

# Issues in studies of the interior evolution of the Moon raised by numerical modeling.

内部進化モデルからの月科学への問題提起

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## ABSTRACT

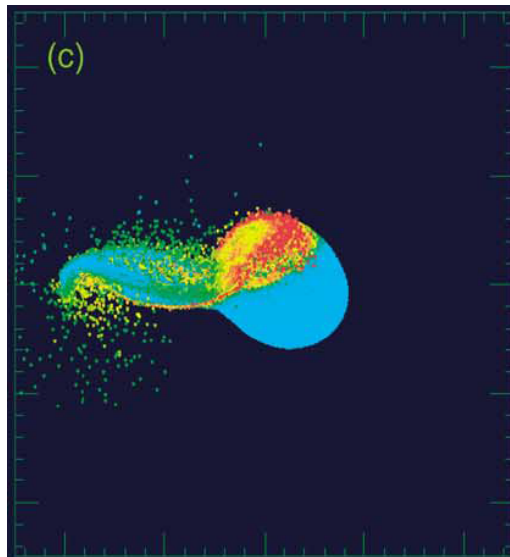
A remarkable feature of the lunar mantle evolution is the mare volcanism that has occurred mostly in a specific region called the Procellarum KREEP Terrane for about 3 Gyr. I carried out numerical simulation of magmatism in convecting mantle to develop a model of mantle evolution that fits in with this feature of the lunar volcanism. In a planet with the stagnant lithosphere like the Moon, magmatism extracts heat producing elements (HPEs) from the mantle and deposits them in the crust until the magmatism itself wanes and ceases. This redistribution of HPEs occurs within 2 Gyr at most and hence magmatism is ephemeral, when the mantle is assumed to have been hot just after the planetary formation 4.5 Gyr ago. When the deep mantle of the Moon is assumed to be initially colder, however, the start of magmatism is delayed and HPEs remain in the deep mantle for geologic time. I could obtain a model where magmatism locally occurs for more than 3 Gyrs, when I started the calculation with the initial temperature of the deep mantle as low as 1100 K. The thermal history of the mantle thus calculated is consistent with the history of radial expansion/contraction of the Moon inferred recently from spacecraft observations, too. It is difficult, however, to explain the observed history of the lunar magnetic field with this model, and also to explain the initial low temperature based on the current giant impact hypothesis for the formation of the Moon. A comprehensive understanding of the history of the Moon from its formation to the present state is still far ahead, and further spacecraft observations on the interior structure and the surface history as well as three-dimensional spherical modeling of the Moon are needed.

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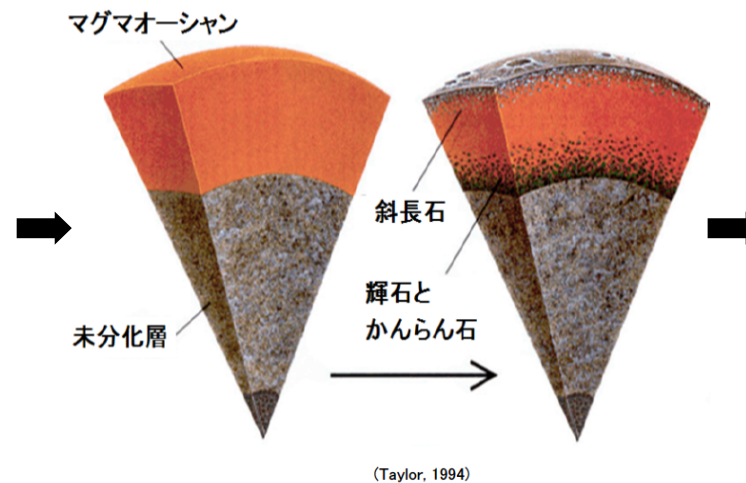
## Models of formation and evolution of the Moon

Giant impact

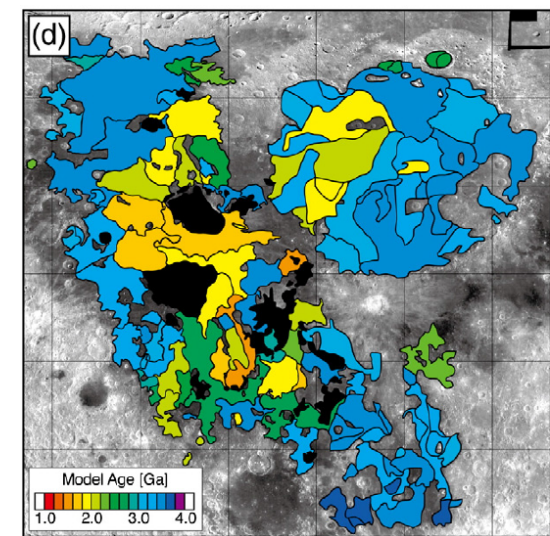


(Canup, 2012)

