A DEPLETED, NONCHONDRITIC BULK EARTH: THE EXPLOSIVE-VOLCANIC BASALT LOSS HYPOTHESIS

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Introduction: It has long been customary to assume that in the bulk composition of the Earth, all refractory lithophile elements (including major oxides Al_2O_3 and CaO, all 15 of the REE, and the heat-producing elements Th and U) occur in chondritic, bulk solar-system, proportion to one another. In detail, as has long been known [1], planetary bulk compositions are not chondritic. Volatility-related depletions are evident even among chondrites. Metal/silicate fractionation left the Moon and Mercury with far from chondritic Fe/Si ratios (and presumably nonchondritic siderophile/lithophile ratios). Differentiation by disruptive collision [2] may be more consequential than previously suspected. For the many nonvolatile-lithophile elements, however, the usual presumption is that in bulk planets each of these elements occurs in precise chondritic proportion to all other such elements.

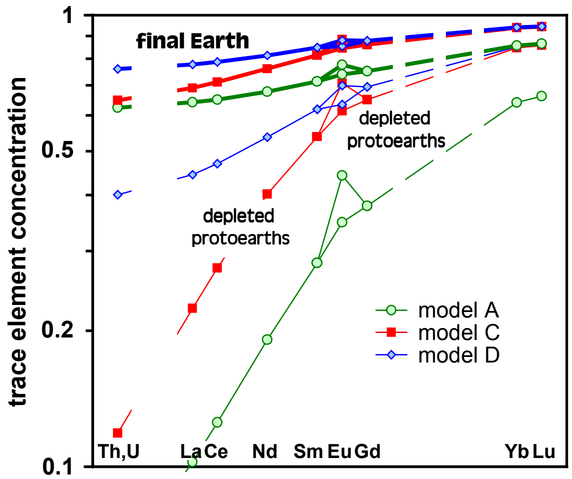
The geochemically coherent REE, including Sm and Nd, are exemplary in being both highly refractory and highly lithophile. However, recent high-precision measurements of ^{142}Nd (formed by decay of short-lived ^{146}Sm) indicate that for much, if not all, of Earth's mantle, the Nd/Sm ratio is decidedly depleted versus the narrow range defined by all known chondrites [3,4]. The upper mantle source regions of mid-ocean ridge basalts (MORB), komatiites, and a variety of other igneous rocks, consistently have ^{142}Nd/^{144}Nd about 20 μ (ppm) higher than the well-defined mean ^{142}Nd/^{144}Nd of a variety of chondrites; and in order to evolve a 20 μ ^{142}Nd/^{144}Nd excess, even assuming the maximum conceivable age (4.566 Ga) for Sm-Nd fractionation, a reservoir must have Sm/Nd 1.073 times the mean chondritic value; i.e., Nd/Sm (wt. ratio) depleted to 0.932 times the mean chondritic value [3,4].

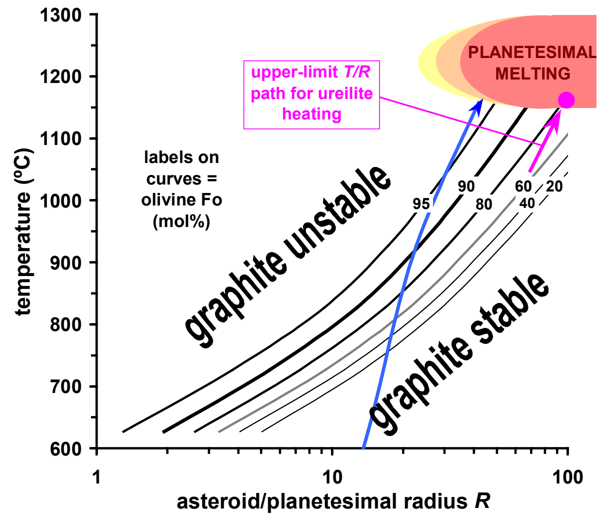
The popular reaction to this type of evidence has been to invoke a "hidden" reservoir of enriched matter, sequestered into the deepest mantle as a consequence of primordial differentiation. However, I propose a hypothesis that potentially explains the evidence for Nd/Sm depletion in a very different way.

Outline of the model: Among the handful of major types of differentiated asteroidal meteorites, two (ureilites and aubrites) are ultramafic restites so consistently devoid of plagioclase that meteoriticists were once mystified as to how all the complementary plagioclase-rich matter (basalt) was lost. The explanation appears to be basalt loss by graphite-fueled explosive volcanism on roughly 100-km sized planetesimals; with the dispersiveness of the process dramatically enhanced, relative to terrestrial experience, because the pyroclastic gases expand into vacuous space [5-8]. By analogy with lunar pyroclastic products, the typical size of pyroclastic melt/glass droplets under these circumstances will be roughly 0.1 mm. Once separated from an asteroidal or planetesimal gravitational field, droplets of this size will tend to spiral toward the Sun, rather than reaccrete, because drag forces such as the Poynting-Robertson effect quickly modify their orbits (given a robust early solar wind, "corpuscular" P-R drag [9] would have been more effective than the widely cited radiation type of P-R drag). The semimajor axis is typically reduced by several hundred km during the first trip around the Sun. Less clear (needing study) is whether these particles would mostly spiral into the Sun, or reaccrete onto other protoEarth planetesimals. Assuming similar processes occurred on and around many of the Earth's precursor, roughly 100 km diameter, planetesimals, the net effect would be a depleted composition for the final Earth.

