

## Early Days of the Earth

Our home planet has reached its current state through 4.56 billion years of dynamic activity – plate tectonics, volcanism, meteorite impacts, mountain building, erosion, and the rise of life. Although usually considered “rock solid”, the solid earth instead is in continual motion. That motion drives resurfacing of the Earth through mountain building, faulting, basin formation, and the volcanism associated with plate creation and subduction. The driving force for this activity is a combination of gravity and the Earth’s internal heat that is derived from the continuing decay of radioactive elements, crystallization of the inner core, and the heat left over from planet formation. These energy sources drive the dynamic Earth we know today, but, compared to the modern Earth, the energy available for heating Earth’s interior was orders of magnitude higher shortly after Earth formation. The expectation, thus, is a very active early Earth that potentially experienced a variety of irreversible differentiation processes; one clear example being core formation. We know surprisingly little, however, about the consequences of this early activity. Recent discoveries suggest that important features of the current Earth owe their origin not to the long-term differentiation of the planet, but to processes occurring within tens to a hundred million years of Earth formation. A better understanding of the behavior and consequences of the energetic early Earth is essential if we are to appreciate its true role in creating the Earth we know today.

Comparative planetology has advanced the idea that the long-term evolution of a terrestrial planet may be dictated, or at least strongly influenced, by events occurring within the first 50-100 Ma of its formation. Improved chronologic methods now show clearly that planetesimal-scale melting was occurring within 2 to 4 million years of the formation of the first solids in the Solar System. These very old ages for planetary magmatism indicate both that extinct radionuclides, particularly  $^{26}\text{Al}$ , are responsible for the initial stages of planetary melting, and that planetary accumulation likely involved already differentiated objects, not pristine solar system condensates. Both Mars (based on data for meteorites believed to derive from Mars) and the Moon experienced global differentiation events by 4.4 to 4.5 Ga. These initial differentiation events separated core from mantle, formed large portions of still-existing crust, and left large compositional differences in their interiors that survived for over a billion years to influence the composition of younger volcanic products. On Earth, the importance of early events is revealed by core formation and mantle degassing ages that are within tens to a hundred million years of Earth formation. The discovery of increasingly old crustal rocks on Earth (Fig. 1) now allows inferences on the state of Earth’s surface and shallow interior within half a billion years or less of Earth formation.

*Figure 1: Images of Earth’s oldest crustal rocks and minerals. Right and left panels are photographs of zircons with labeled ion-probe U-Pb dating spots from*

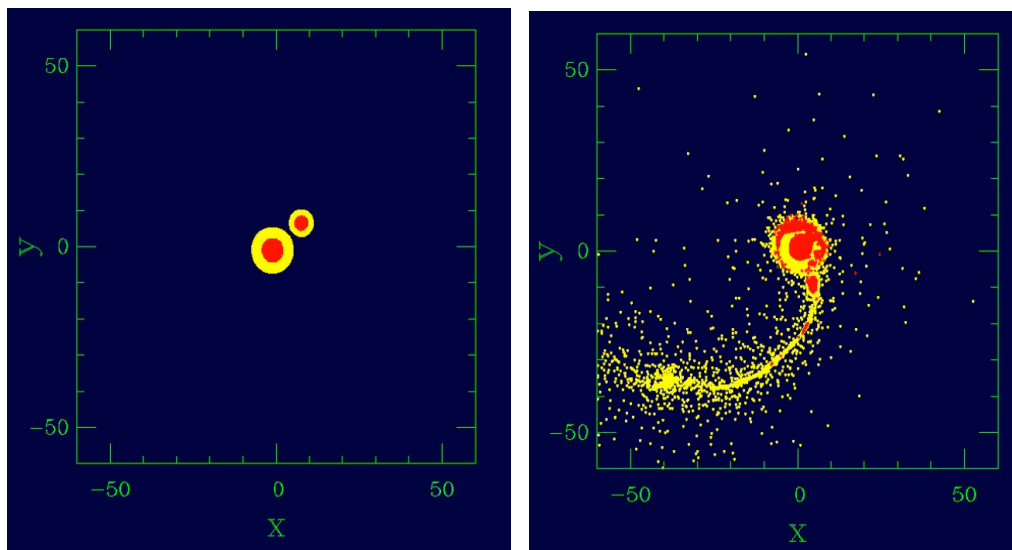
*Jack Hills Australia (Wilde et al., 2001) and the Acasta Gneiss of North-Central Canada (Bowring et al., 1990). The center picture is of the 4.28 Ga “faux-amphibolite” from the Nuvvuagittuq supracrustal belt in northern Quebec (O’Neil et al., 2008).*

Perhaps one of the most surprising results revealed by these old crustal materials is that by 4.36 Ga, Earth’s surface was cool enough to support the presence of liquid water, implying that within 200 Ma of formation, at least the outer parts of the Earth had cooled to temperatures not dramatically different from those on the present Earth. Another, still debated, implication suggested by the data for these old rocks is that plate tectonics may already have been in operation on Earth by 4.3 to 4.4 Ga.