the deep magma ocean

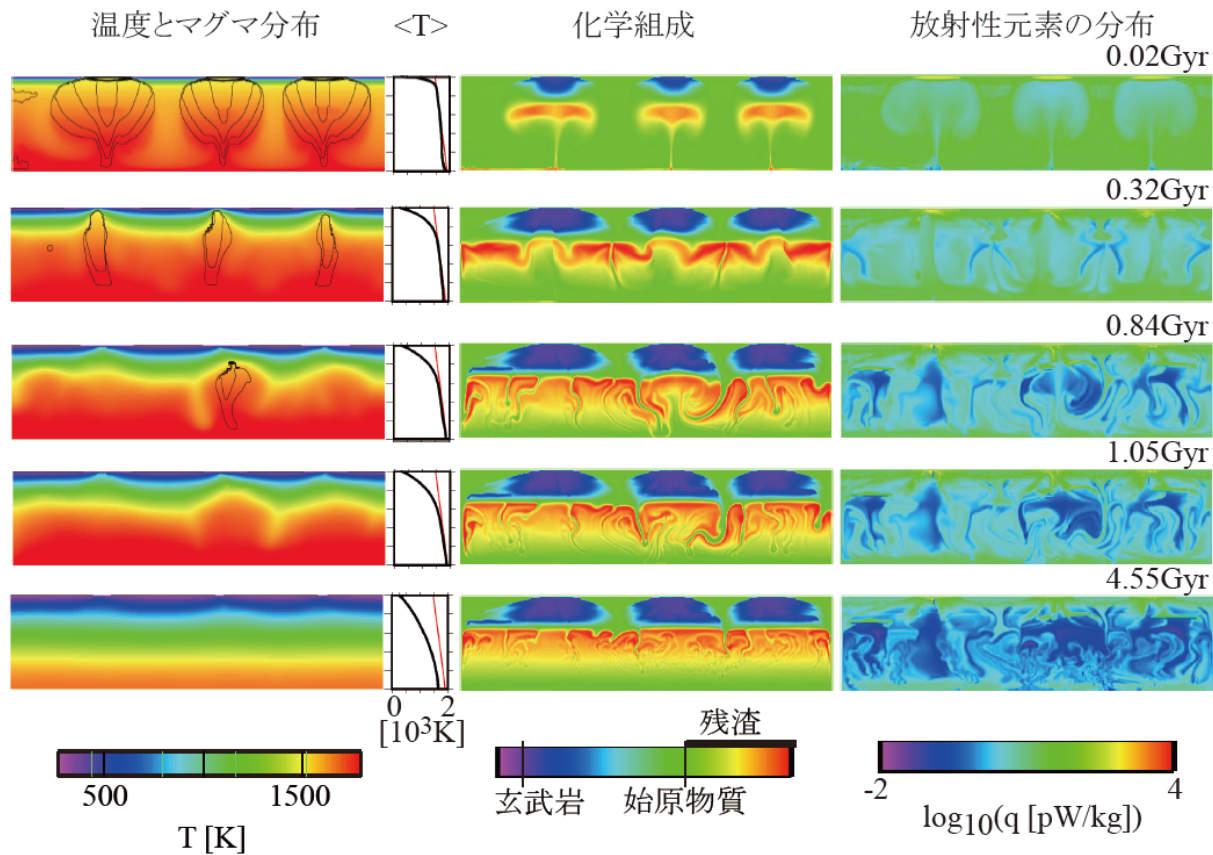
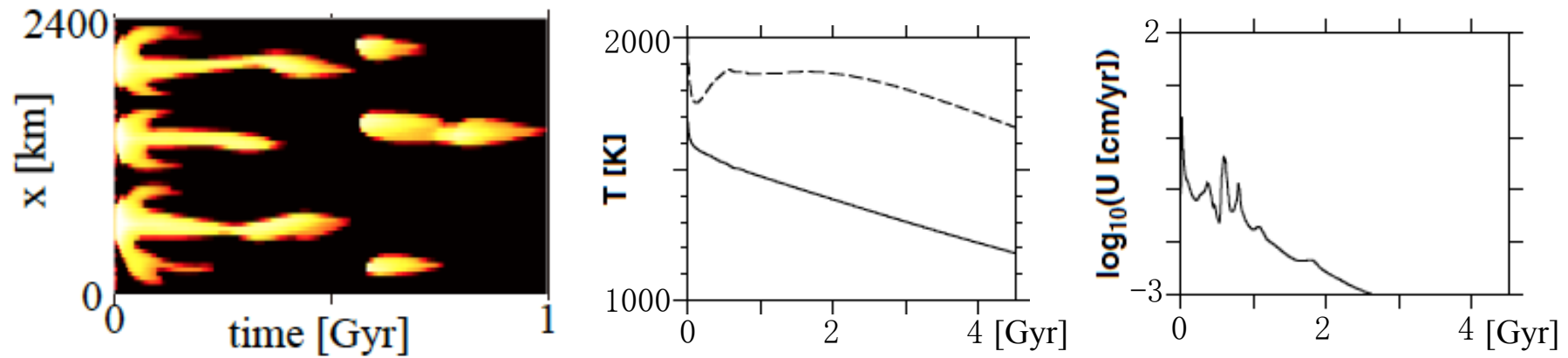


Interior evolution



(Morota et al., 2011)

