Planetary accretion and differentiation:
Clues from silicon isotopes in differentiated meteorites

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Introduction

Inner solar system bodies, including the Earth, Moon, and asteroids, are depleted in volatile elements relative to chondrites. Hypotheses for this volatile element depletion include incomplete condensation from the solar nebula and volatile loss during energetic impacts. These processes are expected to each produce characteristic stable isotope signatures. However, processes of planetary differentiation may also modify the isotopic composition of geochemical reservoirs. Silicon is sufficiently volatile such that it may be isotopically fractionated during incomplete condensation or evaporative mass loss, but theoretical calculations and experimental results also predict isotope fractionation under specific conditions of metal–silicate differentiation. Therefore, the Si isotope systematics of achondrites may provide information on accretion and differentiation processes in the early Solary System.

Si isotope behavior during core formation

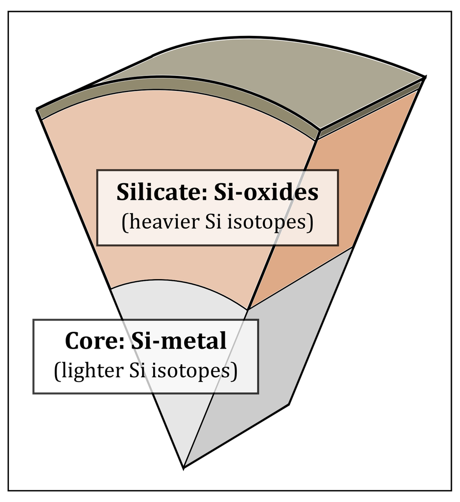


Fig. 1: Schematic representation of Si isotopes in a differentiated planet

Elements may be isotopically fractionated between the core and mantle of a planet due to differences in bonding environment between metal and silicate. Si isotope fractionation during metal-silicate differentiation has been predicted by calculations [1] and demonstrated in partitioning experiments [2-5] and measurements in meteorites [4, 6]: isotopically light Si partitions into the metal phase, leaving the silicate enriched in the heavier isotopes.

The relationship between Si partitioning and core formation conditions

Silicon is only present in the metal phase under specific physiochemical conditions, and the relationship between Si solubility in metal and temperature, pressure, and fO_2 has been experimentally determined [e.g. 7-9]. Therefore, it is possible to use the amount of Si in the core calculated from isotopic mass balance to estimate the conditions during core formation. The reaction describing Si partitioning between metal and silicate is 2 Fe (metal) + SiO_2 (silicate) = 2 FeO (silicate) + Si (metal). The equilibrium constant for this reaction may be modeled as a function of P, T, and chemical composition.

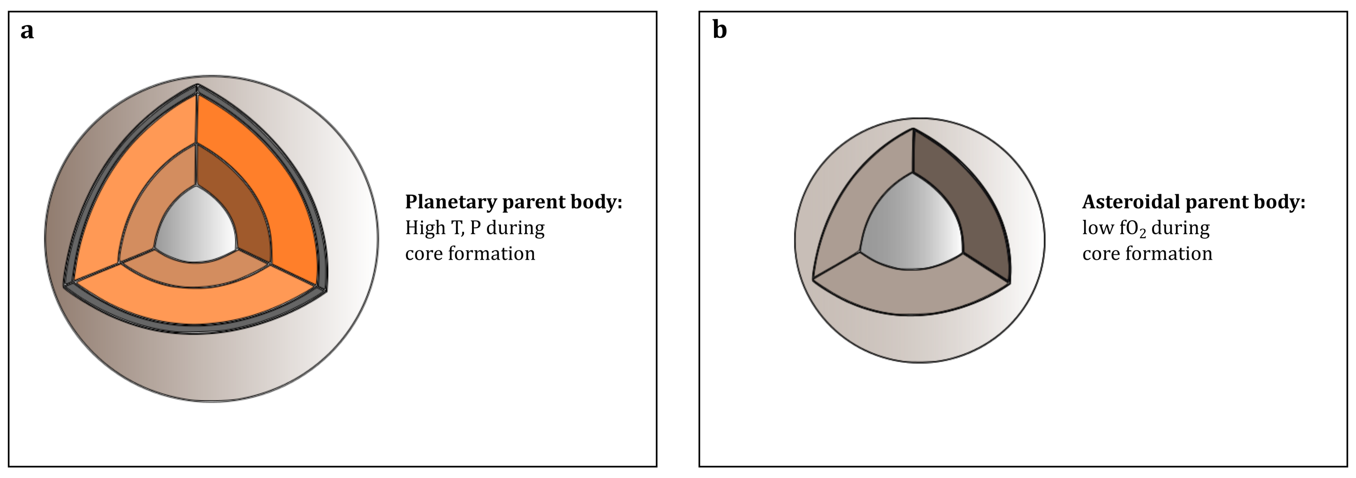


Fig. 2: Schematic of core formation conditions necessary to partition Si into the metal phase.

