Determining the Nature of Olivine Zoning in Nakhlites by *in-situ* Mg and Fe Isotopic Analyses.
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Introduction: Nakhlites are a group of martian meteorites, olivine-bearing pyroxene culumates with varying amounts of mesostasis. It has been argued that nakhlites are comagmatic, based on their identical crystallization age of 1.3 Ga, similar trace elemental and REE patterns and mineralogy [1]. The nakhlites share the same augite core compositions, but their olivine core compositions range from Fo_{35} to Fo_{45}. The general view is that nakhlites were emplaced at different depths in the same igneous body. Cation diffusion in pyroxene is orders of magnitude slower than that in olivine; hence, their core compositions can be preserved. Assuming that chemical gradients in the olivines represent diffusion profiles, [2,3] modeled the cooling rates of 8 nakhlites, and provided their individual burial depths. The goal of our study is to test their assumption that the olivine zonings in nakhlites are records of diffusive transport.

It has been demonstrated that chemical diffusion is accompanied by large and negatively coupled Mg-Fe isotopic fractionations in olivines [4,5]. This is because the light isotopes diffuse faster than their heavier counterparts, and Mg and Fe inter-diffuse [6]. However, if the crystals inherited chemical gradients in the melt, no isotopic fractionations should occur at magmatic temperatures. Therefore, Mg and Fe isotopes can be used to determine the process that produced chemical zoning in olivines.

Samples: We analyzed olivines in NWA 998, Lafayette, Nakhla, Governador Valadares, NWA 817, and MIL 03346. The olivines were characterized using a JEOL SEM at the University of Chicago. Although the olivines in Lafayette and NWA 998 are unzoned, they were analyzed to confirm that the Mg and Fe isotopes in olivines have been completely equilibrated. The largest 2 to 4 grains were analyzed in each sample. All chemical and isotopic profiles shown are rim-to-rim analyses in the longest direction of each grain.

Isotopic analyses: Magnesium and iron isotopes were measured using IMS 1280-HR SIMS at CRPG, Nancy, France. The olivine standards described in [5] were used to characterize matrix-induced instrumental fractionations in SIMS. It was found that for the range of Fo# in the nakhlites, there is no resolvable matrix effects for Mg isotopes within analytical uncertainty (~0.4 ‰ in δ^{26}Mg, 2 SD), and the matrix effect for Fe is ~2 ‰ in δ^{56}Fe between Fo_{10} and Fo_{40}. Isotopic compositions shown are not absolute; only relative fractionation within a sample is discussed here.

Results and Discussion: No resolvable Fe isotopic fractionation can be found in all olivines in the nakhlites analyzed within analytical uncertainty (~0.5 ‰ in δ^{56}Fe, 2 SD). For Fe isotopes, because the olivine is relatively rich in Fe, the diffusion signal may be diluted by a large background of unfractionated iron. Based on modeling prediction, the expected isotopic fractionations by chemical diffusion in these nakhlites are expected to be comparable to the analytical uncertainty. As a result, iron isotopes data are not shown here.

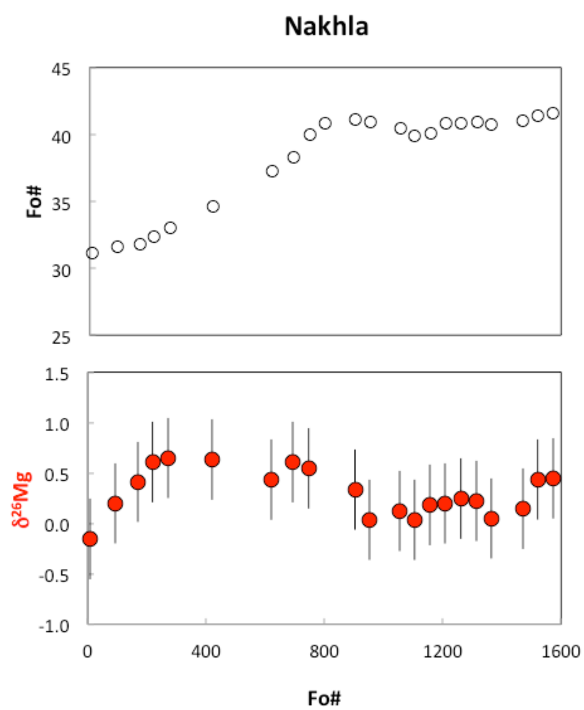

Figure 1. Chemical and isotopic profiles for an olivine in Nakhla. Although there is chemical zoning, there is no clearly resolvable isotopic fractionation.

NWA 998 and Lafayette: No resolvable Mg isotopic fractionation in olivines was found. The lack of fractionation means that little chemical diffusion has occurred or that the olivines have been completely equilibrated through chemical diffusion.

Nakhla: A large olivine, zoned from Fo_{30} in the rim to Fo_{42} in the core, was analyzed. There is no clearly resolvable Mg isotopic fractionation within uncertainty. However, the shape of the isotopic profile suggests diffusive transport. If some Mg has diffused into the interculumus material, heavy isotopes should be left in the chemically zoned region in olivine. The expected isotopic fractionation during chemical diffusion can be modeled using the relative diffusivities of Mg isotopes in olivine [7]. We are currently working on a quantitative model.