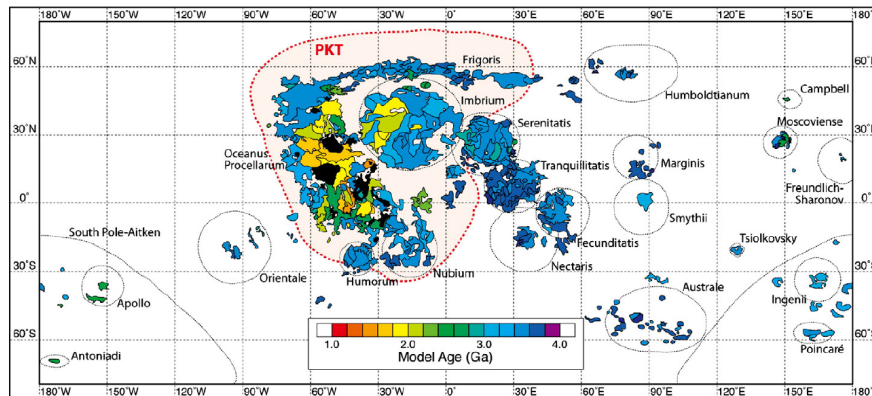
A model of the lunar mantle evolution started from a hot and homogeneous state



## Features of the model

redistribution of HPEs to the crust ➡ ephemeral magmatism  
the heterogeneous uppermost mantle  
substantial cooling of the mantle ➡ a large thermal contraction

localized and long-lasting lunar magmatism

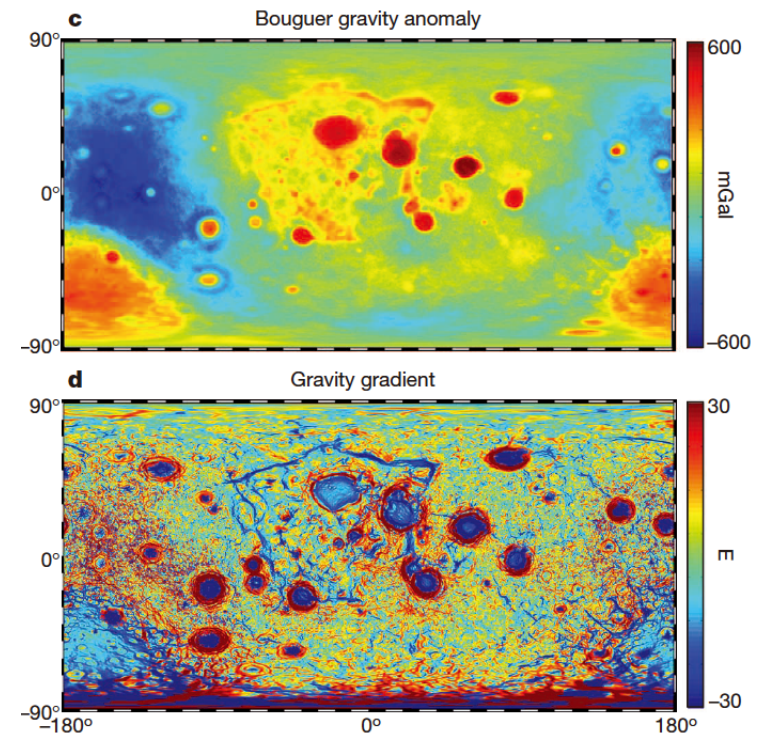


(Morota et al., 2011)

gravity field



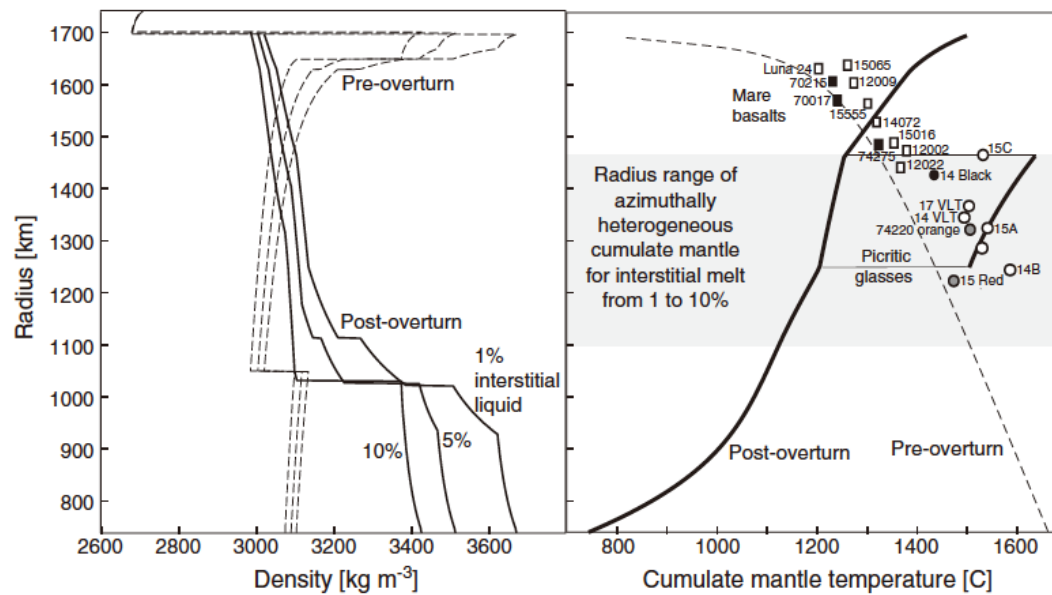
expansion and then contraction  
the rather homogeneous uppermost mantle



