

Ge 131 Chapter 16 Core Formation and Evolution

Core Formation

Core formation is the biggest differentiation event in the life of any planet. At least in the cases of Earth and Mars, we know that it is an ancient event from isotope systematics. In large bodies, it is high energy event because of the large energy released from accretion and the energy released from core formation itself. The process can occur at multiple scales: migration along grain boundaries, migration of iron along cracks, segregation of iron in a magma ocean, and diapiric descent in the deep mantle.

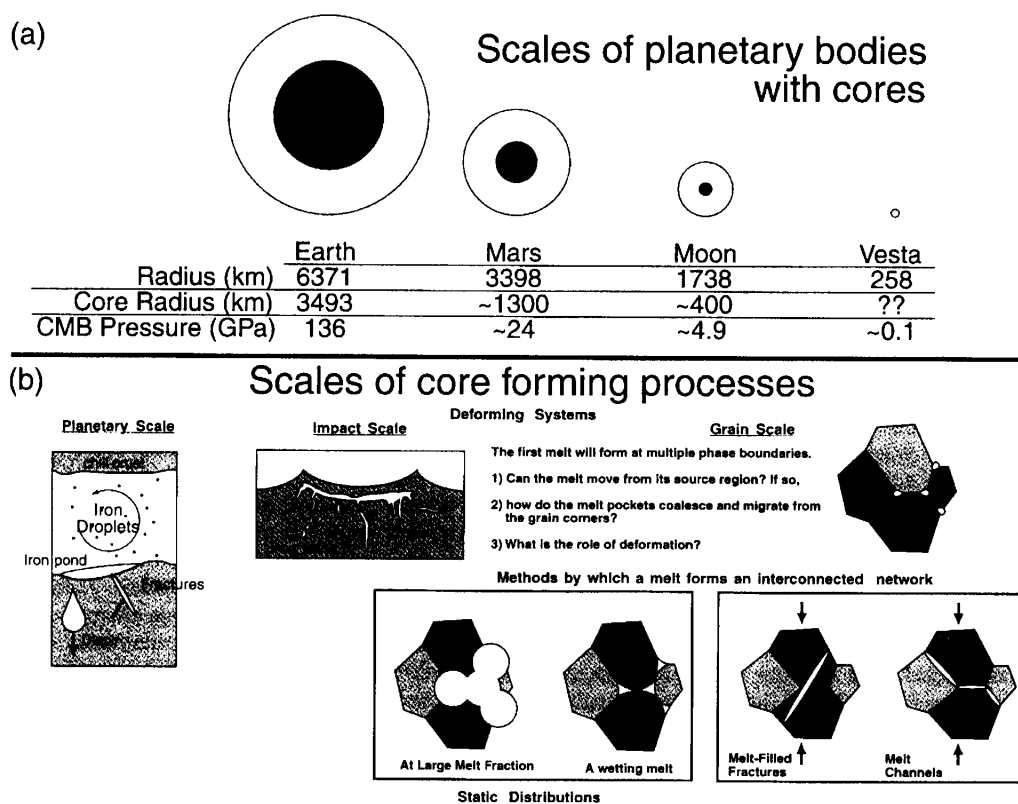


Fig. 10. (a) A true scale comparison of the sizes and core conditions for the terrestrial bodies known to have cores. No or minimum convection is considered in bodies Vesta-sized and smaller. In these bodies regime 1 for metal-silicate separation may be dominant. In larger-sized bodies, Mars-sized and larger, regimes 2 and 3 may become important as active convection likely accompanied core formation. (b) A comparison of the scales and mechanisms considered for the separation of core metal from mantle silicate. Here regimes 1, 2, and 3 are shown and note that more than one regime may occur during the formation of a single planetary core, even in the presence of a hypothetical magma ocean. See text for further discussion.

The above cartoon (from p239, *Origin of the Earth and Moon*) illustrates the likely range of processes.

