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Constraining the origin of moderate volatile element depletion on Vesta: evidence for nebular stage loss and limited post-nebular fractionation

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Moderately volatile elements (MVEs) are prevalently depleted in terrestrial bodies and differentiated asteroids across the inner Solar System, yet the mechanisms responsible for this depletion remain debated. Deciphering the origin of volatile loss is critical for understanding the early thermal and chemical evolution of planetesimals and planetary embryos. Vesta, widely regarded as the parent body of the howardite–eucrite–diogenite (HED) clan, exhibits pronounced volatile depletion. However, the extent of MVE depletion, the origin of its volatile inventory, and the mechanisms responsible for volatile loss remain insufficiently constrained.

Here we compile published compositional data for HED meteorites and integrate these with petrological models of partial melting and fractional crystallization appropriate for Vesta. This combined geochemical–petrological approach allows us to systematically reassess the abundances and depletion patterns of MVEs in bulk silicate Vesta. Our results indicate that the relative depletion among different MVEs on Vesta is characterized by a comparatively narrow range of fractionation. Such a limited dispersion contrasts with expectations from extensive, high-temperature evaporative loss during magmatic processes. Instead, the observed patterns suggest that Vesta's present-day volatile inventory may have been partly inherited from late-accreted materials after the main stage of volatile depletion.

We propose that the primary stage of volatile loss occurred during the nebular stage, likely through incomplete condensation and/or large-scale evaporation under solar nebula conditions. Subsequent secondary volatile loss, e.g., post-nebular magma degassing processes, may have further modified MVE abundances, but only to a limited extent, yielding modest additional fractionation. These findings confirm the importance of early nebular processes in establishing the volatile budget of differentiated planetesimals in the inner solar system and suggest that late accretion may have played an important role in shaping Vesta's present volatile reservoir.