Geochemically heterogeneous Martian mantle inferred from Pb isotope systematics of two depleted shergottites Yamato 980459 and Dar al Gani 476

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Introduction: Geochemical studies of shergottites, Martian basalts, have played key roles in understanding the geochemical evolution of Martian interior such as core segregation, mantle differentiation, crust formation, and magmatic petrogenesis [e.g., 1, 2]. Studies on the ^{87}Rb-^{87}Sr, ^{147}Sm-^{143}Nd, and ^{176}Lu-^{176}Hf systematics of shergottites demonstrate that their parental magmas have distinct geochemical signatures and that they are divided into three subgroups of geochemically depleted, intermediate, and enriched shergottites. Their varied geochemical signatures suggest that there are at least two end-member reservoirs in the Martian mantle: geochemically depleted and enriched reservoirs [e.g., 3]. Although the origin of the geochemically enriched reservoir is still in ongoing debate, it has been widely accepted that the geochemically depleted reservoir represents the primitive Martian mantle which is originated from the early stage cumulates in the Martian magma ocean. Therefore, comprehensive geochemical analyses of depleted shergottite source reservoirs would shed light on the early evolution and primary differentiation processes of Mars.

Lead isotope systematics has been widely used as a powerful geochemical tracer for examining the Earth's crust-mantle evolution, although it has not been well applied to studies on the Martian mantle due to the difficulty in discriminating pristine Pb in Martian meteorites from terrestrial contamination. There are only two reliable Pb isotopic data of the geochemically depleted shergottite source reservoirs, which are from geochemical analyses of Tissint [4] and Queen Alexandra Range (QUE) 94201 [5]. This study newly reports the Pb isotopic compositions and µ-values ($^{238}U/^{204}Pb$) of the source reservoirs of two geochemically depleted shergottites Yamato (Y-) 980459 and Dar al Gani (DaG) 476 in order to investigate the Pb isotopic systematics in the geochemically depleted Martian mantle. These two shergottites were selected because their initial $\varepsilon^{143}Nd$ isotopic compositions suggest that their source reservoirs are distinct from those of Tissint and QUE 94201 [6,7]. Our new Pb isotopic data for two shergottites and the obtained µ-values regarding their source reservoirs led to better understanding of the geochemically heterogeneous Martian mantle and its formation processes.

Analytical methods: We prepared whole-rock powders from Y-980459 and DaG 476 fragments. All fragments examined in this study were from sample interior, which unlikely included terrestrial alteration/weathering phases formed during their residence in the Antarctic and desert, respectively. To eliminate terrestrial contaminants from these whole-rock powders, we conducted the 5-step acid-leaching experiments following the method as described in [4]. Then, the five leachates and the final residue fractions were separated into two aliquots in a ratio of one to nine. One-tenth solutions were used for the trace element concentration analysis by an ICP-QMS (X series II, Thermo-Fisher Scientific) housed at Tokyo Tech, while nine-tenth solutions were used for Pb isotopic analysis by a TIMS (Triton-*plus*, Thermo-Fisher Scientific) housed at Tokyo Tech. The initial Pb isotopic compositions of Y-980459 and DaG 476 were estimated from age-correction calculations based on their measured Pb isotopic compositions and U/Pb ratios in the final residue fractions. We employed their reported ^{147}Sm-^{143}Nd crystallization ages (472 Ma for Y-980459 [6]; 474 Ma for DaG 476 [7]) for the age-correction calculation.

Results and Discussion: The final residues from Y-980459 and DaG 476 have less radiogenic Pb isotopic compositions than their corresponding leachates. Our age-correction calculations provide the initial $^{206}Pb/^{204}Pb$ isotopic compositions of Y-980459 and DaG 476 to be 11.50 ± 0.04 and 11.48 ± 0.04, respectively. These initial Pb isotopic compositions are consistent within their analytical uncertainties, and are more radiogenic than those of Tissint ($^{206}Pb/^{204}Pb$ = 10.82 ± 0.08 [4]) and QUE 94201 ($^{206}Pb/^{204}Pb$ = 11.086 ± 0.008 [5]). Then, we calculated Pb isotopic evolutions and µ-values in the Y-980459 and DaG 476 source reservoirs based on the two-stage mantle evolution model [4]. The µ-values in the Y-980459 and DaG 476 source reservoirs were calculated to be 2.32 ± 0.06 and 2.33 ± 0.07 as the present sources, respectively (Fig. 1). These µ-values of the Y-980459 and DaG 476 source reservoirs are clearly distinct from those in the Tissint and QUE 94201 source reservoirs [4,5]. Thus, our study indicates the existence of the geochemical heterogeneity in the geochemically depleted shergottite source mantle in terms of Pb isotope systematics.

