EARLY SOLAR SYSTEM DYNAMICS INFERRED FROM MOLYBDENUM ISOTOPE ANOMALIES IN METEORITES. G. Budde, C. Burkhardt, and T. Kleine, Institut für Planetologie, University of Münster, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany (gerrit.budde@uni-muenster.de).

Introduction: Nucleosynthetic isotope anomalies arise from the heterogeneous distribution of isotopically anomalous presolar matter, and are powerful tools for investigating early solar system dynamics by establishing genetic relationships among planetary bodies. For instance, building on previous work [1], Budde et al. [2] demonstrated that nucleosynthetic Mo isotope anomalies in bulk meteorites reveal a fundamental dichotomy in the genetic heritage of meteorites, distinguishing between *carbonaceous* (CC) and *non-carbonaceous* (NC) materials. The isotopic difference between the CC and NC reservoirs cannot reflect a temporal change in the disk composition because both groups contain chondrites and iron meteorites, which formed between <1 and ~4 Ma after CAI formation [2–4]. Instead, these observations indicate that CC and NC meteorites derive from two spatially distinct reservoirs that coexisted and remained separated for several million years, most likely as a result of the formation of Jupiter in between them [2,4].

However, this interpretation critically depends on whether or not there are meteorites with compositions that are intermediate between those of the NC and CC reservoirs. Therefore, we obtained Mo isotope data for meteorite groups that have not been investigated before to evaluate whether the Mo isotope dichotomy holds for all meteorites. These data are not only important for testing the fundamental dichotomy between NC and CC meteorites, but they also provide critical new insights into the accretion history of the Earth.

Samples and methods: To date, we have obtained Mo isotope data for CK, CH, CBb, and Rumuruti (R) chondrites as well as for mesosiderites, acapulcoites, brachinites, and numerous ureilites. All samples were carefully cleaned and digested in Savillex beakers using HF-HNO_3-$HClO_4$ and inverse aqua regia. Molybdenum was separated from the sample matrix by ion exchange chromatography following our established procedures [2,3], and Mo isotope compositions were measured using the Neptune *Plus* MC-ICP-MS at Münster. The isotope data are internally normalized to ^{98}Mo/^{96}Mo and reported as ε-unit deviations (*i.e.*, 0.01%) relative to the bracketing solution standard. The precision and accuracy of the Mo isotope analyses were assessed by repeated measurements of the BHVO-2 rock standard, which was processed together with each set of samples and which defines an external reproducibility (2 s.d.) for the Mo isotope ratios of about 0.1–0.3ε (for ~80 ng Mo consumed per analysis).

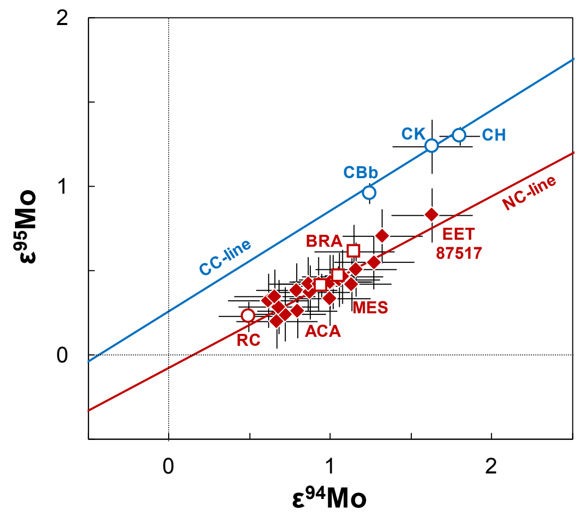

Fig. 1. Diagram of ε^{95}Mo *vs.* ε^{94}Mo for bulk meteorite samples from this study. Ureilites are shown as red diamonds. See Fig. 2 for further details.

Results: All analyzed samples show well-resolved ε^{i}Mo excesses that are consistent with a nucleosynthetic origin and indicative of variable deficits in *s*-process Mo nuclides relative to the terrestrial standard. However, in a diagram of ε^{95}Mo *vs.* ε^{94}Mo (Fig. 1), the carbonaceous (CK, CH, CBb) chondrites plot on an *s*-process mixing line that is distinct from the *s*-process mixing line defined by NC meteorites (enstatite and ordinary chondrites, most achondrites and iron meteorites). In contrast, all investigated Rumuruti chondrites, mesosiderites, acapulcoites, and brachinites plot on the NC line. Of note, the analyzed bulk ureilites show an exceptionally large range in Mo isotope anomalies that exceeds analytical uncertainties; nevertheless, all of them plot on the *s*-mixing line defined by NC meteorites (Fig. 1).

Variability among ureilites: In contrast to most other meteorite groups, ureilites exhibit variable nucleosynthetic Mo isotope anomalies, where EET 87517 stands out by having the largest deficit in *s*-process Mo (Fig. 1). This sample is also characterized by nucleosynthetic Os isotope anomalies, which otherwise are absent from most ureilites [5]. Note that the anomalous isotopic composition of EET 87517 as well as the variability among bulk ureilites predominantly reflect *s*-process variations, and as such do not reflect admixture of carbonaceous material to 'original' ureilites. Instead, these anomalies likely result from the selective destruction of presolar *s*-process components during partial melting on the ureilite parent body [5] or, alternatively, derivation from separate parent bodies. Either way, all ureilites plot on the NC-line, demonstrating that they are genetically linked to non-carbonaceous meteorites, as argued previously on the basis of Cr and Ti isotope systematics [1].

