GENETIC TRACING OF IMPACTORS ON THE HED PARENT BODY USING Mo AND Ru ISOTOPES.

E.A. Worsham[1], T. Kleine[1], [1]University of Münster, Institut für Planetologie, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (worsham@uni-muenster.de).

Introduction: Siderophile elements and volatiles in the Earth's mantle were likely delivered during the later stages of accretion [e.g., 1]. The relationship between late impactors and the major building blocks of the terrestrial planets is ambiguous, however, as is whether those materials varied with time or location. These issues can be investigated using impactites from multiple parent bodies. Here, we focus on impact melts from a eucrite, which belongs to the howardite-eucrite-diogenite (HED) clan of meteorites that likely originated from the asteroid 4 Vesta.

Siderophile elements are strongly depleted in the crusts of differentiated planetary bodies like 4 Vesta, but have comparatively high concentrations in chondrites and iron meteorites. Impactites, thus, are often enriched in siderophile elements inherited from the impactor. Osmium isotopes and relative abundances of siderophile elements in lunar and HED impactites indicate that impactors to these bodies were varied, including both chondritic and evolved impactors, and were sometimes unlike known meteorite groups [e.g., 2-4].

To further characterize impactors that may have affected inner solar system bodies, we utilize genetic tracing; i.e., the parent body-specific isotope anomalies observed at the bulk meteorite scale for Mo and Ru [e.g., 5-6]. Due to their siderophile behaviors, the isotopic compositions of Mo and Ru in impactites likely reflect those of the impactor. These elements are particularly useful because their isotopes can differentiate between the two nebular reservoirs that existed in the early solar system [e.g., 7, 8]. These reservoirs are termed the non-carbonaceous (NC) and carbonaceous (CC) reservoirs and likely represent the inner and outer regions of the protoplanetary disk, respectively. The first Mo and Ru isotope data from an impact melt, extracted from the polymict eucrite breccia NWA 1644 (Fig. 1), are presented here.

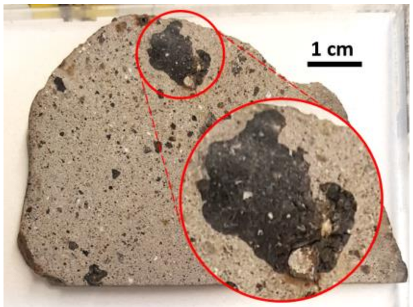

Fig. 1. Polymict eucrite NWA 1644 with impact melt clast circled. A large metal grain is visible in the lower portion of the melt.

Experimental Methods: Impact melts were identified by their dark-colored, glassy appearance in the eucrite basalt matrix, along with the presence of metal grains. Powdered splits or metal separates from large impact melt inclusions were digested in 2:1 conc. HNO_3:HCl using an *Anton Paar* high pressure asher at 320 °C. Ruthenium was separated from the matrix and purified using a three-stage cation and anion exchange chromatographic procedure [9]. Molybdenum was recovered from this chemistry and further purified using three-stage anion and Tru-spec resin ion exchange chromatography [10].

Isotopic compositions of Mo and Ru were determined using a *Thermo-Fisher Neptune Plus* MC-ICP-MS at Münster. The isotopic compositions are reported in ε notation (parts-per-10^4 deviations from terrestrial standards). The data are normalized to ^{98}Mo/^{96}Mo and ^{99}Ru/^{101}Ru. The external reproducibility (2SD) of the repeated analysis of terrestrial standards is ± 28 ppm for ε^{94}Mo, ± 20 ppm for ε^{95}Mo, and ± 16 ppm for ε^{100}Ru.

Results: Preliminary Mo and Ru isotope data from one impact melt, which contained a large metal grain, are shown in Figure 2. It was only possible to analyze this sample twice for both Mo and Ru, so the 2SD external reproducibility is applied as the uncertainty for each. The Mo and Ru isotopic compositions indicate that the impactor component in the eucrite impact melt belongs to the NC suite of the meteorite isotope dichotomy and is most similar to enstatite chondrites, near the terrestrial isotopic composition (or, in the case of Ru, overlapping the terrestrial composition).

Discussion: The NC nature of the eucrite impact melt is not necessarily expected, given that howardites are known to include carbonaceous chondrite clasts, and carbonaceous material has been observed in and around craters on Vesta by the Dawn mission [11, 12]. Because this carbonaceous material is volatile rich, it likely originated in the outer solar system. Therefore, evidence of an NC impactor to Vesta implies that impactors were sourced from both the inner and outer solar system.