The higher µ-values in the Y-980459 and DaG 476 source reservoirs are suggestive of their more incompatible-element-enriched signatures than those of the Tissint and QUE 94201 source reservoirs. These geochemically enriched signatures are consistent with their $^{147}Sm/^{144}Nd$ compositions; the Y-980459 and DaG 476 source reservoirs have lower $^{147}Sm/^{144}Nd$ compositions than those of Tissint and QUE 94201 [6, 7]. The μ-value and $^{147}Sm/^{144}Nd$ variations among the geochemically depleted shergottite source reservoirs are explained by a mixture between two end-member components in the Martian mantle. These results indicate that the Tissint and QUE 94201 source reservoirs represent more primitive Martian mantle signatures, while the Y-980459 and DaG 476 source reservoirs formed by an incorporation of a small component from the geochemically enriched end-member reservoir into the primitive Martian mantle. The μ-values of the geochemically depleted shergottite source reservoirs also show the negative correlation with their short-lived isotopic signatures of $\varepsilon^{182}W$ (Fig. 2). The variation in $\varepsilon^{182}W$ was only produced in the early processes in the solar system, which occurred until their parent nuclide of ^{182}Hf became extinct. Its half-life indicates that the $\varepsilon^{182}W$ variations only reflect igneous events that occurred within ~50 Myr after the solar system formed [e.g., 8]. Therefore, the correlation with the $\varepsilon^{182}W$ compositions suggest that the distinct μ-values among the depleted shergottite source reservoirs resulted from interactions between the two end-member reservoirs that formed during the primary differentiation processes on Mars.

Summary: We determined μ-values in the Y-980459 and DaG 476 source reservoirs to be 2.32 ± 0.06 and 2.33 ± 0.07 as the present sources, respectively. These μ-values are distinct from those of the Tissint and QUE 94201 source reservoirs, suggesting the Pb isotopic heterogeneity in the depleted shergottite source mantle. A correlation between these μ-values and their $\varepsilon^{182}W$ compositions suggests that this geochemical heterogeneity resulted from interactions between two end-member reservoirs that derived from the primary Martian differentiation at ~4.5 Ga.

Figures:

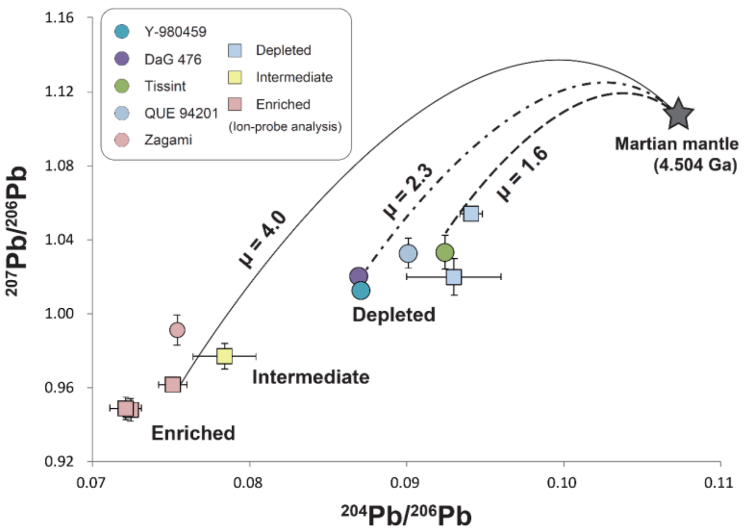

Fig. 1 Pb isotopic evolution of the shergottite source mantle reservoirs. The evolution curves are delineated by solid and dashed lines for geochemically enriched and depleted source reservoirs, respectively. Circles represent the Pb isotopic data from solution analyses by TIMS or ICP-MS [4, 5, 9], while squares represent the ion-probe analyses [10].

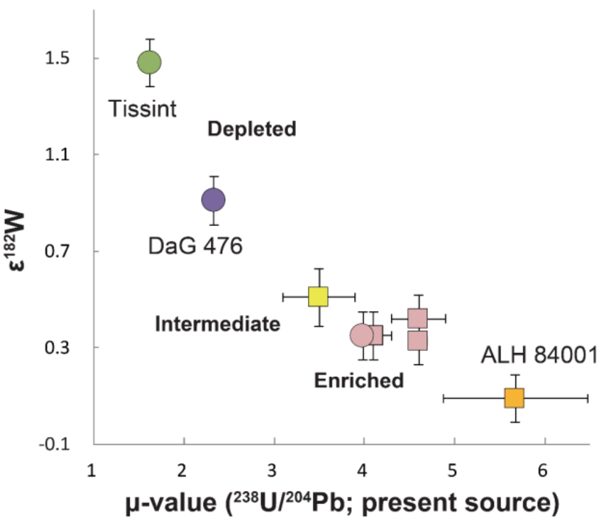

Fig. 2 Calculated μ-values and $\varepsilon^{182}W$ compositions of the shergottite source reservoirs. The symbols are as in Fig.1. The $\varepsilon^{182}W$ compositions are from [8].

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