ONSET OF MAGMA OCEAN SOLIDIFICATION ON MARS INFERRED FROM Mn-Cr CHRONOMETRY. T.S. Kruijer, L.E. Borg, J. Wimpenny, and C.K. Sio. Lawrence Livermore National Laboratory, Nuclear and Chemical Sciences Division, 7000 East Avenue (L-231), Livermore, CA, 94550, USA (kruijerl@llnl.gov).

**Introduction:** The mantle of Mars probably differentiated through the crystallization of a magma ocean during the first tens of million years (Ma) of Solar System evolution [e.g. 1]. However, the exact timescale of large-scale silicate differentiation of the martian mantle as inferred from application of long-lived and short-lived isotope chronometers is debated [e.g. 2-5], and in particular, it remains unclear when differentiation commenced [4,5]. For instance, large-scale mantle differentiation may have started well within ~20 Ma after Solar System formation [5], but could also have been a more protracted process occurring between ~20 and 40 Ma [4], and possibly as late as 60 Ma after Solar System formation [3]. Tighter bounds on the timescales of martian differentiation can be obtained using the short-lived $^{53}$Mn-$^{53}$Cr system (half-life: 3.7 Ma). This is because the relatively short half-life of $^{53}$Mn limits the effective production of radiogenic $^{53}$Cr. Variations to the first ~15-20 Ma of Solar System history. Thus, finding $^{53}$Cr variations among martian meteorites would provide unequivocal evidence for silicate differentiation on Mars within ~15-20 Ma of Solar System formation. However, $^{53}$Cr/$^{52}$Cr data have so far only been obtained for five martian meteorites [6-8], precluding a detailed assessment of the extent of potential $^{53}$Cr variability among martian meteorites.

To more fully assess the differentiation history of Mars, we applied the Mn-Cr system to a comprehensive suite of martian meteorites, including different groups of shergottites, orthopyroxenite ALH 84001, polymict breccia NWA 7034, two nakhlites, and augite basalt NWA 8159.

**Methods:** For the determination of Cr isotopic compositions, we used precision carbon matrix aliquots of martian samples previously analyzed for Nd and W isotope systems [4]. After chemical separation of Cr through several ion chromatography steps, Cr isotopic compositions were determined on the Triton TIMS at LLNL largely following previously published methods [e.g. 7-8]. Measured $^{53}$Cr/$^{52}$Cr and $^{54}$Cr/$^{52}$Cr were corrected for instrumental mass fractionation by internal normalization to $^{50}$Cr/$^{52}$Cr = 0.00518, and are expressed as $\mu$-unit (i.e. parts-per-million) deviations relative to terrestrial reference materials (NBS 979, BHVO-2).

**Results:** All martian meteorites analyzed here exhibit resolved but identical $^{53}$Cr excesses relative to the NBS-979 standard, ranging from +16 to +24 ppm (Fig. 1). Such $^{53}$Cr excesses are consistent with the limited available data for martian meteorites reported in prior studies [e.g. 6-8]. However, the martian meteorites analyzed here have a much wider compositional range indicative of derivation from vastly different source regions. Thus, a key observation from the new results is that there are no resolvable $^{53}$Cr variations among the martian meteorites. The investigated martian meteorites encompass the full extent of compositional and isotopic variability known on Mars, including the full spread in $^{142}$Nd and $^{182}$W compositions observed so far [e.g. 3,4]. Hence, the uniform $^{53}$Cr excess of $+20.3\pm1.4$ (95% conf, N=16) observed for martian meteorite compositions is interpreted to reflect the $^{53}$Cr composition of the bulk martian mantle. The $^{53}$Cr composition of Mars is indistinguishable from enstatite and ordinary chondrites, but significantly more elevated than the bulk silicate Earth. Consistent with prior work [7-9], we interpret this $^{53}$Cr difference between Mars and the bulk silicate Earth to reflect a volatility-induced Mn/Cr fractionation at the start of Solar System history around ~4567 Ma.

**Mn-Cr chronology of martian meteorites:** Our results do not provide evidence for radiogenic $^{53}$Cr variations among the mantle sources of martian meteorites (Fig. 1). This may either reflect: (i) a lack of Mn/Cr variability amongst martian mantle sources resulting in un-resolvable $^{53}$Cr variations among martian meteorites, or alternatively, (ii) that silicate differentiation occurred after the effective lifetime of $^{53}$Mn. Although the first possibility cannot be fully ruled out, it is more likely that the sources of martian meteorites had significant Mn/Cr

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**Fig. 1:** $^{53}$Cr compositions of martian meteorites from this study. Error bars denote external uncertainties (2σ).
The Mn-Cr age for silicate differentiation on Mars was calculated from the measured Mn/Cr in terrestrial and martian mantle derived rocks [2,3], combined Hf-W and Sm-Nd systematics [4], as well as combined Lu-Hf and U-Pb chronometry of zircons [5].

**Fig. 2**: Timescales of mantle differentiation on Mars inferred from Mn-Cr systematics. Model curves illustrate expected $\mu^{53}$Cr variability as a function of differentiation time for different values of $f$, where $f = \frac{[\mu^{53}\text{Mn}/\mu^{53}\text{Cr}]_{\text{mantle source 1}} - 1}{[\mu^{53}\text{Mn}/\mu^{53}\text{Cr}]_{\text{mantle source 2}}}$. Shaded areas depict the maximum possible $\mu^{53}$Cr variability on Mars [expressed as $\Delta(\mu^{53}\text{Cr})$] based on analyses of martian meteorites (Fig. 1).

To quantify the timescales of mantle differentiation on Mars, we calculated the expected range in $\mu^{53}$Cr among martian mantle sources (Fig. 2). Comparing these model curves to the maximum possible observed range in $\mu^{53}$Cr derived from the isotopic data (Fig. 1) yields minimum Mn-Cr model ages ranging from ~15 Ma ($f=2$) to a maximum of ~25 Ma ($f=5$) after Solar System formation (Fig. 2). Thus, we conclude that fractionation of Mn from Cr in the sources of martian meteorites was unlikely prior to 20±5 Ma after Solar System formation, otherwise differences in the measured $\mu^{53}$Cr would be observed. As a result, the minimum Mn-Cr model age of 20±5 Ma derived above implies that any Mn/Cr fractionation associated with magma ocean differentiation on Mars cannot have occurred before that time. The Mn-Cr age for silicate differentiation on Mars corroborates existing Sm-Nd and Hf-W chronology of martian meteorites [2-4], as well as age estimates based on Lu-Hf analyses of martian zircons [5] (Fig. 3).

**Fig. 3**: Chronology for the earliest evolution of Mars. Core formation age based on Hf-W chronometry [1,12] and timescales of magma ocean differentiation on Sm-Nd chronometry [2,3], combined Hf-W and Sm-Nd systematics [4], as well as combined Lu-Hf and U-Pb chronometry of zircons [5].


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