From a geodynamic standpoint, much remains to be understood about the processes and long-term consequences of the early stages of planet formation. Basic questions include:

- The physics and chemical consequences of planetesimal accumulation
- The behavior of magma oceans – their crystallization sequence, the controls on crystal fractionation, and the dynamic stability of the end product of magma ocean crystallization
- The survivability of structures created by early differentiation

### The Process of Planet Growth



*Figure 2: Two time-slices in the animation of a glancing impact into the proto-Earth (from (Canup, 2004)). The silicate mantles of the planetesimals are shown in yellow while their cores are red. The first image is slightly before the impact whereas the second is taken after about two orbital rotations of the central object.*

*In this image, the silicate mantle of the impactor has been dispersed into orbit while the impactor core has mostly been accumulated onto the central object. This type of separation suggests that in an impact of this sort, the material placed into Earth orbit that would re-accumulate to form the Moon, mostly derives from the impactor, not the Earth (Canup, 2008).*

Terrestrial planet growth is believed to involve the accumulation of smaller planetesimals. Many models of this process make the simplifying assumption that when two planetesimals collide, they simply stick together, ignoring the consequences of a high-velocity collision. The potential significance of such collisions for affecting the resulting composition of the growing planet, however, is clearly shown in models of the giant, Moon-forming, impact (Fig. 2). Along these lines, a popular model to explain the proportionately large core of Mercury is that a good fraction of the Mercurian crust and mantle was removed by a giant impact like that illustrated in figure 2. The compositional similarity of Earth and Moon, along with the large angular momentum of the system, led to models that suggest the Moon was formed as the result of a giant impact into a proto-Earth. Dynamic models of this collision now leave us with the somewhat embarrassing result that the Moon indeed can be formed by such a mechanism, but that such a Moon would primarily consist of impactor material, not material from Earth. This issue has given rise to conceptual models that suggest that Earth and Moon chemically equilibrated with one another through a vapor/melt disk shortly after the impact (Fig. 3), but such models are at best a suggestion of what might have happened. Our understanding of the events accompanying such major collisions, and their potential consequences for chemical and physical modification of the growing planet, is thin. Geodynamic modeling of these processes is perhaps the only way in which the basic physics of such high-energy collisions can be extracted.

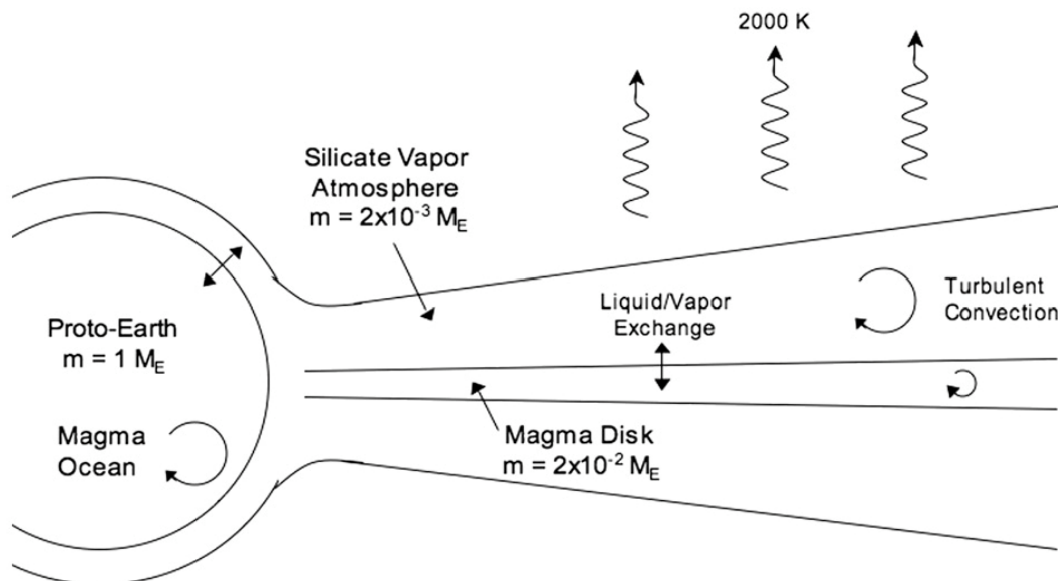


Figure 3: A schematic representation of the liquid/vapor disk surrounding the Earth shortly after a giant impact. The key aspect of this model is that substantial chemical exchange between the Earth and the surrounding disk can occur, potentially explaining the similarity in composition between Earth and Moon. From (Pahlevan and Stevenson, 2007).

