SCALE AND TIMING OF PRIMITIVE MANTLE DIFFERENTIATION IN TERRESTRIAL PLANETS: INSIGHTS FROM GEOCHEMISTRY AND GEOPHYSICS.

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Introduction: How, when, and the degree to which planetary bodies differentiate into core, mantle and crust is fundamental to understanding their origin and evolution. For example, the relative size of core and mantle may help constrain redox conditions during planetary accretion and the radial distribution of heat producing elements over geological time is critical for understanding thermal evolution and influences the capacity of planetary mantles to melt later in their geological history. Both short-lived and long-lived radiogenic isotopes provide compelling quantitative constraints on the geochemical nature and timing of major planetary reservoirs and such data are available for Earth, Mars (SNC meteorites) and the Moon. Another approach, where isotopic data are unavailable (e.g., Mercury, Venus), is to carry out mass balance calculations using geochemical models of crust-mantle-core compositions and geophysical models of planetary structure based on seismology, moment of inertia, gravity and topography. Where both approaches are available (Earth, Moon, Mars) they generally agree.

Planetary differentiation fundamentally takes place as two major processes that may or may not be widely separated in time. The first is separation into metal (±sulfide?) core and silicate primitive mantle and the second involving separation of planetary crusts from their primitive silicate mantle. This paper is concerned with the latter, which in turn may take place early in a planet's history, during creation of primary crusts, and/or relatively late in the form of secondary and tertiary crusts [1]. One convenient way to quantify silicate differentiation is to estimate the degree and timing of the transfer of the most incompatible lithophile elements (e.g., Rb, K, Th, U, La) into planetary crusts.

Earth: After more than a century of geophysical and geochemical study, terrestrial differentiation, not surprisingly, is the best understood. Although many details remain controversial, geophysics, isotopes and geochemical mass balance all are consistent with the tertiary continental crust, representing ~0.5% of the primitive mantle mass, being the primary agent for differentiation of incompatible lithophile elements [1]. Based mainly on Nd-isotopes, the mean age of continental crust is ~2.0-2.5 Gyr. From both isotopic modeling and mass balance calculations using the range of models of crust/mantle compositions and seismic structure, the fraction of the primitive mantle complement of incompatible lithophile elements that has been transferred into the continental crust is approximately 25-35%. The smaller (~0.15% of primitive mantle mass) and much younger (<0.2 Gyr) oceanic crust, although enriched by a factor of ~2-4 over primitive mantle incompatible lithophile levels, represents a relatively minor crustal reservoir for these elements.

Moon: The internal structure of the Moon is now reasonably well known from limited seismic (Apollo 12, 14) and other geophysical data [2]. Average crustal thickness is ~52 km, thinner than previously thought, and assuming a crustal density of 3,100 kg/m^3, represents about 8% of the mass of lunar crust-mantle system. The lunar crust is composed almost entirely of ancient (~4.46–4.2 Gyr) lunar highland material – anorthosite, permeated by KREEP – with younger mare basalts representing a trivial fraction. The composition of the Moon is characterized by extreme depletion of moderately volatile elements (K/U~2,700) with the primitive mantle having only about 83 ppm K [1]. Although the lunar highland crust is mafic-anorthositic in nature with fairly low absolute levels of incompatible elements (average K~600ppm, Th~0.90 ppm; U~0.24 ppm) [1] the large mass of crust results in approximately 56% of the incompatible elements, represented by K, being present in the crust.

Mars: Our understanding of the differentiation of Mars has increased dramatically over the past two decades with an influx of geophysical and geochemical data from Mars orbital and landed missions and geochemical and isotopic data from the rapidly growing Mars meteorite collection [3]. Although no useful seismology is available, combined gravity/topography suggests the martian crust averages ~50km in thickness, representing ~4.1% of the mass of the primitive mantle. Odyssey GRS and soil geochemistry indicate modestly elevated levels of incompatible elements in the crust (average K~3740 ppm, Th~0.70ppm; U~0.18ppm) [1], also consistent with apparently common alkaline igneous rocks at the surface [4]. The martian primitive mantle composition is also reasonably well established from SNC meteorites [5] and suggests that ~50% of the incompatible elements have been transferred to the crust. This happened relatively early since the mean age of the crust appears to be significantly greater that 3.5 Gyr and most of the young volcanism (e.g., basaltic shergottites) is LIL-depleted.

