

Imperfect Equilibration of Hf-W System by Giant Impacts

Takanori Sasaki and Yutaka Abe

Department of Earth and Planetary Science, University of Tokyo

ABSTRACT

Hf-W chronometry provides constraints on the timing of planetary accretion and differentiation. In previous studies, it was assumed that a giant impact would perfectly reset the Hf-W chronometer. In this study, we showed the difficulty of achieving perfect equilibration of the Hf-W system by means of giant impacts. When the equilibration is imperfect, the collision conditions and the number of giant impacts must be known in order to estimate the age of core formation of the Earth.

1. INTRODUCTION

Hf-W Chronometry

- $^{182}\text{Hf} \rightarrow ^{182}\text{W}$ (half-life $\sim 9\text{My}$)
- Hf, W: both refractory element
- Hf: lithophile, W: siderophile

Hf-W system is an ideal chronometer for tracing metal/silicate segregation events such as core formation of the Earth!

Previous Studies

- Lee and Halliday 1995: Core formation event $\sim 62\text{ My}$ after iron meteorite formation
 - Yin et al. 2002, Kleine et al. 2002: Revised data $\rightarrow \sim 29\text{ My}$ after iron meteorite formation
- In these studies, a giant impact was assumed to reset the Hf-W chronometer perfectly.

Purpose of This Study

"Whether the perfect equilibration between silicate and metal by means of giant impacts?"

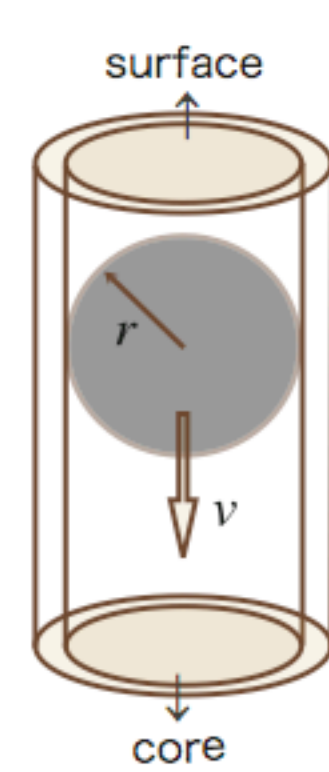
We consider several situations as consequences of giant impacts to examine this question.

