

論文の内容の要旨

Monazite as a tracer of crustal evolution

(モナザイトからたどる地殻進化)

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Orogeny has played an important role in the evolution of continental crust. Orogeny is divided into two types (Dewey and Bird, 1970; Matsuda and Uyeda, 1971): Pacific and collisional types. Pacific type orogeny, associated with the subduction of oceanic plate, is vital for the formation of juvenile continental crust. In contrast, collision type orogeny, causing buoyant continental collision, is significant for the reworking of continental crust. Constraints on the nature and timing of orogeny are essential for a better understanding of crustal evolution over the Earth's history.

Monazite, a light rare earth element (REE) phosphate, has a potential to be a powerful tracer for crustal processes. Monazite has been used as a geochronometer, geochemical tracer, and Nd isotopic tracer. The wide occurrence of monazite enables its various applications to the petrogenesis of granitic and metamorphic rocks. Monazite is also suited as a detrital high-resolution archive of orogenic events. The objective of this study is to advance our understanding of monazite geochemistry in order to use monazite as a tracer of crustal evolution.

It has been demonstrated that detrital monazite potentially provides more detailed insights in various scale orogenic events as compared to detrital zircon (Hietpas et al., 2010). Unfortunately, the various origins of monazite bring the difficulty in an interpretation of detrital monazite age peak. This difficulty can be overcome by linking geochemical fingerprints of monazite and its source rock types. Trace element composition is the key to understand the linkage due to its high dependence on co-existing minerals via element partitioning. However, there are two obstacles in monazite trace element geochemistry: (i) analytical problem in REE determination by laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) and (ii) shortage of trace element data especially for igneous monazite. To overcome these obstacles, I attempted to develop a method of accurate REE analysis. Furthermore, trace element systematics of igneous monazite has been studied by the comprehensive analyses of monazites from various granitic rocks. The synthesis of reliable datasets of monazite chemical compositions demonstrates the utility of monazite REE-Th-U systematics as

an indicator of source rock type. The improved analytical method and geochemical provenance indicator were applied to detrital monazites from major African rivers to obtain the constraints on the timing and nature of Pan-African orogenic events.

Accurate REE determination of monazite by LA-ICP-MS can be inhibited by oxide interferences. Yet, the oxide production mechanism has been poorly understood. Here I determined the oxide production rates (MO^+/M^+ ratios) of 15 REEs, Th, and U using synthetic and natural phosphates. I found two contrasting oxide production behaviors against the Ar sample gas flow rate, depending on the MO^+ dissociation energy ($D_0(MO^+)$): the MO^+/M^+ ratios of elements with $D_0(MO^+) \geq 7$ eV increased with the gas flow rates from 0.85 to 1.00 L min^{-1} , whereas those with $D_0(MO^+) < 7$ eV were nearly constant. Moreover, while there is a generally positive relationship between $\log(MO^+/M^+)$ and $D_0(MO^+)$ among all elements, only the former showed a linear correlation whose slope increased with the gas flow rate. These results indicate that oxide production is a combined result of the following two processes: (i) the equilibrium reaction of $MO^+ \leftrightarrow M^+ + O$ within the plasma and (ii) the bonding of M^+ and O through collisions followed by radiative transition in the interface region. Oxide production through the first process was significant relative to the second process only when the elements had $D_0(MO^+) \geq 7$ eV and the gas flow rate was high enough to decrease the plasma temperature to ~ 8000 K. We further demonstrate the significance of middle-REE oxide interference on heavy-REEs during the analyses of monazites from pegmatites and garnet-bearing metamorphic rocks, which should be corrected using the determined oxide production rates.

Trace element systematics of igneous monazite has not been well understood so far. I conducted trace element and Nd isotope analyses of monazite in granitic rocks from the Busetsu pluton of the Japan arc to investigate the change of monazite geochemical signatures with granitic magma evolution. Furthermore, by integrating of monazite Nd-isotope and plagioclase Sr-isotope microanalyses, I revisited the magma sources, which were inferred from conventional whole-rock chemistry. The studied monazite grains show variations in the degree of negative Eu anomaly, Ce/Gd, and Th/U ratios. These variations correlate with each other, which can be accounted for by the fractionation of plagioclase and monazite considering the strong partitioning of Eu to plagioclase and of light-REE and Th to monazite, respectively. In the context of Rayleigh fractionation model, the degrees of plagioclase and monazite fractionation were quantitatively evaluated and found to be compatible with the geologic and petrologic observations. The isotopic data revealed significant variations in monazite $^{143}Nd/^{144}Nd$ ratio and plagioclase $^{87}Sr/^{86}Sr$ ratios, which are obviously larger than those of whole-rock samples. This finding reflects that the multiple sources were involved in the generation of the granitic magma. It is demonstrated that an integration of geochemical and isotope microanalyses of monazite enables tracking open system magmatic processes.

To link monazite composition with igneous petrogenesis and differentiation, we carried out

comprehensive LA-ICP-MS measurements of REE-Th-U abundances in monazites from magnetite-series and ilmenite-series granitic rocks across the Japan arc. The data revealed systematic differences in monazite composition between magnetite-series and ilmenite-series samples, and between pegmatites and granites. In ilmenite-series granitic rocks, monazites from pegmatites showed larger negative Eu anomalies, lower light-REE/middle-REE ratios, and higher middle-REE/heavy-REE ratios than those from granites. These geochemical variations were attributed to significant fractional crystallization of feldspars, monazite, xenotime, and garnet during differentiation in relatively reduced peraluminous granitic magmas. In contrast, there was no remarkable difference in the REE fractionation pattern between magnetite-series pegmatites and granites. Furthermore, the magnitudes of the negative Eu anomalies in the magnetite-series monazites were smaller than those observed in the ilmenite-series samples. These features were interpreted to reflect the suppression of monazite, xenotime, and garnet fractionation and limited Eu incorporation into fractionating feldspars in relatively oxidized and non-peraluminous magmas. A comparison of the present data with previously reported data indicates that igneous monazites from granitic rocks are distinct from metamorphic monazites in REE composition, especially due to their larger negative Eu anomalies. Metamorphic monazites are further grouped into garnet-rich metamorphic with high middle-REE/heavy-REE and garnet-poor metamorphic origin with the low ratio. This finding highlights the potential utility of monazite REE-Th-U systematics as a provenance indicator for detrital monazites.

The geochemical indicator for source rock type was applied to detrital monazite from large rivers in Africa. We carried out U-Pb dating and geochemical analyses of approximately 500 detrital monazites from the Nile, Niger, Congo, Zambezi and Orange Rivers. The U-Pb dating defined age peaks at ~600 Ma for the Nile, ~580 Ma for the Niger, ~630, ~610 and ~550 Ma for the Congo, ~500 Ma for the Zambezi and 1200–1000 Ma for the Orange. All but the Orange age peaks correspond to the period of the Pan-African Orogeny. In the Niger, Congo and Zambezi, the Pan-African age peaks are 20–40 Myr younger than those defined by the detrital zircons from the same rivers. Based on the geochemical provenance indicator, the transition between igneous, garnet-rich, and garnet-poor metamorphic events were described in the age spectra of detrital monazite. The interpreted age peaks, together with the discrepancy between the detrital monazite and zircon ages, suggest that the Pan-African monazite age peaks essentially reflect the timing of syn- to post-collisional metamorphic events in the source terranes, whereas the detrital zircons ages provide a more representative record of magmatic events. The results imply that the Pan-African Orogeny was promoted by pre- to syn-collisional felsic magmatism during the early stages and, 20–40 Myr later, it was dominated by syn- and/or post-collisional metamorphism.