Accretion and core formation adds heat to the Earth, while mantle convection removes it from the Earth's interior

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Formation of the Earth's mantle at about 4.6-4.5 Ga is the result of a series of processes, including planetary accretion and core separation. These processes collectively lead to a very hot outer shell of the Earth that convected vigorously in order to remove heat from the planet's interior. Below are some considerations regarding the the initiation of mantle convection.

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1 INITIAL STATE OF THE SOLAR NEBULA -- HOT

- The formation of our solar system was likely to be initiated by a supernova trigger, causing the rotation and gravitational collapse of the proto-solar cloud to form a star (the sun).
- The presence of correlated short-lived isotope species in meteorites is most consistent with a rapid Sun formation (< 1 Ma). These short-lived radio-nuclides were likely to have been produced in a TP-AGB star (thermally pulsing - asymptotic giant branch star) and then injected into our proto-solar cloud.
- Thus, the inner solar system (e.g., 3- 4 AU) experienced high temperature processing, including the melting of grains, inclusions, and chondrules (high temperature components of meteorites). These melted materials are likely products of bi-polar jets (@ ~ 3-4 AU) surrounding our early and rapidly formed sun.

2 CONDENSATION AND ACCRETION -- HOT:

- The initial accretionary materials formed out of the solar cloud included high temperature condensates of oxides, metals, and silicates. The earliest formed materials are chondrules and Ca-Al-inclusions (CAI), both with formation ages on the order of < 3 Ma of T0 (where T0 = 4.6Ga, the age of our solar system).
- These initial condensates coalesced to form grains and larger sized fragments, and later then planetismals and ultimately planets. Collisions of smaller planetismals to form larger ones and ultimately planets adds significantly to the energy budget of planets, much of this kinetic energy is converted to thermal energy and must be dissipated from the planet's interior.
- Moon formation: it is commonly suggested that the Moon formed from a giant impact event; a commonly invoked model considers a Mars-sized body hitting the Earth at about 4.5 Ga, with a fraction of the total mass fissioning off to form the Moon. In addition to the many other effects of such a process, this impact event had enormous consequences for the heating of the Earth.
- If the Earth had a significant gaseous envelope surrounding it throughout most of its accretion, then this would have enhanced the chances of the upper portion of the mantle having been wholly molten. The presences of such an atmosphere reduces the radiation of the Earth's internal heat to space and produces a magma ocean scenario for the early Earth. Alternatively, if there is no surrounding atmosphere, the planet'sheat is then rapidly lost to space by radiation and one might expect little to no extensive melting of the mantle.

3 CORE FORMATION:

- The Earth is assumed to have initially accreted as a mixture of silicates and metal particles, with core separation following rapidly after much of the planet's accretion.
- Separation of the Earth Core heats up the mantle! Urey '52 (and later Elsasser '63; Birch '65; Flasar and Birch '73) realized that the gravitational energy released by core formation would be converted into thermal energy (best estimate: ~640 cal/gm), which would be enough to heat up the mantle by about 1000- 2000° C - thus driving mantle convection!
- Core Formation is early: Elsasser '63 and Birch '65 both assumed that core formation was late, ~0.5 Ga after accretion. However, recent studies on short-lived radio-nuclides (e.g., 182Hf, 98Tc) constrain core formation to being on the order of 1-5*10E7 years.
- Chemical observations of the relative abundances of elements in the mantle are consistent with the separation of an Fe-Ni alloy at mid to upper mantle conditions due to intense heating of the planet. It is also likely that this alloy contained sulfur

and other light element components, which reduces the melting temperature of this alloy phase.

4 MANTLE DIFFERENTIATION:

- The above considerations leads to the suggestion that the Earth's mantle experienced large scale melting during accretion and core formation. Together these processes start the convective engine for the mantle.
- Given the likely event of the outer portion of the mantle as having experienced global melting, then one would expect that the mantle would have also experienced some degree of differentiation (crystal-liquid separation).
- However, there is no geochemical and/or isotopic evidence, based on a wide spectrum of crustal and mantle rocks (including peridotites and komatiites), in support of this global differentiation process.
- Thus, if differentiation of the mantle occurred in the Hadean, then its effects have been completely erased by the processes of rapid and vigorous convection.

5 ORIGIN OF THE NOBLE GASES IN THE EARTH:

- The nature, origin, and composition of the Noble Gas (i.e., He, Ne, Ar, Kr, Xe) signature in the present-day mantle and in the early Earth is not well understood. Much of our discussion throughout this semester will rely on the models we assume for the past and present Noble Gas signature of the mantle.
- During accretion Noble Gases were trapped in the incoming materials and some amount of gases were ingassed into the planet from an assumed gaseous enveloped that was likely to have surrounded the early Earth. However, there are large gaps in our understanding of these early conditions and processes. Moreover, it is widely believed that presently we have degassed a substantial amount (perhaps >95%) of our inherited gas component.
- The most powerful observation recently is that of Honda's et al (1992), in which they demonstrated that the He-Ne isotopic systems are linked which means that, at least for these isotopes, the Earth inherited this gases from a solar component. There still remains a question of whether the heavier Noble Gases have planetary or solar compositions.
- There are also considerable questions surrounding the amounts of Noble Gases in different mantle reservoirs and, more importantly, the isotopic compositions of these gases in the different mantle reservoirs. At best we are only placing limits on the isotopic compositions of the Noble Gases in the mantle.

6 COMPOSITION OF CHONDRITES AND PLANETS (an aside):

- The rocky planetary bodies (including the Earth) are assumed to be composed of chondritic materials. There are many different types of chondrites that contain variable amounts of volatile components (see also the handout). Note: chondrites are made of a mixture of CAI and chondrules and differening amounts of matrix material, which is where most of the volatile element component is found.
- The refractory elements (e.g., Ca, Al, Ti, Sc, Sr, Zr, Mo, REE, Re, Os, Th, U) are those elements whose 50% condensation temperatures are above ~1300 K for an assumed partial pressure of oxygen (e.g., 10-4 atmospheres). Ratios of refractory elements (e.g., Ca/Al, Sm/Nd) are essentially equal in all the chondritic meteorites, and by assumption the rocky planets.
- The non-refractory elements include, Mg, Si, Fe, O, and Ni as the major elements and, for example, Na, K, Rb, S, Cu, and Pb as trace elements. In chondritic meteorites these elements show marked variations in absolute and relative abundances with respect to each other and with respect to the refractory elements. Therefore, there is a range of K/Rb, Rb/Sr and K/U values in chondritic meteorites. Because of this the abundances of the non-refractory elements in planets must be derived through various models.

- The refractory elements show isotopic homogeneity in meteorites, Earth, Moon and other planets. For example, the Earth and chondritic meteorites all have the same Nd isotopic composition and likewise the same Hf isotopic composition, because they share chondritic ratios for Sm/Nd and Lu/Hf.
- However, the non-refractory elements do not always show isotopic homogeneity. For example, there is a considerable range of oxygen isotopic compositions in meteorites. Oxygen is not considered a refractory element and thus the heterogeneity seen in O isotopes, like the heterogeneous distribution of volatile elements (inner rocky planets) reflect some of the nebula wide processes associated with its early and rapid phase of initial cooling down and planetary formation stages. (Note, some of the variation seen in oxygen isotopic compositions are due to parent body processes.)