HOW DID MESOSIDERITES FORM AND DO THEY COME FROM VESTA OR A VESTA-LIKE BODY?

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Introduction: Mesosiderites are enigmatic mixtures of metallic Fe,Ni and crustal silicates including basalts, gabbros and pyroxenites like those in howardites [1-3]. Metal abundance ranges from 4±1 wt.% in the km-sized Eltanin meteoroid [see ref. 1] to 50% or more in kg samples. The uniform chemical composition of metal requires an unfractionated source, probably a molten core [2, 3]. Here we reassess the origin of mesosiderites in the light of new constraints on the thermal and impact histories of iron and stony-iron meteorites [4, 5], the Dawn mission to Vesta, studies of V type asteroids and their dynamics [e.g. 6], and asteroid impact histories [14]. We infer that despite contrary arguments [7] and the lack of supporting evidence from the Dawn mission [8], mesosiderites are more likely to be derived from Vesta than any other body [9].

Thermal and impact history: Mesosiderites cooled rapidly above ~700°C and very slowly thereafter at ~0.2-0.5°C/Myr [5, 10]. These remarkably slow metallographic cooling rates are supported by exceptionally coarse cloudy taenite particle sizes of 400-500 nm cf. 12-240 nm in all other meteorites [5]; the highest Ni concentrations in taenite at the kamacite-taenite interface and lowest Ni in kamacite [5]; and wide rims of tetrataenite (FeNi). This robust evidence for uniquely slow cooling of metal, the near absence of shock deformation in silicates and metal [10], the systematic increase in the Ar-Ar age of ~0.2-0.3 Gyr obtained during stepwise heating [11], and the cooling rate of ~0.2 °C/Myr derived from Ar diffusion data [11] make a compelling case that the Ar-Ar plateau ages of 3.8-4.1 Gyr reflect slow cooling [11], not shock reheating, as was previously inferred [12]. Since cloudy taenite forms at ~300°C, within the range of Ar closure temperatures (75-340°C) [11], mesosiderites are unlikely to have been excavated and rapidly cooled at Ar closure. The uniquely slow cooling rates are also unlikely to reflect proximity to large impact melt sheets or hot ejecta blankets. If the Ar-Ar ages of mesosiderites are unrelated to the late heavy bombardment, they are probably due to deep burial in a large well insulated, large asteroid [10, 11]. A km-thick layer of regolith on a Vesta-sized body would ensure that the interior takes ~1 Gyr to cool [10, 28]. However, a less porous and deeper layer of insulating megaregolith would be more consistent with the high proportion of brecciated HEDs.

Source of mesosiderites: Making the mesosiderites is hard if they are not from Vesta. Anomalous eucrites like NWA 011 probably formed on one or more Vesta-like bodies [see 13] but these could have been destroyed early. However, mesosiderites were probably not extracted from their parent body until <3.7 Gyr ago. Vesta-like objects (and their fragments) are both hard to hide and to eliminate in the current main belt. Moreover, the current population of V-type asteroids are small (D < 10 km) and therefore unlikely to have provided the slow cooling rates of mesosiderites. The absence of a prominent family with spectral properties consistent with the destruction of a large differentiated asteroid may be telling us that that mesosiderites formed on Vesta. If true, they were probably removed during the excavation of the Rheasilvia impact basin ~1 Gyr ago [14].

Nature of metal-silicate mixing event: A Vestan origin for mesosiderites requires that metal and silicates were mixed by the impact of a near-naked molten metallic body into the Vestan crust at relatively low velocity (~1 km/s) [2, 3] rather than by catastrophic disruption of the parent asteroid [1, 10].

Time of metal-silicate mixing: Stewart et al. [15] equated the time of metal-silicate mixing with the 4.42±0.02 Gyr Sm-Nd age of the youngest of four analyzed clasts. They argued that Sm-Nd ages had not generally been reset by metal-silicate mixing or slow cooling. However, REE are concentrated in phosphates generated after metal-silicate mixing [20], so Sm-Nd ages probably post-date mixing. Ganguly and Tirone [16] calculated that the Sm-Nd closure temperature of ~600°C was reached after slow cooling commenced at ~700°C. They inferred that cooling from ~700 to ~600°C took ~100 Myr and that metal-silicate mixing occurred at ~4.56 Gyr, consistent with the U-Pb age for silicates of 4560±31 Myr [17]. Evidence from IVA irons favoring early formation suggests that large molten metallic bodies were exposed by impacts ~2-3 Myr after CAI formation by hit-and-run collisions [4]. Thus metal-silicate mixing to form mesosiderites may have occurred during the first 10 Myr when other asteroidal basalts were crystallizing and hit-and-run collisions may have disemboweled asteroid-sized bodies [18].

