The Effect of Partial Resetting on Hf-W System by Giant Impacts

Takanori SASAKI & Yutaka ABE

Department of Earth & Planetary Science, Graduate School of Science, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

takanori@sys.eps.s.u-tokyo.ac.jp

ABSTRACT

Hf-W chronometry provides some constraints on the timing of planetary accretion and differentiation, as segregation of a metal core from silicates should induce strong fractionation of hafnium from tungsten. In previous studies, it was assumed a giant impact raise up perfect resetting on Hf-W chronometer. We considered the effect of partial resetting on Hf-W system in this study. We also estimated the degree of achievable resetting by giant impacts. Our study provided us two important results: (1) we cannot determine the age of a giant impact or the metal-silicate separation with Hf-W chronometry before quantitative assesment of equilibration at giant impacts and (2) achieving large resetting ratio by giant impact or other equilibrating events is not so easy.

Subject headings: planets and satellites: formation—planets and satellites: general

1. Introduction

Hafnium and tungsten are both highly refractory elements, and hafnium is a lithophile element whereas tungsten is a moderately siderophile element that should strongly partitioned into metal phases during metal/silicate segregation. The Moon may have formed from debris created by a giant impactor that hit the Earth with a glancing blow, after terrestrial core formation. The decay of now extinct ^{182}Hf (half-life, 9Myr) to ^{182}W is an ideal chronometer for tracing this process, because Hf is retained in the silicate mantle while W is largely partitioned into the core during core segregation (Halliday et al. 1996; Lee et al. 1997).

It has been argued that the age of terrestrial core formation was limited by accretion time, that it started very early, and that it was largely completed within the first 10-20 Myr or less of Earth history (Jacobsen & Harper 1996; Lee & Halliday 1995, 1996). And recently, according to the new results of measurements of W isotope compositions and Hf/W ratios of several meteorites, it shows that the main growth stage for the Earth is largely completed in 10 Myr, and the Moon-forming giant impact is dated at 29 Myr (Kleine et al. 2002; Yin et al. 2002). However, they applied only magma ocean model and two-stage model. Magma ocean model considers exponentially decreasing rates of accretion and the rate of core formation limited by the accretion rate, and two-stage model has strict time significance only in the case where there is complete equilibration between the core and the silicate mantle at a single point in time, with no subsequent additions of material to the Earth (Harper & Jacobsen 1996; Jacobsen 1998). They assumed that a single giant impact could give rise to this perfect resetting on Hf-W chronometer.

In this paper, we consider the effect of partial resetting on Hf-W system by multiple giant impacts. We show limit of the age estimation by Hf-W chronometry, and on the other hand, possibility to constrain the required resetting ratio by giant impacts or other equilibrating events.

2. Basic Equations

We reference the ^{182}W abundance to ^{183}W as ^{182}W/^{183}W, using the conventional CHondritic Uniform Reservoir (CHUR) -normalized ϵ-unit notation. This is defined for a sample for reservoir j

by

$$\epsilon^{j}_{182W} = \left[\frac{(^{182}W/^{183}W)_j}{(^{182}W/^{183}W)_{CHUR}} - 1\right] \cdot 10^4 \qquad (1)$$

The simplest model of fractionation is a two-stage model with a single episode of core formation at an age $t = \tau$ occurring sometime after the origin of the solar system $t = T_0$ (Harper & Jacobsen 1996). The isotopic time evolution of j is given by

$$\epsilon(t) = Q \cdot f_j \cdot \left(\frac{^{182}Hf}{^{180}Hf}\right)_{T_0} \cdot \left[e^{-\lambda_{182}\tau} - e^{-\lambda_{182}t}\right] \quad (2)$$

In the above equations λ_{182} is the ^{182}Hf decay constant (0.077 Myr $^{-1}$), and $Q = 1.55 \times 10^4$, and the Hf/W fractionation in reservoir j is defined relative to CHUR by f-values:

$$f_j = \frac{(^{180}Hf/^{183}W)_j}{(^{180}Hf/^{183}W)_{CHUR}} - 1 \qquad (3)$$

Our preferred values are $f_j = 12$ and $\left(\frac{^{182}Hf}{^{180}Hf}\right)_{T_0} = 1 \times 10^{-4}$ (Yin et al. 2002).

3. Partial Resetting on Hf-W Chronometer

Recent works on planetary formation show that several tens of Mars-sized protoplanets are formed through a successive accretion of planetesimals in the terrestrial planet region (Kokubo & Ida 1998; Wetherill & Stewart 1989). Then we consider two different stages: (1) protoplanets formation stage and (2) giant impacts stage.