Governador Valadares: Olivines are zoned from Fo_{28} in the rim to Fo_{38} in the core. The core of the olivine shown is isotopically heavier by ~1.2 ‰ in δ^{26}Mg compared to the rim. This is indicative of chemical diffusion that has affected the core, because the light isotopes have diffused outward to leave an isotopically heavy core behind.

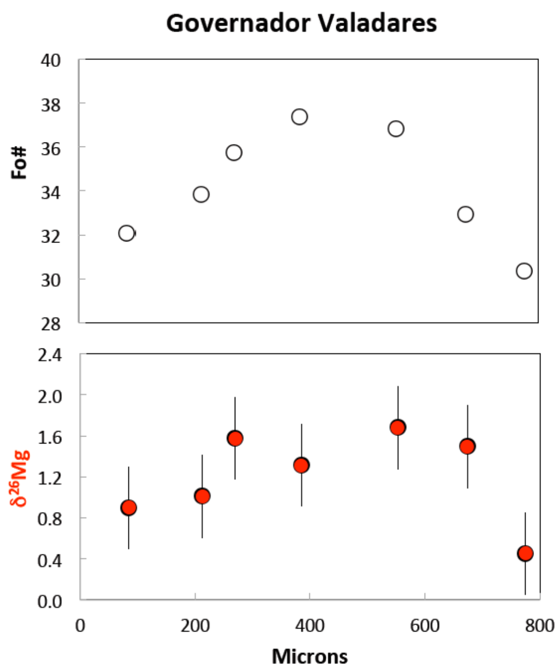

Figure 2. Chemical and Mg isotopic profiles for an olivine in Governador Valadares, showing kinetic effects of diffusion causing large isotopic fractionations within grain.

NWA 817: Olivines are zoned from Fo_{14} in the rim to Fo_{43} in the core. Toward the rim, Mg isotopic composition rises sharply to +2 ‰ compared to the core. The shape of the profile can be explained by diffusion that has not, or barely, affected the core. Light isotopes of Mg diffuses outward, leaving isotopically heavy regions where diffusion has affected the crystal. It is not clear why there are two isotopically heavy data points in the core.

MIL 03346: Olivines are zoned from Fo_{15} in the rim and Fo_{42} in the core. Due to the small sizes and low abundance of olivine, only three points could be obtained in the zoned region. These rim spots are heavier by ~2.5 ‰ in δ^{26}Mg compared to the core. However, SEM and electron probe analyses reveal that these fractionated spots overlap on phases produced by alteration of olivines. Therefore, it is not known whether these fractionations are real or artifacts. More zoned olivines would need to be analyzed.

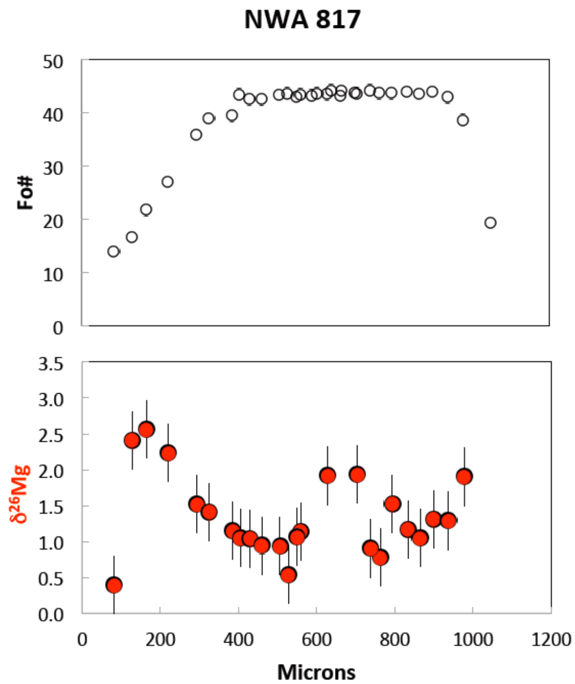

Figure 3. Chemical and Mg isotopic profiles for an olivine in NWA 817, also showing large Mg isotopic fractionations produced by chemical exchange with intercumulus material.

Conclusion: Our study shows that diffusive transport in nakhlites can be identified using Mg isotopes in zoned olivines. The olivines in Governador Valadares and NWA 817 show clear evidence of chemical diffusion. Diffusion may have been responsible for the olivine zoning in Nakhla. Isotopic profiles in these olivines will be used to determine whether these nakhlites could have evolved in a single igneous body.

References: [1] Treiman (2005), Chemie der Erde 65, 203-270. [2] Mikouchi et al. (2002), LPSC abstract #1343. [3] Mikouchi et al. (2012), LPSC abstract #2363. [4] Teng et. al. (2011) EPSL 308, 317-324. [5] Sio et al. (2013) GCA 123, 302-321. [6] Dauphas et al. (2010) GCA 74, 3274-3291. [7] Sio et al. (2013) Goldschmidt abstract.