Models for the accretion and early differentiation of the Earth

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A number of important questions relating to the evolution of the early Earth may be investigated by utilizing extinct as well as long-lived radionuclide chronometers. What was the time scale and functional shape of accretion and core formation? Did accretion proceed by a hierarchical series of progressively larger scale mergers of differentiated bodies? Was there an early magma ocean, and did a giant impact give rise to the moon? Was there a massive proto-atmosphere? What was the nature and fate of the Hadean crust? Was it recycled by onset of early subduction, and if so, when? What was the role of large, ~3.8–4.0 Ga, basin forming impacts observed in the lunar record?

Transport models for radionuclides and trace elements provide powerful tools for investigating time scales associated with planetary accretion, given appropriate data on extinct and long-lived chronometers. They may be used to constrain the rate of accretion and core formation as well as the growth of the earliest crust on the Earth. The models are based on isotopic and chemical mass balance between a primitive nebular reservoir, the primitive mantle, the core, and the early crust.

Models of planetary accretion imply rapid initial coagulation processes leading to runaway accretion of proto-planetary 'embryo' nuclei on a time scale of only 0.1 Ma. The growing Earth can be identified from very early times as a 'runaway embryo' that grows much faster than other objects eventually accreted to it. According to Wetherill, the total accretion interval is about 100 Ma. However, the mean time of accretion (mass-averaged) is only about 10 Ma. Accretion models suggest that the rate of accretion can be reasonably well approximated as an exponential function. Core-formation is primarily rate-limited by accretion, and the mean time of core formation can be determined from the isotope effect in a system that is fractionated by core formation.

Systems affected by the volatile element depletion in the Earth such as U-Th-Pb, ^{53}Mn-^{53}Cr, and the I-Pu-Xe chronometers may also be affected by accretion and/or core formation. The volatile elements Pb, Mn, Cr, I and Xe all show depletions in the Earth, but this may be primarily related to gas/dust separation in the solar nebula rather than accretion itself. The ^{53}Mn-^{53}Cr and U-Pb systems may also have been fractionated by core formation in the Earth. However, uncertainty over the exact decomposition of the respective fractionations precludes the use of these chronometers to constrain the time scale of terrestrial accretion and core formation.

The ideal extinct radionuclide accretion chronometer is one in which the parent/daughter ratio is fractionated both strongly and uniquely by core formation. This requires i) both the parent and daughter elements to be refractory, and ii) a strong fractionation between these elements due to core formation. Two systems that possess these properties are ^{182}Hf (half-life: 9 Ma)-^{182}W, and ^{97}Tc (half-life: 2.6 Ma)-^{97}Mo. Core segregation has produced nearly three orders of magnitude of fractionation between Hf-W-Mo-Re (and Tc by inference, assuming that Tc behaves geochemically like Re) in the residual silicate mantle. Iron meteorites show a 'deficit' in ^{182}W relative to the silicate Earth. This is due to the strong partitioning of the parent ^{182}Hf into the silicate phase, while W is partitioned into the metal phase during the formation of the Earth as well as meteorite parent bodies. In contrast, iron meteorites show an 'excess' of ^{97}Mo relative to the silicate Earth. This is expected due to the decay of ^{97}Tc and the fact that Re (Tc) is substantially more depleted than Mo in the silicate Earth. The time elapsed from the production of ^{97}Tc to the core/mantle segregation is calculated to be ~20 Ma using a simple two-stage model. A magma-ocean model, with a short mean time (10–20 Ma) of core formation, provides a mechanism to account for both the Mo isotope data as well as the W isotope data.

The ^{146}Sm–^{142}Nd chronometer makes it possible to constrain the age of the initial silicate differentiation of the Earth and therefore events related to formation of the earliest crust as well as crystallization of both the terrestrial and lunar magma oceans. The present data suggest an accretion interval of ~100 Ma.

Our Finnigan MAT262 mass spectrometer has been essential for our high precision measurements of Nd, W and Mo isotopes. However, a new generation TIMS instrument with improved precision and sensitivity is clearly needed to take better advantage of these isotopic systems in the future.