Evolution of an Initially Stratified Liquid Core and Onset of a Dynamo.

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Abstract: During accretion of a terrestrial body, the metal merging with the core has a higher temperature than the previously accreted material, forming a stably stratified core. Here, we investigate the thermal evolution of such an initially stratified core in order to estimate the onset of convection and early dynamo in terrestrial bodies.

Introduction: Various workers [1-4] proposed recently that the core of terrestrial planets are likely to be formed stratified. The accretion and differentiation of terrestrial bodies occur on similar time scales, with metal segregation occurring shortly after each impacts. The metal equilibrates with the silicates at a pressure and temperature similar to the conditions at the bottom of the surrounding magma ocean before sinking through the solid mantle, either by dykes or diapirs. Because the body is growing with each addition of material, the temperature and pressure of equilibration increase after each accretion steps. The metal merging with the core at each steps is thus hotter and lighter that the previously-segregated material, forming a layered core with material colder at the center (the early formed core) and hotter at the core mantle boundary (the latest material added). Figure 1 present an example of a typical accretion scenario to form an Earth size planet, without late giant impact. The temperature of equilibration increases with time, with discrete steps. In this presentation, we investigate the thermal evolution of such an initially stratified core, with special interest on the onset of convection and dynamo action.

Thermal model: For a typical diffusivity value of 100 W/m/K, heat diffuses on a characteristic timescale of a few billion years on the whole Earth's core. Therefore for an accretion timescale of about 100 Ma, it is safe to decouple the two processes and compute thermal evolution after accretion is complete the initial temperature profile set. We thus solve the spherical 1-dimensional heat diffusion equation for Earth's core with variable diffusivity. We consider the diffusivity of an Fe-Si alloy as a function of temperature and pressure from Gomi et al. [5], as shown on Figure 2 For the usual isentropic temperature profile, representing pre-existing convection and thus mixing, the variation of conductivity through the core is about a factor 2, with the highest conductivity in the center. However, with very low temperature at the center of the core, the profile can be inverted, with low conductivity in the center. The white solid line on Figure 2 is the result of one accretion scenario, with very low temperature at the very center (about 2000 K) and thus very low conductivity. The characteristic time for the temperature profile to reach the isentropic one by heat diffusion is thus lower and convection is expected to start earlier than usually considered. Figure 2 also shows the initial temperature profile from Helffrich and Brasser [4]. We use this profile as an initial condition, and compute diffusivity consistently with Gomi et al. [5]. In a purely 1-dimension model, convection will be considered through an effective diffusivity [6].

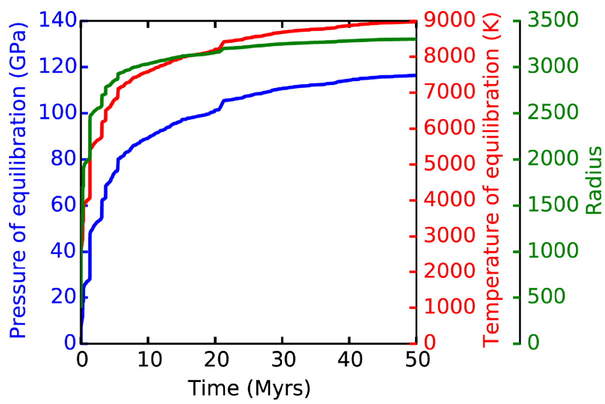

Fig 1: ***Example of accretion scenario showing the steps in the temperature profile (personnal communication, G. Helffrich. See [4]). Pressure and temperature at which the metal equilibrate with time increase with the radius of the impacted body. In this scenario, most of the core is formed after about 50 Myrs.***

Mixing of the stratified layer: During the accretion, each impact is susceptible to mix the mantle and the core. Giant impacts are likely to completely mix up to the core by mechanical effects, but smaller impacts can also mix part or total of the stratification by hydrodynamical mixing. By spreading a lighter material at the surface of the impacted core, medium core impactor would enhance Rayleigh Taylor instabilities. However, such gravitational currents are not expected to mix a stratified layer, similarly for example to a pyroclastic flow for which the mixing with the higher atmosphere is negligible. Nevertheless, an important effect need to be taken into account and quantified: each impacts, even "hit-and-run" ones, are likely to modify the rotation rate of the impacted body. Such a rotation variation is transmitted down to the deeper part of the body through either viscous friction or Ekmann pumping [7]. For liquid layer such as atmosphere, ocean and liquid core, Ekmann pumping is the most efficient way to advect angular momentum inside the bulk of the layer. However, no litterature is available yet on Ekmann pumping in stratified fluid, and we will investigate this effect later.

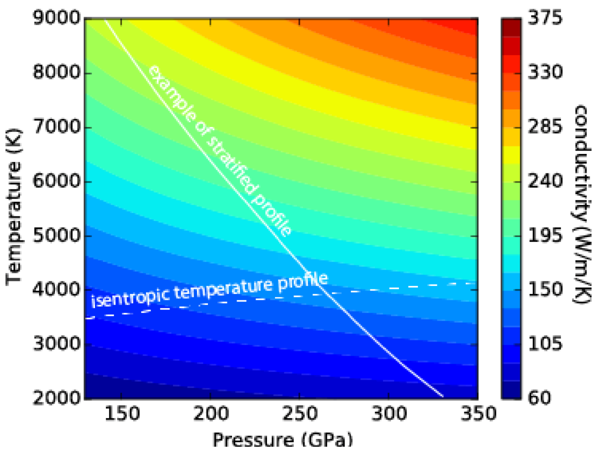

Fig 2: Conductivity profile of Fe-Si alloy as function of pressure and temperature [5]. White dashed line is the isentropic temperature for the Earth's core, anchored at 3500K at 130GPa. White solid line is the solution from one accretion scenario of a body of size similar to the Earth [4].

Discussion: In this problem, we have not discussed the evolution of composition of metal with the accretion. As the temperature and pressure of equilibration increase, the amount of light elements incorporated in the metal also increases. This decreases the density of the newly accreted material, and creates a compositional stratification. Because of the very low compositional diffusivity of light impurities in metal alloy, the destabilization of this stratification is even more difficult than the thermal stratification. However, the exact compositional stratification is difficult to estimate. It requires to know the percentage of chemical equilibration between metal and silicates during the differentiation as well as the depth of this equilibration, which depends on the physical processes (for example, [8]).

Conclusion: To simplify this problem, we studied only the thermal stratification of the core of a silicate body of size similar to Earth. The very early evolution of such a stratified core is important to study to understand the early onset of dynamics either for the Earth and for other planetary bodies, such as Mars. The key question we are addressing is how and when can a dynamo be started in a strong density stratification? We showed that, for scenarios of accretion proposed by [4], the variation of thermal conductivity over the whole core is very different from the one estimated by looking at an almost isentropic profile.

References: [1] S. Jacobson et al., AGU Fall Meeting 2015, DI41B-04 [2] G. Helffrich and R. Brasser, AGU Fall Meeting 2015, DI41B-01 [3] J. Arkani-Hamed, AGU Fall Meeting 2015, P33D-04 [4] G. Helffrich and R. Brasser, subm. to EPSL [5] Gomi et al., Phys. of the Earth and Plan. Int. 224 (2013) 88–103 [6] S. Sasaki, and K. Nakazawa, J. Geophys. Res. 91, 9231 (1986) [7] Greenspan, The theory of rotatin fluids, The University Press, 1990 [8] R. Deguen, M. Landeau, P. Olson, Earth and Plan. Sc. Lett. 391 (2014): 274-287.