ORIGIN OF MAJOR VOLATILES (H,C,N,S) IN THE BULK EARTH: INSIGHTS FROM MODERATELY VOLATILE ELEMENTS, AND FROM C/S VS. C SYSTEMATICS OF CHONDritic AND ACHONDritic METEORITeS

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Models for accretion and retention of Earth’s major volatile elements (H,C,N,S) must be consistent with processes that produced Earth’s systematic depletion in moderately volatile elements (MVEs) [1,2], meaning those with “condensation” temperatures ($T_C$) <1400 K [3]. To better understand the acquisition of major volatile elements to the growing Earth, we consider the relationship between Earth’s C and S and MVE abundances and compare estimated bulk earth (BE) C and S to available concentrations from chondritic and achondritic meteorites.

The well-known correlation of CI-normalized lithophile element concentrations in the Bulk Silicate Earth (BSE) [4] with $T_C$ [3] (Fig. 1) reflects a depletion process that likely occurred owing to heating and degassing on precursor planetesimals or embryos. Here, $T_C$ is taken as a measure of the propensity of an element to volatilize into a H-rich vapor, and does not necessarily imply actual condensation of solids from a gas. Unlike MVE depletions in chondrites, which could derive from an admixture of processed depleted material with a primitive volatile-rich “matrix” [5], the MVE depletion pattern of the BSE does not show a plateau at low $T_C$. The favored site of depletion is in small bodies because volatile loss from bodies with significant gravity should correlate with molecular mass, rather than chemical propensity to reside in the gas [1]. The systematic depletion of MVEs with condensation temperature is not easily reconciled with models of Earth accretion chiefly from large embryos formed by pebble accretion or streaming instabilities, which are thought to deliver comparatively primitive (e.g., chondritic) highly volatile (e.g., H$_2$O) cargos to the growing planet [6].

Because C and S are both siderophile, much of their BE inventories are likely in the core. The trend in lithophile MVE concentrations and effective condensation temperature can be used to estimate BE C and S, similar to previous efforts based chiefly on Zn [7,8]. This correlation using the BSE concentrations of 11 MVEs (chiefly lithophile, showing a coherent trend on Fig. 1) indicates a BE S concentration of 9400 ppmw, which in turn implies 2.8±0.4 wt.% S in the outer core, consistent with constraints from seismology [9,10]. Similar estimates for C depend on the assumed principle phase controlling C condensation: clathrate ices ($T_C$=40 K [3]), refractory organics ($T_C$~400 K [11]), or graphite ($T_C$=626 [3]). Resulting BE C concentration estimates range from 670-5300 ppmw C, or a maximum of 0.18-1.6 wt.% in the outer core, if inner core C is negligible. These BE abundances are based on the assumption that $T_C$, the temperature controlling volatilization of elements on planetesimals, correspond to those occurring in an H-rich gas, which could be appropriate for planetesimals differentiating before the dissipation of the solar nebula. Later devolatilization in the presence of a protoplanetary vapor [12] would predict somewhat different BE S and C.

Unsurprisingly, the estimated BE S and C concentrations, plotted as log(C/S) vs. log(C), are distinct from those of chondrites (Fig. 2), consistent with the observation that MVE depletions in the BE arise from different processes than those responsible for MVE patterns on chondritic parent bodies. Achondritic C/S vs. C concentration patterns provide possible insights into the effects of planetesimal differentiation on major volatile depletions. Caution is warranted because achondrite sample populations likely represent only part of their parent bodies, e.g., achondritic basalts give indication about the concentrations in planetesimal crusts, but not (directly) their interior. Also, sampling biases adds considerable uncertainty to parent body concentration estimates, particularly for irons.

Stony achondrites plot along a linear trend in log C/S vs. log C space (Fig. 2). The reason for this empirical correlation is not clear, as the trend includes parent
bodies ranging from highly depleted in C (HED) to highly enriched (ureilites) and both differentiated achondrites (HEDs, angrites, etc.) representing planetesimal crusts, and primitive achondrites (acapulcoites, winonaites), representing possible whole parent body compositions. Displacement of this trend relative to the chondritic trend and to the BE composition reflects greater S depletion in stony achondrite parent bodies.

Concluding Remarks Because depletion of BSE and BE MVEs likely occurred on small precursor planetesimals and embryos, these volatile-loss processes also affected major (H,C,N,S) volatiles. Models attempting to account for the BSE or BE inventory of major volatiles and especially their relative depletions compared to chondrites must not only consider possible primitive (chondritic) sources and planetary differentiation processes, but also the effects of volatile loss on small differentiated precursor bodies.