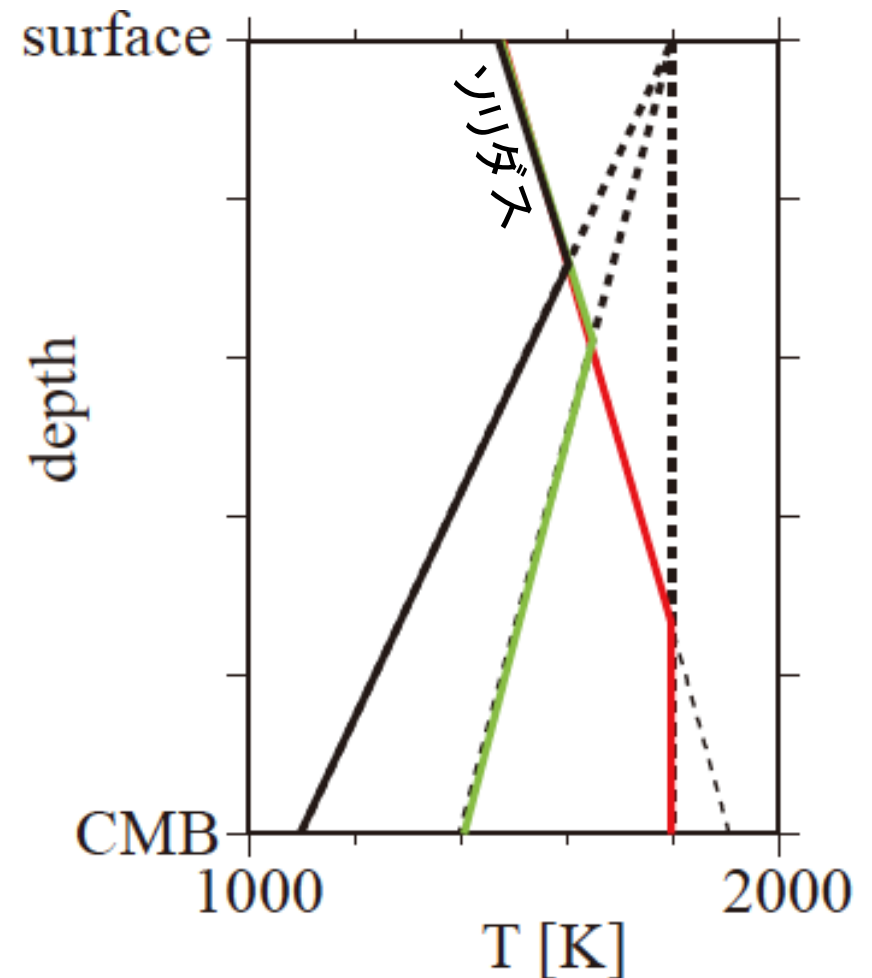
Andrew-Hanna et al., 2014

# The dependence of mantle evolution on its initial condition

The magma ocean and mantle overturn ➡ initially rather cold mantle?



(Elkins-Tanton et al., 2011)



the initial condition = low T in the deep mantle; a model of PKT; homogeneous



localized and long-lasting magmatism: early thermal expansion of the planet;  
the rather homogenous uppermost mantle

# The dependence of thermal and magmatic history on the initial condition

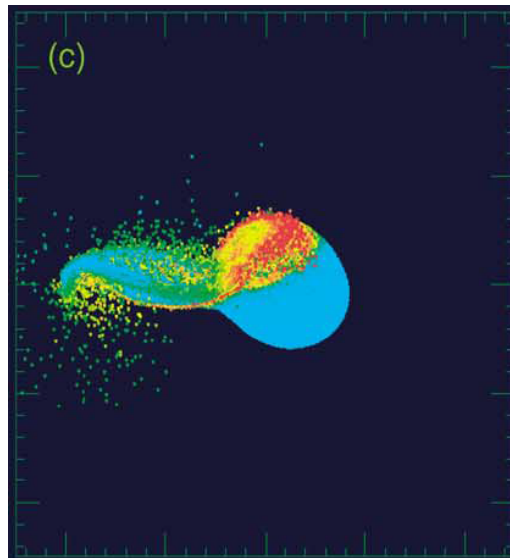
The effect of initial layering of the mantle  
widespread magmatism that is rather ephemeral



The initial condition that leads to a realistic thermal and magmatic history  
a cold and compositionally homogeneous mantle

