GIANT IMPACTS, LATE VENEERS, AND THE GRADUAL HYDRATION OF THE EARTH’S MANTLE BY SUBDUCTION. E. H. Hauri, A. M. Shaw and A. E. Saal, DTM, Carnegie Institution of Washington, 5241 Broad Branch Rd. NW, Washington DC 20015, 2Department of Geology & Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, 3Department of Geological Sciences, Brown University, 324 Brook Street, Providence, RI 02912

Introduction: The likelihood of one or more giant impact events occurring during the accretion of the Earth is very high [1,2], and some of these late-stage impact events could have imparted enough energy to completely melt the silicate portion of the proto-Earth [3,4]. Despite the uncertain nature and composition of the terrestrial atmosphere immediately after such impacts, it seems inescapable that the Earth’s mantle suffered a catastrophic loss of volatiles (including H₂O, CO₂ and noble gases) within the first 100 Ma of the planet’s history.

For these volatile species, the subsequent evolution of the Earth’s mantle has thus been characterized by a gradual re-hydration from without, via the subduction of oceanic lithosphere altered by water from an exosphere whose existence has been dated to 4.4 Ga [5,6]. The estimated composition of this exosphere shows many similarities to a mass-fractionated proto-atmosphere mixed with volatiles released during impact degassing of a chondritic late veneer.

Initial Accretion: Based on the geochemistry of ordinary and enstatite chondrites, formation of planetesimals and planetary embryos in the terrestrial planet region likely took place in a region of the primordial disk that was depleted in volatile elements. This initial zonation resulted in a proto-Earth that was depleted in the most volatile elements, with a thin tenous atmosphere.

Giant Impacts: Numerical simulations of planetary accretion indicate a very high likelihood of at least one (more likely several) giant impact events involving planetary embryos of ≥ 0.1 Me [2]. Another common feature of these simulations is the occurrence of collisions with sufficiently high angular momentum to satisfy the requirements of the present Earth-Moon system.

Giant impacts can further deplete the proto-Earth in highly volatile elements via three mechanisms. Impact erosion takes place due to violent ground motions that push the atmosphere to escape velocities [7]. Thermal escape of hydrogen and helium will be driven by solar activity and heat generated from magma ocean events triggered by giant impacts. Finally, hydrodynamic escape of heavier gases is accomplished via collisions with thermally-escaping H and He. Such a process is required from the relative abundances and isotopic compositions of terrestrial noble gases.

Magma Ocean Formation: Scaling laws derived from collisional modelling indicate that giant impacts will result in widespread melting of the proto-Earth [4, 8]. Though these melting events almost certainly happened on the growing Earth, the extent of melting is highly uncertain; melting of the upper mantle seems very plausible, but melting of the lower mantle requires sufficient heat to melt Mg-silicate perovskite. Better estimates of the extent of melting are hampered by a lack of appropriate collision modelling and disparities in the experimentally-determined melting point of Mg-perovskite [9,10].

Late Volatile Veneer: Highly siderophile element abundances in the Earth’s mantle appear to require the addition of a carbonaceous chondrite late veneer with a mass of 0.7% of the Earth’s mantle. The associated volatile budget contains 2 oceans of water and sufficient C, S and Cl to make up the present-day volatile abundances of the atmosphere and mantle. Stable isotope similarities of this chondritic late veneer and the Earth’s volatile budget provide support for the addition of this late veneer after solidification of the magma ocean, although some fraction of a mass-fractionated primordial atmosphere is also required.

Hydration of Earth’s Mantle: Due to impact degassing, it is likely that much of the Earth’s volatile budget was present at the surface, with an ocean volume ~2X higher than today. Forward modelling of the evolution of volatiles in the Earth’s interior via subduction hydration of an initially dry mantle, with an emphasis on H₂O, matches the present-day concentrations estimated from reservoir balance and mantle volatile estimates for H₂O, CO₂, S and Cl. Mantle convection is characterized by an initially high mantle viscosity, with gradual growth of a low-viscosity upper mantle due to the introduction of water at subduction zones. Today the Earth’s mantle may be characterized by a wet low-viscosity upper mantle and a dry, stiff lower mantle, though details of this scenario await proper numerical modelling.