THE MN-CR ISOTOPE SYTREMATICS OF BULK ANGRITES. A. Shukolyukov and G.W. Lugmair, Scripps Institution of Oceanography, University of California, San Diego, La Jolla CA 92093-0212, USA

We have shown earlier that studies of Mn-Cr systematics of bulk samples from a differentiated planetesimal can yield important constraints on its time of differentiation and valuable information on large scale processes within early solar system bodies [1]. Specifically, we have studied bulk samples of non-cumulate and cumulate eucrites and diogenites. It was shown that the $^{53}Cr/^{52}Cr$ ratios are correlated with their respective $^{55}Mn/^{52}Cr$ ratios. The best-fit line resulted in a *bulk* meteorite isochron. As such, it carries no information on the time of crystallization or cooling of individual meteorites. Instead, the slope of the line dates the *last Mn/Cr fractionation* and *Cr isotope equilibration* in the howardite-eucrite-diogenite parent body (HED PB) mantle and, thus, probably the time of *core formation.* The slope of the isochron yields a $^{53}Mn/^{55}Mn$ ratio of (4.7±0.5) x 10^{-6} at this time. Using this ratio, a Pb-Pb age of the angrite LEW 86010 (LEW) of 4557.8±0.5 Ma [2] and a $^{53}Mn/^{55}Mn$ ratio at the time of isotope closure for LEW of (1.25±0.07) x 10^{-6} [1] yields an absolute age of 4564.8±0.9 Ma for the HED PB. This age is only about 2–3 Ma younger than the age of first condensates in the early Solar system [3].

This work is an attempt to conduct a similar study for the angrite parent body (APB) in order to obtain constraints on the time of its differentiation. The angrites are early equilibrated planetary differentiates that do not show signs of any later severe disturbance and, thus, are very suitable as time markers using various isotope systems. Baker et al. [4] reported recently a very precise (and surprisingly ancient) Pb-Pb age of 4566.18±0.14 Ma for the angrite SAH99555 (SAH). This age is only 1.0±0.6 Ma younger than a Pb-Pb age of the CAIs from the CV chondrite Efremovka (4567.2±0.6 Ma [3]). Some short-lived isotope chronometers, however, yield much younger ages. The ^{26}Al-^{26}Mg age of SAH is 4562.5±1.2 Ma [5] and the ^{53}Mn-^{53}Cr systematic in SAH implies an absolute age of 4562.2±0.9 Ma [6]. These discrepancies were an additional motivation for our attempt to re-construct the chronology of the APB itself.

We have measured the Mn/Cr ratios and the Cr isotopic composition in large (several hundred mg) bulk samples of the angrites LEW86010 (LEW), D'Orbigny (D'ORB), SAH99555 (SAH), and NWA2999 (NWA). As in the past, in order to achieve higher precision, we also have applied the second order fractionation correction to the $^{53}Cr/^{52}Cr$ data based on the $^{54}Cr/^{52}Cr$ ratios [1]. This procedure assumes no excesses or deficits of ^{54}Cr. However, it was shown, that the bulk samples of carbonaceous chondrites have variable excesses of ^{54}Cr [7,8]. There are recent additional data [7,9-11] that indicate deficits of ^{54}Cr in several other meteorite classes. Here we present both the 'normalized' (with the second order fractionation correction applied) and the 'raw' ratios (no second order fractionation correction applied). The results are presented in the Figure.

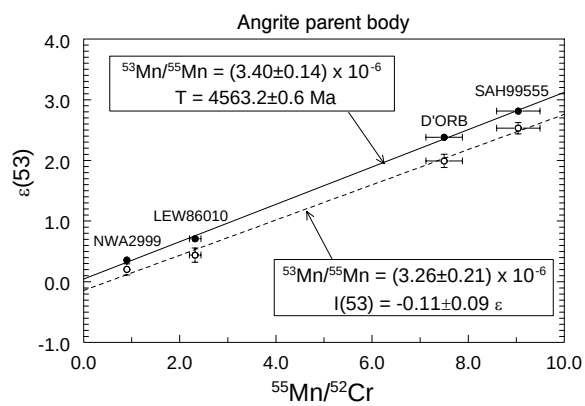

Figure. ^{53}Mn-^{53}Cr isotope systematics in the bulk samples of angrites. The 'normalized' ε(53) are presented using filled symbols, the 'raw' ε(53) with open symbols. D'ORB stands for D'Orbigny.