284 *Origin of the Earth and Moon*

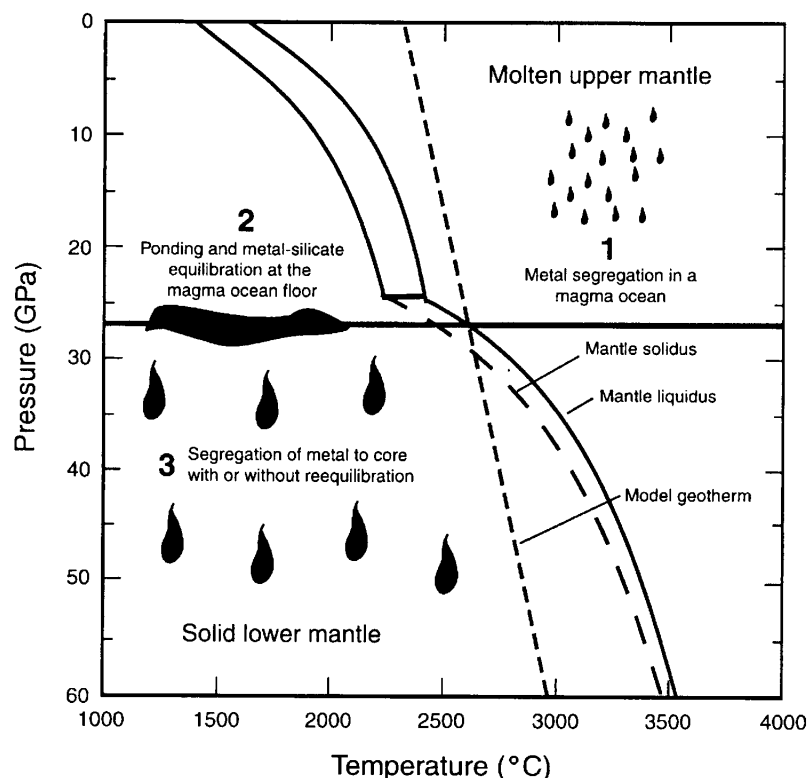


Fig. 10. Pressure-temperature diagram showing a conceptual model of metal/silicate equilibrium and segregation in a deep magma ocean. The solidus and liquidus are for pyrolytic mantle and are based on experimental data of *Zhang and Herzberg* (1994) at <25 GPa and *Zerr et al.* (1998) at >25 GPa. The cusp along the solidus at the upper-mantle/lower-mantle boundary is placed at about 25 GPa and corresponds to the subsolidus transition from a ringwoodite-rich (γ phase) upper mantle to a Mg-perovskite-rich lower mantle. For the model magma ocean geotherm shown, the entire upper mantle would be molten, a "magma ocean," whereas the lower mantle would be solid. Such a situation might arise as a consequence of a "giant impact" with a Mars-sized body. Equilibrium metal segregation from the upper mantle occurs by precipitation of small liquid metal globules, a "metallic rain" over a wide range in T and P (see *Stevenson*, 1990), and the metal ponds at the solid magma ocean floor. The metal finally equilibrates at this depth giving the upper mantle its present siderophile elements signature (see Fig. 9), before subsequent gravitational instability permits segregation and sinking of large metal diapirs through the lower mantle with little reequilibration. Alternatively, the magma ocean floor may exist at a greater depth and the upper mantle siderophile-element signature may reflect an accumulated average of polybaric metal segregation in the upper mantle (see *Li and Agee*, 1996; *Righter et al.*, 1997; *Righter and Drake*, 1999).

The next cartoon (immediately above) is from the same book, and intended specifically for Earth. Here is a sketch of a likely scenario for a large planet such as Earth: As the planet forms, enormous amounts of energy are released, sufficient to melt outer portions of the planet. The energy available from accretion, expressed as a temperature rise is

$$\Delta T = \frac{GM}{RC_p} \approx 40000K \left(\frac{M}{M_{\oplus}} \right)^{2/3}$$

using terrestrial values for specific heat. Of course, some of this energy may escape as radiation from the planet surface, but extensive melting seems unavoidable because much of the accreting mass arrives in big chunks rather than as a fine “rain” of small particles. Extensive melting and comminution leads to an “emulsion” of iron and silicates but the iron can then “rain out” to a level where the material is less extensively melted. The presence of such a level is likely because of the steep increase of melting point with depth within the planet. Descent of iron the rest of the way is then by diapiric flow, which is geologically fast (one suspects) because the silicates are soft at this time and the blobs are large. The level at which the blobs form is the depth of last equilibration for the iron, so the core-forming fluid (and the mantle left behind) may carry a memory of this pressure and temperature. There is some evidence to support this picture from a consideration of siderophile elemental abundances in the mantle. (see next figure, also same book, p283).

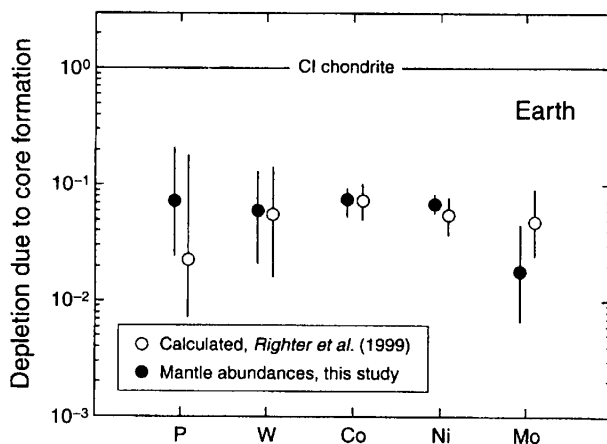


Fig. 9. Depletion due to core formation in Earth for P, W, Co, Ni, and Mo (solid circles) relative to the calculated depletion for equilibrium segregation in a hydrous peridotite magma ocean at 27 GPa and 2250 K (open circles) on the basis of the parameterizations of *Righter and Drake (1999)*.