The key issue at the heart of this discussion is that most attempts to estimate the bulk composition of Earth start from the assumption that the Earth should be close to Solar, as approximated by the composition of primitive meteorites, in bulk composition. Earth, however, clearly is depleted in volatile elements compared to these primitive meteorites. Whether this reflects nebular sorting of volatile and refractory components, or is the result of the type of violent collisions illustrated in figure 2 is a subject of continued discussion. What is clear, however, is that modeling Earth formation by assuming the gentle, and complete, accumulation of undifferentiated planetesimals is unlikely to approximate the true process of rapid planet growth that involves very energetic collisions between already differentiated planetesimals. Geodynamic modeling provides essentially the only approach that can investigate the physical consequences of such energetic planet growth. For example, the degree to which incoming planetesimals interact with a growing planet greatly affects the ability to date the timing and mechanism of core formation (Fig. 4). Using the Hf-W system to deduce the time of core

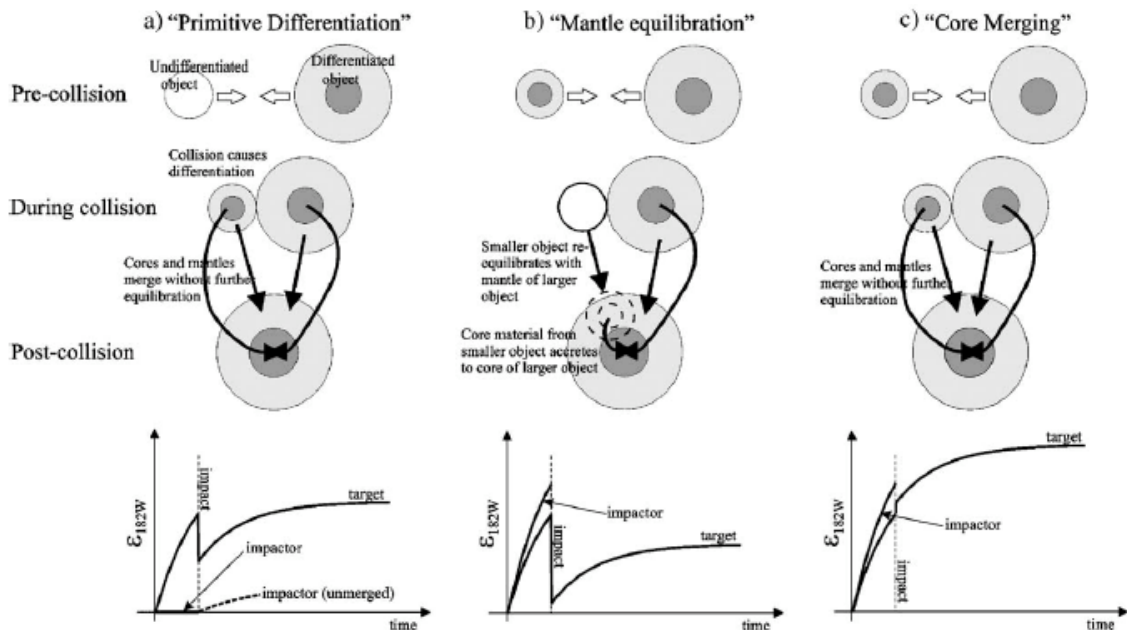


Figure 4: Schematic models for core growth during planetesimal accretion and its consequences for the Hf-W isotope system and the interpretation of the information regarding the timing of core formation that it provides. From (Nimmo and Agnor, 2006).

formation on a large planet, like Earth, depends on the degree to which the cores of accumulating, already differentiated, planetesimals, equilibrate with the growing Earth (Fig. 4). If no equilibration occurs, then the Hf-W system provides an age that gives only some approximation to the average age of core formation on the planetesimals from which Earth accumulated. If complete equilibration between Earth's core and mantle is maintained during Earth formation, then the Hf-W system dates the time when chemical communication between core and mantle shut down. Giant impact models, for example, suggest that the impactor's core plunges rapidly through the Earth to join with Earth's core (Fig. 2), implying little, if any, chemical equilibration with Earth's mantle. Whether this is an accurate prediction, or simply a result of the large particle size used in these models, is a question that needs further study. Geodynamics thus has much to contribute to our understanding of the formative stages of the terrestrial planets. Indeed, theoretical investigations often are the primary means to address the type of questions described above as observational evidence of this era of planet formation is nearly absent, and appropriate samples that can address these issues are few.

