NEODYMIUM ISOTOPIC EVOLUTION OF THE SOLAR SYSTEM INFERRED FROM ISOCHRON STUDIES OF PLANETARY MATERIALS. L. Borg[1], G. Brennecka[1], N. Marks[1] and S. Symes[2]. [1]Chemical Sciences Division, LLNL, Livermore CA 94550 USA. [2]University of Tennessee Chattanooga, TN. 37403.

Introduction: The Sm-Nd isotopic system is uniquely suited for evaluating early Solar System history because it is comprised of both a long-lived decay chain (^{147}Sm→^{143}Nd) and a short-lived decay chain (^{146}Sm→^{142}Nd). Furthermore, Sm and Nd are relatively immobile during fluid-based alteration and thermal metamorphism associated with impacts, allowing this system to record the timing of Sm-Nd fractionation events in many non-pristine materials. However, despite its potential usefulness, many parameters associated with the Sm-Nd system are poorly constrained. For example, values for the initial ^{146}Sm/^{144}Sm ratio of the Solar System vary from 0.0084 ± 5 to 0.0094 ± 5 [1-2]. Likewise, published half-lives for ^{146}Sm vary from 68 ± 7 Ma to 103 ± 5 Ma [2-4]. Finally, estimates of the initial ε^{142}Nd of the bulk solar system vary by ~0.2 depending on whether chondritic meteorites, CAIs, or terrestrial samples are considered to represent the bulk Solar System [5-6].

In the last several years we have completed numerous Sm-Nd mineral and whole rock isochron analyses designed primarily to establish formation ages of CAIs and lunar samples, as well as mantle source regions on the Moon and Mars. Isochrons allow isotopic disturbances to be easily identified, permit half-lives to be directly evaluated, and define the initial ^{142}Nd/^{144}Nd of individual samples without the need to correct for radiogenic decay. From this body of work it has become apparent that the initial ^{146}Sm/^{144}Sm of the Solar System is best represented by 0.00828 ± 44, the ^{146}Sm half-life of 103 Ma best reproduces ages of samples determined by other chronometers, and that the ^{142}Nd/^{144}Nd ratio of CAIs, Moon, Mars, and Earth are similar and distinct from the average determined from primitive meteorites. Below we present the observations and rationale that has led us to these conclusions.

Discussion: Mineral fractions from Allende CAI Al3S4 were recently analyzed by Marks et al. [6] yielding a 4569 ± 36 Ma ^{147}Sm-^{143}Nd age and an initial ^{143}Nd/^{144}Nd ratio of 0.506646 ± 48. This isochron is in excellent agreement with Pb-Pb ages determined on CAIs [7-8], as well as initial ^{143}Nd/^{144}Nd ratios determined from primitive meteorites. This implies, that despite evidence for small nucleosynthetic anomalies observed in Nd from CAIs [9], the Sm-Nd system was largely undisturbed in Al3S4. The ^{146}Sm-^{142}Nd isochron determined on the same mineral fractions is presented in Fig. [1]. The slope defined by this isochron corresponds to a ^{146}Sm/^{144}Sm ratio of 0.00828 ± 44. This is the best representation of the initial ^{146}Sm/^{144}Sm ratio of the Solar System because it is defined from an isochron demonstrating no evidence of disturbance on a sample representing the first Solar System solids. This initial is in good agreement with most previous estimates derived from differentiated meteorites [e.g., 1,10-11]. The initial value differs substantially from the ^{146}Sm/^{144}Sm ratio recalculated by Kinoshita et al. [2] using the newly determined ^{146}Sm half-life of 68 Ma. This implies that that half-life of 68 Ma may be underestimated.

