a mantle potential temperature (MPT) from ~500 Ma subduction-related ophiolite, Hayachine-Miyamori ophiolite. We developed a novel method to overcome difficulties in MPT estimation for an arc environment by using porphyritic ultramafic dikes showing flow differentiation, which have a record of intact chemical composition of a primitive magma including its water content because of their high pressure (~0.6 GPa) intrusion and rapid solidification. The melt segregation conditions for the primary magmas are estimated to be ~1430 ℃, ~5.0 GPa. Geochemical data of the dikes show decompressional melting of a depleted source mantle in the garnet stability field without a strong influence of slab-derived fluids. These results combined with the extensive fluxed melting of the wedge mantle prior to the dike formation indicate sudden changes of the melting environment, its mechanism, and the source mantle from extensive fluxed melting of the wedge mantle to decompressional melting of sub-slab mantle most plausibly triggered by a slab breakoff. The MPT of the sub-slab mantle is estimated to be ~1350 °C. The value is within the range of MPTs estimated from rare Cambrian-Ordovician mid-ocean ridge type ophiolites (1330 – 1410 ℃) by applying our MPT estimation method. The range of MPT thus represents the global thermal state of the Cambrian-Ordovician upper mantle. Furthermore, they are essentially the same as the global MPTs of the present-day upper mantle. We conclude that the Cambrian-Ordovician ophiolite pulse dominated by the supra-subduction type is not attributable to high-temperature of the upper mantle as proposed by the superplume model. The common generation of magmas by decompressional melting of MORB mantle source at high pressure during the Cambrian-Ordovician ophiolite pulse is also supported by the compilation of REE ratios of extrusive rocks from the world ophiolites belonging to the ophiolite pulse. We propose frequent occurrence of slab breakoff during the Cambrian-Ordovician ophiolite pulse (slab breakoff model). The assembly of the Gondwana supercontinent accompanied by continent-continent and/or continent-arc collisions caused frequent occurrence of slab breakoff and following obduction of many ophiolites.

We further examined evolutional dynamics of the slab breakoff process in the Cambrian-Ordovician northeast Japan in high time resolution on the time scale of a few million years. We used chondrite-normalized REE ratios of clinopyroxene in the cumulate to develop proxies for magma generation conditions in the mantle: (Sm/Gd)n, (Dy/Yb)n, and Ce/Sm)n for degree of melting (F), percentage of melting in the garnet stability field in total melting (PMGF), material influx rate (β), respectively. We clarified temporal change of melting conditions recorded in the Cumulate Member and ultramafic dikes of the Hayachine-Miyamori ophiolite after establishing stratigraphy of the cumulate. The stratigraphic variations of the PMGFs, Fs, and βs show large variations in the middle and lower zones but are consistent and close to those of the ultramafic dikes in the upper zone, showing a tendency of convergence to the values of the ultramafic dikes. The F and β show overall decreases with stratigraphic horizon from the lower to the upper zone, but the PMGF does not. There is no correlation between F and β if data with high values of β are ignored, indicating that the melting mechanism is dominated by decompressional melting with minor contribution of slab-derived fluid. There is a weak overall correlation between F and PMGF, and the correlation is very tight if data with high values of β are ignored. On the basis of these variations, we propose the following scenario for the evolution of slab-breakoff in the Cambrian-Ordovician northeast Japan arc (Fig. 1). The slab breakoff took place at the depth of ~140 km and triggered counter flows and passive upwelling of the sub-slab mantle from various depths ranging 140 – 250 km, which induced decompressional melting generating magmas for the lower and middle zones of the Cumulate Member (Figs. 1a and b). In this initial stages, melting of the wedge mantle affected by slab-derived fluids may have taken place. As the slab sunk, the flux melting became suppressed, and upwelling and decompressional melting continued, but the upwelling depths tend to have been narrowed and confined in the depth range 160 – 190 km, which generated magmas for the upper zone of the Cumulate Member (Fig. 1c). After the formation of the Cumulate Member, the counter flows waned, and the only a very small amount of magma formed by decompressional melting at the depth of ~170 km, which generated magmas for the ultramafic dikes (Fig. 1d).

The Fe-Mg heterogeneity developed in tectonite xenoliths in cumulate and that at the boundary between the ultramafic dike and the host cumulate give constraints on the duration of magmatism of the Cumulate Member and subsequent cooling and the duration of the cooling after cessation of the magmatism, respectively, the difference of which gives the time scale of magmatism of the Cumulate Member. We thus succeeded in estimation of time scale of slab breakoff event, which is shorter than a few million years. The catastrophic nature of slab breakoffs may trigger episodic cooling of the mantle from the upper thermal boundary layer of the Earth if its frequent occurrence culminates in an ophiolite pulse.

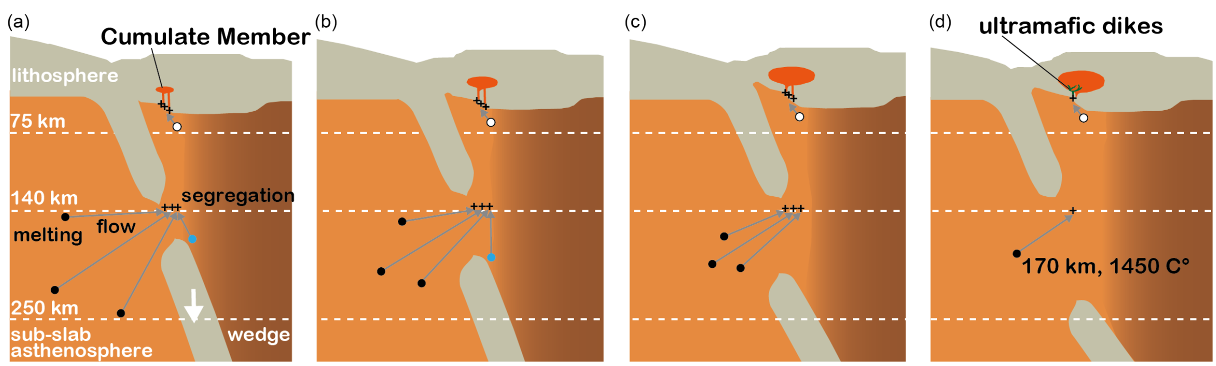

Fig. 1: Evolutional slab breakoff model for the Cambrian-Ordovician northern Japan. (a) A slab rupture took place at a depth of ~140 km and triggers passive upwelling of sub-slab mantle from various depths ranging 140 – 250 km (shown by black dots with arrows). A limited upwelling from the wedge mantle affected by slab-derived fluids (shown by a blue dot with arrow) may have taken place. (b) As the slab sunk, the depths of upwelling were converged to 140 – 220 km. (c) In the later stage, the flux meltings became suppressed and the upwelling depths were converged to 160 – 190 km. (d) After the formation of the Cumulate Member, a small amount of melting took place at ~170 km by waned upwelling of the sub-slab mantle.