

# Isotope systems and geochemistry

## Lecture by Stan Hart

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### Bulk Composition of the Earth

#### *Refractory Lithophile Elements*

To understand the development of the Earth chemically, we must have some idea of where we started. The vast majority of the Earth is hidden from us, so we are left inferring the initial composition from more indirect sources. The classical approach is to investigate chemical trends in upper mantle-derived lherzolites (the depleted products of mantle differentiation) and meteorites. Specifically, ratios of Mg/Si, Al/Si, and Ca/Si are plotted against one another and a two reasonable linear trends are observed, one terrestrial and the other meteoritic. The intersection of the two trends is taken to represent the primary upper mantle (PUM) composition. The intersection falls somewhere near the ordinary CI carbonaceous chondrites, leading to the common statement that these reflect the bulk composition of the Earth. There are two obvious weaknesses with this widely applied argument. The first is that we have no idea what process creates the meteorite array. The second is that in order to make a decent straight-line fit through the meteorite array, one is forced to ignore CM2, CV, and CO chondrites. There is no clear justification for doing so. In fact, it is entirely possible that the meteorite array does not form a linear trend at all, but rather curves. This would have rather profound impact on our understanding of the Earth. Brad Hager noted that these problems potentially reduce this area of geochemistry to the level of "numerology."

#### *Oxygen Isotopes*

An alternative approach involves the use of oxygen isotopes. This data suggests that the bulk Earth more closely resembles enstatite chondrites, with only the upper mantle being represented by the composition described above. This view, which indicates a dramatic shift in composition from the upper to lower mantle, strongly favors a two-layered convective system. In this case, the lower mantle would consist primarily of high-silica enstatite rather than perovskite. It is not obvious what the density contrast, and therefore the propensity towards maintaining a sharply layered system, would be.

### Plumes and Mantle Taxonomy

If true in its purest interpretation, the two-layered picture of mantle convection would deny us surface-dwellers any direct information whatsoever of its composition. Convention has it, however, that we do have at least one window to the lower mantle. *Plumes*, currently held responsible for hot spot volcanism around the world, carry

material from some thermal boundary layer (commonly taken to be the core mantle boundary (CMB) but sometimes suggested to be the 670 km discontinuity) and entrain material on their way. This presents us with some integrated picture of the material in between. These plumes are much more heterogeneous than the source region for mid ocean ridges, as evidenced by the much wider variation in isotopic composition of ocean island basalts (OIB). When viewed in 10-dimensional isotopic space, consistent trends emerge in the data (due to similar methods of fractionation) and we find that we only need 4 end member compositions to create the full range in basalts. Data are usually plotted based on their Sr, Nd, and Pb isotopic compositions, as these systems are representative of the other isotopic dimensions. The extreme compositions are as follow:

### *Mid-Ocean Ridge Basalts*

MORB represents the most depleted (lacking in incompatible trace elements) of the basalts. As such, it is characterized by low  $^{87}\text{Sr}/^{86}\text{Sr}$  and high  $^{143}\text{Nd}/^{144}\text{Nd}$ . MORBs are generally much more homogeneous than OIBs, although the Indian Ocean is notably more heterogeneous and enriched in incompatible trace elements than either the Pacific or the Atlantic.

### *HIMU*

Himu basalts are so named for their high U/Pb ratios, giving them anomalously high  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios. Sr and Nd ratios plot very close to the PUM composition. Type-islands include Tubuaii, Mangaia, and St. Helena.

### *EM1*

The first of the enriched (in incompatible trace elements) end members has extremely low  $^{143}\text{Nd}/^{144}\text{Nd}$ , moderately high  $^{87}\text{Sr}/^{86}\text{Sr}$ , and very low  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios. Common examples are Pitcairn and the Walvis Ridge.

### *EM2*

There are very few samples which typify this intermediate Pb, extremely low  $^{143}\text{Nd}/^{144}\text{Nd}$ , extremely high  $^{143}\text{Nd}/^{144}\text{Nd}$  basalt. Samoa and Taha (Societies) are good examples, and Kerguelen trends towards EM2.

We can also look at the compositions for individual islands in more detail. Assuming that linear trends (or "worms" in higher dimensional space) represent mixing lines, we can try to piece together the entrainment history of the plumes. Surprisingly, we commonly find that these trends do not commonly implicate MORB as a mixing component, but rather suggest that a poorly defined fifth composition is prevalent. This composition, called FOZO (for focal zone) or C (for common) is closer to the inferred bulk earth composition and may represent the dominant material in the lower mantle.

Finally, we can look for deeper meaning in the isotopic signal through spatial correlation with other observables. The simplest observation is that there is an isotopic bias, indicating higher levels of enrichment and greater heterogeneity in the southern hemisphere, concentrated near the equator. If we compare the geography of this "DUPAL anomaly," we find that it correlates very well with lower mantle tomography, the geoid,

etc. However, one should be cautious of spherical harmonics based on a very limited number of sampling points.

Note: Brad Hager also spoke in class on this day. His notes can be found in the Mantle Convection module of Geosystems home page.