The $^{53}Cr/^{52}Cr$ ratios (or $\varepsilon(53)_{norrn}$ and $\varepsilon(53)_{raw}$) are given as the relative deviation from the terrestrial standard value and are expressed in ε - units (1 ε is one part in 10^4). The 'normalized' ε(53) versus the respective $^{55}Mn/^{52}Cr$ ratios are shown in the Figure by the filled symbols. The uncertainties in $\varepsilon(53)_{norm}$ are 0.02 - 0.03 ε ($2\sigma_{mean}$). The ^{53}Cr excesses are very well correlated with the respective $^{55}Mn/^{52}Cr$ ratios. Similar to the HED parent body, the absence of a resolvable scatter of the data points from the line implies that the source reservoirs of all four meteorites were formed contemporaneously and that the Mn-Cr systems of the bulk samples of these meteorites remained closed since their formation. The slope of the isochron yields a $^{53}Mn/^{55}Mn$ ratio of (3.40±0.14) x 10^{-6} at this time. Using this ratio and LEW as an absolute time marker gives an age of 4563.2±0.6 Ma. The 'raw' ε(53) versus $^{55}Mn/^{52}Cr$

ratios are shown in the Figure by open symbols. The uncertainties are of course larger than for $\varepsilon(53)_{norrn}$. However, due to dozens of repeat measurements, they are still acceptably small (0.10 – 0.12 ε). The slope of this isochron is similar to that obtained with the $\varepsilon(53)_{norm}$ and is (3.26±0.21) x 10^{-6}. The true initial ε(53) at the time of isotope closure, derived from the 'raw' data, is –0.11±0.09 ε. The uncertainty in the $^{53}Mn/^{55}Mn$ ratio is necessarily larger. The $\varepsilon(53)_{raw}$ isochron falls ~0.2 ε below the $\varepsilon(53)_{norm}$ isochron. This suggests that similar to some other meteorite classes the angrites have a deficit of ^{54}Cr. Indeed, a preliminary value for $\varepsilon(54)_{raw}$ is ~ - 0.5ε and falls into the range found for ordinary chondrites and eucrites [10]. During the application of the second order fractionation correction the deficit of ^{54}Cr translates into elevated $\varepsilon(53)_{norm}$. This results in a parallel shift of the whole $\varepsilon(53)_{norm}$ isochron along the y-axis. It is important to stress that the $^{53}Mn/^{55}Mn$ ratio (and, thus, the ^{53}Mn-^{53}Cr age) are defined solely by the *slope* of the isochron. It is, thus, reasonable to use the slope defined by the higher precision $\varepsilon(53)_{norm}$ line. It is clear, however, that for samples with deficits or excesses of ^{54}Cr the correct initial ε(53) value can be determined only from the 'raw' data set.

Our results thus indicate that the various mantle sources of the angrites measured here were in isotopic equilibrium 4563.2±0.6 Ma ago. This age most probably also indicates the time of planet-wide differentiation, which occurred only ~2 Ma after that of the HED PB and ~4 Ma after CAI formation. It appears also quite reasonable that the crystallization ages of the 'older' generation of angrites (e.g. D'Orbigny - 4562.9±0.6 Ma [12]), representing the earliest lava flows on the surface of the APB, are similar. Comparable ages are indicated for SAH99555 by the ^{26}Al-^{26}Mg [5] and ^{53}Mn-^{53}Cr [6] chronometers. If one applies the new and refined Pb age obtained for LEW by Amelin (4558.6±0.2 Ma; this volume) the 'APB age' would become 0.8 Ma older (4564.0±0.4 Ma). However, the high precision Pb-Pb age of 4566.18±0.14 Ma [4] for the same meteorite is ≥2 Ma higher. If 4563.2 (or 4564.0) Ma indeed represents the final time of isotopic equilibrium within the APB mantle after completion of a planet wide Mn/Cr fractionation and considering that SAH has the highest and most fractionated Mn/Cr ratio then the Pb-Pb age is difficult to reconcile.

In summary, the ^{53}Mn-^{53}Cr systematics in bulk samples of angrites indicate that the last Mn/Cr fractionation and Cr isotope equilibration in the angrite parent body mantle occurred 4563.2±0.6 Ma ago. The first generation of angrites has crystallized at the same time or shortly thereafter. The APB is characterized by an anomalous $^{54}Cr/^{52}Cr$ ratio that is deficient in ^{54}Cr and similar to ordinary chondrites or HED meteorites [10]. It is clear, however, that this ^{54}Cr deficit does not support the derivation of angrites from carbonaceous chondritic material [e.g. 13]. Finally, the second order fractionation correction procedure is a useful tool to achieve improved age resolution, even for samples with an anomalous abundance of ^{54}Cr.

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