Origin of the Earth and Moon

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Based on strong resemblances in the abundance ratios of non-volatile elements among peridotites from the Earth's mantle, the present-day Solar Winds, and CI carbonaceous chondrites that have fallen recently on the Earth, geochemists have suggested that the Earth was built mostly with CI-carbonaceous-chondritic materials. However, Javoy et al. (2010) recognized the strong similarity in the isotopic compositions of oxygen and many other elements between terrestrial rocks and enstatite chondrites, and they have suggested that the Earth was built mostly from materials with enstatite chondrites in composition. Consequently, the ages of the Solar System and the Earth have been estimated from the radiometric ages of a variety of meteoritic minerals that have fallen recently on the Earth. The question has remained as to whether the planetary materials that built the Earth ~4.56 Ga ago had the same ages and compositions as those that have fallen recently on the Earth.

At the JpGU 2017 meeting, we reported the discovery of numerous fragments of meteorites in the ~3.46 Ga-old Apex Basalt from the East Pilbara Craton of Western Australia. Comprised mostly of titanite ($CaTiSiO_5$) and rutile (TiO_2), they are much richer in Ti, Ca, and V, and much poorer in Mg, Fe, Ni, P and S, than any of the chondrites previously discovered. They are associated with carbon-nanotubes, iridium-rich (up to ~10 wt%) metallic iron, and alloys of Fe-Ni-Co-Cr, Cu-Al-Si, Au-Si, and C-Ca-Al-Fe-Si.

Based on thermodynamic analyses of the formation conditions for minerals in various types of chondrites, we suggest the following scenarios for the formation of the Earth: (1) the Earth's formation began with an accumulation of planetesimals with compositions similar to the Apex Meteorites (i.e., Ti-Ca >> Mg-Fe) that condensed under very reducing conditions ($H_2/H_2O = 10^{6\pm1}$) at T = ~1650-1500 K near the Proto Sun (~1 AU) at >4.567 Ga; (2) the Earth continued to grow in mass with the addition of planetesimals with compositions similar to enstatite chondrites (Ti-Ca << Mg-Fe), which condensed at ~2-3 AU under less reducing conditions, and the subsequent addition of planetesimals with ordinary- and carbonaceous chondritic compositions (Ca-Ti << Mg-Fe), which condensed under moderately oxidizing conditions ($H_2/H_2O = 10^{-1\pm1}$) at T = ~1400-1300 K far away from the Proto Sun (~8-13 AU) at ~4.564 Ga; (3) the additions/mixing of the planetesimals that formed at different regions of the Solar Nebula occurred due to the inward migration of the Proto Jupiter that may have taken place ~2-5 Ma after the formation of the Proto Sun.

Our study also suggests that the Early Solar System, the bulk Earth, and the Core may have contained much more Ti, Ca and V, and much less Fe, Ni and S, than previously thought, and that the Ti-rich lunar basalts may have inherited the Ti-rich materials of the magma oceans of the early Earth and/or the Ti-rich impactors of the Late Heavy Bombardment.

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