## **Early Planetary Differentiation**

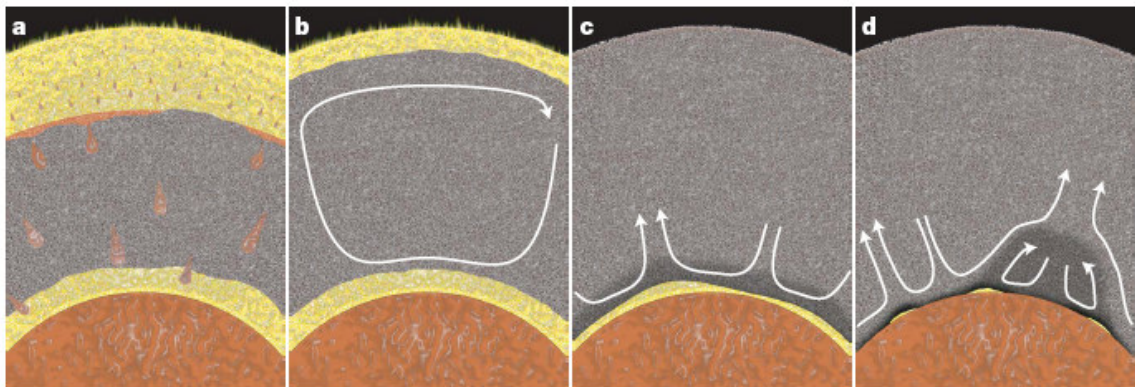
The combination of rapid planet growth, the presence of short-lived radioactive isotopes of major elements (e.g.  $^{26}\text{Al}$ ), plus the gravitational potential energy released during core formation provide the energy that drives extensive melting of growing planets. The likely result of quick terrestrial planet formation thus is an extensively melted planet – a magma ocean. Magma oceans were first proposed to explain the globe-encircling plagioclase-dominated crust of the Moon. Magma ocean differentiation of Mars also is believed to be primarily responsible for producing, prior to  $\sim 4.5$  Ga, the wide range in composition of the source regions of Martian meteorites. In contrast, evidence for an analogous early global differentiation on Earth is much more subdued, consisting primarily of abundance patterns of the elements affected by core formation, and by isotopic evidence for early mantle differentiation and atmosphere outgassing.

A potentially important variable in whether or not a magma ocean leads to extensive chemical differentiation of a planet is planet size. We know from iron meteorites that separation of immiscible liquids (in this case, iron from silicate melts) with greatly different densities can be accomplished rapidly, within a million years or less of Solar System formation, even on small planetesimals. Because of its low internal pressures, the crystallization sequence of a silicate magma ocean on a relatively small planetary object like Earth's Moon is reasonably well understood. Like many terrestrial layered mafic intrusions, the Moon provides a good example of the buoyancy-driven separation of relatively dense Mg- and Fe-rich silicates from the lower density Ca and Al-rich mineral plagioclase. On the Moon, this separation was efficient enough to produce a thick flotation crust composed predominantly of plagioclase. On Earth, however,

the greater internal pressures introduce many potential departures from the magma ocean evolution seen on the Moon. At issue in understanding the evolution of a terrestrial magma ocean are such basic questions as:

- Does crystallization of a deep terrestrial magma ocean occur from the bottom-up, or from the middle upwards and downwards?
- Are deep melts denser, or less dense, than the minerals that crystallize from a cooling magma ocean?
- What is the sequence of crystals formed?
- Are the densities of the crystals sufficiently higher or lower than the surrounding liquid to cause their separation?
- Does magma ocean crystallization create a buoyantly stable interior or one destined for major overturns with accompanying subsequent differentiation?