2. REQUIRED CONDITION TO ACHIEVE PERFECT EQUILIBRATION

Achievable Resetting Ratio

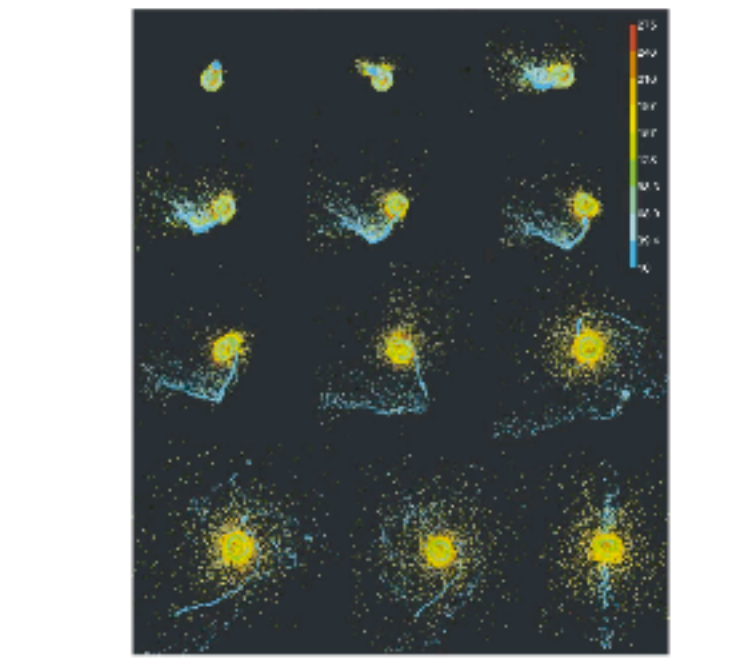
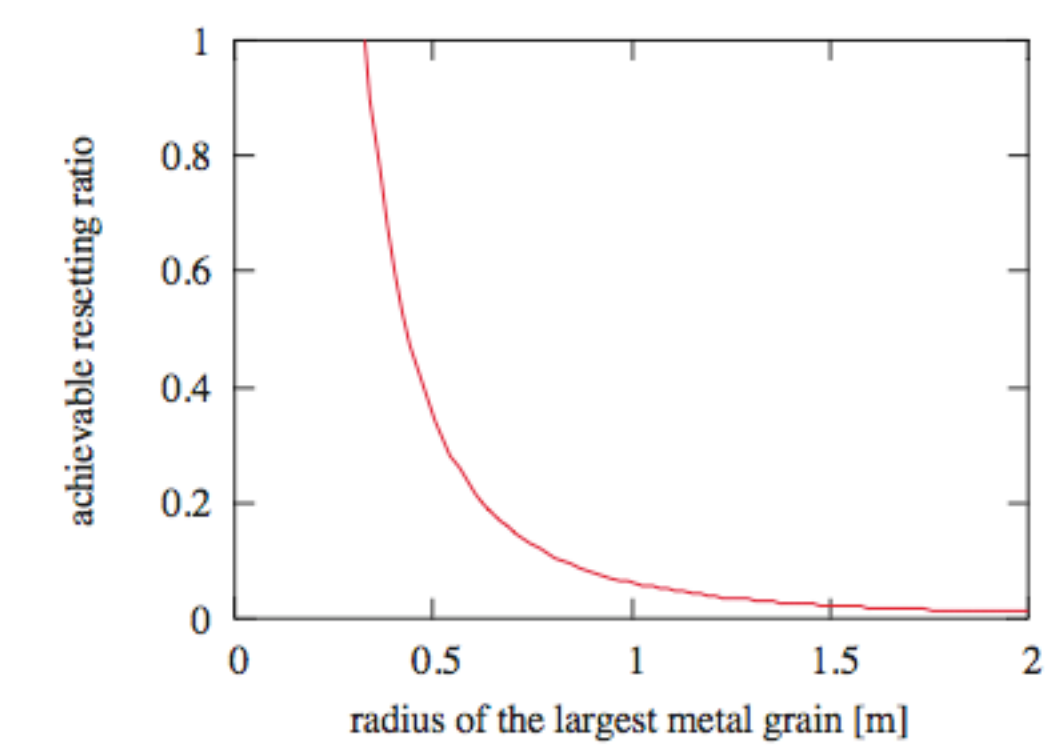
Equilibration of Hf-W system takes place through the diffusion of W in the sinking metal droplets into the silicate melt.

Degree of equilibration of Hf-W system in the mantle = Total volume where metal droplets go through



$$V_{\text{reset}} = \int_{r_{\text{min}}}^{r_{\text{max}}} 2\pi r \cdot \sqrt{\kappa\tau} \cdot H dr, \quad \tau = \frac{2r}{v}$$

- κ : diffusivity of W in the silicate melt = 10^{-8}
- v : Stokes velocity of a metal droplet
- $\Delta\rho$: density difference (metal - silicate) = 8×10^3
- η : viscosity of silicate melt = 10^{-2}



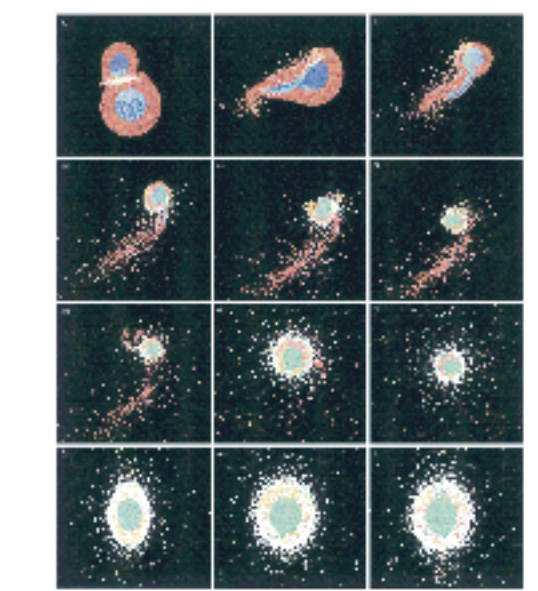
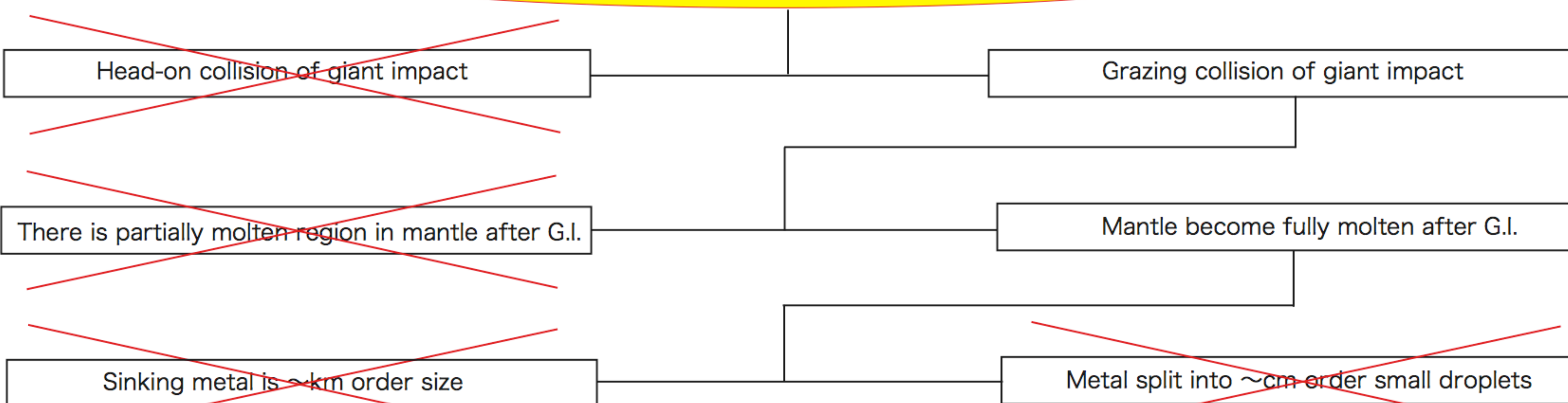
[Canup and Asphaug, 2001]