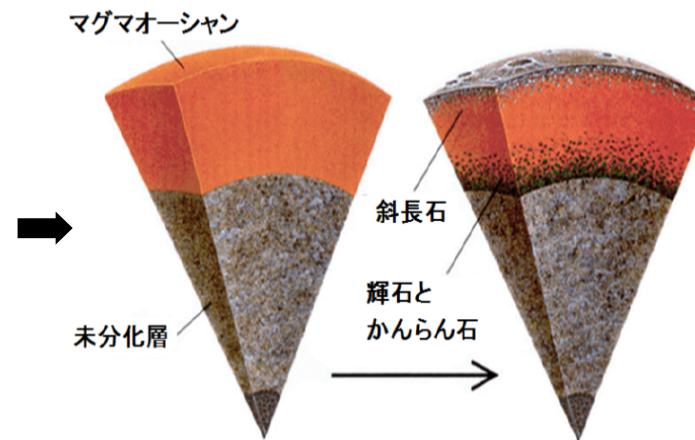
↑  
consistent?  
↓

giant impact



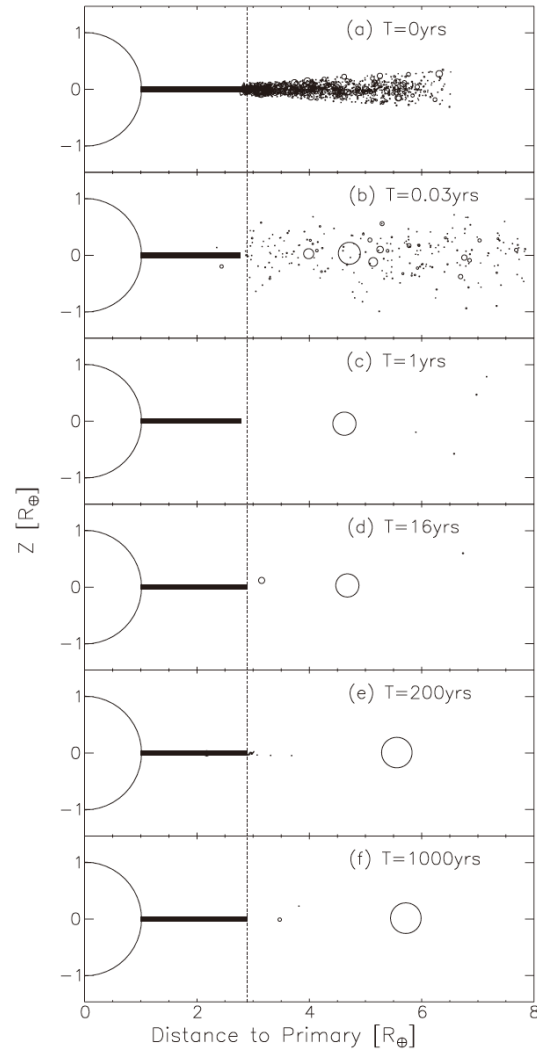
(Canup, 2012)

the deep magma ocean

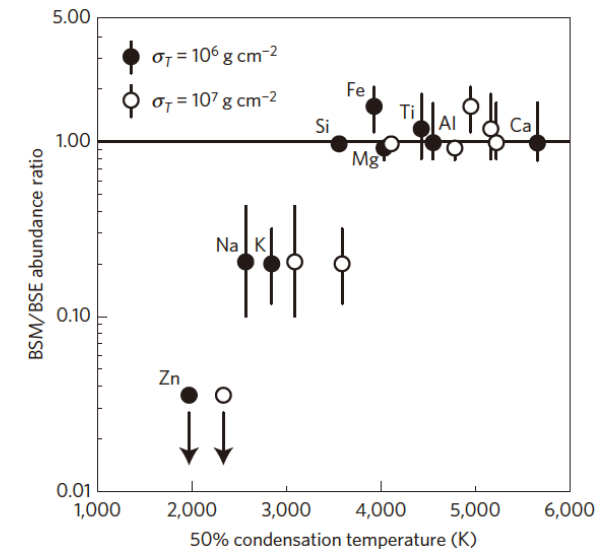
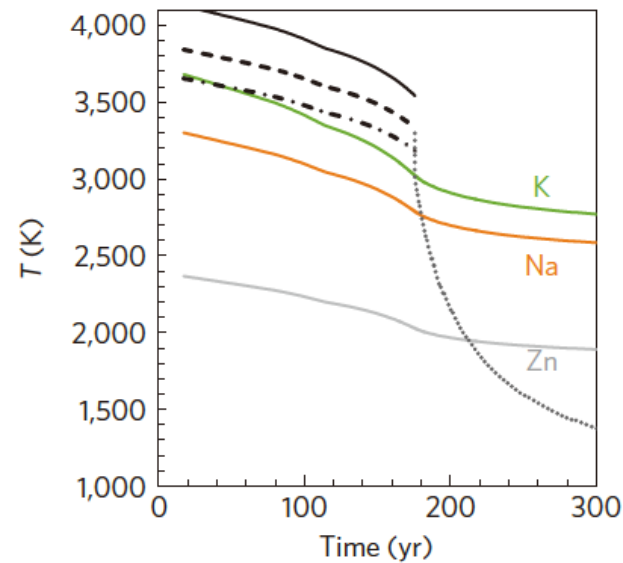
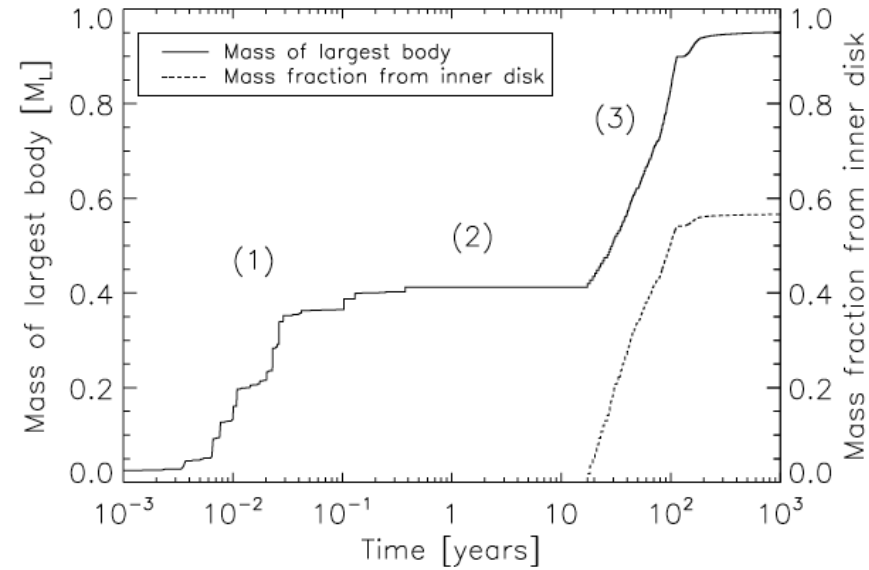


