A YOUNG DIFFERENTIATION AGE FOR MARS DEDUCED FROM HIGH-PRECISION 142Nd ANALYSES OF MARTIAN METEORITES.
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Introduction: Understanding the timescales of major planetary processes such as accretion, core formation, and silicate differentiation is central to models of overall planetary evolution. Efforts to deduce the timing of these events utilize both theoretical models and age determinations based on short-lived isotopic chronometers. Considerable limitations on the accuracy and precision of many age determinations for these processes exist, largely because they are dependent on assumed initial conditions in the early solar system or on the planet of interest. Basaltic samples from the planet Mars, the shergottites, offer a unique opportunity to investigate the timing of silicate differentiation as their source regions are ancient, show significant lithophile element fractionations, and have preserved substantial isotopic anomalies from both long and short-lived systems [1-4]. Here we present Sm and Nd isotopic data combined with a new mathematical approach to define the age of silicate differentiation on Mars that is independent of the assumptions that have limited the precision and accuracy of previous age determinations.

Samples and Methods: High precision Sm-Nd isotopic measurements have been completed on 10 basaltic martian meteorites exhibiting trace element characteristics indicative of derivation from the observed range of enriched and depleted source regions. These include 5 meteorites with Sr and Nd isotopic systematics of an enriched source region (LA, NWA1068; Dho378; NWA4468; and NWA4878), 3 with Sr and Nd isotopic systematics of a depleted source region (Tissint, DaG476, SaU005) and 2 of intermediate composition (EET79001A, NWA480). Large fractions of these samples were dissolved after washing in water and 0.1M acetic acid in a Class 100 laboratory at Lawrence Livermore National Laboratory (LLNL). Small fractions were spiked using a mixed ^{149}Sm-^{150}Nd tracer to obtain whole rock ^{147}Sm/^{144}Nd values. The remainder was purified using a combination of ion-exchange chromatographic procedures. Rubidium, Sr, and rare earth elements (REE) were purified using 2N HCl, 2N HNO_3, and 6N HCl acids and an AG 50W-X8 200-400 mesh resin. The Sm and Nd were purified using pressurized quartz columns with 0.2M alpha-hydroxyisobutyric acid buffered to pH = 4.4 and an AG 50W-X8 200-400 mesh resin that was converted to NH_4^+ form. Procedural blanks were Sm = 6 pg and Nd = 18 pg. Samples were run on a ThermoScientific Triton thermal ionization mass spectrometer at LLNL.

High precision ^{142}Nd/^{144}Nd ratios were obtained through multidynamic analyses at high intensity (up to 4.9×10^{-11} amperes ^{144}Nd) and long duration (up to 13.5 h). Neodymium was corrected for instrumental mass fractionation using ^{146}Nd/^{144}Nd = 0.7219. Samarium was corrected for mass fractionation assuming ^{147}Sm/^{152}Sm = 0.56081. Isobaric interferences for Nd were monitored using ^{140}Ce and ^{149}Sm. Cerium corrections ranged from 0 to 36 ppm, whereas Sm interferences were less than 2 ppm. Repeat analyses of Nd isotopic standards (n=40) yield external precision of 6 ppm, whereas typical individual mass spectrometry runs show internal precision of better than 3 ppm. Replicate Nd analyses completed on martian meteorites and terrestrial standards during the course of this investigation agreed within 3 ppm. The maximum difference between four samples analyzed by both Debaille et al. [5] and this study was also 3 ppm.

Results and Calculations: We have applied three approaches in order to calculate the age of silicate differentiation on Mars; (a) three-stage model ages of individual samples, (b) construction of a ^{146}Sm-^{142}Nd whole rock isochron, and (c) construction of a ^{142}Nd-^{143}Nd whole rock isochron. All of these approaches require the ^{147}Sm/^{144}Nd ratio of the shergottite source regions to be known. It has been shown that whole-rock compositions are not a good proxy for their source regions, due largely to the effects of both Sm/Nd fractionation during partial melting and accumulation of mineral phases [1-2]. Instead, the source region ^{147}Sm/^{144}Nd composition must be calculated for each basalt. This is accomplished by using the measured ^{143}Nd/^{144}Nd ratio of the basalts and assuming that this ratio reflects growth in three stages of evolution. The first occurs in a chondritic reservoir, with present-day ^{147}Sm/^{144}Nd = 0.1967 and ^{143}Nd/^{144}Nd = 0.512638, between solar system formation at 4567 Ma [6] and the time of silicate differentiation. The second stage occurs in a now-differentiated reservoir between the time of differentiation and the crystallization age of the sample, while the third stage occurs in the rock itself from eruption until the present time. Because the calculated composition of the source region is itself dependent on the age of differentiation, all of the approaches must be solved in an iterative fashion.

Calculation of three-stage model ages for individual samples is found to be highly dependent on the assumed $^{142}Nd/^{144}Nd$ of the bulk planet. If a chondritic value ($^{142}Nd/^{144}Nd$=1.141813) is used, the iterative calculations do not converge at all for the enriched shergottites and the intermediate shergottites yield average source ages that are older than the solar system. On the other hand, if a terrestrial-like value of 1.141830 is assumed, then the equations converge for all shergottites and yield an average differentiation age of 4500 ± 42 Ma.