Size distribution of metal droplets from the impactor are given by a power law ($b=1$).

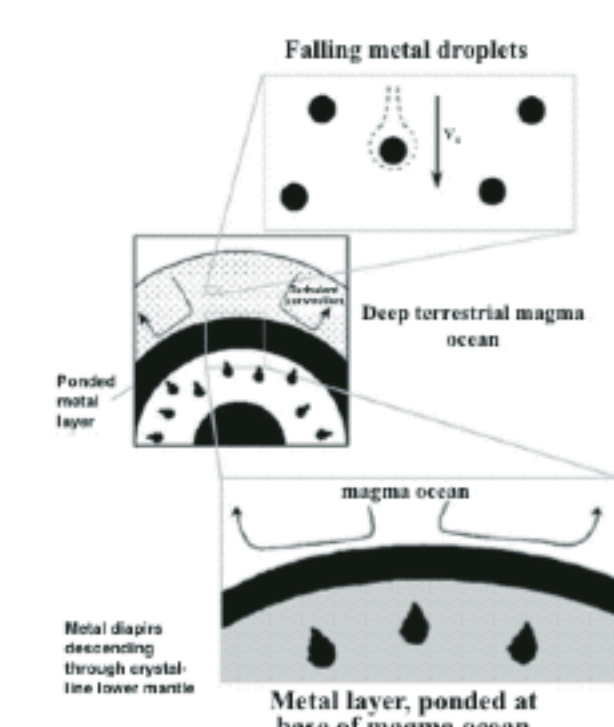
\rightarrow Radius should be $\leq 50\text{cm}$ for perfect equilibration.

SPH simulations do not have enough resolutions

Perfect Equilibration of Hf-W System can occur?



Impactor core breaks into pieces, then these debris accrete onto the surface of protoearth. [Cameron 1997]



If metal can break into small droplets in molten mantle, and the droplets sink through the mantle like "rainfall droplets", there is chance of perfect equilibration? [Rubie et al. 2003]

3. RAYLEIGH-TAYLOR INSTABILITY OF MIXTURE LAYER

Timescale Comparison

There is a possibility of the Rayleigh-Taylor instability between metal-silicate mixture layer and metal-free silicate melt layer.

[Kobayashi et al. 1993]