The significance of this figure lies in the possible identification of the pressure (27Gpa) and temperature (2250K) of last equilibration. These correspond plausibly with the base of a magma ocean ~500 km deep.

Heating During Core Formation

In addition to the heating that arises from accretion, there is a lot of heat released as the core forms. Consider the gravitational energy of a differentiated body relative to that of a undifferentiated body:

$$E_{grav,undiff} = -\frac{3GM^2}{5R}$$

$$E_{grav,diff} = -\int_0^M \frac{Gmdm}{r(m)} = -\frac{3GM_o^2}{5R} \left\{ 1 - x^5 + x^3 \left[A^2 x^2 + \frac{5}{4} (1 - x^2)(A - 2) \right] \right\}$$

$$M_o \equiv \frac{4}{3} \pi \rho_o R^3$$

for our “usual” model of core and mantle (core with radius xR and density $A\rho_o$, mantle with density ρ_o). Typically, the change in gravitational energy is about 0.1 times the total, which is still equivalent to a 4000K or so heating of everything for an Earth mass.

The consequence of this together with the accretional heating suggests that the core is likely to form completely molten despite the fact that pressure freezing could in principle occur.

Core Convection

A terrestrial planetary core, like the mantle, will only convect if it has an unstable density distribution. If there are no compositional gradients, then this means that the mean temperature gradient must reach the adiabat. As we have discussed, the convective state will be close to the adiabat because it has such a low viscosity. Unlike the mantle, this is not an easy constraint to meet because it implies a substantial heat flow *by conduction alone*. The reason is that the core is a metal and hence a much better thermal conductor than the mantle.

For a Gruneisen gamma of about unity, the adiabatic temperature gradient in Earth’s core is about -0.5K/km. The thermal conductivity is about 3×10^6 cgs, so the conductive heat flow along the adiabat is about

$$F_{cond} = -k(dT/dr)_{ad} \approx 15 \text{ erg/cm}^2\text{-sec}$$

The actual heat flow out of the core, F_{core} , might plausibly be given by the time rate of change of the thermal heat content divided by the surface area. This cooling of the core is determined by the overlying mantle (mantle convection).

$$F_{\text{core}} \approx -[MC_V dT/dt]/4\pi R^2$$

where M is the core mass and C_V is the specific heat. For a drop of 100K per billion years, this gives $F_{\text{core}} \approx 20 \text{ erg/cm}^2\text{.sec}$, which is uncomfortably close to the conductive heat transport. *Irrespective of the uncertain numbers, notice that a core can only convect if it is cooling!* We do not know whether the cores of Mars and Venus (for example) are cooling.

Seismology tells us that the innermost part of the core is solid. While this is only a small fraction of core mass, it is generally believed that the inner core is important and perhaps essential to driving outer core motions. The argument is as follows: Since the adiabat is less steep than the melting curve of iron (or the pressure dependence of the liquidus of any plausible iron alloy), it follows that the inner core is a simple consequence of pressure freezing. But since the core is cooling over geologic time, it follows that the inner core must *grow* over geologic time. We can quantify this crudely as you did in the homework. Roughly speaking, you get

$$R_{\text{ic}} \approx (800\text{km})t^{1/2}$$

where t is the elapsed time in billions of years since inner core nucleation. This requires that about 2.5 billion years have elapsed since the onset of inner core growth because R_{ic} is now 1220km or thereabouts. (However, this is a sufficiently rough calculation that we cannot exclude with certainty that the inner core has persisted throughout geologic time.) Importantly, it also implies two other things of energetic significance; a latent heat release that currently corresponds to an extra heat flux

$$F_{\text{latent heat}} \approx 5 \text{ erg/cm}^2\text{.sec}$$

and (more importantly) the likely exclusion of some light material from the inner core, causing *compositional convection*.

The buoyancy of light, rising material can be very important, as we can see from the following argument. The inner core is now about 5% of the core mass. If this is pure iron, then a mass of order $(0.1)(0.05) \sim 0.005$ total core masses of light material has been displaced upwards (recall that the core is 10% less dense than pure iron). In other words, the outer core density has been reduced by perhaps 0.5% due to compositional effects. But meanwhile, the core has cooled about 250K. Suppose that conduction alone would have cooled the core by 500K. Then the compositional convection needs to “heat” the core (carry hot stuff downward) to the extent of a density anomaly of 250K times the coefficient of thermal expansion ($\alpha = 5 \times 10^{-6}$). This is 0.1%. Clearly the compositional convection is able to do it. Of course, this is a very crude calculation.

Cores cannot convect unless they are cooling. Even when they are cooling, they may not convect if they do not possess an inner core.