Oxygen isotopes: Formation of mesosiderites on Vesta by impact of a metallic projectile readily accounts for the nearly identical oxygen isotopic compositions of HEDs and mesosiderites [9]. However, the origin of the olivine in mesosiderites is less certain [19]. Olivine is more abundant in mesosiderites (~2% of the silicate) than in most HEDs and occurs as mineral fragments up to many cm in size [19]. However, compositional ranges are similar and these differences may simply reflect a deeper origin for mesosiderites.

Duration of metal-silicate mixing: Mesosiderites were not formed in a single metal-silicate mixing event: there is clear evidence for complex processing. The extraordinarily high Eu/Sm ratios in some mesosiderite clasts require crustal remelting, which was probably caused by impact mixing of molten metal [7]. Mixing of P-rich molten metal with silicates generated phosphates and drastically modified the composition and texture of silicate clasts [20]. Some clasts show evidence for remelting of Fe-Ni-S and silicate [e.g. 21]. In addition, many eucritic clasts appear to have crystallized in the presence of metallic Fe,Ni. However, impact reheating and remelting did not last from 4.6 to 3.9 Ga period [7] as mesosiderites were cooling during this period. A much shorter period of a few to tens of Myr seems more likely.

If mesosiderites formed in the first ten Myr when Vesta was volcanically active**,** rather than during the first 700 Myr, **t**he absence in HEDs of clasts with high Eu/Sm ratios like those in mesosiderites does not exclude a Vestan origin for mesosiderites [cf. 7]. Mesosiderites may have been buried more deeply than most HEDs until excavation by the Rheasilvia impact.

Possible links between HEDs and mesosiderites: Most Fe metal in HEDs is generally sparse and Ni-poor, as a result of formation by reduction of Fe^{2+}. However, Ni-enriched metal is present in some mafic clasts in howardites [29], and tetrataenite (FeNi) has been reported in a mesosiderite-like clast in a howardite [22]. The anomalous cumulate eucrites, Dhofar 007 and EET 92093, provide interesting but still enigmatic links between HEDs and mesosiderites as they contain metal grains, which cooled very slowly and formed cloudy taenite intergrowths and tetrataenite rims like those in mesosiderites [23, 24]. However, these meteorites have heterogeneous oxygen isotopic compositions that differ from those of normal HEDs [13]. Aberrant O isotopic compositions are also found in several clasts in polymict breccias like Bunburra Rockhole and are accompanied in some cases by siderophile enrichments. This implies that some anomalous eucrites could result from impact mixing on Vesta [13]. Siderophile enrichments in eucrites and diogenites [25] and chondritic clasts in howardites demonstrate that Vesta was contaminated before and after eucrites crystallized.

HEDs contain evidence that Vesta has had a long history of contamination by diverse projectiles. Mesosiderites may simply represent the product of an especially large and unusual metallic projectile that struck during the first 10 Myr when Vesta was still volcanicallly active. Dhofar 007 and EET 92093 could have resulted from the impact of a metal-silicate projectile.

Conclusions: Our preferred Vestan origin for mesosiderites can be tested in various ways. Dawn data should be scrutinized for hints of localized metal enrichment on Vesta. Ar-Ar ages of more unshocked HEDs might identify rare eucrites like Serra de Magé that may have cooled exceptionally slowly like mesosiderites. Oxygen isotopic analyses of large olivine clasts in mesosiderites would help to identify their source. Anomalous HEDs and mesosiderites should be studied in more detail and dated using the Ar-Ar technique. In addition, Near-Earth asteroids [26] and Vestoids should be searched for metal-bearing basaltic bodies like the Eltanin meteorite or smaller basaltic asteroids that could resemble other mesosiderites.

Mn-Cr isotopic evidence for global differentiation on the mesosiderite parent body 2 Myr after that on Vesta [27] favors separate parent bodies for mesosiderites and HEDs but this may reflect remelting due to metal-silicate mixing and also requires further study.

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