THE EARTHLINGS THAT MADE THE EARTH. N. Dauphas[1], J.H. Chen[2], J. Zhang[3], D.A., Papanastassiou[2,4], C. Burkhardt[1], A.M. Davis[1], P.H. Warren[5], [1]Origins Lab, Department of the Geophysical Sciences, The University of Chicago, USA (dauphas@uchicago.edu), [2]JPL, Pasadena, USA, [3]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, [4]Division of Geological and Planetary Sciences, Caltech, USA, [5]IGPP, UCLA, USA.

Introduction: Calcium is a major lithophile refractory element that is ubiquitous in terrestrial rocks and meteorites. Previous studies have revealed the presence of isotopic anomalies of nucleosynthetic origin for Ca in presolar grains, Ca-Al-rich inclusions –CAIs, hibonite-rich grains, and acid leachates of primitive chondrites. H.-W. Chen et al. found evidence for ^{48}Ca isotope anomalies in a few groups of achondrites [1]. To evaluate whether ^{48}Ca isotope anomalies are present in bulk planetary materials and search for correlations with other elements, we have measured the Ca isotopic compositions of various groups of meteorites that have never been analyzed before [2]. We have discovered widespread ^{48}Ca isotope anomalies in chondrites and achondrites (Fig. 1) that are correlated with ^{50}Ti anomalies and provide important constraints on the nature of Earth's building blocks.

Methods: To facilitate comparison, the calcium isotope measurements were done on the same solutions that were analyzed previously for titanium [3,4] and the reader is referred to these publications for details on the digestion method and the Ti-Ca separation chemistry. Calcium was purified by conventional cation ion exchange column chemistry (Bio-Rad AG 50W-X8 resin, 2 mL) in hydrochloric acid [5]. To eliminate Al, the Ca cut from the first column was redissolved in 0.1 mL 1 M HNO_3 and loaded onto a TODGA column [6]. The resin was rinsed twice with 0.3 mL 1 M HNO_3 to remove Al and Mg. Calcium was collected in 0.5 mL 0.25 M HCl. This cut was loaded onto a third column containing 0.1 mL Eichrom TRU spec resin. The resin was rinsed with 0.3 mL 7 M HNO_3 and Ca was collected in the load and rinse solutions. This step removes any residual Ti and Fe. The total chemistry yield was >85 % for Ca and the procedural blank was negligible (~30 ng).

Aliquots of 1–2 mg Ca were evaporated, redissolved in one drop of 0.5 N H_3PO_4 and then loaded on zone-refined Re double filaments as calcium phosphate [7]. All measurements were made with a multicollector ThermoFinnigan Triton at the Jet Propulsion Laboratory. Care was applied in choosing a cup configuration, so as to avoid negative baselines produced by scattered electrons from high abundance ^{40}Ca. Titanium interferences were monitored at masses 47 and 49 but were always too low to be resolved from the baselines. The maximum correction on ^{48}Ca from ^{48}Ti interference is ~0.5 ε-unit.

Results: Significant isotopic anomalies are found for ε^{48}Ca in both chondrites and achondrites. The total span of ε^{48}Ca values is from –2 in ureilites to +4 in CVs. Overall, achondrites tend to have lower ε^{48}Ca values than Earth while carbonaceous chondrites tend have higher ε^{48}Ca values. Enstatite chondrites and aubrites have the same ε^{48}Ca value as Earth (–0.32±0.56 for EH, –0.38±0.26 for EL, and –0.44±0.59 for aubrites). A puzzling feature of the data set presented by H.-W. Chen *et al.* is that eucrites have different ε^{48}Ca value than diogenites (–0.9 *vs*. –1.5, respectively) and that within each meteorite group, the isotopic compositions are homogeneous. This is difficult to comprehend because previous work has shown that eucrites and diogenites usually have the same isotopic compositions and, together with howardites, are thought to come from the same parent-body. We have measured eucrite Camel Donga in both static and multidynamic modes and have found a ε^{48}Ca value of ~–2. This is close to the diogenite measurements of H.-W. Chen *et al.* but is much lower than the eucrite measurements by these authors. Our results have precision of ±0.5 and ±23 for ε^{43}Ca and ε^{46}Ca, respectively, and no anomaly can be resolved for these two isotopes. The ε^{48}Ca isotopic anomalies in bulk meteorites correlate well with anomalies in ε^{50}Ti measured in the same meteorite groups (Fig. 1).