One possibility is that this simply reflects the compositional variety of asteroids within the asteroid belt, where asteroids presumed to have formed in the inner and outer solar systems were mixed together, potentially by early giant planet migration (e.g., the Grand Tack) [13]. However, an important distinction between impact breccias (including those with carbonaceous chondrite clasts) and impact melts is the impact velocities required to generate them. Impact velocities are related to the orbit of the impactor relative to the target, and velocities larger than the most probable impact velocity in the asteroid belt are required to generate significant degrees of melting [e.g., 14]. Thus, it can be surmised that most impact melts in HEDs may have been generated by impactors on high eccentricity or high inclination orbits, indicating that the impactors were perturbed to those orbits from within the asteroid belt, or originated outside of it [14, 15]. Given the NC nature of the impact melt in NWA 1644 and the evidence for carbonaceous material in HEDs and on Vesta, it is possible that impact melts and impact breccias may sample different impactor populations; e.g., one population from outside the asteroid belt, and one population, with typical orbits, from within it. More data will be required to test this hypothesis.

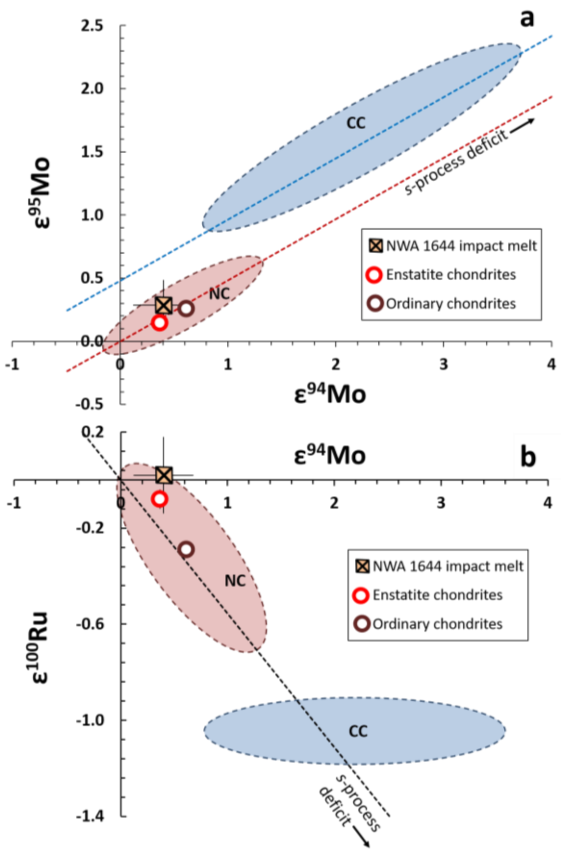

Fig. 2. (a) Mo and (b) Ru isotopic composition of NWA1644 impact melt, shown with NC chondrite groups [6, 16]. The meteorite dichotomy is shown as fields representing the NC (red) and CC (blue) suites. Also shown are theoretical s-process mixing lines from [17].

The similarity of the impact melt to enstatite chondrites and the Earth suggests not only that the impactor originated in the inner solar system, but also that it may have formed in or near the terrestrial planet-forming region. The impactor may have been scattered into the asteroid belt and later perturbed into a high eccentricity/high inclination orbit by another event, or it remained where it formed until it was perturbed into an asteroid-belt-crossing orbit. Two possible impactor populations which would be consistent with these scenarios are the late heavy bombardment (LHB) [14] and debris from the Moon-forming giant impact [15].

The LHB has been used to account for a possible spike in impact reset ages on the Moon [e.g., 18] and the HED parent body [14] around 3.9 Ga. A proposed source of the increased impact flux is a relatively late change in the orbits of the giant planets (e.g., the Nice model), which may have scattered compositionally variable objects in the asteroid belt (and elsewhere) into high eccentricity/high inclination, planet-crossing orbits. If this is the source of the impact melt in NWA 1644, the impactor population would have been heterogeneous, and we may expect CC material to be identified in other eucrite impact melts.

Alternatively, [15] showed that significant debris from the Moon-forming impact may escape the Earth-Moon system and evolve into asteroid belt-crossing orbits. This scenario would be supported if further eucrite impact melts have a nearly homogenous isotopic composition. Assuming the Moon-forming impactor was similar in composition to the proto-Earth [19] (and NC), this would require that the isotopic compositions of other eucrite impact melts are very near that of the Earth, as in the NWA1644 impact melt.

Finally, we note the interesting result that the Ru isotopic composition of the impact melt appears to be identical to the terrestrial mantle (and, thus, the late veneer). This may suggest that the impactor to Vesta was part of a population(s) of impactors that contributed to the late accretion of the Earth. Further analyses of several impact melts from different eucrites will be required to determine how variable these high-velocity impactors may have been and, thus, to what population of impactors they may have belonged. Regardless, this first use of isotopic genetic tracing in an impact melt demonstrates the potential of such an approach to inform us of the nature and origin of impactors to the terrestrial planets.

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