- Timescale for an iron sphere to sink a distance of H by Stokes sedimentation

$$\tau_s = \frac{9\eta H}{2\Delta\rho_s g r^2}$$

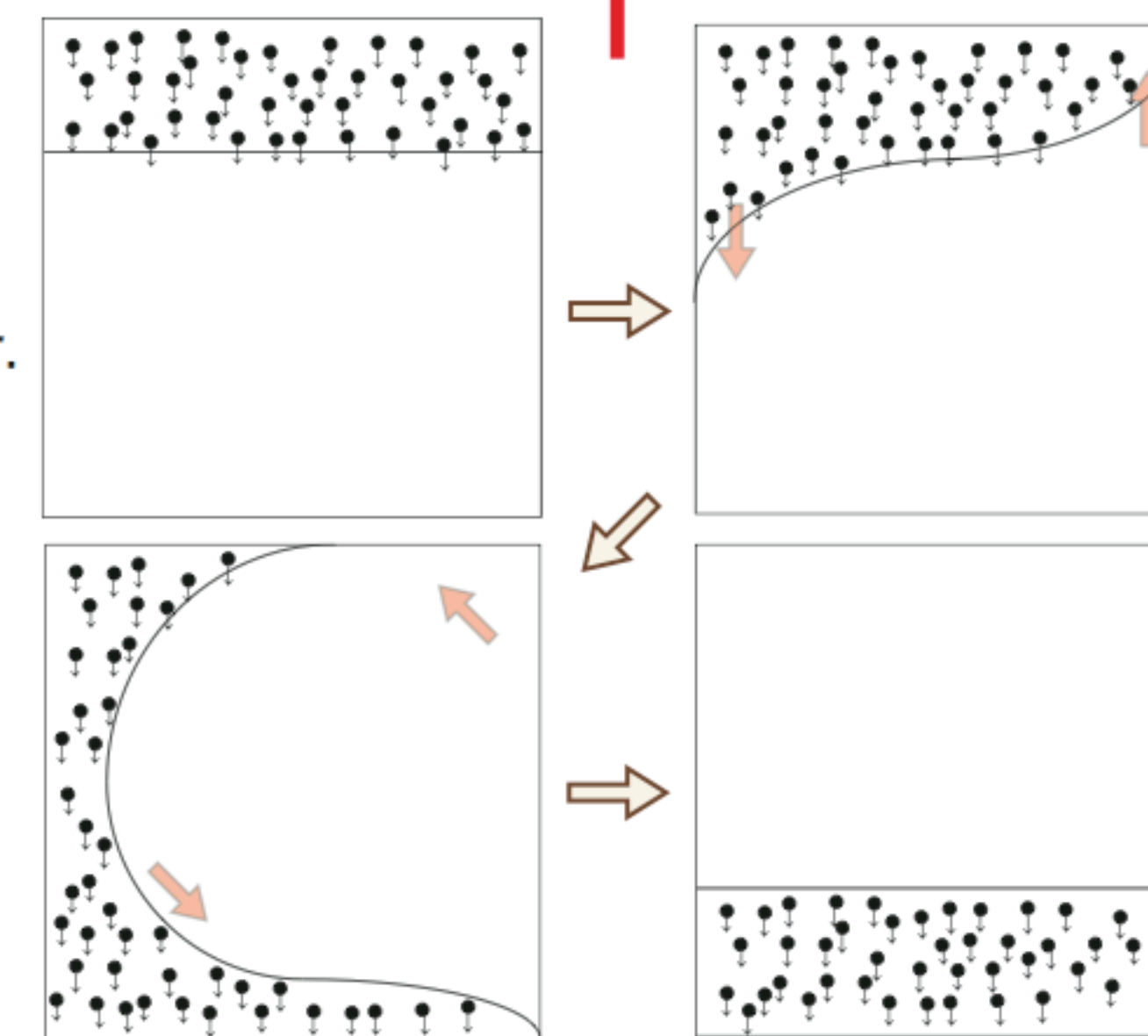
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- Growth timescale of the fastest growing disturbance of R-T instability for mixture layer with thickness H/2

$$\tau_{rt} = \frac{13.04\eta}{\Delta\rho_m g H/2}$$

Accreted mixture (metal + silicate) is separated into silicate and $\sim\text{cm}$ scale metal droplets, then these droplets sink in metal-silicate mixture layer.

Once the Rayleigh-Taylor instability has grown, the mixture layer sink into the bottom of mantle as a cluster, thus the mixture layer and silicate melt layer overturn immediately.



The Rayleigh-Taylor instability between metal-silicate mixture layer and metal-free silicate melt layer occurs immediately.

Metal droplets in mixture layer cannot interact with silicate outside the mixture layer.