3.1. Protoplanet Formation Stage

Through each planetesimals impacts, certain part of target body is equilibrated and the ϵ of this part is reset to initial value. After n-times planetesimals impacts, the expression for the isotopic effect from this process is given by

$$\epsilon_{n+1} = k \cdot \frac{dV}{V} \cdot \epsilon(t) + (1 - k \cdot \frac{dV}{V}) \cdot \epsilon_n \qquad (4)$$

where V is the mass of target body, dV is the mass of each planetesimal, and $\epsilon(t)$ is given by Eqn(2). A degree of the equilibration by a planetesimal impact, k, is the parameter in this model. We iterate this calculation a hundred million times.

3.2. Giant Impacts Stage

Each giant impacts make the target body equilibrate partially and partial reset its chronometer, then the ϵ of the protoplanet is given by

$$\epsilon_{n+1} = p \cdot \epsilon(t) + (1 - p) \cdot \epsilon_n \qquad (5)$$

A value for the partial resetting ratio, p, and the number of giant impacts, n, are the parameter in this model. We assume the first giant impact occurred at 10 Myr, then subsequent giant impacts occurred at even intervals.

In this study, we estimate the required resetting ratio p for Earth's observational data ($\epsilon = 2$, Yin et al. (2002)) with Eqn(5) inversely.

4. Results

A plot of ϵ versus the protoplanet formation age is shown in Fig.1, the degree of the equilibration, k, is 0.1 to 10. This results in ϵ at 10 Myr of 10-12, substantially larger than the observed value of SNC meteorites ($\epsilon \simeq 4$) that are widely considered to be from Mars (Lee & Halliday 1997; Yin et al. 2002).

A required resetting ratio to achieve ϵ value of the bulk silicate Earth versus the Earth formation age is shown in Fig.2, the number of giant impacts, n, is 2 to 10. It shows that the Earth formation age depends on the partial resetting ratio and the number of giant impacts; therefore, we cannot determine the giant impact age or the metal-silicate separation age with Hf-W chronometry. On the other hand, this result indicates that the resetting ratio of each giant impact is required to be greater than 0.2.

5. Discussions

In the early stage of planetary accretion, runaway growth of planetesimals results in forming protoplanets in several million years (Kokubo & Ida 1998; Wetherill & Stewart 1989). Mars is considered a protoplanet left intact after Earth-formation stage unaffected by giant impacts in the standard scenario of planetary formation . Therefore, assuming SNC meteorites represent bulk silicate Mars, the result of Fig.1 requires that Mars must be experienced certain equilibrating event after formation of protoplanets. We estimate required resetting ratio of this event for SNC me-

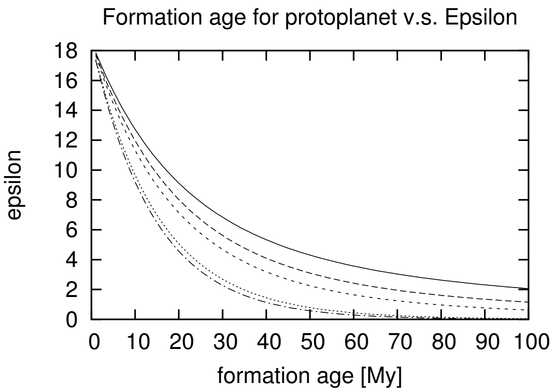

Fig. 1.— Isotopic evolution of ϵ as a function of protoplanet formation age. Parameter k (Eqn(4)) is 0.1, 0.5, 1, 5, 10 from top to bottom.

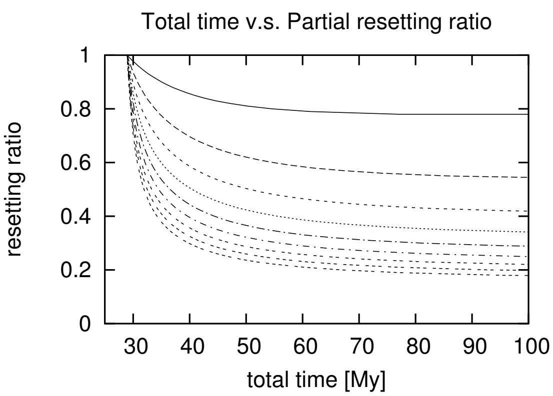

Fig. 2.— Required resetting ratio for observed value of Earth's samples as a function of Earth formation age. The number of giant impacts is 2 to 10 from top to bottom. Initial state is $\epsilon = 8$ and $t = 10$. Total time for perfect resetting (resetting ratio = 1) is about 30 Myr, corresponds to previous study (Yin et al. 2002).

