DURATION OF A MAGMA OCEAN AND SUBSEQUENT MANTLE OVERTURN IN MARS: EVIDENCE FROM NAKHLITES. V. Debaille1, A.D. Brandon2, Q.-Z. Yin3, B. Jacobsen3, 1Lunar and Planetary Institute, Houston TX; present address: Université Libre de Bruxelles, Brussels, Belgium (vinciane.debaille@ulb.ac.be), 2NASA-Johnson Space Center, Houston, TX 77058, 3University of California, Davis, CA 95616.

Introduction: It is now generally accepted that the heat produced by accretion, short-lived radioactive elements such as $^{26}\text{Al}$, and gravitational energy from core formation was sufficient to at least partially melt the silicate portions of terrestrial planets resulting in a global-scale magma ocean. More particularly, in Mars, the geochemical signatures displayed by shergottites, are likely inherited from the crystallization of this magma ocean (e.g., [1-4]). Using the short-lived isotope system (with a full coverage of ~500 Myr after solar system formation). This could result in large discrepancies between the source of nakhlites and a crystallizing ocean (e.g., [1-4]). Using the short-lived isotope system, i.e. when $^{142}\text{Nd}$/$^{144}\text{Nd}$ ratios of all nakhlites range from 0.8 to 1.2. This is consistent with melts derived from residues with garnet segregation [11]. Nakhlites do not plot in a two-stage evolution diagram for $^{142}\text{Nd}$/$^{144}\text{Nd}$ versus $^{142}\text{Nd}$/$^{144}\text{Nd}$ ([1, 9], this study - Fig. 1), indicating that their source has not always been a closed system; Instead, it requires a more complex origin, which may be related to garnet/majorite segregation.

Results: The three nakhlites studied here are characterized by homogeneous isotope compositions with $^{176}\text{Hf}/^{177}\text{Hf} = 0.282998 \pm 3 \times 10^{-3}$ to 0.283108 $\pm 10^{-4}$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512854 \pm 1$ to 0.512873 $\pm 1$ and $^{142}\text{Nd} = 0.61 \pm 0.02$ to 0.67 $\pm 0.03$, (errors at 2σ). These values correspond to initial $^{176}\text{Hf} = 12.6 \pm 19.7$ and $^{143}\text{Nd} = 16.1 \pm 16.9$. The $^{176}\text{Hf}/^{144}\text{Nd}$ ratios of all nakhlites range from 0.8 to 1.2. This is consistent with melts derived from residues with garnet segregation [11]. Nakhlites do not plot in a two-stage evolution diagram for $^{142}\text{Nd}/^{144}\text{Nd}$ versus $^{142}\text{Nd}/^{144}\text{Nd}$ ([1, 9], this study - Fig. 1), indicating that their source has not always been a closed system; instead, it requires a more complex origin, which may be related to garnet/majorite segregation.

Discussion: Large positive $^{182}\text{W}$ anomalies are predicted in a moderately fractionated source formed early in planetary differentiation (Fig. 2). An alternative mechanism that generates large positive $^{182}\text{W}$ is by crystallization of a more fractionated source in presence of garnet/majorite [10]. This could result in a range of large $^{182}\text{W}$ and $^{142}\text{Nd}$ as the $^{146}\text{Sm}$ may have recorded later differentiation events in $^{142}\text{Nd}$ not observed in $^{182}\text{W}$ values.

With these potential complexities in short-lived chronology, the $^{182}\text{W}$ and $^{142}\text{Nd}$ have been obtained from three nakhlites (Nakhla, MIL03346 and Yamato000593). These new data are combined with previous data [3, 7], to investigate potential discrepancies between the $^{182}\text{Hf}/^{182}\text{W}$ and $^{146}\text{Sm}/^{142}\text{Nd}$ systematics, and the relationship between the source of nakhlites and a crystallizing magma ocean.

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nakhlites ([3], this study), indicating that their source did not remain a closed-system since its differentiation at ~30 Myr, likely because of garnet/majorite has been removed. It implies that the nakhlite source could never reach a \( ^{142}\text{Nd} \) value of +1.2.

Using an initial \( ^{142}\text{Sm}/^{144}\text{Nd} \) of 0.305 [3], and using the \( ^{147}\text{Sm}/^{144}\text{Nd} \) of majoritic garnet (~1.89) [14], it can be estimated that 4% of majoritic garnet has to be removed from the nakhlite source to generate the observed \( ^{147}\text{Sm}/^{144}\text{Nd} \) in nakhlites (0.235).