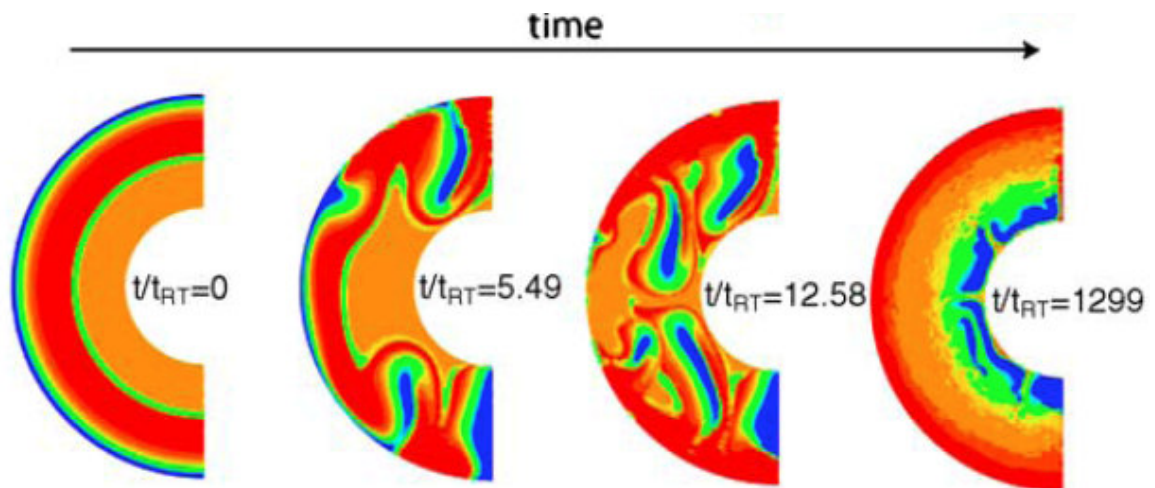
Answering these questions likely will require a combination of geodynamic investigations constrained by improved understanding of the petrology of melts in the deep earth and seismic imaging of mantle heterogeneity, particularly at the base of the mantle. One example of a dramatically different evolutionary path for a terrestrial magma ocean involves the possibility of a liquid-solid density crossover at some mantle depth, leading to a basal magma ocean (Fig. 5).



*Figure 5: Schematic evolution of the initial growth and eventual crystallization of surficial and basal magma oceans (yellow) in the Earth. This model is based on the premise of a deep-mantle density cross over between melt and solid, leading to upward segregation of melts in the upper mantle, but downward migration of melt in the lower mantle. Because heat from the buoyantly stable melt layer at the base of the mantle would be removed primarily by conduction rather than advection, a melt layer like this could stay molten for a considerable fraction of Earth history. Evidence for melt at the base of the mantle is observed in the ultra-low seismic shear wave velocities seen in some regions of the D'' layer at the base of the mantle (e.g. (Lay et al., 2004). Figure from (Labrosse et al., 2007).*

Downwards segregation of melt in the deep mantle has a number of interesting consequences ranging from potentially detectable structures at the core-mantle boundary to the formation of a deep analog to the continental crust that would be enriched in incompatible elements, and hence the major heat producing elements U, Th and K. A basal layer with high internal heat generation could substantially alter many aspects of solid earth dynamics ranging from the heat flux leaving the core, to generating a convective style in the overlying mantle driven primarily by bottom, rather than internal, heating.

Another aspect of this problem concerns the stability of the crystallization products of a magma ocean. At pressures appropriate for lunar and Martian magma oceans, cooling and crystallization of a magma ocean leads to residual liquids, and hence late-stage cumulates, that are rich in iron and titanium. These iron-rich cumulates are quite dense compared to earlier crystallizing phases. In an undisturbed pile of cumulates, the end product of magma ocean crystallization thus produces dense layers overlying low-density cumulates: a buoyantly unstable result. Such a package will undergo overturn (Fig. 6) creating a buoyantly stable layering that will impede further mantle convection until a thermal gradient is restored that will overcompensate for the chemical density of the layers. There is evidence in the degree of isotopic variation in pre-3.5 Ga crustal rocks for preservation of ancient heterogeneities (formed pre-4.5 Ga). This isotopic heterogeneity was erased between 3.9 and 3.5 Ga potentially supporting this model of vigorous initial differentiation followed by a period of quiescence in the mantle.



*Figure 6: Results of geodynamic calculations following the overturn of a buoyantly unstable layering of cumulate minerals formed through magma ocean crystallization. Figure from (Elkins-Tanton et al., 2005) with similar models have been presented by (Boss et al., 1984) and (Parmentier et al., 2002).*

Many aspects of this type of model need to be addressed, including such basic issues as whether such density stratification would form in a terrestrial

magma ocean or whether turbulence in the ocean would impede separation of crystals from liquid. The examples provided by Mars and the Moon suggest that planet formation ends with a highly differentiated interior. As discussed below, the continuing dynamic activity of Earth's interior may have diluted the signal of early differentiation, but a variety of recent results, ranging from isotopic evidence for early differentiation to seismic imaging of deep mantle structures that may be remnants of early-formed chemically distinct layers suggest that remnants of early differentiation remain detectable and potentially have major implications for our understanding of the chemical structure and dynamic evolution of Earth's interior.