(Taylor, 1994)

# A recent giant impact model



(Salmon & Canup, 2012)

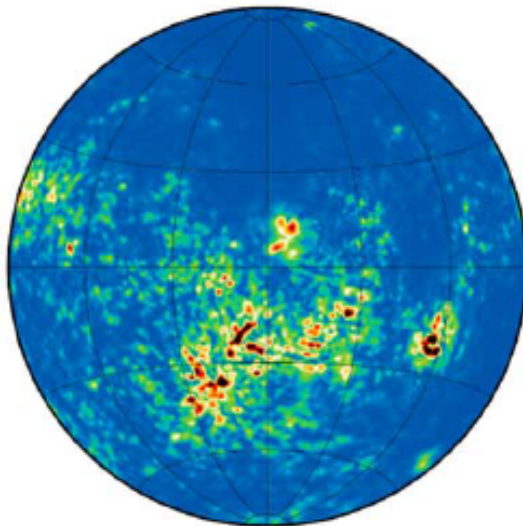


(Canup et al., 2015)

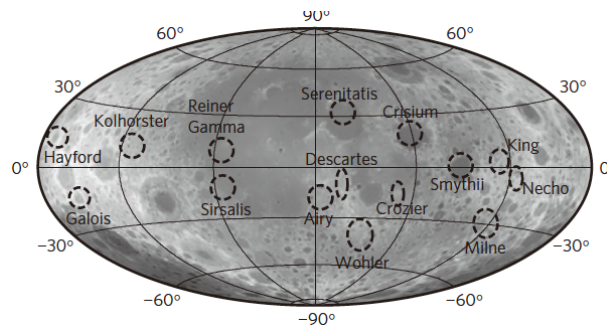
# Heating up of the early mantle

↑  
consistent?  
↓

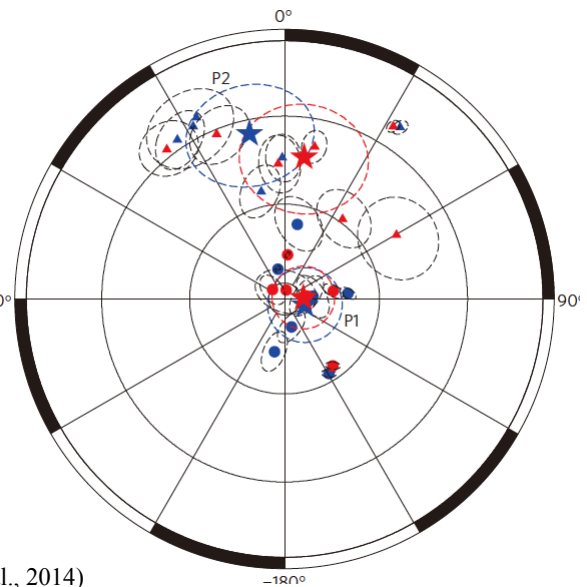
# the core dynamo of the Moon



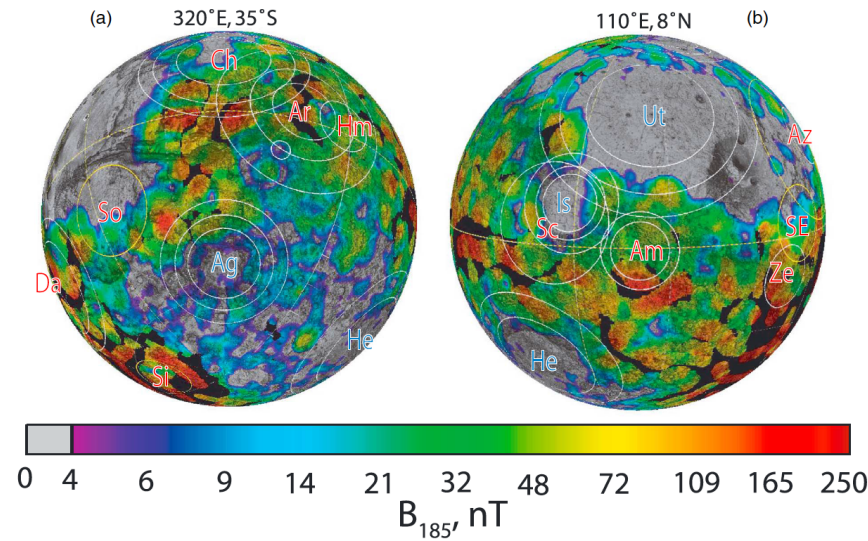
(Tsunakawa et al., 2015)