**Figure 1:** \( ^{148}\text{Nd} \) vs. \( ^{182}\text{Hf} \) in the nakhlites (black curves adapted from [3] considering a turbulent magma ocean; Grey curves from [8]). Black square: Nakhla; white square: average value for all nakhlites (\( ^{148}\text{Nd} \): this study, \( ^{182}\text{Hf} \): [3, 7]). Error bars are 2\( \sigma \). Symbols on the curves represent the present-day \( ^{182}\text{Hf} \) and \( ^{148}\text{Nd} \) attained in a source region for the age indicated in Myr. \( ^{147}\text{Sm}/^{144}\text{Nd}, ^{182}\text{Hf}/^{182}\text{W} \) pairs are indicated for each curve. The grey arrow indicates the \( ^{148}\text{Nd} \) vs. \( ^{182}\text{Hf} \) value that nakhlite source should have reached when crystallizing in the majorite stability field (upper black curve) ~30 Myr after solar system formation. In Fig.2, Symbols on the curves represent the present-day \( ^{182}\text{Hf} \) and \( ^{148}\text{Nd} \) attained in a source region for the age indicated in Myr. \( ^{147}\text{Sm}/^{144}\text{Nd}, ^{182}\text{Hf}/^{182}\text{W} \) pairs are indicated for each curve. The grey arrow indicates the \( ^{148}\text{Nd} \) vs. \( ^{182}\text{Hf} \) value that nakhlite source should have reached when crystallizing in the majorite stability field (upper black curve) ~30 Myr after solar system formation if no garnet segregation has occurred after \( ^{182}\text{Hf} \) extinction.

Assuming garnet segregation occurred as a single event, the nakhlite source can be modeled by a three-stage model, where \( T_0 = 4.5685 \text{ Ga} \), \( t_0 \) is the time of differentiation in majorite stability field, \( t_2 \) is the time of garnet segregation and \( t_0 \) is the crystallization age of the nakhlites (~1.3 Ga). Because garnet segregation is postulated from the discrepancy in \( ^{148}\text{Nd} \) (i.e. ~+0.63 versus predicted +1.2), but not in \( ^{182}\text{Hf} \), \( t_0 \) must lie between 50 Myr and 500 Myr after solar system formation. In Fig.2, \( t_0 \) is estimated at 30 Myr after \( T_0 \) for an \( ^{182}\text{Hf} \) of ~3 in cumulates crystallizing from a turbulent magma ocean in the majorite stability field (grey arrow). Using time-integrated source ratios calculated from \( ^{147}\text{Sm}/^{144}\text{Nd} \) and \( ^{182}\text{Hf}/^{182}\text{Hf} \) measured in nakhlites (= source \( t \); i.e., after majoritic garnet segregation) and source ratios before majoritic garnet segregation (= source \( t \); closed-system in majorite stability field) with an estimated 4% majoritic garnet loss, assigning a value of \( t_2 = 100 \text{ Myr} \) gives \( ^{148}\text{Nd}(t_2) = +16.9, ^{182}\text{Hf}(t_2) = +15.6 \) and \( ^{142}\text{Nd} = +0.57 \). These values can be compared to the average measured values in nakhlite, respectively +16.4, +15.3 and +0.63. Thus, a nakhlite source that first crystallized ~30 Myr after solar system formation in the majorite stability field and then experienced majoritic garnet segregation ~70 Myr later can reproduce values observed in nakhlites.

The question now is - how can mantle cumulates in a crystallized deep mantle experience garnet segregation 100 Myr after solar system formation? During the solidification of a magma ocean, it is likely that early cumulates are rich in MgO and less dense, while late cumulates are richer in FeO and denser. If the late cumulate crystallize higher up given that crystallization proceed from bottom-up, this creates an inverse density gradient, gravitationally unstable and resulting in mantle overturn [5, 6, 15, 16]. Hot and less dense materials brought from the deep parts of the Martian mantle may be molten up to 50% by adiabatic decompression [6]. These partially molten regions may develop a low viscosity and majorite/garnet can be removed from the nakhlite source because it will sink between 7.5 and 14 GPa in the Martian mantle [6, 16]. Thus, the segregation of majorite/garnet in the source of nakhlites is related to the mantle overturn, which is estimated to occur ~100 Myr after solar system formation. This timing is coherent with the end of crystallization of the MMO obtained from \( ^{142}\text{Nd} \) in shergottites [4].

**Conclusions:** New \( ^{182}\text{Hf}/^{177}\text{Hf}, ^{143}\text{Nd}/^{144}\text{Nd} \) and \( ^{147}\text{Sm}/^{144}\text{Nd} \) combined with published \( ^{182}\text{W} \) for nakhlites are consistent with a three-stage model in their source for the silicate portion of the Martian mantle. A first differentiation event occurred ~30 Myr after solar system formation in the majorite garnet field. Majoritic garnet was removed from the nakhlite source ~70 Myr later. The garnet segregation event may be related to a mantle cumulate overturn, thus occurring 100 Myr after solar system formation. As the mantle overturn is expected to occur at the end of the crystallization of the magma ocean, this timing is in agreement with a previous study estimating the duration of the MMO ~100 Myr after solar system formation, recorded in \( ^{142}\text{Nd} \) values in the shergottite suite.