WAS THE EARLY EARTH COMPLETELY MOLTEN? Donald L. Turcotte, Joan C. Pflugrath, Department of Geological Sciences, Cornell University, Ithaca, NY 14853

The existence of an early magma ocean on the moon is widely accepted. A variety of heating processes have been proposed including the energy of accretion, short lived radioactive isotopes, and electromagnetic induction. All of these processes would also be applicable to the terrestrial planets, in fact the heats of accretion would be substantially larger. Also, for the earth and Venus, core formation would contribute a substantial amount of energy. It is estimated [1] that core formation the earth could heat the entire body on averge 2,000 C°. Mechanisms for the removal of this heat during core formation appear to be inadequate to prevent substantial melting [2]. Thus it appears logical to conclude that the earth was entirely molten shortly after its formation. Yet this possibility has received relatively little attention in the literature. Hofmeister [3] restricted her attention to a relatively shallow (≈120 km) magma ocean on the earth because of the lack of relevant data.

Although energy considerations strongly favor an early molten earth, there are several major objections. If the earth was molten why did it not fractionate? The lunar crust is evidence of fractionation associated with the early lunar magma ocean. An essential question is whether a molten mantle on the earth would fractionate while a liquid or during solidification. The presence of primordial noble gases, i.e. ^{3}He, in the mantle today is taken as additional evidence against an early molten earth. However, the upper mantle of the earth has certainly been through the plate tectonic cycle several times yet retains measurable quantities of ^{3}He. If ^{3}He and other noble gases are sufficiently soluble in mantle minerals at moderate to high pressures there is no problem in explaining their presence in young volcanics rocks. The subduction of sediments and hydrated ocean crust at ocean trenches provides a mechanism for recycling volatiles into the mantle of the earth.

A striking difference between the earth and the moon is the average age of the crustal rocks. Active plate tectonics on the earth can explain the young age of oceanic crust but does not directly explain the mean age of the continental crust. It is doubtful that a significant fraction of the continental crust is recycled into the mantle; thus the mean age of the continental crust is indicative of when it was formed. A substantial fraction of the continental crust was formed between 2 Ga BP and 3 Ga BP; a very small fraction is older than 3 Ga. On the moon the highland crust is older than 4 Ga. One explanation for the absence of old continental crust on the earth is that the earth's mantle was solidifying during this period, thus preventing the formation of a significant volume of continental crust.

It is of interest to consider mechanisms of mantle solidification and to estimate the time required. Heat loss from the surface of the earth would lead to the formation of a solid outer shell. An essential question is whether this outer shell would be stable. If the solid outer shell were more dense than

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System

Early Earth Completely Molten?

Donald L. Turcotte , et. al.

the liquid mantle it would be expected to founder in much the same manner that subduction occurs at ocean trenches today. However, it is not possible to determine the required thickness of the lithosphere before it becomes unstable. The age and thickness of subducted lithosphere appears to be related to the geometry of plates rather than to an absolute instability. The instability of a solid crust on a basaltic lava lake has been observed in Hawaii. As extreme limits we take the thickness of an unstable crust on a mantle magma ocean to have the range 1 cm - 10 km. The corresponding solidification times for the mantle are 10^3 yrs. to 10^9 yrs. If the solidified outer shell foundered and sank to the base of the mantle it would be expected that the magma ocean would solidify from bottom to top.

However, it has been argued by Stolper et al. [4] that magmas may be more compressible than their equivalent solid phase and thus at a depth greater than about 100 km the magma will be more dense that the equivalent solid. Also, the roles of phase changes relative to a liquid magma are unclear. Thus it is possible that a mantle wide magma ocean could have solidified from top to bottom. If this were the case, solid state correction within the solid lid would be the primary mechanism for the transport of heat to the freezing front at the base of the lid. Using parameterized mantle convection in the solid lid [5] we have determined that mantle with a viscosity of 10^{17} poise would take 10^8 years to solidify and a mantle with a viscosity of 10^{20} poise would take 10^9 years to solidify. This range of viscosities should bracket the expected mantle during a period of high heat flow [6].

We conclude that an early molten earth is a hypothesis that deserves further study. Our calculations of solidification times indicate a period of 10^8 - 10^9 years would be a reasonable estimate for the time required to solidify a molten mantle. Many interesting questions remain particularly concerning the petrologic and geochemical effects of an early molten mantle.

References

[1] F.M. Flasar and F. Birch, Energetics of core formation: a correction, J. Geophys. Res., 78, 6101-6103 (1973).
[2] D.L. Turcotte and S.H. Emerman, Dissipative melting as a mechanism for core formation, J. Geophys. Res., in press, 1984.
[3] A.M. Hofmeister, Effect of a Hadean terrestrial magma ocean on crust and mantle evolution, J. Geophys. Res. 88, 4963-4983 (1983).
[4] E. Stolper, D. Walker, B.H. Hager, and J.F. Hays, Melt segregation from partially molten source regions: the importance of melt density and source region size, J. Geophys. Res. 86, 6261-6271 (1981).
[5] D.L. Turcotte, On the thermal evolution of the earth, Earth Planet. Sci. Let. 48, 53-58, (1980).
[6] D.L. Turcotte, F.A. Cook, and R.J. Willeman, Parameterized convection within the moon and the terrestrial planets, Proc. Lunar Planet. Sci. Conf. 10th, 2375-2392 (1979).

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System