

H, N, C ABUNDANCES AND ISOTOPIC COMPOSITIONS OF ENSTATITE METEORITES AND IMPLICATIONS FOR EARTH'S VOLATILE INVENTORY. M. L. Gray^{1,3}, M. K. Weisberg^{1,2,3}, C. M. O'D. Alexander⁴, J. Wang⁴, D. I. Foustoukos⁴, D. S. Ebel^{3,1}, ¹Earth and Environmental Sci., CUNY Graduate Center, New York, NY 10016. (mgray1@gradcenter.cuny.edu) ²Physical Sci., Kingsborough College CUNY, Brooklyn, NY 11235. ³Earth and Planetary Sci., American Museum of Natural History, New York, NY 10024. ⁴Earth and Planets Laboratory, Carnegie Institution for Science, Washington, DC 20015.

Introduction: Earth likely accreted from a mixture of primitive solar system materials [1-3], but there are uncertainties about what materials represent its primary building blocks. Potential contributors, particularly of Earth's volatiles, are chondrites, undifferentiated meteorites that contain clues to the early evolution of the solar system and formation of the terrestrial planets [2, 4-6]. Only one group of chondrites, the enstatite chondrites (EC), share (O, Cr, Ti, Ni, Zn, and volatiles H, N, C) stable isotopic compositions with the Earth-Moon system [e.g., 1, 6-10], suggesting a relationship between the two. Furthermore, the very low abundance of hydrous minerals in ECs suggests they originated within the nebular snow line [11], which is also the presumed formation location of the terrestrial planets.

We have now analyzed the bulk volatile (H, N, C) abundances and isotopic compositions of a petrologic suite of ECs (EH3-6, EL3-6) and four aubrites, enstatite achondrites. Our goals are to gain a better understanding of the distribution of volatiles in the early solar system and test EC's potential contribution to the accretion of Earth, its oceans, and its atmosphere.

Methods: Interior chips of seven equilibrated EH and EL chondrites (both *falls* and *finds*) and four aubrites (*falls*) were powdered and sieved to <150 μm . The magnetic component was removed, leaving non-magnetic portions of 0.61-1.03 g. Their H, N, and C bulk contents and isotopic compositions were measured using the analytical techniques in [2]. We compare the results to our previously analyzed unequilibrated EC samples [6, 10], to carbonaceous (CC) and ordinary chondrite (OC) data [2, 12-13].

Results: Volatile abundances. The H contents of our ECs range from 0.02 (EL6) to 0.32 wt.% (EL3). There is a relationship between petrologic type and H content (1/H) ($r = 0.88$), suggesting dehydration and/or destruction of organics due to thermal metamorphism [5, 14]. The N content ranges from 0.01 (EH4) to 0.05 wt.% (EL6), and the C content ranges from 0.07 (EH6) to 0.59 wt.% (EL3). Aubrites show a wide range of values, with an average H content of 0.06 ± 0.05 wt.%, N content of 0.02 ± 0.03 wt.%, and C content of 0.17 ± 0.17 wt.%.

Isotopic compositions. The isotopic data are reported as δD , $\delta^{15}\text{N}$, and $\delta^{13}\text{C}$, and are compared to

other chondrite groups [6, 10, 12, 13] and Earth [15-18] in Figure 1. Most of our EC and aubrite samples fall within the range of Earth's mantle for H and N isotopes, while C is isotopically lighter for most of the samples we analyzed. With respect to C isotopes, only some ELs (all *finds*) plot within the range of Earth's mantle, while other ECs are isotopically lighter. Compared to ECs, aubrites are anomalous. They are more enriched in ^{15}N and have light C isotopic compositions, similar to some OCs. The only other chondrites that have H, N, and C isotopic compositions like Earth are COs and one CM.

Discussion: With respect to stable H, N, and C isotopes, EL chondrites are the closest match to estimates for solid Earth, consistent with other isotope systems [e.g., 1, 7-9]. (H, N, C isotopic compositions of some CCs also overlap with values for Earth's mantle, but not in other isotope systems.) Earth's oceans and atmosphere, however, are heavier in H and N isotopes than the ECs [15-17]. Also, if modeling Earth from ELs, there are other difficulties. For example, EC's Mg/Si, Al/Si, Ca/Si ratios, among others, are lower than those of bulk Earth [19]. A Si-rich mantle reservoir has been suggested as compensation [22], but there is no direct evidence for this. Additionally, bulk $\delta^{30}\text{Si}$ values of ECs are too low to match the Earth [20]. Metal-silicate Si isotope fractionation in a reduced nebular environment and/or vapor loss of lighter Si isotopes during planetary volatilization have been proposed to explain the Si isotopic differences between the Earth and ECs [21].