Thus, there would exist two regions in mantle (equilibrated and non-equilibrated region)

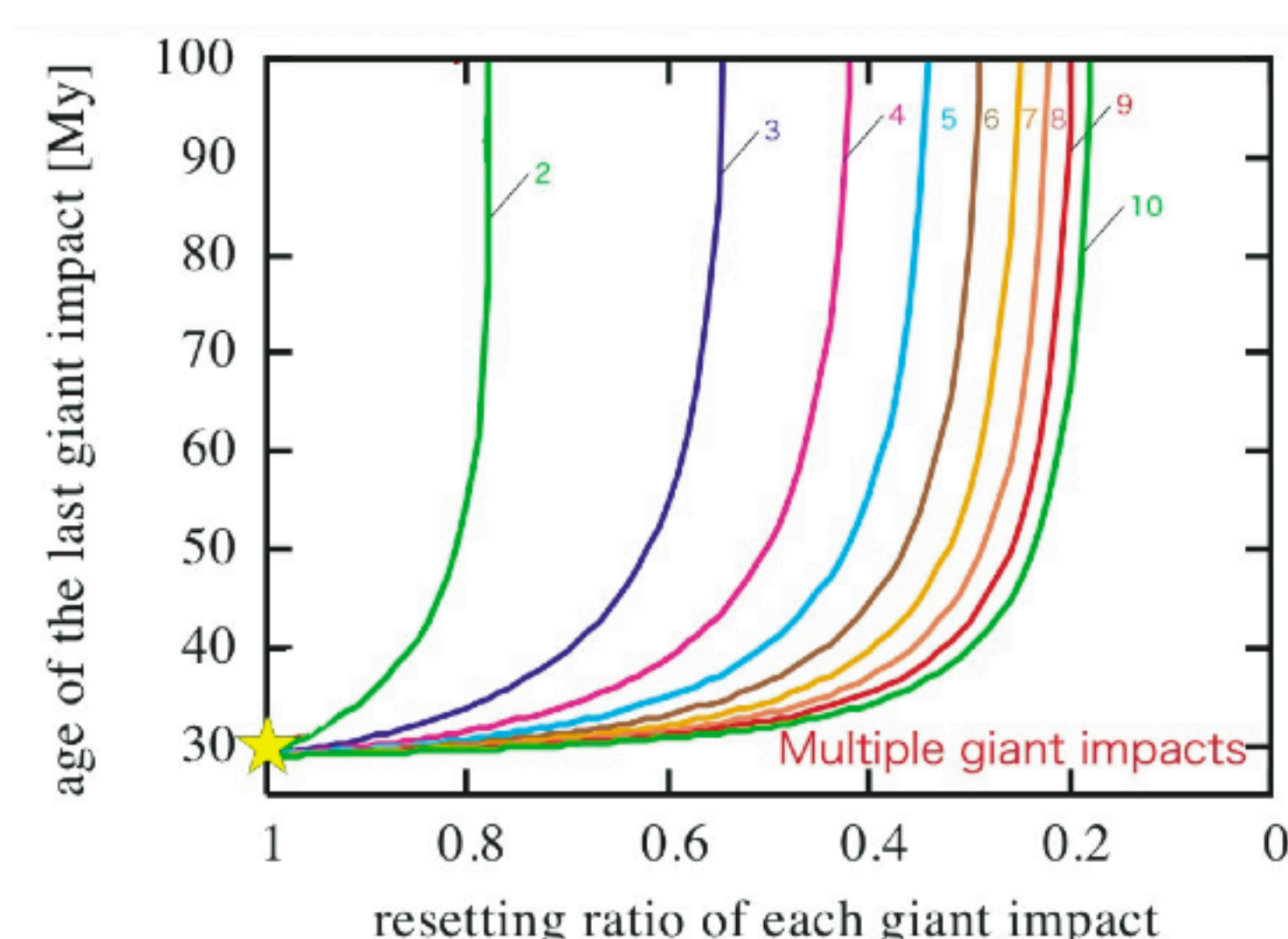
4. CONSEQUENCES OF IMPERFECT EQUILIBRATION

Isotopic Evolution of Hf-W System

We calculated isotopic evolution taking into account the partial resetting of Hf-W chronometer by giant impacts.

Results

- Collision conditions and the number of giant impacts heavily affect the age estimation of core formation event.
- Earth W isotope ratio indicates that more than 2/10 of the volume of the protocore mantle must have been equilibrated at each giant impact.



5. IMPLICATIONS

High Pressure Equilibrium for Siderophile Elements

Rayleigh-Taylor instability and the Stokes sedimentation of the mixture layer are very vast, equilibration between metal droplets and silicate mantle scarcely occur till the mixture layer settle down, i.e. metal-silicate equilibration is expected to occur under high pressure at the base of the molten mantle.

\rightarrow consistent with a high pressure metal-silicate equilibrium for moderately siderophile elements.

[e.g. Righter et al. 1997]

Inversely, required conditions for present observed abundances of moderately siderophile could provide some constraints of equilibration ratio by each G.I.

\rightarrow could provide some constraints of age estimation by Hf-W system?