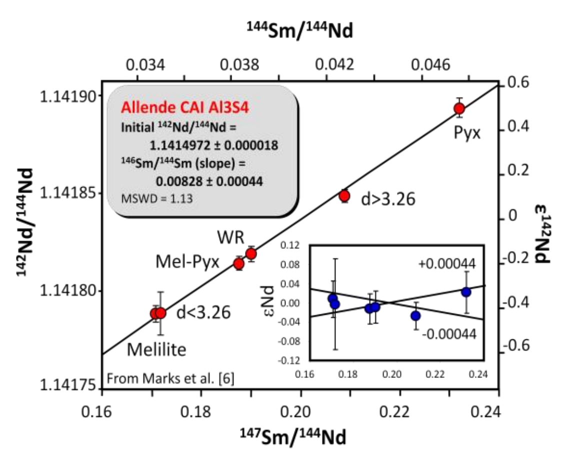

Fig. 1. **^{146}Sm-^{142}Nd isochron plot of Allende CAI Al3S4.**

The ^{146}Sm-^{142}Nd isochron for CAI Al3S4 defines the initial ^{146}Sm/^{144}Sm ratio of the Solar System and therefore cannot be used to test the ^{146}Sm half-life. In fact, the uncertainties associated with most ^{146}Sm-^{142}Nd isochron measurements reported in the literature are not precise enough to evaluate the reliability of the ^{146}Sm half-life. However, we have recently analyzed several young lunar samples that have ages determined by ^{147}Sm-^{143}Nd and Pb-Pb [12-13]. The ^{146}Sm-^{142}Nd ages calculated for these samples using the 68 Ma half-life are not a good fit to the ages determined with other isotopic systems. A plot of the ^{146}Sm-^{142}Nd ages calculated from all published Sm-Nd data, including the lunar samples, using ^{146}Sm/^{144}Sm = 0.00828 to 0.0094 and ^{146}Sm t½= 68 to 103 Ma is presented in Fig. [2]. From this figure it is apparent that the ^{146}Sm-^{142}Nd ages calculated using the 103 Ma ^{146}Sm half-life are a better fit to the ages determined by other chronometers than ^{146}Sm-^{142}Nd ages calculated using the 68 Ma half-life. This conclusion is independent of the ^{146}Sm/^{144}Sm ratios assumed for the calculation [Fig. 2]. If taken at face value, these data imply that the 68 Ma half-life is erroneous. A critical caveat, however, is that the slopes of these lines are strongly influenced by a few young

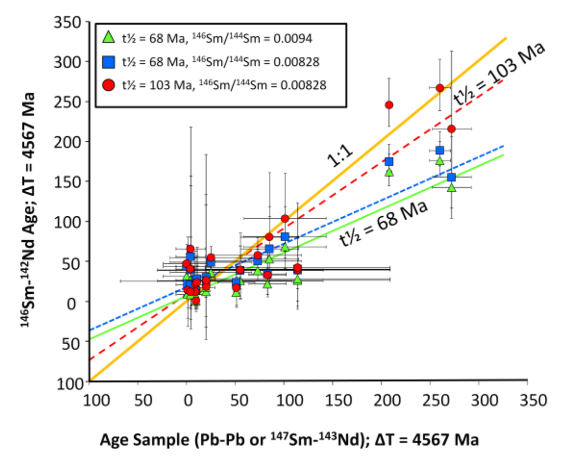

Fig. 2 Comparison of ^{146}Sm-^{142}Nd ages calculated using diffent initial ^{146}Sm/^{144}Sm and ^{146}Sm half-lives.

samples. Thus, additional data are probably needed before the half-life can be unambiguously evaluated.

Many primitive meteorites have present-day ^{142}Nd/^{144}Nd ratios that are ~0.2 ε-units below the values measured in terrestrial samples. This is illustrated on Fig. 3 where present-day ^{142}Nd/^{144}Nd versus ^{143}Nd/^{144}Nd of carbonaceous, enstatite, and ordinary chondrites [5, 14-15] are plotted with data obtained from CAI bulk [9] and mineral fractions [6]. This figure illustrates that the CAI mineral fractions define a 4571 ± 7 Ma isochron (i.e. Nd geochron), whereas the bulk CAIs scatter about the Nd geochron. In contrast, the chondrite samples define a vertical field that is orthogonal and below the Nd geochron. Single-stage growth curves constructed on this figure demonstrate that these samples did not evolve in a single stage of evolution from a common source. Thus, Nd variability in chondritic meteorites must reflect either complex multi-stage growth in multiple reservoirs with different Sm/Nd ratios or derivation from materials with heterogeneous isotopic compositions. Note that if ^{142}Nd variability reflects differences in the initial ^{146}Sm isotopic composition resulting from nucleosynthesis, then these differences must be ~250 times larger than those observed for ^{144}Sm and attributed to p-process [9].

