^{60}FE-^{60}NI CHRONOLOGY OF ANGRITES. L. J. Spivak-Birndorf[1], M. Wadhwa[1], and P. E. Janney[1]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287 (Lev.Spivak-Birndorf@asu.edu)

Introduction: The abundance and distribution of ^{60}Fe ($t_{1/2}$ = 2.62 Ma) in the early Solar System has important implications for its origin and evolution. However, the amount of ^{60}Fe present at the time of Solar System formation is still poorly constrained. Recent estimates of the initial Solar System ^{60}Fe/^{56}Fe ratio are highly variable and depend on the samples and analytical techniques used [1-4]. While *in situ* measurements of components in primitive chondrites suggest Solar System initial ^{60}Fe/^{56}Fe ratios from ~10^{-7} to ~10^{-6} [1, 2], measurements of mineral separates and bulk samples of achondrites provide lower estimates of ~10^{-8} [3, 4].

The D'Orbigny angrite is a rapidly quenched basalt that has been minimally altered since its formation [5, 6]. The ancient crystallization age of D'Orbigny is well constrained by a number of long- and short-lived radionuclide chronometers [7-10], and the presence of extant ^{60}Fe at its formation time was recently also reported by [4]. As such, D'Orbigny is an ideal sample to better constrain the initial Solar System abundance of ^{60}Fe.

Chronological studies of bulk meteorite samples from a common parent body can yield information about the timing of formation of the chemical reservoirs from which the individual meteorites eventually formed (e.g., [11]). It was recently suggested that the Fe-Ni systematics of bulk angrites define a "whole-rock" isochron that reflects the contemporaneous formation of the various angrite source reservoirs [4]. However, that study included only one plutonic angrite sample with a near-chondritic Fe/Ni ratio [4], and mesurements of the ^{60}Fe-^{60}Ni systematics of additional plutonic angrites are needed to interpret the whole-rock Fe-Ni data presented in [4].

Here we report the most recent data from our investigation of the ^{60}Fe-^{60}Ni systematics of angrites, preliminary results of which were reported by [12, 13].

Samples and Analytical Methods: This investigation includes two bulk samples and two mineral separates (olivine and pyroxene) from the quenched angrite D'Orbigny. Bulk samples of three plutonic angrites, NWA 6291 (NWA 2999 pair), NWA 4801, and NWA 4590 were also analyzed. Procedures used for Ni purification and isotopic measurement using the Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) in the Isotope Cosmochemistry and Geochronology Laboratory (ICGL) at Arizona State University (ASU) are described previously by [12]. The Fe/Ni ratios reported here were measured on the Neptune MC-ICPMS. The instrument was calibrated using a set of gravimetrically prepared ICPMS standard solutions with variable Fe/Ni ratios that spanned the range in the unknown angrite samples.

Results: The plutonic angrites have a range in ^{56}Fe/^{58}Ni ratios from ~80 to ~9000. Nevertheless, all Ni isotope compositions of these sample are indistinguishable, within the errors, from the terrestrial value. The two bulk samples and two mineral separates of D'Orbigny have ^{56}Fe/^{58}Ni ratios ranging from ~4300 to ~9100 and all have excesses in ^{60}Ni* that correlate with their Fe/Ni ratios. The D'Orbigny samples define a ^{60}Fe-^{60}Ni isochron that corresponds to a ^{60}Fe/^{56}Fe = $(4.3 \pm 1.7) \times 10^{-9}$ and $\varepsilon^{60}Ni_0 = -0.28 \pm 0.34$ at the time of last equilibration of Ni isotopes in this meteorite (Fig. 1).

Discussion: An investigation of the ^{53}Mn-^{53}Cr systematics of bulk angrite samples, both quenched and plutonic, reported that all of the angrites define a single Mn-Cr "whole-rock" isochron, corresponding to the time when the various angrite sources formed [14]. A recent study on the ^{60}Fe-^{60}Ni systematics of angrites has additionally suggested that these meteorites also define an analogous "whole-rock" Fe-Ni isochron based on analyses of bulk samples of one plutonic (NWA 2999) and two quenched (D'Orbigny and Sahara 99555) angrites [3]. However, D'Orbigny and Sahara 99555 crystallized at the same time [10, 15]. Therefore, their bulk samples should fall along the same ^{60}Fe-^{60}Ni isochron provided the isotope systematics of both meteorites have not been disturbed since their formation. The Ni isotope composition and Fe/Ni ratio of the NWA 2999 bulk sample are similair to bulk chondrites. Therefore, it is unclear whether the correlation reported by [3] for bulk angrites represents a true "whole-rock" Fe-Ni isochron, or the contemporaneous formation of D'Orbigny and Sahara 99555 from a mantle source characterized by bulk chondritic ^{60}Fe-^{60}Ni systematics.