The second approach uses the calculated source region compositions and the measured bulk rock $^{142}Nd/^{144}Nd$ to generate the ^{146}Sm-^{142}Nd whole-rock isochron shown in Fig. 1. This isochron is interpreted to represent a mixing line that has chronologic significance. As a result, the source regions of the shergottites must be derived from a common reservoir at the age of 4502 ± 5 Ma defined by the isochron. Importantly, despite a very weak dependence of the age on the source region $^{147}Sm/^{144}Nd$, the age is completely independent of an assumed bulk planet $^{142}Nd/^{144}Nd$. In fact, the y-intercept determines the initial $^{142}Nd/^{144}Nd$ to be 1.141615 at 4502 Ma, which, when calculated forward in time, results in a present-day bulk Mars $^{142}Nd/^{144}Nd$ value of 1.141830. This calculated value is much closer to the terrestrial value (1.141837) than that of chondrites (1.141813).

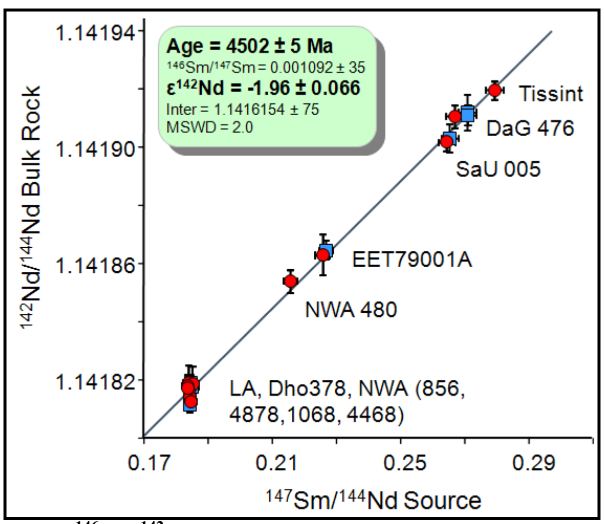

Fig. 1. ^{146}Sm-^{142}Nd isochron plot of shergottites yielding a differentiation age of 4502 ± 5 Ma. Red circles represent data from this study, while blue squares are from [5].

The third approach uses the present-day $^{142}Nd/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios of the shergottite sources to generate the ^{142}Nd-^{143}Nd model isochron shown in Fig. 2. The differentiation age calculated from the slope of this line is 4502 ± 5 Ma, in perfect agreement with the ages calculated by the other techniques. Furthermore, the y-intercept corresponds to a present-day bulk Mars $^{142}Nd/^{144}Nd$ value of 1.141830 which is within uncertainty of the bulk Earth value.

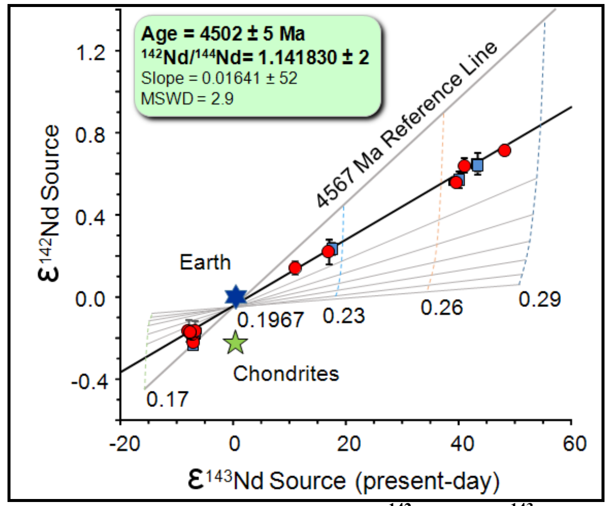

Fig. 2. Present-day whole-rock $\varepsilon^{142}Nd$ vs. $\varepsilon^{143}Nd$ of shergottites. Near-vertical, dashed lines are the loci of constant $^{147}Sm/^{144}Nd$ composition. Reference isochrons calculated at 4.5, 4.4, 4.3 etc Ga. Note age is calculated iteratively from the slope of the isochron, not the fit of the data to the reference isochrons.

Discussion: The silicate portion of Mars that ultimately generated the shergottites differentiated from a common reservoir at 4502 ± 5 Ma and was preceded by both planetesimal accretion and core formation. In addition, Hf-W isotope systematics record metal-silicate segregation at 4559 ± 8 Ma [3-4, 7]. Combined, this chronology implies relatively slow cooling of the mantle since it requires a lengthy 55 ± 7 Ma between core formation and the end of differentiation. Alternatively, mantle cooling rates could be much faster if accretion were to take place over a much longer interval of ~60 Ma which could delay mantle differentiation until 4502 Ma. This would be consistent with recent modelling suggesting that Mars cooled in less than 5 Ma [8].

A scenario in which Mars underwent a prolonged accretion history combined with early core formation and late silicate differentiation is perhaps the simplest explanation for the observed isotopic and geochemical characteristics of the martian meteorites.

References: [1] Borg et al. (1997) *GCA, 61*, 4915–4931. [2] Borg et al. (2003) *GCA*, *67*, 3519–3536. [3] Foley et al. (2005) *GCA*, *69*, 4557–4571. [4] Kleine et al. (2004) *GCA*, *68*, 2935–2946. [5] Debaille et al. (2007) *Nature*, *450*, 525–528. [6] Amelin et al. (2002) *Science*, *296*, 1678–1683. [7] Halliday and Kleine (2006) *MESS II*, 775. [8] Elkins-Tanton (2008) *EPSL, 271*, 181-191. This work was performed under the auspices of the U.S. DOE by LLNL under contract DE-AC52-07NA27344.