The initial ^{142}Nd/^{144}Nd ratios of bulk planets can also be evaluated using the initial Nd compositions obtained from undisturbed isochrons from samples inferred to have single-stage evolutionary histories. Our ^{146}Sm-^{142}Nd isochron results are presented in this format in Fig. 4. These samples include primary Solar System condensates, magma ocean solidification products, and basalts derived from primary planetary differentiation products. Specifically, data plotted on this figure are obtained from mineral isochrons of Al3S4 CAI, lunar ferroan anorthosite 60025, and lunar troctolite 76535 [6, 12-13]. The age and initial Nd isotopic composition determined from martian basaltic rocks is also plotted [17]. Finally, present-day ^{142}Nd/^{144}Nd of Al3S4 and bulk Mars determined from Nd-Nd evolution diagrams are plotted with values obtained on terrestrial rock standards. This plot suggests that CAIs, Mars, Moon, and Earth are derived from materials with similar ^{142}Nd/^{144}Nd ratios and that chondritic meteorites may be a poor proxy for the terrestrial planets.

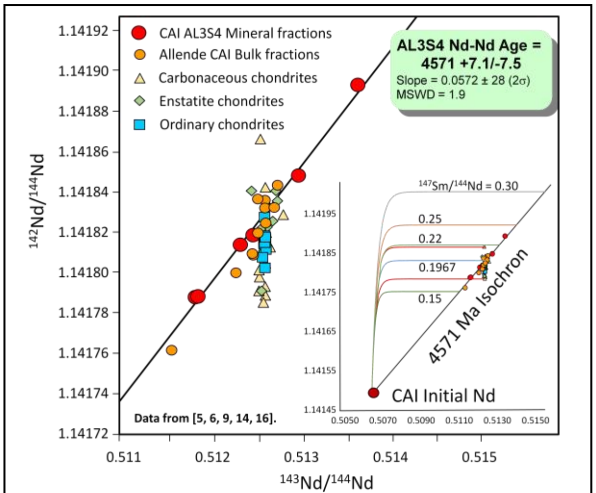

Fig. 3 Nd-Nd evolution diagram with CAI isochron defined by AL3S4 data yielding an age of 4571 ± 7 Ma. Curves represent one and two-stage (red) Nd isotopic evolution.

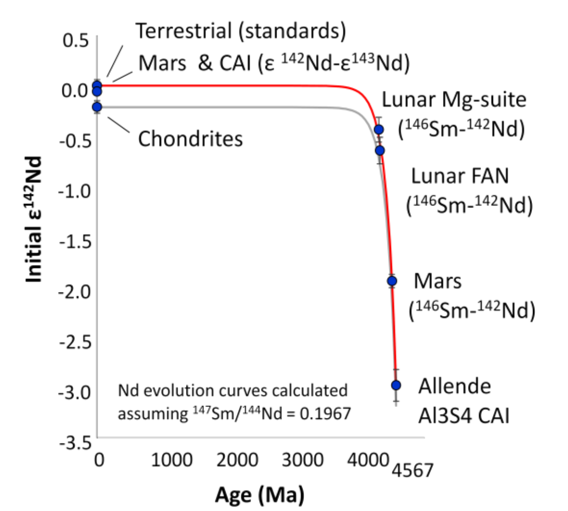

Fig. 4 Plot of age vs. initial ε^{142}Nd from isochron results.

References: [1] Boyet et al. (2010), *EPSL* **291,** 172. [2]Kinoshita et al. (2012) *Sci.* **335**, 1614. [3]Friedman et al. *Radiochim Acta* 5, 192. [4] Meissner et al. (1987) *Phys. A.* 327, 171. [5] Boyet & Carlson (2005) *Sci.* **309**, 576. [6] Marks et al. (2013) *PNAS* in press. [7] Amelin et al. (2002) *Sci.* **297,** 1678. [8] Connelly et al. (2008) *Sci.* 651. [9] Brennecka et al. (2013) *PNAS*, **108,** 17631. [10] Lugmair & Galer (1992), *GCA* **56,** 1673. [11]Nyquist et al. (1994) MAPS 29, 872. [12] Borg et al. (2011) *Nature* **477,** 70. [13] Borg et al. (2013) *43rd LPSC* Abstr# 1563. [14] Carlson et al. (2007) *Sci.* **316,** 1175-1178, [16] Gannoun et al. (2011) *PNAS* **108,** 7693. [17] Symes et al. (2014) *LPSC.* Work performed under the auspices of the U.S. DOE by LLNL under contract DE-AC52-07NA27344.