Inner vs. outer solar system and isotope carriers. The isotopic gap between non-carbonaceous (E and O) chondrites and CCs [1] has gained considerable attention, suggesting separate sources for inner and outer solar system materials, respectively. While there is a sharp difference between these materials in some isotope systems (e.g., Cr and Ti), volatiles, such as O, do not show any distinction. From our work, C and N also show overlap between ECs and some CC groups. This suggests a similarity in the carriers of volatiles (potentially organics and ices) across the solar system and/or the possibility of heterogeneously distributed carriers of more refractory isotopes like Cr and Ti.

Terrestrial contamination. A concern when measuring the volatile contents of chondrites is the potential for terrestrial contamination [2, 14]. Some

minerals in ECs are particularly susceptible to weathering, since they readily react with atmospheric moisture [2], something even more probable for the more porous unequilibrated ECs [7]. Silicates in ECs contain only a fraction of the H present in the bulk samples [23]. One explanation for this is the inclusion of terrestrial H, although primary organics in the matrix may also be the carriers. Further work is needed to resolve the effects of weathering. The light bulk $\delta^{13}\text{C}$ signatures of the aubrites are comparable to terrestrial organic matter ($\delta^{13}\text{C} = \sim -24\text{‰}$). However, it was found that light $\delta^{13}\text{C}$ in the aubrite Bustee was released at high combustion temperatures [12], suggesting a refractory, potentially primary carrier of the light C. Regarding N, aubrites have signatures closest to atmospheric N ($\delta^{15}\text{N} = \sim 0\text{‰}$), again possibly indicating terrestrial contamination [24]. However, the aubrites we analyzed are all *falls* and would be expected to be less affected by weathering than the EC *finds*, which are closer to atmospheric values of C ($\delta^{13}\text{C} = \sim 0\text{‰}$) (Fig. 1). We are continuing to measure volatiles in individual phases (*in-situ*) to determine their carriers and the effects of terrestrial weathering.

Models for Earth. Earth's volatiles likely accreted from a mixture of materials [4-6, 25-27], potentially including materials not represented in our current meteorite collections. To account for the oceans and atmosphere, heavier H and N isotope-enriched materials (e.g., CCs) are required to complement the isotopically lighter chondrites, if assuming a precursor isotopically similar to ECs. Besides CCs, cometary material is thought to have contributed marginally to Earth's volatile inventory, being enriched in D [2, 4, 16, 28]. EL chondrites are the best match (isotopically) to solid Earth. Late accretion of icy comets or CC material may have contributed to the oceans and atmospheres, mixing with the volatiles that outgassed from an EL-like protolith.

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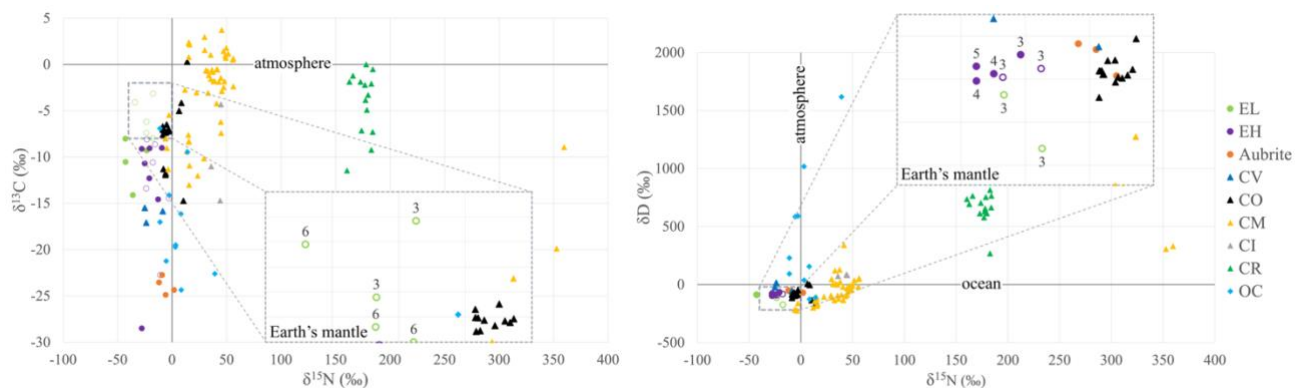


Figure 1. H, N, C isotopic compositions of ECs, aubrites, CCs, and OCs. Open symbols are *finds*, filled symbols are *falls*. The numbers next to the symbols correspond to the petrologic type. Dashed grey area represents Earth's mantle.