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The age of SNC meteorites and the antiquity of the Martian surface

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Abstract

We report new Sm–Nd, Lu–Hf, and Pb–Pb mineral and whole-rock isotope data for the basaltic shergottite Zagami, as well as Pb–Pb whole-rock isotope data for the basaltic shergottite Los Angeles, the lherzolitic shergottite Dar-al-Gani 476 (DaG 476), and the clinopyroxenite Nakhla. In agreement with previous findings, our new Sm–Nd and Lu–Hf mineral ages on the Martian meteorite Zagami are young (155 and 185 Ma, respectively). The $^{207}Pb/^{206}Pb$–$^{204}Pb/^{206}Pb$ compositions of the insoluble fractions of shergottites (Zagami, Los Angeles, and literature data for Shergotty and EETA79001) form an excellent alignment indicative of a 4.0 Ga crystallization age. The range of Pb isotope compositions observed in the leachates of these samples attests to negligible contamination of the shergottites by terrestrial Pb and argues against mixing relationships. The age of 4.048 ± 0.017 Ga (MSWD = 1.5) provided by the Pb isotope compositions of the Zagami whole-rock and residues is therefore taken to date the crystallization of this rock, which, so far, was believed to be only ~180 Ma old. Based on this result, we argue that the lithosphere of Mars is extremely old and that most mineral ages were reset recently by acidic aqueous solutions percolating through the Martian surface. This interpretation is consistent with photographic interpretations of erosional features on Mars. It also relieves the constraint imposed by the presence of anomalies of ^{142}Nd and ^{182}W (both products of extinct radioactive nuclides) that the Martian mantle should have preserved primordial isotopic heterogeneities, thus allowing for the planet interior to be actively convecting.

Keywords: Mars; Zagami; SNC meteorites; Pb isotopes; Hf isotopes; Nd isotopes; chronology; aqueous alteration

1. Introduction

It is widely accepted that the SNC meteorites, which take their name from the three type meteorites Shergotty, Nakhla, and Chassigny, are of Martian origin. Their oxygen isotope compositions define a common mass-fractionation trend indicating they originated from a single planetary object [1,2]. Among the SNCs, the shergottites are differentiated mafic to ultramafic plutonic rocks, most of them as young as ~180 Ma [3–7]. Together with their occluded rare gases, which closely resemble the Martian atmosphere [8], these young ages were instrumental in pointing to Mars as the parent planet of the SNC group. A persistent difficulty with this scenario, however, is the scarcity of equally young volcanic activity on the surface of Mars [9]. The arguments for and against a young Martian lithosphere have been summarized by Jones [10], McSween [11], Nyquist et al. [12,13], and others. Most notably, the ~180 Ma ages conflict with the apparent rarity of uncratered surface young enough that it would allow for

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voluminous volcanic activity ~180 My ago. Furthermore, large ^{182}W and ^{142}Nd isotopic anomalies, produced by the short-lived and now extinct isotopes ^{182}Hf ($T_{1/2}$=8.9 My) and ^{146}Sm ($T_{1/2}$=103 My) [14–16], are present in these meteorites. These anomalies require that either the Martian crust was formed by very early volcanism or the SNC mantle source has remained poorly stirred since the formation of the planet. Alternative views have been discussed by Jagoutz [17], who first emphasized the old character of Pb in maskelynite, a characteristic high-pressure, near-vitreous form of plagioclase found in shergottites that is produced when plagioclase is subjected to high shock pressures [18]. Nyquist et al. [19] argued that the ~180 Ma ages may reflect impact melting, while Blichert-Toft et al. [20] ascribed isotopic resetting and inconsistent Lu–Hf and Sm–Nd fractionation during the late fractionation events to water pressurization during impact.

