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Isotopic evidence for early solar system-wide planetary growth by high-energy planetesimal collisions?

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Abstract

The Main-Group pallasites are a stony-iron meteorite group that may have formed at a core-mantle boundary or from an impact. We look for evidence of multiple precursor isotopic reservoirs in pallasites by targeting metal-hosted chromite and coexisting olivine for high-precision oxygen isotope analyses. We then evaluate an impact mechanism for the formation of these meteorites. We find that there is a small but statistically significant isotopic disequilibrium that may be recording different isotopic reservoirs in constituent parts of pallasites.

1. Introduction

Main-Group pallasites (PMGs) are characterized by roughly equal proportions of olivine and Fe,Ni metal [9]. In addition to these phases, some PMG contain minor amounts of chromite, troilite, schreibersite, phosphates, and other minerals [2]. The canonical view is that pallasites are samples from the core-mantle boundary or some kind of 'pallasite zone' of a disrupted planetesimal [2]. Recently, new evidence has been presented indicating that pallasites may have formed as a direct consequence of a large-scale impact event [7, 9]. Such models are testable by employing isotopic techniques on silicate and metal-borne phases separately to establish whether the respective minerals are in isotopic disequilibrium.

1.1 Testing an impact model

Chromite analysed from 6 pallasites has low Al, near end-member compositions, consistent with a lack of silicate melt present during crystallization [2]. This, combined with the globular, poorly-formed crystallographic texture of the metal-hosted chromites, suggests that they likely crystallised out of the metal. In contrast, two of the PMG chromites analysed, Fukang and Imilac, exhibit higher (~8 – 20%) Al_2O_3 suggesting of the presence of significant amounts of silicate melt during their crystallization. If pallasites form as a result of impact-injection of molten core material into a planetary mantle [7], or re-aggregation of the constituent parts of two impacting planetesimals [9], metal-borne chromite might be expected to carry a distinct oxygen isotope signature to that of coexisting mantle olivine.

Whilst past studies have sought to constrain the oxygen isotope signature of PMG olivines [1, 4], none to date have examined in detail their other oxygen-bearing phases. The utility of oxygen isotope systematics for linking meteorites by the planetary provenance is well established [3, 4]. This study has collected oxygen isotope results for olivine and co-existing metal-hosted chromite in 8 PMG in order to establish whether an isotopic disequilibrium is present.

2. Method

Oxygen isotope data was obtained for 14 olivine and 15 chromite samples from the same eight PMGs using laser-assisted fluorination at The Open University. Prior to reaction, samples were treated with 6M HCl for 2-3 minutes to remove any terrestrial weathering following a procedure outlined in a previous study [1]. The samples were reacted with BrF_5 and heated using a CO_2 IR laser. The sample gas was subsequently fed along a clean-up line consisting of two liquid N_2 cryo-traps and a bed of heated KBr. The purified O_2 was then expanded into a MAT 253 dual-inlet mass spectrometer. $\Delta^{17}O$ data are linearized after [6], results have been calculated using $\lambda = 0.5262$.

3. Results

The oxygen isotope results for the PMG olivine are consistent with the results obtained in a previous study from this laboratory [4] and show no evidence for bimodal $\Delta^{17}O$ compositions as reported by [1]. The average $\delta^{18}O$ for PMG olivine is 3.258 ± 0.32 ‰ (2σ) and the average $\Delta^{17}O = -0.196 \pm 0.012$ ‰ (2σ). The PMG chromites display two isotopic populations that are correlated with their Al_2O_3 compositions. The low-Al subgroup $\delta^{18}O = 1.046 \pm 0.407$ ‰ (2σ) and $\Delta^{17}O = -0.218 \pm 0.016$ (2σ). The high-Al subgroup

$\delta^{18}O$ = 2.032 ± 0.552 (2σ) and $\Delta^{17}O$ = -0.211 ± 0.008 (2σ). A Student's T-test on the $\Delta^{17}O$ difference between PMG olivine and chromite shows that it is statistically significant (99%) at all values for λ up to and including 0.5305, the high-T upper limit.

4. Discussion and conclusion

The $\delta^{18}O$ and $\Delta^{17}O$ difference between the high-Al chromite and the low-Al chromite may be related to the amount of silicate melt present during the crystallization of the chromite and the amount to which it equilibrated with this melt. One way of interpreting the disequilibrium between PMG olivine and chromite is that they sample two distinct parent bodies, brought together by an impact. This would be consistent with some current models for pallasite formation [7]. Although in disequilibrium, the phases exhibit similar $\Delta^{17}O$ values, this could be attributed to the accretion of their respective isotopic reservoirs in proximal feeding zones in the proto-planetary disk. Given that there are multiple pallasite groups, some of which likely formed in the outer solar system [8], such large impacts creating pallasites would have a been solar system wide process. An alternative model for creating this disequilibrium is the presence of multiple fractionation steps in a system at equilibrium between the minerals analysed and some unknown phase [10]. However, we find this explanation to be unlikely as the fractionation in $\delta^{18}O$ required to accommodate such a $\Delta^{17}O$ difference seems unrealistically large for a high-T environment. A third reason for this disequilibrium could be some type of crystal-chemical mechanism affecting the fractionation of oxygen between silicate and oxide minerals. A similar effect may have been observed in felsic plutonic rocks previously [5], we are currently exploring this possibility.

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