Possible Origins of Magmatic and Isotopic Heterogeneity in Zagami.

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Introduction:

Initial $^{87}Sr/^{86}Sr$ ratios, textural variations, and other indicators of lithologic diversity show that the shergottite Zagami formed in a heterogeneous lava flow [1,2]. Here we evaluate possible origins of this heterogeneity and conclude that processes of crustal contamination similar to those described, for example, for continental flood basalts of Yemen [3] and Kirkpatrick basalts of the Queen Alexandra Range of Antarctica [4] probably were involved.

Magmatic history of Zagami:

McCoy et al. [2] suggested that observed lithologic heterogeneity in Zagami could result from pulses of new magma being injected into a partially-crystallized near-surface magma body. Treiman and Sutton [5] concluded that similarities and differences among Zagami samples could be explained within the context of a slightly differentiated magma body – either a shallow intrusive, or lava flow. The large grain size of a coarse-grained lithology, evidence for a two-stage cooling history, and the presence of cumulus pyroxene caused Brearley [6] to favor final crystallization within a shallow sill or dike. McCoy et al. [7] suggested that the lithologic diversity represented by “Normal Zagami” (NZ), a Dark Mottled Lithology (DML), and late-stage melt pockets was a sequence of progressively increasing fractional crystallization of a single magma unit.

The single-magma-unit interpretation ignores the evidence of Sr isotopic heterogeneity [8,9,10] recently confirmed by [11] in their study of a newly acquired sample of “Kanagawa” Zagami containing both DML and an olivine-rich lithology (Za OL)[12]. These authors conclude that “Normal Zagami” comprising both the coarse- and fine-grained lithologies crystallized in a deep magma chamber slowly enough to create homogeneous pyroxene cores, after which magma rose to the surface where it cooled rapidly enough to create zoning of pyroxene rims. They observed both DML and the Ol-rich lithology in the same thin sections (,51-1, -2, -3), and concluded that pyroxene zoning patterns are significantly different between these two lithologies. Moreover, the plagioclase compositions also are different, although they are homogeneous within each lithology. The Ol-rich lithology is a few centimeters wide, suggesting that it intruded as a thin dike into almost completely solidified NZ magma. These observations combined with Sr-isotopic heterogeneity suggest complex magmatic evolution.

Initial $^{87}Sr/^{86}Sr$ in Zagami lithologies:

The intitial $^{87}Sr/^{86}Sr$ ratio determined for the Ol-rich lithology [11] is similar to that of highly evolved shergottites such as Los Angeles. The observed range of initial $^{87}Sr/^{86}Sr$ within the single ~18 kg [13] Zagami meteorite is nearly as great as the entire range of initial $^{87}Sr/^{86}Sr$ within the enriched shergottite subgroup of Martian meteorites.

Enriched and intermediate shergottites related?

Some previously estimated values of $^{87}Rb/^{86}Sr$ for bulk Mars lie in the range ~0.13-0.16. Time averaged $^{87}Rb/^{86}Sr$ in the source of the geochemically intermediate shergottite NWA 1460 is 0.16, and those of the “lherzolitic” group of intermediate shergottites are ~0.18 (See [14] for references). These observations suggest that the trace element characteristics of lherzolitic shergottites are only moderately fractionated from those of bulk Mars. Moreover, the crystallization ages of the lherzolitic and enriched shergottites are identical within error limits, suggesting the possibility of contemporaneous magmatism from similar mantle sources. Thus, we examine the hypothesis that (a) the overall enrichment in initial $^{87}Sr/^{86}Sr$ of enriched shergottites can be explained by assimilation of “crustal” material by basaltic magma with the Sr isotopic characteristics of lherzolitic shergottites, and (b) that small-scale variations in initial $^{87}Sr/^{86}Sr$ within and among the enriched shergottites are due to slight variations in the amount and type of assimilated crustal material.

Early and late differentiation:

In this model, an approximate time of

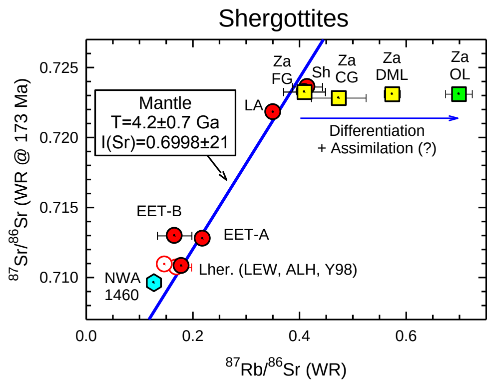

Figure 1. Bulk (“whole rock”) Rb-Sr data for lherzolitic shergottites LEW88516 (LEW), ALHA 77005 (ALH), and Yamato 984028 (Y98), geochemically intermediate basaltic shergottites EET 79001 A,B (EET-A, -B), and geochemically enriched basaltic shergottites represented by Los Angeles (LA), Shergotty (Sh), and Zagami Fine Grained (FG). Whole rock data for Zagami Coarse Grained (CG), Dark Mottled Lithology (DML), and the Ol-rich lithology (OL) are displaced towards higher $^{87}Rb/^{86}Sr$ values as a result of magmatic differentiation and/or assimilation.

differentiation of a trace-element enriched crust from the mantle source of the lherzolitic shergottites is given by the 4.2±0.7 Ga tie-line between the Rb-Sr data for the lherzolitic shergottites and the relatively undifferentiated enriched shergottites Los Angeles, Shergotty, and Zagami FG in Figure 1. The effect of late-stage magmatic differentiation and/or crustal assimilation is clearly seen in progressive displacement of "whole rock" ^{87}Rb/^{86}Sr ratios to the right in Figure 1 for Zagami CG, DML, OL, resp.

