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

Introduction: It is now generally accepted that the heat produced by accretion, short-lived radioactive elements such as ^{26}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 chronometer ^{146}Sm-^{142}Nd ($t_{1/2}$ = 103 Myr), the duration of the Martian magma ocean (MMO) has been evaluated to being less than 40 Myr [2, 3], while recent and more precise ^{142}Nd/^{144}Nd data were used to evaluate the longevity of the MMO to ~100 Myr after the solar system formation [4]. In addition, it has been proposed that the end of the crystallization of the MMO may have triggered a mantle overturn (e.g., [5, 6]), as a result of a density gradient in the cumulate layers crystallized at different levels. Dating the mantle overturn could hence provide additional constraint on the duration of the MMO.

Among SNC meteorites, nakhlites are characterized by high ε^{182}W of approximately +3 [3, 7, 8] and an ε^{142}Nd similar to depleted shergottites of +0.6-0.9 [3, 4, 9, 10]. It has hence been proposed that the source of nakhlites was established very early in Mars history (~8-10 Myr [3, 8]). However, the times recorded in ^{182}Hf-^{182}W isotope system, i.e. when ^{182}Hf became effectively extinct (~50 Myr after solar system formation) are less than closure times recorded in the ^{146}Sm-^{142}Nd isotope system (with a full coverage of ~500 Myr after solar system formation). This could result in decoupling between the present-day measured ε^{182}W and ε^{142}Nd as the ^{146}Sm may have recorded later differentiation events in ε^{142}Nd not observed in ε^{182}W values.

With these potential complexities in short-lived chronological data for SNC's in mind, new ^{176}Hf/^{177}Hf, ^{143}Nd/^{144}Nd and ^{142}Nd/^{144}Nd were obtained for three nakhlites (Nakhla, MIL03346 and Yamato000593). These new data are combined with previous ε^{182}W data [3, 7], to investigate potential discrepancies between the ^{182}Hf-^{182}W and ^{146}Sm-^{142}Nd systematics, and the relationship between the source of nakhlites and a crystallizing magma ocean.

Results: The three nakhlites studied here are characterized by homogeneous isotope compositions with ^{176}Hf/^{177}Hf= 0.282998±31 to 0.283108±10, ^{143}Nd/^{144}Nd= 0.512854±1 to 0.512873±1 and ε^{142}Nd= 0.61±0.02 to 0.67±0.03, (errors at 2σ). These values correspond to initial ε^{176}Hf=+12.6-+19.7 and ε^{143}Nd=+16.1-+16.9. The ε^{176}Hf/ε^{143}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}Nd/^{144}Nd versus ^{143}Nd/^{144}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.

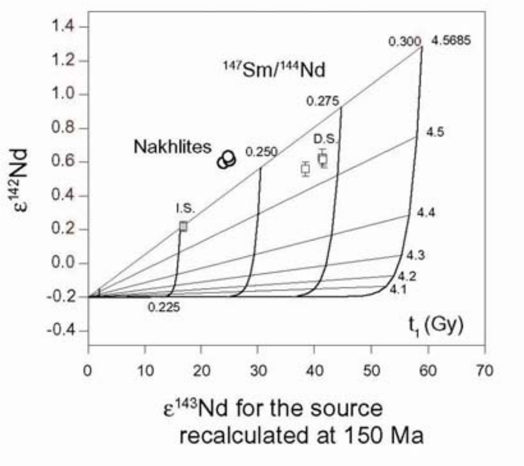

Fig. 1: Two-stage coupled ^{142}Nd–^{143}Nd evolution model for the source recalculated at the present-time. Black bold curves are loci of equal ^{147}Sm/^{144}Nd ratios in the source at present time, black lines are loci of equal differentiation ages. Grey square: intermediate shergottite (I.S.), white squares: depleted shergottites (D.S.) [4]. Circle: nakhlites (this study). Error bars (comprised in symbol size) are 2σ.

Discussion: Large positive ε^{182}W anomalies are predicted in a moderately fractionated source formed early in planetary differentiation (Fig. 2). An alternative mechanism that generates large positive ε^{182}W is by crystallization of a more fractionated source in presence of majorite (Fig. 2), but in a later stage of planetary differentiation. The presence of majorite will increase both Sm/Nd and Hf/W ratios [12]. This could result in large excesses in ε^{142}Nd and ε^{182}W if fractionation occurs early in the planet's history (Fig. 2), in addition to Hf/W fractionation resulting from core formation that can affect the ^{182}Hf-^{182}W system. Majorite is thought to be an important phase constituting ~45% of the Martian mantle between 17 and 23.5 GPa [13]. A ε^{182}W value of +3 is expected, with a ε^{142}Nd of +1.2 for a nakhlite source formation in the majorite stability field at ~30 Myr after solar system formation (grey arrow, Fig.2). However, such a large ε^{142}Nd value is not observed in 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 ε^{142}Nd value of +1.2.