Mercury: The success of MESSENGER has fundamentally improved our previously meager understanding of the innermost planet. Mercury's cratering record indicates a (primary?) crust was in place and stable prior to the heavy bombardment, or >3.9 Gyr. Combined moment of inertia, topography and gravity data reveal a complex internal structure but with a crust averaging ~50km in thickness [6]. Mars has a large core representing ~57% of the planet's volume and a considerably greater fraction of the mass [6]. Thus, assuming similar densities for mantle and crust, the mercurian crust represents ~14% of the silicate fraction of the planet. The MESSENGER GRS instrument indicates a surface with modest levels of incompatible elements but with moderately volatile element loss of the same magnitude as Earth and Mars and much less than the Moon. Thus, the mercurian surface has K~1150 ppm, Th~0.22 ppm and U~0.090 ppm, leading to K/U~13,000 and K/Th~ 5,200 [7]. There are no good estimates of primitive mantle composition but a wide range of compositional models (lunar, martian, terrestrial) leads to the likelihood that >50% of the incompatible lithophile elements resides in the crust.

Venus: The geochemical evolution of Venus is now is the least understood of terrestrial planetary bodies. The best estimate of uncompressed density is within uncertainty of Earth leading to the general assumption that the bulk composition and internal structure of the two planets are broadly similar [1]. The best geophysical estimate of crustal thickness is a uniform ~30 km or about 1.5% of the planet's volume. Geochemical data from Venera and Vega landing sites indicate a basaltic crust, but one variably enriched in incompatible elements (K, Th, U) similar to alkali–rich terrestrial oceanic islands. The median value of 7 landing sites is ~0.5% K. However, these concentrations are from the ~0.85 Gyr resurfacing material and so not clearly representative of the underlying crust. One useful constraint comes from the amount of radiogenic ^{40}Ar in the venusian atmosphere, which is approximately a factor of four less than present in the terrestrial atmosphere [8]. The amount of ^{40}Ar depends on the amount of K in the primitive mantle, which of course is uncertain. However, for a reasonable range (e.g., terrestrial-like), the amount of K in the venusian primitive mantle that has been transferred into the crust is about one-third to one-half of the terrestrial values or about 10-20% of venusian primitive mantle levels.

Discussion: Fig. 1 plots the degree of silicate differentiation, measured as the fraction of primitive mantle K in the crust, versus mean age of crust for terrestrial planets and the Moon. Similar results are obtained for refractory elements Th and U, where available. A surprising observation is that the planets with the geochemically most evolved crustal compositions (i.e., most LIL-enriched) and most extensive history of mantle melting – Earth with its continental (granitic) and oceanic crusts and Venus with its ~0.85 Gyr resurfaced crust – are the ones that are least differentiated. In contrast, the small planetary bodies that likely have substantial remnants of early primary crusts, produced by magma ocean processes, are more differentiated by a factor of ~2 on average, in spite of them having as little as 600 and 1150 ppm crustal K concentrations (Moon and Mercury respectively). The relative mass of the crust, as much as the exact composition, controls the level of planetary silicate differentiation.

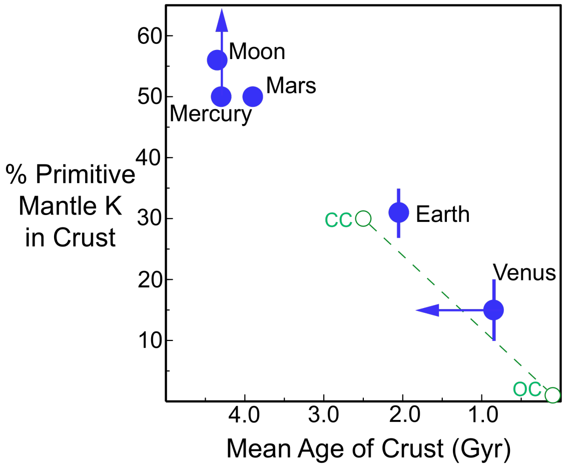

Fig. 1. *Amount of primitive mantle potassium that has been differentiated into crusts versus mean age of crust. For Earth, individual contributions of continental and oceanic crusts are also shown.*

These results also suggest that formation of primary crusts is an efficient mechanism for differentiating planetary bodies, at least small ones. This is likely due to the fact that it is easier to generate large volumes of relatively LIL-enriched residual liquids during crystallization of a magma ocean than by later partial melting [1]. It is generally assumed that Earth and Venus possessed early primary crusts that have been lost through some variety of recycling processes but the size and composition of these crusts is not known. Perhaps later geological history served to rehomogenize early crust-mantle systems of Earth and Venus as much as it did to further differentiate them.

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