The absence of ^{60}Ni excesses in the plutonic angrites measured here, despite having ^{56}Fe/^{58}Ni ratios up to ~9000, indicates that ^{60}Fe was extinct by the time these meteorites were last equilibrated with respect to Ni isotopes. As such, in contrast to the Mn-Cr system [14], bulk angrites do not define a "whole-rock" Fe-Ni isochron as was previously suggested by [3]. This result indicates that the Fe-Ni system closed at a later time than the Mn-Cr system in the angrite sources, possibly due to different closure temperatures for the two chronometers. If it is assumed that the plutonic angrites NWA 4801 and NWA 4590 formed simultaneously we determine an upper limit on the ^{60}Fe/^{56}Fe ratio of ≤ 1× 10^{-9} at that time. This translates to an age of ≤4557.9 Ma relative to D'Orbigny, which is consistent with the Pb-Pb ages determined for these two plutonic angrites [16, 17].

The slope of the D'Orbigny ^{60}Fe-^{60}Ni isochron can be combined with the known age difference between this meteorite and the CAIs (~4-5 Ma; [10, 18, 19]) to extrapolate back to the initial Solar System $^{60}Fe/^{56}Fe$ ratio. From these data we calculate a range of $^{60}Fe/^{56}Fe$ from $(1.2 \pm 0.5) \times 10^{-8}$ to $(1.6 \pm 0.6) \times 10^{-8}$ at the start of the Solar System (assuming a half life for ^{60}Fe of 2.62 Ma [20]). This value is in good agreement with recent estimates from other investigations of achondrites [3,4].

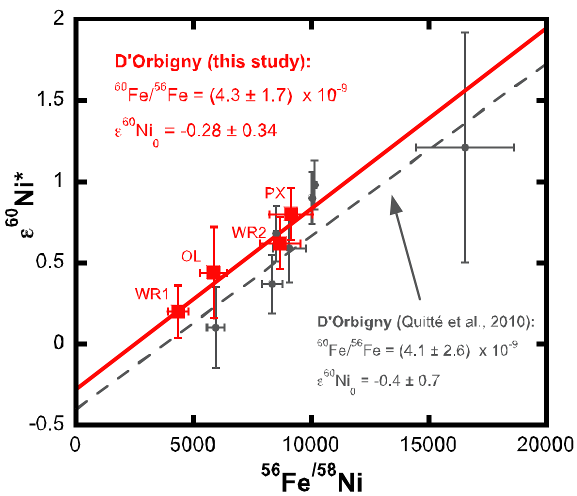

Fig. 1. D'Orbigny ^{60}Fe-^{60}Ni isochron. Errors on our data are ±2SD on $\varepsilon^{60}Ni^*$ and ±10% on $^{56}Fe/^{58}Ni$ ratios. Data from [3] are shown for comparison; uncertainties on these data are ±2SE.

Iron-60 is only produced efficiently by stellar nucleosynthesis processes and not by spallation reactions [21]. An initial Solar System ^{60}Fe abundance significantly higher than that in the average interstellar medium (ISM) would therefore be considered strong evidence for a late addition of stellar material to the solar protoplanetary disk. Estimates of the ISM $^{60}Fe/^{56}Fe$ ratio, ranging from ~10^{-8} to ~10^{-7}, have been determined using closed-box galactic chemical evolution (GCE) models and measurements of ^{60}Fe gamma ray emissions ([22, 23] and references therein). If more realistic open-box GCE models are used, $^{60}Fe/^{56}Fe$ ratios that are a factor of ~3 higher are predicted for the ISM (e.g., [24, 25]).

Estimates of the Solar System initial ^{60}Fe abundance based on *in situ* analyses of chondritic components [1, 2] exceed those for the ISM and seem to require a late stellar addition. However, the initial ^{60}Fe abundance determined from the D'Orbigny data presented here, as well as from other recent studies of achondrites [3, 4] are close to, or lower than, the estimated abundance in the ISM. These data are consistent with the initial Solar System abundance of ^{60}Fe being inherited from the ISM and, therefore, do not require a late stellar addition. The reasons for the apparent discrepancy between the estimates of the initial Solar System ^{60}Fe abundance using diffferent meteoritic materials and analytical techniques are not clear at this time but may include: 1) heterogeneous distribution of ^{60}Fe in the early Solar System, 2) disturbance of the ^{60}Fe-^{60}Ni systematics in some or all of the meteorites that have been studied, or 3) analytical artifacts. Future work will be required to more rigorously evaluate these possibilities.

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