### Long-term Consequences of Early Differentiation

Continent extraction has left an obvious chemical imprint in the portion of Earth's mantle that melts to make the oceanic crust. The oceanic crust shows a complementary depletion in the elements that are particularly enriched in continental crust (Fig. 7). Although there remains considerable debate about the rate of continent formation through time, there is little disagreement that this process has occurred throughout Earth history. Hence, unlike Mercury, Mars and the Moon, almost all of Earth's present crust is a product of the long-term dynamics of Earth's interior. The continental crust, at least that which exists today, is not a product of magma ocean differentiation. The mechanism by which continental crust production and recycling has modified the compositional structure of the mantle has been the subject of a large number of geodynamic models of mantle convection pursued over the past 30 years.

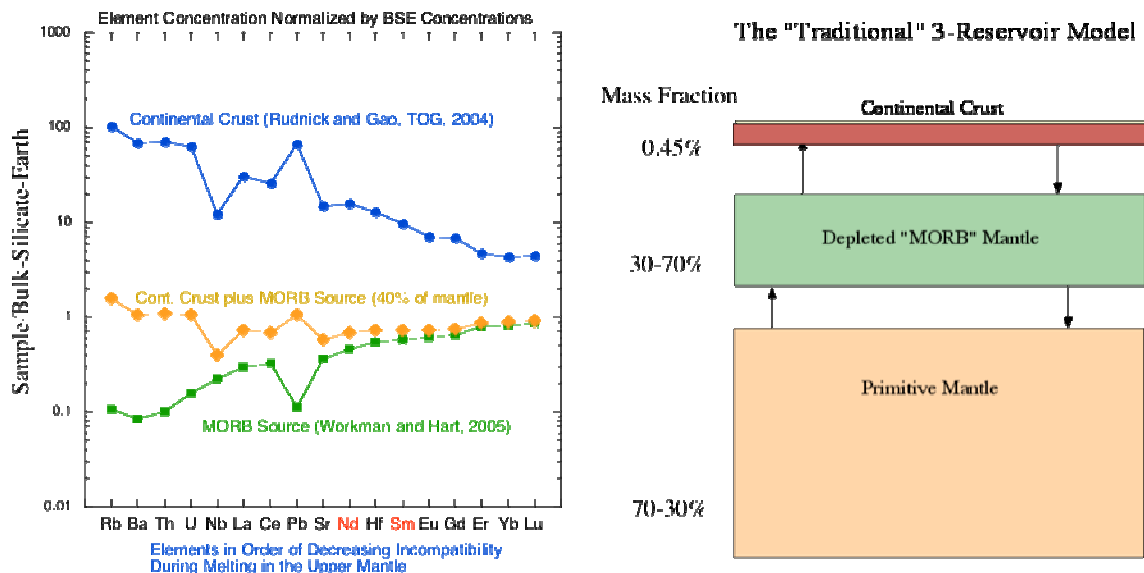
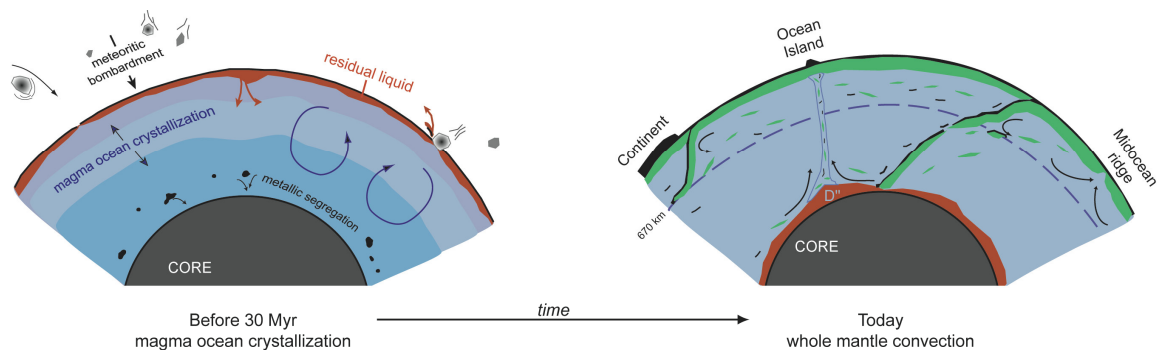


Figure 7: The chemical complementarity of continental crust and the mantle source of mid-ocean ridge basalts (MORB). Average continental crust (Rudnick and Gao, 2003) is enriched in the more highly incompatible elements and Pb,

whereas the mantle source of oceanic crust (Workman and Hart, 2005) is depleted in these same elements. This relationship, and the assumption that this differentiation began from a “primitive mantle” with concentrations of these elements deduced from comparison with primitive meteorites (Palme and O'Neill, 2003), allows calculation of the relative sizes of these chemical reservoirs within Earth's interior (Allegre, 1982; Hofmann et al., 1986; Jacobsen and Wasserburg, 1979).