Volatility-driven Si isotope fractionation

HEDs and angrites are depleted in volatile elements compared to chondrites (e.g. very low Rb/Sr and K/U ratios), and Si is among the most volatile of the major elements (Tc = 1310 K) [18]. In addition, it has been shown that Si isotopes are highly fractionated during evaporation [19]. Therefore, Si isotopic fractionation during evaporation (resulting in a residue enriched in the heavy isotopes of Si) may be the cause of the heavy Si isotope enrichments in some achondrites.

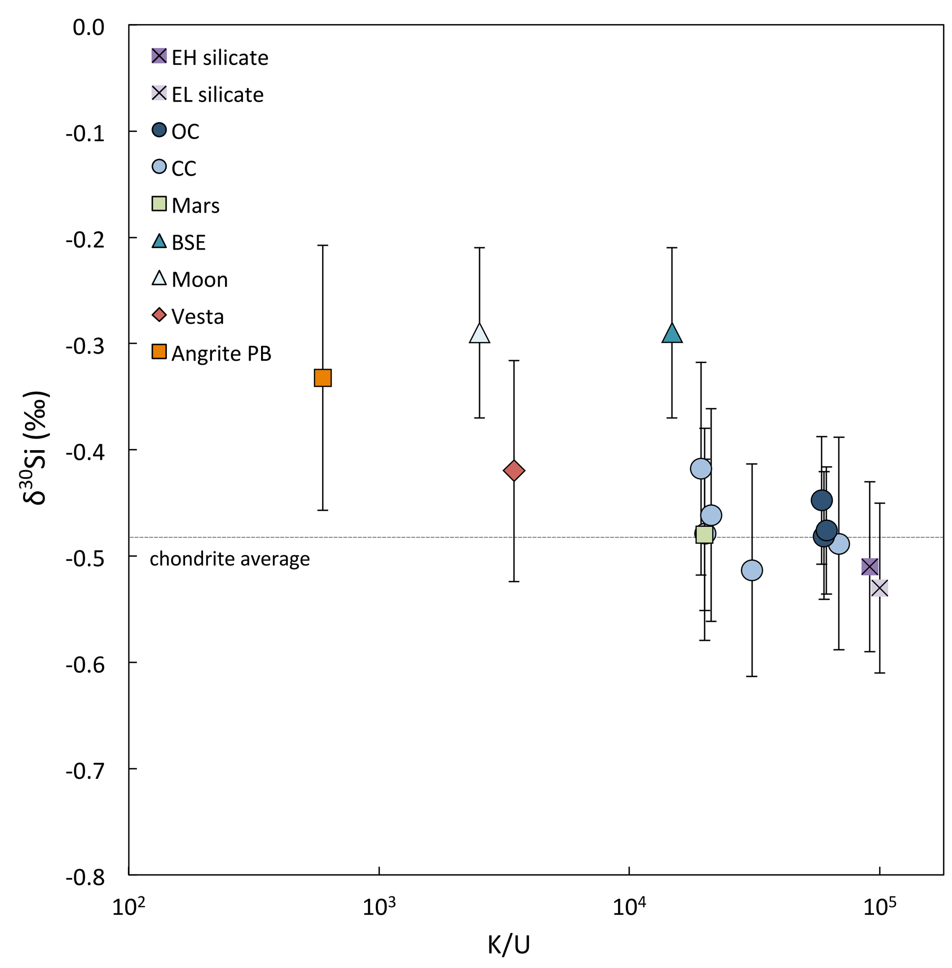


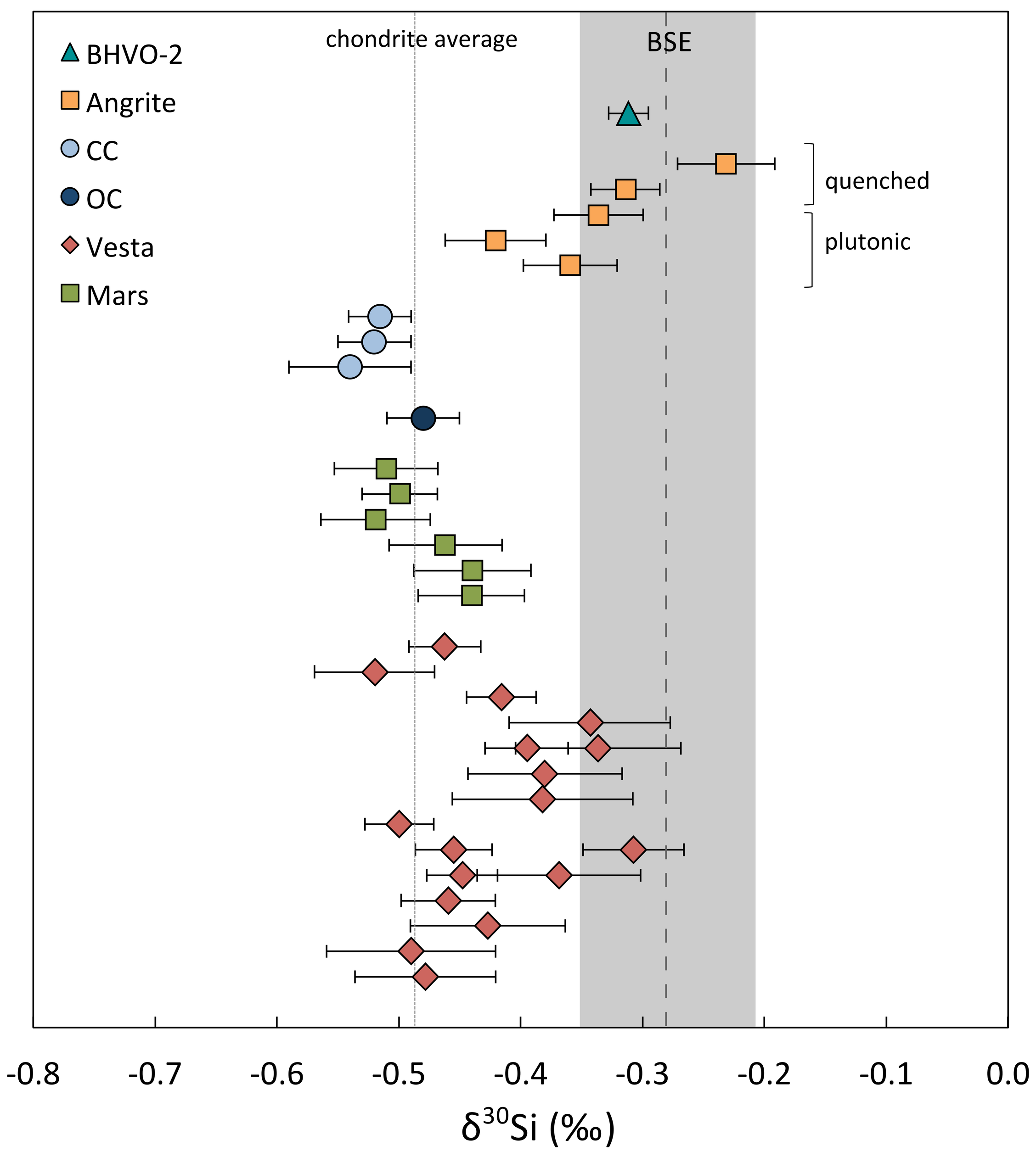
Fig. 5: Plot of δ^{30}Si vs. K/U ratio for chondrite groups and estimates for the bulk silicate portion of Mars, Earth, the moon, Vesta, and the angrite parent body. Data sources are as listed in Fig. 4.

Conclusions and implications

-Planetesimals initially formed from material rich in moderately volatile elements, which were lost during accretion through early impact events. These volatile-depleted materials may represent the primary building blocks of Earth, consistent with heterogeneous terrestrial accretion models

-If Earth accreted from such material, bulk Earth may be isotopically heavier in Si isotopes than previously assumed based on a chondritic model. This would lower the Si content required in Earth's core based on the Si isotopic offset between Earth's mantle and bulk Earth.

Results: The Si isotope composition of achondrites



Angrites are significantly enriched in heavy Si isotopes with respect to chondrites. On average, the Si isotopic composition of angrites is δ^{30}Si = -0.33 ± 0.12‰ (2 sd). The carbonaceous chondrite average is δ^{30}Si = -0.52 ± 0.05‰ (2 sd). The ~0.2‰ offset in the ^{30}Si/^{28}Si ratio in angrites relative to chondrites represents the largest Si isotopic fractionation observed to date in bulk achondrites; the angrite Si isotope compositions are similar to values previously reported in terrestrial basalts [1, 10-14]. In contrast, martian meteorites have Si isotopic compositions that are indistinguishable from chondritic values. The HEDs have Si isotopic compositions intermediary between chondrites and angrites.