Discussion and Conclusion: The finding of terrestrial Ca isotopic composition in enstatite chondrites and aubrites adds to the list of elements that display isotopic anomalies at a bulk scale but are identical between Earth, E chondrites, and aubrites. A very important observation is that isotopic anomalies for ^{17}O, ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{64}Ni, and ^{92}Mo, which are formed by various photochemical and nucleosynthetic processes, are not all correlated. In the standard model of formation of the terrestrial planets, the accretion of the Earth resulted from stochastic impacts between the proto-Earth and embryos formed at various heliocentric distances [8]. In this picture, the isotopic composition of the silicate Earth would have represented an average of the isotopic signatures of the embryos that formed the Earth. Enstatite chondrites represent a snapshot of the isotopic composition of dust at a par-

ticular point in time and space in the solar protoplanetary disk. One ponders how likely it can be that a fully-grown planet can match the isotopic composition of a particular type of chondrite from a parent-body that is more than a million time less massive than Earth. One can call for a coincidence but because the isotopic anomalies are not correlated, several special circumstances are needed to reproduce the isotopic composition of the enstatite chondrites by mixing. This can be formalized by writing that the terrestrial isotopic composition is a mixture between n isotopic reservoirs ($1, \ldots, i, \ldots, n$), each contributing a fraction f_i to the mass of the Earth. Thus far, O, Ca, Ti, Cr, Ni, and Mo are the only elements that display planetary scale isotopic anomalies and have been measured in a broad array of samples. Because ^{48}Ca-^{50}Ti and ^{54}Cr-^{62}Ni anomalies tend to be correlated, one cannot reliably decompose a mixture with more than 5 components. The groups EH+EL (E), H+L+LL (O), CI, CM, CO+CV have approximately constant isotopic compositions, so these are used as end-members in the isotope mixing calculations. Minimization of the system for oxygen, titanium, chromium and molybdenum yields a mixture composed of ~91% E + 7% O+ 2% COCV. The proportion of E cannot be significantly reduced without leading to a severe mismatch between the terrestrial composition and calculated mixtures for several elements.

The most straightforward interpretation is that the Earth was accreted from material having approximately constant isotopic composition corresponding to that sampled by E chondrites and aubrites. This interpretation agrees with molybdenum-ruthenium isotope data that failed to detect any change in the isotopic composition of the material that was accreted by the Earth before and after core formation [9]. Making the Earth with E-like material is problematic as these meteorites have a high Si/Mg ratio and inappropriate silicon isotopic composition [10], so one has to invoke the presence of a hidden reservoir rich in silicon to offset the relative deficit of silicon in the upper-mantle. However, one should use caution, as identity in isotopic composition does not mean identity in chemistry. Most likely, the building blocks of the Earth are not in meteorite collections but enstatite chondrites and aubrites sampled the same region of the disk, which was modified by nebular, disk, and planetary processes.

Simulations of chaotic growth indicate that terrestrial planets grew by the accretion of embryos formed at various heliocentric distances, so that the final planets should be isotopically distinct from any of the accreted embryos [*e.g.*, 11]. This result is predicated on the idea that there was a significant gradient in isotopic anomalies within 1.5 AU. Instead, we posit that the material within 1.5 AU had similar isotopic composition to EH, EL chondrites and aubrites. Most of the Earth drew its mass from this region named IDUR (Inner Disk Uniform Reservoir), which would explain the isotopic similarity of the Earth with those meteorites. The Moon-forming impactor may have originated from the same IDUR region, which would explain the identical isotopic compositions of terrestrial and lunar rocks [12].

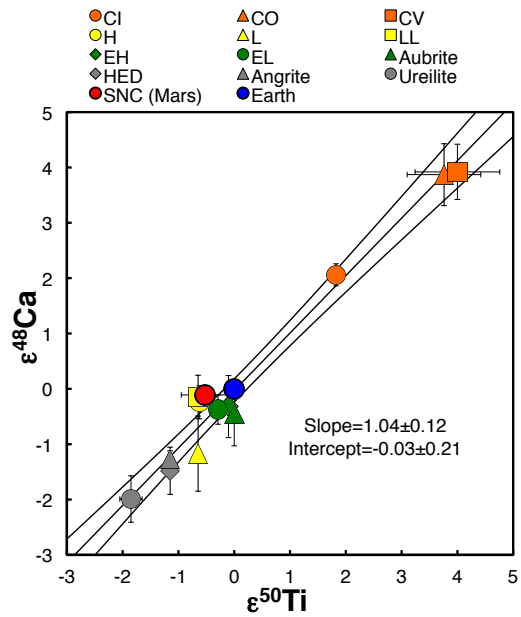

Fig. 1. Correlation between ε^{50}Ti and ε^{48}Ca isotope anomalies in bulk meteorites; $\varepsilon^{48}Ca=[(^{48}Ca/^{44}Ca)_{sample}/(^{48}Ca/^{44}Ca)_{STD} -1]\times10^4$, $\varepsilon^{50}Ti=[(^{50}Ti/^{47}Ti)_{sample}/(^{50}Ti/^{47}Ti)_{STD}-1] \times10^4$, where ^{48}Ca/^{44}Ca and ^{50}Ti/^{47}Ti ratios have been corrected for mass fractionation by internal normalization. ε^{48}Ca data from [this study, 1,2]; ε^{50}Ti data from [3,4].

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