A question of increasing importance, however, is whether the process of continent formation and consequent mantle differentiation acted on a mantle that initially was a homogeneous mixture approximating the average composition of the planet (minus the core). This assumption is implicit in many of the mantle differentiation models pursued since the 1980's. Evidence is building, however, that the “starting mantle” was the differentiated remnant of early Earth differentiation events (Fig. 8).



*Figure 8: Cartoon of an initial magma ocean differentiation of Earth's interior. Subduction of an early-formed crust (red) forms a layer at the core mantle boundary. The still continuing formation of continental and oceanic crust and the partial recycling of the crust through plate-tectonics then superimposes another chemical differentiation on mantle that was already differentiated through the removal of the early-formed crust. This model developed from the observation that all Earth rocks measured so far have a different  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio compared to primitive meteorites (Boyet and Carlson, 2005).  $^{142}\text{Nd}$  is derived from the radioactive decay of  $^{146}\text{Sm}$ , which has a half-life of 103 Ma. Because of the short half-life of  $^{146}\text{Sm}$ , variation in  $^{142}\text{Nd}/^{144}\text{Nd}$  testifies to differentiation events that must have occurred within the first couple of hundred million years of earth history (Carlson and Boyet, 2008). This evidence for early mantle differentiation supports previous inferences for early mantle degassing derived from isotopic variations in xenon created by the decay of short-lived  $^{129}\text{I}$  and  $^{244}\text{Pu}$  (Pepin and Porcelli, 2006).*

Variations in Xe isotope abundances between Earth's atmosphere and mantle indicate changes in volatile abundances in the mantle that occurred while the short-lived radioactive isotopes  $^{129}\text{I}$  and  $^{244}\text{Pu}$  were still present, in other words,

prior to 4.4. Ga. Mantle gases with  $^4\text{He}/^3\text{He}$  ratios lower than the atmosphere indicate the presence of relatively undegassed reservoirs in Earth's interior. Although originally associated with "primordial undifferentiated mantle", several recent studies instead indicate that the low  $^4\text{He}/^3\text{He}$  mantle is depleted in incompatible elements compared to any estimate of primordial mantle. All terrestrial rocks measured so far have  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios higher than chondritic. Produced by the decay of 103 Ma half-life  $^{146}\text{Sm}$ , the elevated  $^{142}\text{Nd}/^{144}\text{Nd}$  testifies to production of a high Sm/Nd ratio (or incompatible element depleted) mantle reservoir while  $^{146}\text{Sm}$  was still extant, or within a couple of hundred million years of Earth formation. All of these observations question the basic assumption that the differentiation of Earth's interior was accomplished primarily through the operation of plate tectonics and continent building over Earth history. Of critical importance is that a chemically differentiated mantle formed early in Earth history could have decidedly different physical and chemical properties compared to a "primordial undifferentiated mantle" that would lead to dramatically different dynamic behavior. Some models for early mantle differentiation predict abundances of radioactive heat producing elements in the bulk of the mantle nearly a factor of 2 lower than previous estimates for "fertile" mantle (Fig. 9). Because water behaves as an incompatible "element" during mantle melting, the observation that the "undegassed" or low  $^4\text{He}/^3\text{He}$  mantle is depleted in incompatible elements could imply that it is also depleted in water, and hence stronger than more water-rich mantle. The point here is that early differentiation could have left the mantle with physical properties quite different from the parameters used for decades to model the dynamic evolution of Earth's interior on the assumption that it was undifferentiated.