Trace-element modeling: I [10] have modeled the process of trace-element depletion in the planetesimal mantles, assuming the partial melting was nonmodal and either batch or dynamic in terms of melt-removal style [11]. Assuming the process is moderately efficient, typical final-Earth Nd/Sm ratios are 0.93-0.96 times chondritic. Major uncertainties that affect the degree of final-Earth depletion include the extent of basalt loss, the mineralogy of the initial source matter, and the physical style of melting during the genesis of the basalt. The overall extent of basalt loss was modeled by assuming various combinations of X (the extent of basalt removed from a given planetesimal) and Y, the proportion of the planet assumed (for modeling purposes) to consist of entirely unfractionated material.

The most plausible initial mineral assemblage for protoEarth-planetesimals, given the reduced nature of this planet (high proportion of Fe-metal, coupled with high oxide *mg* ratio [12]), has 30-50 wt% olivine, 39-59 wt% pyroxene, 10 wt% plagioclase, and 1 wt% opaque oxides; the pyroxene is an 80:20 mix of orthopyroxene and high-Ca pyroxene. Models based on this reference mineralogy typically result in a final-Earth Nd/Sm in the range 0.93-0.96 times the unfractionated-chondritic ratio, assuming moderate X and Y (Fig. 1; the illustrated models are "batch" type; in A, the initial minerals include 50 wt% olivine and 39 wt% px; C and D assume 30 wt% olivine and 59 wt% px; residual melt porosity after batch-melt removal is as-





sumed 0.5 wt% for A and C, 3 wt% for D).

In general, a high pyroxene/olivine ratio results in a higher degree of final-Earth Nd/Sm fractionation. Substituting pigeonite for some of the opx + high-Ca pyroxene of the reference model tends to result in dampened final-Earth Nd/Sm fractionation. For any given initial mineralogy, models predicated on batch-style partial melting are most effective, in terms of yielding fractionated final-Earth Nd/Sm, if the residual porosity after melt segregation is assumed to be small. The opposite holds for models predicated on dynamic-style partial melting: a high residual porosity during melting translates (over most of the plausible range in *X*) into a higher degree of final-Earth Nd/Sm fractionation.

The ureilite analogy: Ureilites are a major class of achondrites that formed as mantle restites [6-8] with depletions similar to those modeled by [10]. They also retain high (average 3 wt%) proportions of graphitic C. The ureilites thus prove that it was possible for planetesimal thermal evolution to bring the mantle to the *T* range for anatexis without oxidizing away the carbon during the heat-up. In Fig. 2 (graphite stability relationships modeled thermodynamically after [6], with pressure translated into *R* by assuming a uniform density of 3300 kg/m^3) the blue curve represents a heating model from [13], which would cause graphite to oxidize away as *T* passes roughly 750-900°C (depending upon fO_2, as reflected in the olivine Fo). The survival of carbon in ureilites is especially reassuring because these are relatively oxidized (Fo as low as 75 mol%) compared to the Earth (~90 mol% [12]).

Side effects: As discussed by [10], important final-Earth side effects of basalt loss by explosive volcanism include highly depleted contents of the heat-generating elements, Th, U and K; a depleted Al/Ca ratio; a depleted Hf/Lu ratio; and a small but conceivably noticeable Eu anomaly. One of the most inevitable side effects, depletion of Al/Ca, is consistent with an otherwise puzzling aspect of the composition of the upper mantle [14]. The suggestion of Th, U and K depletion has worrisome implications regarding the Urey ratio and Earth's thermal evolution. However, this effect might be dampened if, by various potential mechanisms, the earliest ~1% of basalt generated tended to be dissipated less efficiently. Such mechanisms include interaction of the earliest melts with a less mature (i.e., weak, uncompacted) variety of planetesimal surface; a tendency for the earliest melts tended to be quenched by the cool near-surface material, and thus end up intrusive; or, the earliest blow-off products may have had a greater statistical probability for reaccretion.

Conclusion: It is certainly debatable whether basalt loss by explosive volcanism resulted in sufficient Nd/Sm fractionation, to ~0.93 times chondritic, to engender the full 20 μ of ^{142}Nd/^{144}Nd excess inferred for the "early depleted reservoir" by Boyet and Carlson (2006). However, modeling suggests that basalt loss by explosive volcanism tends to yield roughly that degree of Nd/Sm fractionation. In relation to the high precision of modern isotopic measurements and isotopic-tracer modeling, a perfectly undepleted composition for the bulk Earth appears highly dubious.

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