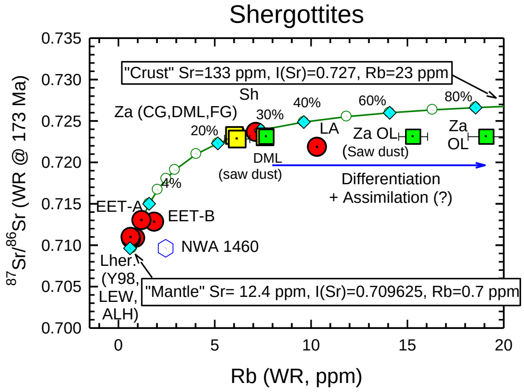

Figure 2. Modeled Rb abundances and initial ^{87}Sr/^{86}Sr ratios in bulk enriched shergottites assuming contributions from a basaltic mantle melt with the Rb-Sr characteristics of Yamato 984028 and the crustal compositions shown.

Assimilation and magma mixing:

Figure 2 shows variation of Rb concentrations and ^{87}Sr/^{86}Sr ratios in a "lherzolitic shergottite source" model for genesis of the enriched shergottites by crustal assimilation by mantle melts like the lherzolitic shergottite Y984028. The measured Rb concentrations and initial ^{87}Sr/^{86}Sr ratios of enriched shergottites are modeled by mixing ~70-80% of the basalt and ~20-30% of a hypothetical "crustal" component with ~23 ppm Rb and ^{87}Sr/^{86}Sr ~0.727. A similar model for Sr (not shown) gives the same mixing proportions for crustal Sr = 133 ppm. Figure 3 shows a similar model for Nd for "basalt" Nd = 0.6 ppm (1.3 X CI), "crustal" Nd = 23 ppm (~51 X CI) and slightly altered "crustal" Rb-Sr characteristics. Modeling the extreme fractionation of Rb and Nd for Za OL and Za OL (saw dust) compared to other Zagami samples in Figs. 2 and 3 requires more sophisticated models.

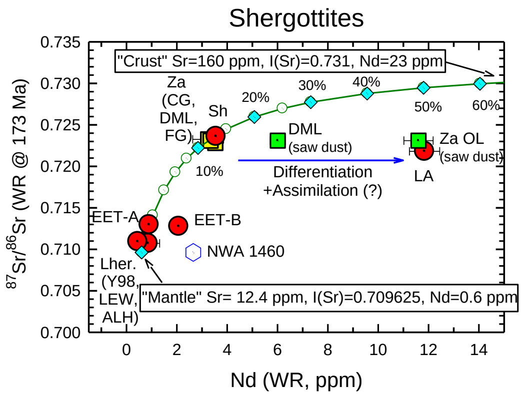

Figure 3. Modeled Nd abundances and initial ^{87}Sr/^{86}Sr ratios in bulk enriched shergottites assuming contributions from a basaltic mantle melt with the Rb-Sr-Nd characteristics of Yamato 984028 and the crustal compositions shown.

Ar-Ar evidence of near-surface crystallization:

Ar-Ar data for plagioclase and pyroxene mineral separates [15] are shown in Fig. 4. Most of the data lie along a mixing line between the ^{39}Ar /^{40}Ar ratio corresponding to an age of 177 Ma and ^{36}Ar/^{40}Ar ~2000. The data have been corrected for cosmogenic contributions at each temperature step using the measured ^{36}Ar/^{37}Ar ratios. Bogard and Park [15] suggested that excess ^{40}Ar was inherited from the Zagami magma, and that it was introduced into the magma either by degassing of a larger volume of material or by assimilation of old, K-rich crustal material early in the magma crystallization history. The latter scenario is most consistent with the type of crustal assimilation envisioned here.

Conclusions:

The Rb-Sr isotopic data of DML are consistent with differentiation from a CG magma [10], but lower initial ^{87}Sr/^{86}Sr and very high Rb abundances in OL [11] as well as mineral compositions [12] suggest OL is not simply derived from DML. Relatively high initial ^{87}Sr/^{86}Sr in CG may reflect magma chamber conditions [9] or crustal assimilation during transport of a magma derived from a lherzolitic shergottite source. However, derivation of normal Zagami from an enriched source cannot be excluded, and also will be considered.

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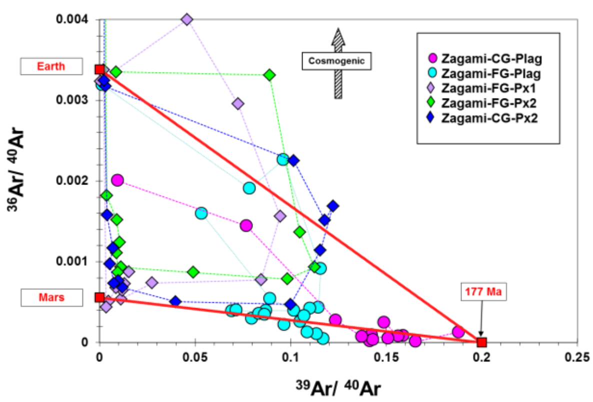

Figure 4. Ar-Ar data for plagioclase and pyroxene mineral separates of Zagami Coarse Grained (CG) and Fine Grained (FG) lithologies. Data from [15].