Goldschmidt 2000
September 3rd–8th, 2000
Oxford, UK.

Journal of Conference Abstracts
Volume 5(2), 281

The Distribution of Niobium, Uranium, Cerium, and Lead in the Earth and its Constraint on the Mass of the Depleted Mantle and Solar Nebula Temperature

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Previous studies have demonstrated that Nb/U and Ce/Pb ratios for both mid-ocean ridge basalts (MORBs) and ocean-island basalts (OIBs) are globally uniform. These values differ from Nb/U and Ce/Pb ratios inferred for both the primitive mantle and the continental crust, and this difference has been exploited in a prior study (Hofmann et al., 1986) using a simple two reservoir mass balance model to estimate the mass of the present day depleted mantle. They concluded that only ~50% of the whole mantle had been depleted by the extraction of the continental crust from the primitive mantle, a result which is in conflict with results from recent mineral physics models, high resolution, seismic tomography models, and updated Sm-Nd crust-mantle evolution models. These other studies are in agreement that to first order, the whole mantle is uniform in both major and trace element composition, with mantle flow extending from the surface to the core-mantle boundary. The resolution of the discrepancy between mass balance models involving Nb/U and Ce/Pb ratios and these other studies is the focus here.

First, updated estimates for the concentrations of Nb, U, Ce, and Pb in the major reservoirs of the Earth (continental crust, lithosphere, depleted mantle, and core) are used to construct a new elemental mass balance model for these elements in the Earth. The model satisfies the twin constraints that accepted concentrations and ratios are adopted for the various reservoirs and that the calculated Bulk Earth must sum to values consistent with C1 chondrite values. From the resultant model, updated concentrations for the Nb, U, Ce, and Pb concentrations in the primitive mantle (PM), equivalent to the Bulk Silicate Earth, are derived. For lead, the Primitive Mantle and core concentrations are independently checked by calculating these concentrations using an experimental high temperature (2,585 C) and pressure (6GPa) experimental partition coefficient. For an initial C1 chondritic Pb concentration of 2,471 ppb, the partition coefficient predicts primitive mantle and core concentrations of 72ppb and 7.46ppm, respectively, compared with 108 ppb and 7.39ppm from the mass balance model. Interpolating between higher pressure partitioning experiments and the 6GPa one indicates that equilibrium fractionation of Pb between a magma ocean and molten metal at ~10GPa would exactly match the mass balance derived Primitive mantle and core concentrations. Nevertheless, the difference in predicted core lead concentrations is only ~1% for the 6GPa partition experiment and supports the assumption that the Earth accreted with the full C1 chondritic lead abundance and that the majority of primordial lead was sequestered into the core during core formation.

Second, the new primitive mantle values, together with the latest values for the Nb/U and Ce/Pb ratios for oceanic basalts and the U and Pb concentrations in the continental crust are used to revisit the estimate of the mass of the present day depleted mantle. Contrary to previous work, the oceanic Nb/U and Ce/Pb ratios are consistent with the whole mantle being depleted by the extraction of the continental crust from a primitive mantle. Numerical experiments show this conclusion is not sensitive to the preferred primitive mantle concentrations adopted here. Therefore, when the latest values for both concentrations and ratios are adopted, there is no discrepancy between estimates of the mass of the depleted mantle derived from the present day Nb/U and Ce/Pb ratios for oceanic basalts and the latest results from independent mineral physics, seismological, and isotope geochemical studies. The conclusion that the Earth contains the full C1 chondritic abundance of Pb indicates that the global temperature in solar nebula, at ~1AU heliocentric distance from the Sun, was below 519K, the 50% condensation temperature of lead. This low temperature refutes conventional wisdom that the solar nebular at 1AU was globally hot, with an ambient temperature above ~1,200K, a temperature hot enough to completely vaporize potassium silicates. In contrast, it is concluded here that the Earth should have accreted with the full C1 chondritic abundance of so-called moderately depleted elements (e.g. K, Na, Rb, Cs, S, I) since all these elements possess 50% condensation temperatures in excess of lead. This finding will effect geochemical models for the composition of the Earth's core.