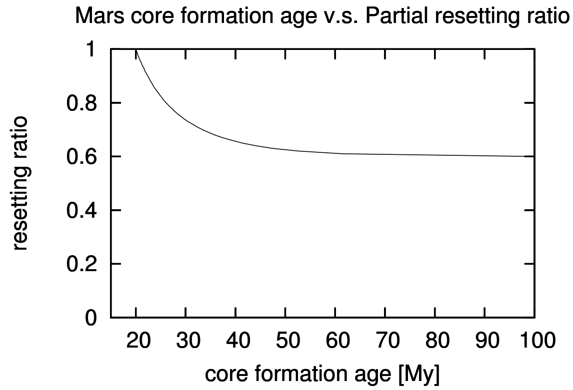

Fig. 3.— Required resetting ratio for SNC meteorites' data as a function of Mars core formation age. This result is estimated to achieve average epsilon value of SNC meteorites, $\epsilon = 4$.

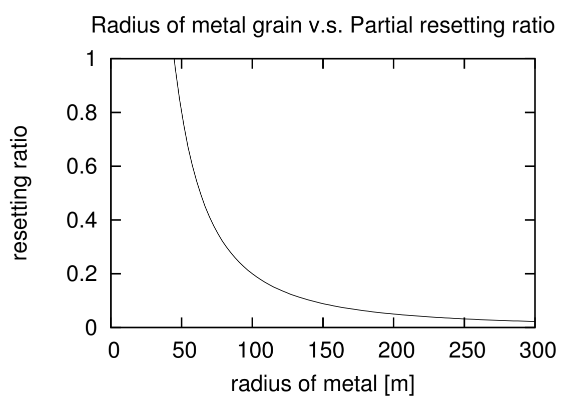

Fig. 4.— Achieved resetting ratio by giant impact as a function of a radius of fragmented metals. It is assumed a metal of impactor break into small metals of the same size.

teorites' ϵ (Fig.3). This result requires resetting ratio of equilibrating event on Mars is 0.6 or more.

It is necessary that resetting ratio of each giant impacts is more than 0.2, and Mars should be experienced equilibrating event that resetting ratio is more than 0.6. Then next, we estimate actually achieved resetting ratio by giant impacts or other any equilibrating events.

Primarily, in the stage of planetary accretion, metal of impactor and silicate of target are equilibrated each other, then Hf-W chronometer of this equilibrated region is reset. This resetting continues during the metal sink in the silicate to reach the core of target body. We assume metal of impactor split into lots of metal sphere grains with radius r sinking in a silicate melt at a velocity following from Stokes sedimentation equation:

$$v = \frac{2\Delta\rho g r^2}{9\eta} \tag{6}$$

where $\Delta\rho$ is difference in density between silicate melt and metal, g is gravitational acceleration, and η is viscosity of silicate melt. The typical values are $\Delta\rho = 8\cdot 10^3$ kg/m^3 and $\eta = 10^{10}$ ms/kg. Then we can estimate the volume reset its chronometer by diffusion of silicate melt into metal during sinking:

$$V_{reset} = 2\pi r\sqrt{\kappa\tau}Hn, \qquad \tau = \frac{2r}{v} \tag{7}$$

where κ is diffusivity of silicate melt ($\simeq 10^{-20}$), H is a radius of target body, and n is a number of metal grains. Achieved resetting ratio is estimated through the volume of target add the volume of impactor divided by V_{reset} (Fig.4).

Fig.4 shows the radius of metal sphere grains must be less than 100 meter to yield 0.2 resetting ratio. This result seems to be hard to be realized considering the size of impactor's core that is about 10^{10} km^3. And so, 0.6 resetting ratio required for Mars equilibrating event would be even harder.

6. Conclusion

We consider the effect of partial resetting on Hf-W chronometry, and show this chronometer cannot determine the age of melt-silicate separation precisely and achieving large resetting ratio is not so easy by giant impact or other. To determine the age of core formation of Earth by Hf-W chronometry, we should determine the number and the resetting ratio of each giant impacts, and to achieve the high resetting ratio of Mars (= 0.6), we should reexamine the theory of planetary formation or introduce certain drastic events for Mars.

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