Fig. 3: Si isotope compositions of carbonaceous chondrites (CC), ordinary chondrites (OC), Martian meteorites (Mars) and HED meteorites (Vesta) (±2 se). The dotted line represents the weighted average of carbonaceous chondrites, ordinary chondrites, and the silicate phase of enstatite chondrites from the literature (1, 3, 6, 10, 13-15). The shaded box represents the estimated Si isotope composition of BSE (±2 sd) (16). Angrites are significantly offset from chondrites and overlap with the estimate of BSE.

Fractionation of Si isotopes in the solar nebula?

The large Si isotope offset between angrites and chondrites cannot be explained by models of core formation, since they come from a small, oxidized parent body with insufficient pressure or redox conditions to partition adequate Si into the core. Fractionation of Si isotopes during evaporation/condensation reactions in the solar nebula has been proposed to explain Si isotope systematics in meteorites, and a correlation between δ^{30}Si vs. Mg/Si ratio among inner solar system materials could indicate that Si isotopes were fractionated during condensation of materials from the solar nebula through a range of temperatures [10, 17]. However, carbonaceous chondrites, ordinary chondrites, and the silicate phases of enstatite chondrites span a wide range of Mg/Si values but have similar Si isotope compositions. In contrast, differentiated bodies exhibit increasing δ^{30}Si with a higher Mg/Si ratio, suggesting that parent body processes are responsible for their Si isotope composition.

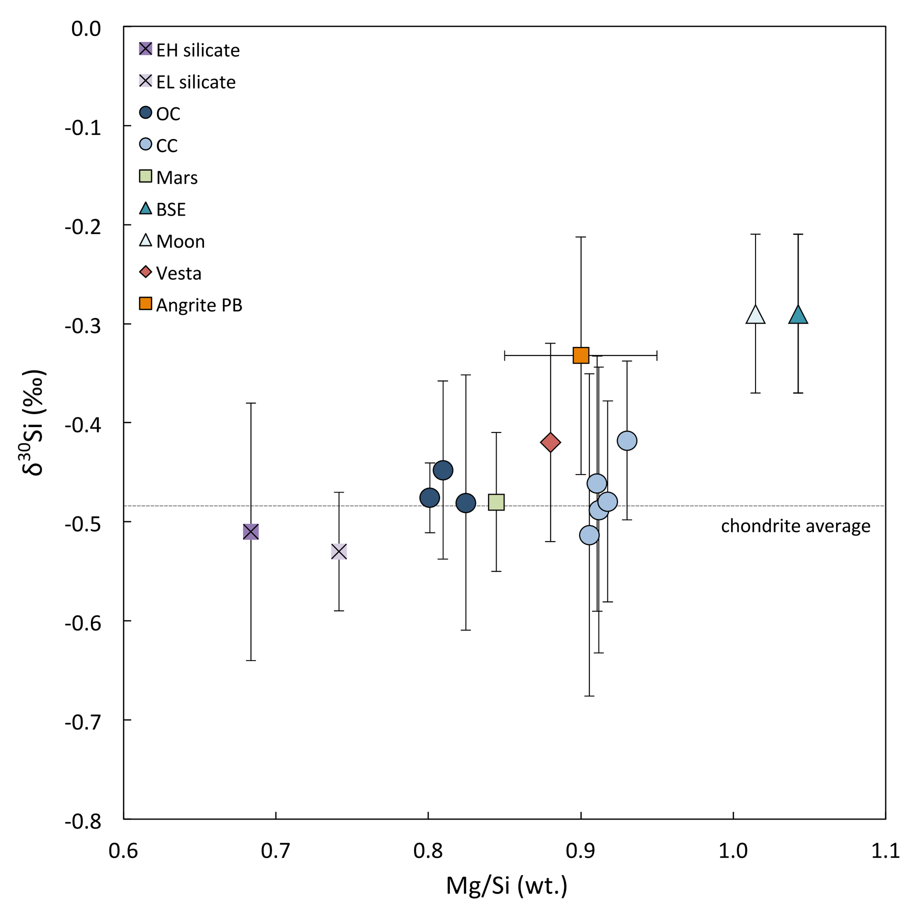


Fig. 4: Plot of δ^{30}Si vs. elemental Mg/Si wt. ratio for chondrite groups and estimates for the bulk silicate portion of Mars, Earth, the moon, Vesta, and the angrite parent body. Data for carbonaceous, ordinary, and enstatite chondrites as well as Mars, Earth, Moon, and Vesta are weighted group averages from the literature (1, 3, 6, 10, 13-15).

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