Using an initial ^{147}Sm/^{144}Nd of 0.303 [3], and using the ^{147}Sm/^{144}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}Sm/^{144}Nd in nakhlites (0.235).

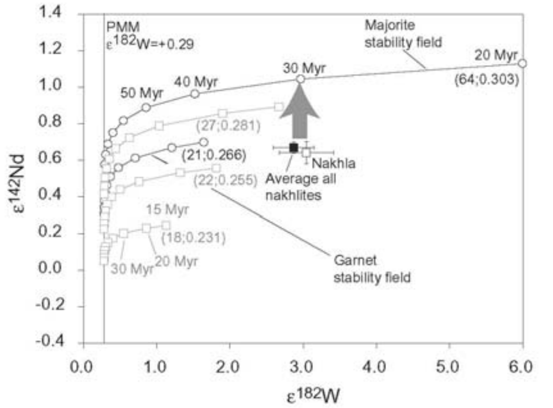

Figure 1: ε^{142}Nd vs. ε^{182}W in the nakhlites (black curves adapted from [3] considering a turbulent magma ocean; Grey curves from [8]). Black square: Nakhla; white square: average value for all nakhlites (ε^{142}Nd: this study, ε^{182}W; [3, 7]). Error bars are 2σ. Symbols on the curves represent the present-day ε^{182}W and ε^{142}Nd attained in a source region for the age indicated in Myr. (^{147}Sm/^{144}Nd, ^{180}Hf/^{183}W) pairs are indicated for each curve. The grey arrow indicates the ε^{142}Nd vs. ε^{182}W 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}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 Ga, t_1 is the time of differentiation in majorite stability field, t_2 the time of garnet segregation and t_3 is the crystallization age of the nakhlites (~1.3 Ga). Because garnet segregation is postulated from the discrepancy in ε^{142}Nd (i.e. ~+0.63 versus predicted +1.2), but not in ε^{182}W, t_2 must lie between 50 Myr and 500 Myr after solar system formation. In Fig.2, t_1 is estimated at 30 Myr after T_0 for an ε^{182}W of ~3 in cumulates crystallizing from a turbulent magma ocean in the majorite stability field (grey arrow). Using time-integrated source ratios calculated from ^{143}Nd/^{144}Nd and ^{176}Hf/^{177}Hf measured in nakhlites (= source t_2; i.e., after majoritic garnet segregation) and source ratios before majoritic garnet segregation (= source t_1; closed-system in majorite stability field) with an estimated 4% majoritic garnet loss, assigning a value of t_2=100 Myr gives ε^{143}Nd(t_3) = +16.9; ε^{176}Hf(t_3) = +15.6 and ε^{142}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 ε^{142}Nd in shergottites [4].

Conclusions: New ^{176}Hf/^{177}Hf, ^{143}Nd/^{144}Nd and ^{142}Nd/^{144}Nd combined with published ε^{182}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 ε^{142}Nd values in the shergottite suite.

References: [1] Borg, et al. (1997) *Geochim. Cosmochim. Acta 61* 4915-4931; [2] Borg, et al. (2003) *Geochim. Cosmochim. Acta 67* 3519-3536; [3] Foley, et al. (2005) *Geochim. Cosmochim. Acta 69* 4557-4571; [4] Debaille, et al. (2007) *Nature 450* 525-528; [5] Elkins-Tanton, et al. (2003) *Meteorit. Planet. Sci. 38* 1753-1771; [6] Elkins-Tanton, et al. (2005) *J. Geophys. Res. 110* E12S01; [7] Lee, et al. (1997) *Nature 388* 854-857; [8] Kleine, et al. (2004) *Geochim. Cosmochim. Acta 68* 2935-2946; [9] Harper, et al. (1995) *Science 267* 213-217; [10] Carlson, et al. (2004) *Lunar and Planetary Science Conference XXXV* #1442; [11] Vervoort, et al. (1996) *Geochim Cosmochim Acta 60* 3717-3733; [12] Righter, et al. (2003) *Geochim. Cosmochim. Acta 67* 2497-2507; [13] Bertka, et al. (1997) *J. Geophys. Res. 102* 5251-5264; [14] Draper, et al. (2003) *Phys. Earth Planet. Inter. 139* 149-169; [15] Hess, et al. (1995) *Earth Planet. Sci. Lett. 134* 501- 514; [16] Elkins-Tanton, et al. (2005) *Earth Planet. Sci. Lett. 236* 1- 12.