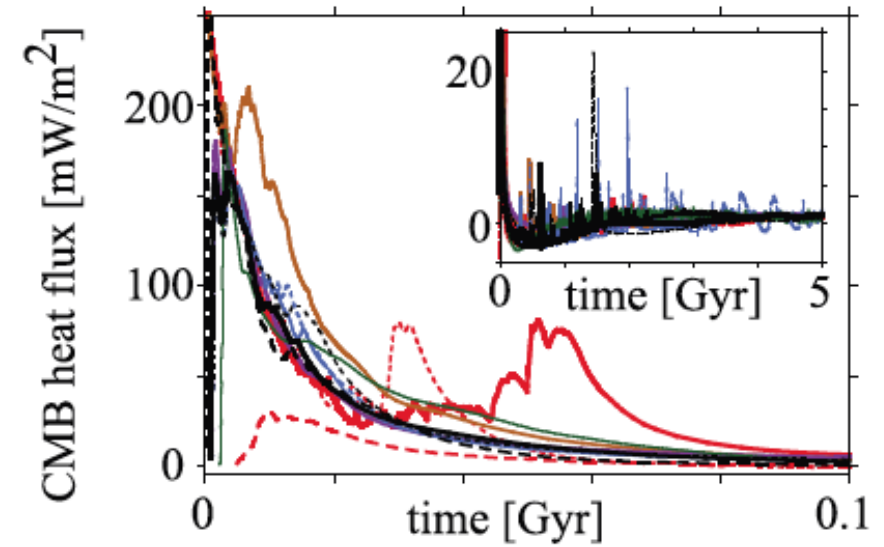
(Takahashi et al., 2014)



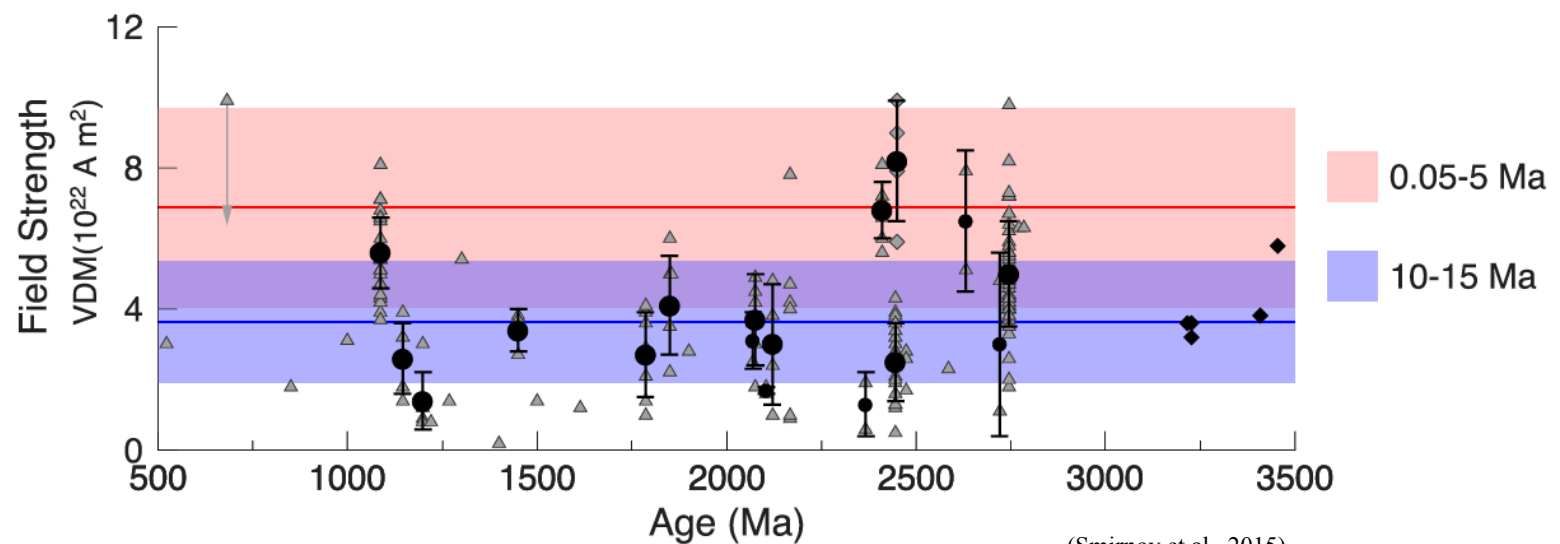
# Implications for Martian and terrestrial dynamo



(Lillis et al., 2013)