Implications of Mo isotope dichotomy: Our new data presented here confirm and extend the fundamental dichotomy between CC and NC materials observed in previous studies to a much larger range of meteorite groups (Fig. 2). So far, the Mo isotope dichotomy holds for all analyzed meteorite groups, where the fact that all meteorites plot either on the CC- or on the NC-line (and not in between) supports an efficient separation of two genetically distinct source regions of planetesimals. The most plausible mechanism for such an efficient separation over several million years is the formation of Jupiter, which acted as a barrier against exchange of material between the NC (inside Jupiter's orbit) and CC reservoirs (outside Jupiter's orbit) [2,4].

As Mo isotopes can readily be measured for basically every meteorite type, Mo isotope systematics provide a new and powerful means for distinguishing between CC and NC materials. Given the significance of this dichotomy in the provenance of asteroids, it should be included in classification schemes for meteorites, where the first-order division should be that between CC and NC meteorites [1].

Constraints on Earth's building material: In addition to constraining early solar system dynamics and meteorite genetics, the Mo isotope data also have far-reaching implications for constraining the origin and nature of Earth's building material. As the Earth predominantly formed from inner solar system material, it is expected to plot on the NC-line. However, based on the current data set, the NC-line has a resolved negative intercept and, therefore, the Earth's mantle plots slightly above the NC-line (Fig. 2). Note that the Earth's mantle is here represented by the Mo solution standard (ε^{i}Mo ≡ 0) and the terrestrial rock standard BHVO-2, which have indistinguishable Mo isotope compositions.

This offset, if confirmed by analyses of a more representative suite of terrestrial samples, most likely results from the addition of carbonaceous meteorite-type material to the Earth. As the Mo isotope composition of the Earth's mantle likely reflects that of the last ~10–20% of accreted mass [6], one possibility is that carbonaceous meteorite-type material was added to the Earth during the late stages of Earth's accretion. Surprisingly though, Ru isotope data strongly suggest that the late veneer (*i.e.*, the material added to Earth's mantle after cessation of core formation) was distinct from carbonaceous meteorites [7]. Thus, an alternative possibility is that the small offset of the Mo isotope composition of Earth's mantle from the NC-line reflects the homogenized composition of inner solar system material after the addition of CC bodies. Scattering and efficient mixing of CC bodies into the inner solar system is a natural outcome of the growth and/or migration of the gas giant planets [8,9], and may have, therefore, led to a small shift in the composition of later-formed inner solar system bodies towards the CC-line. A corollary of this is that the Earth would have predominately formed from bodies with similar isotopic compositions, consistent with the observation that the isotopic nature of Earth's building blocks did not change over time [6].

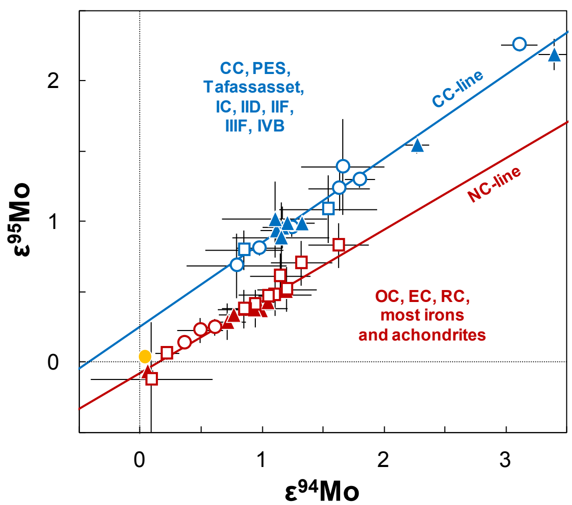

Fig. 2. Diagram of ε^{95}Mo *vs.* ε^{94}Mo for bulk meteorites, modified after [2]. Open circles: chondrites, open squares: achondrites, solid triangles: iron meteorites. Carbonaceous (blue, CC-line) and non-carbonaceous (red, NC-line) meteorites plot on distinct *s*-mixing lines, reflecting a uniform excess of *r*-process Mo in CC over NC meteorites [2]. The terrestrial rock standard BHVO-2 is shown as orange circle. Data are from this study and [4,10–12]. Note that the NC-line is now more precisely defined based on the newly obtained data, resulting in a resolved non-zero intercept.

References: [1] Warren P. H. (2011) *EPSL*, 311, 93–100. [2] Budde G. et al. (2016) *EPSL*, 454, 293–303. [3] Budde G. et al. (2018) *GCA*, 222, 284–304. [4] Kruijer T. S. et al. (2017) *PNAS*, 114, 6712–6716. [5] Goderis S. et al. (2015) *EPSL*, 431, 110–118. [6] Dauphas N. (2017) *Nature*, 541, 521–524. [7] Fischer-Gödde M. and Kleine T. (2017) *Nature*, 541, 525–527. [8] Fischer R. A. et al. (2018) *EPSL*, 482, 105–114. [9] Raymond S. N. and Izidoro A. (2017) *Icarus*, 297, 134–148. [10] Poole G. M. et al. (2017) *EPSL*, 473, 215–226. [11] Render J. et al. (2017) *GPL*, 3, 170–178. [12] Worsham E. A. et al. (2017) *EPSL*, 467, 157–166.