

MARS ACCRETED A VOLATILE ELEMENT-DEPLETED LATE VENEER INDICATING EARLY DELIVERY OF MARTIAN VOLATILES

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Introduction: Approximately chondritic ratios of the highly siderophile elements (HSE) in shergottites and Os isotopic data have been used to argue that, similar to Earth's mantle, the Martian mantle has accreted a minor fraction of primitive material after formation of its core [1]. Others have argued that HSE abundances in the Martian mantle may have been established by core formation at high pressure-temperature conditions [2]. The mass fraction of the presumed Martian late veneer estimated based on HSE abundances would be about 0.3 ± 0.1 % the mass of Mars or 0.003 to 0.004 x CI chondrites [1, 3]. Because most of Mars may have formed 1-2 Ma after formation of the solar system [4-6], its late veneer may record material of different composition compared to the Earth. A key issue for Mars is the question if its late accreted material was rich in volatile elements and may have delivered the water believed to have been present on the early Martian surface. This issue cannot be addressed by HSE abundances, but requires an assessment of the abundances of the siderophile and chalcophile volatile elements Cu, S, Se and Te in the Martian mantle based on the SNC model composition.

Results and Discussion: As shown in the companion presentation [7], new isotope dilution data for Cu, S, Se and Te concentrations in SNC meteorites, combined with previous data, show negative correlations of abundances of incompatible chalcophile elements with MgO contents in shergottites. These variations are indicative of sulfide-undersaturated magma compositions, consistent with the high FeO contents of Martian magmas [8]. At sulfur-undersaturated magmatic conditions, ratios of incompatible elements such as Cu/S, Se/Te or S/Se in basalts and their cumulates directly reflect mantle values and concentrations in the mantle may be determined at the proper MgO of the model mantle composition. This approach in combination with new data suggests that the S content in the Martian mantle may be only 360 ± 120 $\mu\text{g/g}$ (1s), Se 100 ± 27 ng/g (1s) and Te = 0.5 ± 0.2 ng/g (1s).

CI chondrite normalized Se/Ir and S/Ir ratios of the Martian mantle are 1.31 ± 0.35 and 1.85 ± 0.62 , respectively, higher than in CI chondrite. This suggests that a large fraction of S and Se in the Martian mantle was left over after metal-silicate segregation and core formation. Core formation models based on moderately siderophile element abundances [9] suggest mean core formation conditions of 14 ± 3 GPa and 2100 ± 200 K, which are also capable of explaining most of the Martian mantle inventories of S and Se at 0.007 and 0.005 x CI chondrites, respectively [7]. In contrast, Te is very depleted in the Martian mantle (0.0002 x CI chondrites), very likely because of core formation, because Te is highly siderophile at high P-T, whereas Se and S are less siderophile [10,11]. Thus, Te and the HSE were mostly derived from the late veneer. Judging from the factor 20 depletion of Te relative to the HSE, the late veneer must have been strongly depleted in volatile elements. A volatile element-depleted late veneer provides a critical constraint on the timing of the delivery of water on Mars. Because Mars' late veneer was strongly volatile element-depleted, it cannot have delivered substantial quantities of water. From this it follows that the delivery of Martian water must have occurred before the late veneer, and thus not later than the cessation of accretion and core formation within 1-2 Ma after formation of the solar system [4-6]. The new results support the view that the delivery of water to Mars, Vesta, Earth and the Moon by accretion of volatile-rich materials occurred over a period from a few Ma to 100 Ma.

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