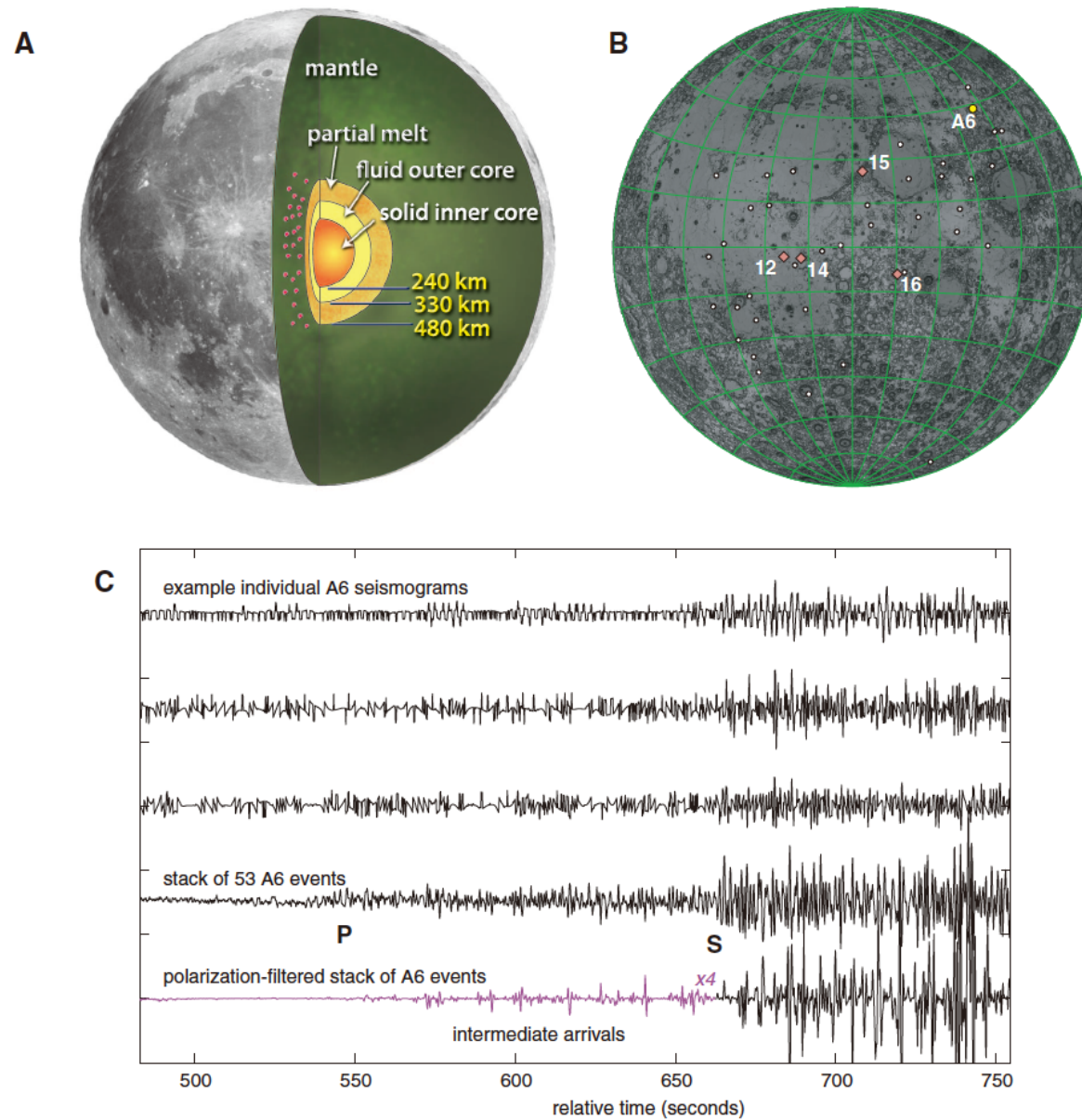


(Ogawa & Yanagisawa, 2011)



(Smirnov et al., 2015)

# the core in the Moon?



(Weber et al., 2011)

# Toward a comprehensive understanding of the Moon from its formation to the present state

## Was the early mantle rather cold?

observational constraints needed: [seismic and magnetotelluric studies](#)

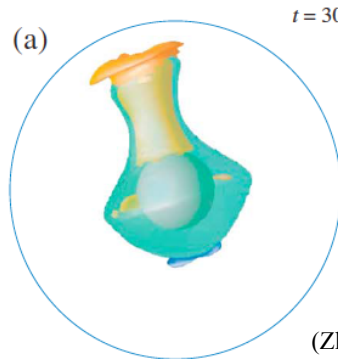
(1) the presence of the core > the meaning of the remanent magnetic field > thermal history

(2) the interior structure of the mantle

Crystal fractionation in the magma ocean or by the later magmatism?

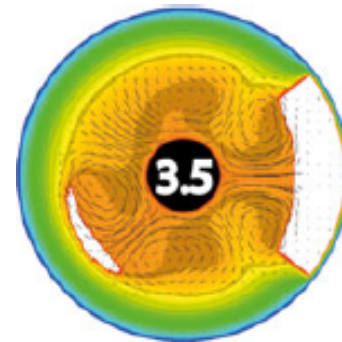


Implications for the Procerallum KREEP terrane



(Zhang et al., 2013)

difficult?



(Laneuville et al., 2013)

consistency with the lunar mare volcanism?