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Constraints on the Delivery of Carbonaceous Materials to the Earth from Core Formation Modeling and Dynamical Simulations

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The nucleosynthetic isotopic compositions of meteorites reveal a fundamental dichotomy in Solar System materials: non-carbonaceous (NC) and carbonaceous (CC) groups, thought to originate from the inner and outer Solar System, respectively. Determining the relative contributions of NC and CC materials accreted by the Earth therefore provides critical insights into its accretionary history and volatile delivery. Previous studies have used isotopic and geochemical data to constrain Earth's NC–CC composition. However, they have largely overlooked the dynamical context – i.e., how and when materials from different regions were mixed and delivered during accretion. Additionally, the isotopic signatures recorded in the bulk silicate Earth (BSE) are affected by both the metal–silicate partitioning behaviors of elements during core formation and their volatilities. Here, we track the provenance and evolution of the stable isotopes of six elements – Ni, Mo, Cr, Ti, Zn, and Ge – by applying a multi-stage core formation model to outputs of *N*-body simulations under four dynamical scenarios: Classical (EJS/CJS), Grand Tack, Early Instability, and Annulus. Among these elements, Ni, Mo, Cr, Ti, and Zn have isotopic anomalies of nucleosynthetic origins and all may help trace NC–CC provenance. Additionally, Zn and Ge, as moderately volatile elements, further constrain the Earth's volatile inventory and its volatile delivery during accretion. For the EJS scenario, our preliminary results suggest that the NC–CC divide would need to be located at ~2.3–2.8 AU to match the BSE's nucleosynthetic isotopic composition, and that CC bodies would need to be enriched in Zn by a factor of 8–50 compared to NC to match the BSE's Zn isotopic data. Most of the Earth's CC material was delivered later, likely during the last 30% of main stage accretion. We will compare our results from other accretion scenarios with observed terrestrial values to evaluate which accretionary pathways are most consistent with Earth's present-day isotopic composition. Our results will offer new constraints on volatile delivery history with broader implications for Earth's habitability.