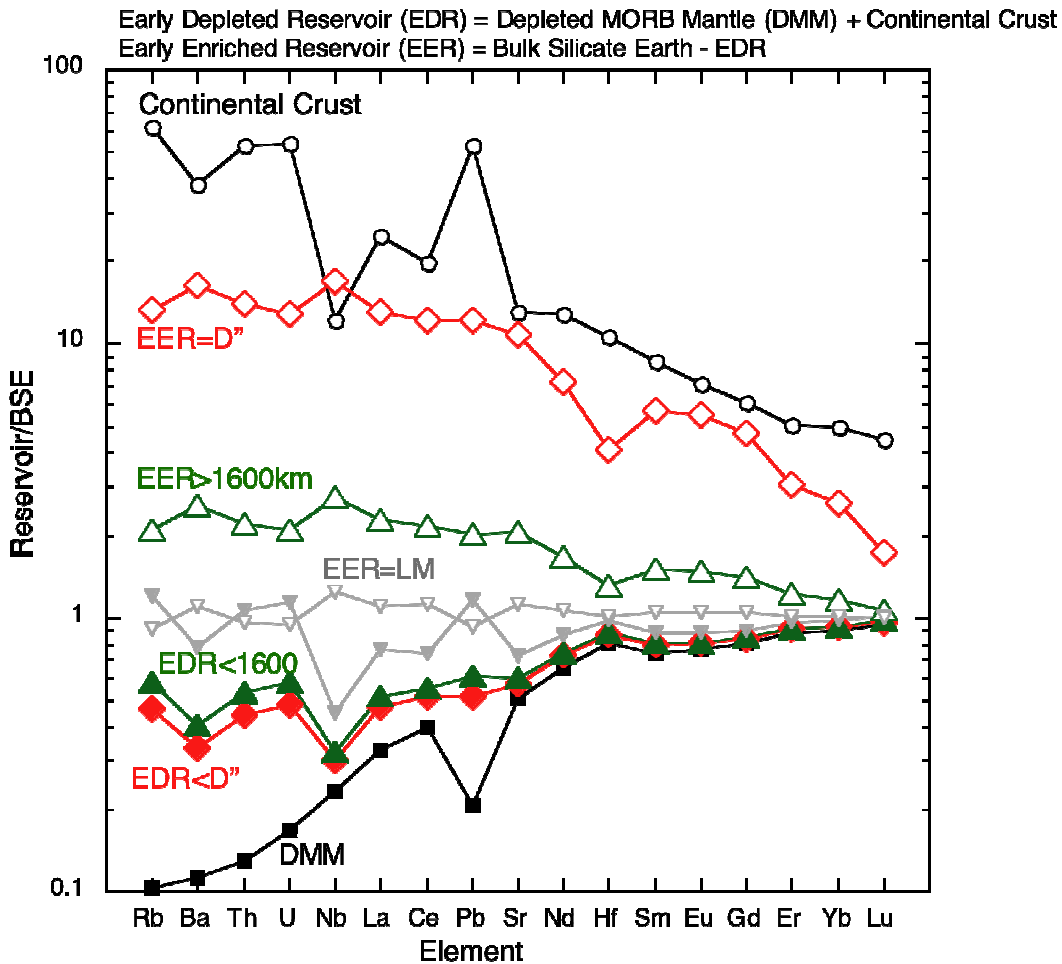


Figure 9: Incompatible element abundances, normalized to an estimate of the composition of the bulk-silicate earth (BSE (McDonough and Sun, 1995)) for the depleted mantle that is the source of mid ocean ridge basalts (DMM, (Workman and Hart, 2005)), average continental crust (Rudnick and Gao, 2003), and various models for early incompatible element depleted (EDR) and enriched (EER). The abundance patterns for EDR and EER are a function of the size of these reservoirs, which is unconstrained, so examples are provided for enriched reservoirs that range in size from the D" layer, to the whole mantle below 1600 km depth, to the whole lower mantle below 670 km depth. Figure from (Boyet and Carlson, 2005).

Another important consequence of early mantle differentiation is the possibility that an incompatible-element enriched complement (the EER shown in figure 9) to the generally incompatible element depleted mantle (the EDR shown in figure 9) still exists in the deep mantle. Although still speculative, geochemical evidence (e.g. figure 8), the suggestion from mineral physics for a melt-solid density cross-over in the lower mantle (Mosenfelder et al., 2007; Stixrude et al., 2009), observations of melting in the D" layer, and seismic observations of the lowermost mantle that apparently require the presence of compositionally distinct

materials, all suggest that the lowermost mantle may have properties that lie outside those expected for a homogeneous mantle. Whether the D" layer at the base of the mantle is a pile of subducted oceanic slabs, a chemical interaction zone between core and mantle, or a remnant of early differentiation, is a topic of increasing discussion. Whatever the answer, modeling the deep earth as a homogeneous medium with bulk-earth chemical properties is an increasingly oversimplified approach to an area that shows seismic complexity second only to the crust. The prospect that the deep mantle contains remnants of early differentiation opens a huge parameter space of internal heat production, compositional density, and mineral properties that have not yet been explored in geodynamic models. This is a fertile geodynamics research area with the best prospects to answer the question of how the initial differentiation of Earth may have affected its long-term dynamic behavior.

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