The present work reports new Sm–Nd, Lu–Hf, and Pb–Pb mineral and whole-rock isotope data for a 2.3 g piece of the basaltic shergottite Zagami, as well as Pb–Pb whole-rock isotope data for powders in our possession from previous work of the basaltic shergottite Los Angeles, the lherzolitic shergottite Dar-al-Gani 476 (DaG 476), and the clinopyroxenite Nakhla. We suggest here that our Pb–Pb data support an ancient (~4.0 Ga) emplacement age of the shergottites and propose that such an age is more easily reconciled with the apparent lack of recent voluminous volcanic activity on the surface of Mars.

2. Analytical techniques

A 2.3 g piece of Zagami was crushed for mineral separation in a clean environment at the WSU (Washington State University at Pullman) laboratory facilities. The whole-rock powder was obtained from a 190 mg inner piece ground in an agate mortar. The remainder of the sample was coarsely crushed to a grain size <200 μm and sieved under high-purity acetone flux to get 200–63 μm, 63–30 μm, and <30 μm fractions. Mineral separations were performed at the UI (University of Idaho at Moscow) mineral facilities. A large part of the oxides (chromite and magnetite) were removed using a hand-magnet, while magnetic (i.e., pyroxene) and non-magnetic (i.e., plagioclase and phosphate) minerals were separated using a Frantz isodynamic magnetic separator. Minerals were purified using the heavy liquids methylene iodide and bromoform (Geoliquids, IL, USA), primarily to separate maskelynite from phosphate and sulfides. Mineral separates from the 200–63 μm fraction were finally hand-picked using stainless steel tools to obtain ~99% pure separates of pyroxene and maskelynite.

While our Zagami sample was large enough to allow for combined Sm–Nd, Lu–Hf, and Pb isotope analyses of each fraction, we were only able to obtain small amounts of Los Angeles, DaG 476, and Nakhla. Leached whole-rock samples were therefore the only "fraction" analyzed for these SNCs and only Pb isotopes were measured. To remove as much contamination (due to storage and handling) as possible, and also to eliminate soluble accessory minerals, which could readily have been perturbed, we leached each sample except for the very fine-grained Zagami whole-rock powder, as this would have risked severe modification of its parent–daughter ratios (in the present context damaging notably to Lu–Hf and Sm–Nd).

Mineral separates from Zagami were successively leached with 3 M HF and 2 N HCl for 15 min each at room temperature in ultrasonic bath and then rinsed with distilled H_2O. We checked the weights of the dry residues to ensure that no more than 10% of the original mineral samples had been removed by leaching. We assume this level of leaching is a sufficiently mild treatment to preserve Lu–Hf and Sm–Nd ratios in the silicate mineral residues.

Whole-rock powders from Los Angeles, DaG 476, and Nakhla were first washed in distilled H_2O to remove the finest fractions containing most of the secondary minerals (=L1). The next steps were aimed at removing phosphates and sulfates: the whole-rock residues were leached with cold 0.5 M acetic acid for 30 min followed by successive 1-h steps at 90 °C in 1 M HNO_3, 2.5 M HCl, and 6 M HCl, each followed by 10 min in an ultrasonic bath and a rinse in distilled H_2O. The acetic acid and nitric acid leachates were combined (=L2), while both HCl leachates and H_2O rinses were kept apart (=L3). All the leachate solutions were analyzed for their Pb isotopic compositions. All the whole-rocks and mineral separates were dissolved in HF–HNO_3 using steel-jacketed PTFE bombs held at 155 °C for 1 week. ^{176}Lu–^{180}Hf and ^{149}Sm–^{150}Nd spikes were added to the Zagami samples before dissolution. Perchloric acid was used to ensure complete sample-spike homogenization and to eliminate fluorides prior to Hf separation (this step was superfluous for the simple unspiked dissolution and Pb separation procedures used for the Los Angeles, DaG 476, and Nakhla whole-rocks). Total procedural blanks were <25 pg for Nd, Sm, Hf, and Lu, <200 pg for Pb when perchloric acid was used, and <140 pg for Pb when perchloric acid was not used. All the leachates were dissolved with