IMPERFECT EQUILIBRATION OF HF-W SYSTEM BY GIANT IMPACTS. T. Sasaki[1] and Y. Abe[1], [1]Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan, takanori@eps.s.u-tokyo.ac.jp

Introduction: Hf-W chronometry provides constraints on the timing of planetary accretion and differentiation, as segregation of a metal core from silicates should induce strong fractionation of Hf from W. The decay of now extinct ^{182}Hf (half-life, 9Myr) to ^{182}W is an ideal chronometer for tracing core formation events, because Hf is retained in the silicate mantle while W is largely partitioned into the core during core segregation [1]. In many previous studies, it was assumed that a giant impact raise up perfect resetting on Hf-W chronometer [3, 4]. On the other hand, there are some studies that considered the effect of imperfect equilibration of Hf-W chronometer [4, 5]. These studies suggest that we cannot determine the age of a giant impact or the age of a metal-silicate separation with Hf-W chronometry before quantitative assessment of equilibration at giant impacts. In this study, we show the difficulty of achieving perfect equilibration of Hf-W system by giant impacts.

Mechanism of Imperfect Equilibration: The giant impact can make a global magma ocean on a protoearth, then it is frequently assumed that complete metal-silicate equilibration is realized by a giant impact. Rubie et al. [6] concluded that small metal droplets were formed and their settling through the magma ocean could achieve chemical equilibration between metal droplets and silicate liquid. In this study, however, we point out a difficulty of perfect equilibration of Hf-W system, even if small droplets are formed.

To achieve perfect equilibration of Hf-W system of mantle with metal added on the Earth's surface, this metal must split into small metal droplets and sink through the mantle with equilibrating the mantle around. If the equilibration of Hf-W system takes places through diffusion of W in the sinking metal droplets into the silicate melt, degree of equilibration of Hf-W system in the mantle depends on a total amount of surface area of metal droplets. The smaller each metal droplet is, the easier the mantle can be equilibrated.

In this study, we consider two situations as consequence of giant impacts: (1) two layers such as fully molten layer (upper layer) and partially molten layer (lower layer) are produced, and (2) entire mantle becomes fully molten.

(1) After a giant impact, if two layers (low viscosity upper layer and high viscosity lower layer) are formed, metal grains descend and deposit over the lower layer, and then fall through the lower layer as a big blob produced by the Rayleigh-Taylor instability between the metal layer and high viscosity lower silicate layer [7]. So, perfect equilibration of Hf-W system cannot be achieved.

(2) If all mantle is fully molten by a giant impact, and falling impactor's metal split into small droplets [6], these droplets descend through the molten mantle. Then, if metal-containing layer is mixed well between the mantle and metal droplets, this layer could be equilibrated completely. However, even in such a situation, the Rayleigh-Taylor instability between the metal-containing layer and metal-free layer causes the overturn of these two layers (Fig. 1). So, these droplets cannot continue to descend to the last like "rainfall droplets" and cannot equilibrate all mantle. Thus, though metal-containing layer can be equilibrated, metal-free layer cannot be equilibrated for Hf-W system. Therefore, complete metal-silicate equilibration by a giant impact cannot be expected in this case, too.

The perfect equilibration seems to possible only when the iron droplets are very small and are distributed in the entire mantle in the first place without making a metal-free layer. However, such situation seems to be possible under a very limited impact condition. Actually, SPH simulations generally showed that while some of the impactor's core may diffuse into the target's mantle, much of the impactor's core would be ejected and fall back to the Earth [8], so whole impactor's metal cannot distribute in the entire mantle initially.

Consequences of Imperfect Equilibration: We have previously calculated the isotopic evolution of Hf-W system in consideration of partial resetting of this chronometer [4]. Our study provided three implications: (1) collision conditions and the number of the giant impact events affect the age estimation of the core formation, (2) the Earth's W isotope ratio indicates that more than two-tenth of the volume of protoearth's mantle must be equilibrated at each giant impact, and (3) Mars should have experienced a late extensive equilibration event that involve metal-silicate more than three-tenth volume of Mars' mantle, which is potentially a single giant impact.

Discussions: Giant impacts would also bring about some effective consequences for metal-silicate equilibration such as partial vaporization of target's mantle and breaking not only impactor's core but also target's core. With very high temperature just after a giant impact, some part of target's upper layer of mantle could vaporize and mix with the impactor's metal effectively. So, such vaporizations would enhance the metal-silicate equilibration on the upper layer, however, the vaporization of the deep mantle unlikely because of very high pressure.

A giant impact could break target's core and distribute the iron droplets in the mantle. This droplets could equilibrate some part of the mantle, however, unless the iron droplets are evenly distributed in the while mantle, whole mantle cannot be equilibrated because of the Rayleigh-Taylor instability again. So, after all, perfect equilibration would occur under very limited conditions such as fully vaporization of target's mantle by a giant impact or distribution of breaking target's core to whole metal-free layer of the mantle.

On the other hand, after the Rayleigh-Taylor instability as shown in Fig. 1, the segregated mixture layer including liquid metal droplets are deposited at the base of the molten mantle. Because the growth of the Rayleigh-Taylor instability and the Stokes sedimentation of the mixture layer are very fast, equilibrations between metal droplets and silicate mantle are scarcely occurred 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. Each giant impact brings about the overturn of molten mantle, then multiple giant impacts could mix round the molten mantle many times. Unlike tungsten, other siderophile elements were not produced by a decay of other elements. So, almost all siderophile elements except W in the mantle are removed into the core through the multiple giant impacts with equilibrations under high pressure at the base of the molten mantle. Thus, our result is consistent with a high pressure and temperature equilibrium between metal and silicate for moderately siderophile elements in a magma ocean scenario [9].

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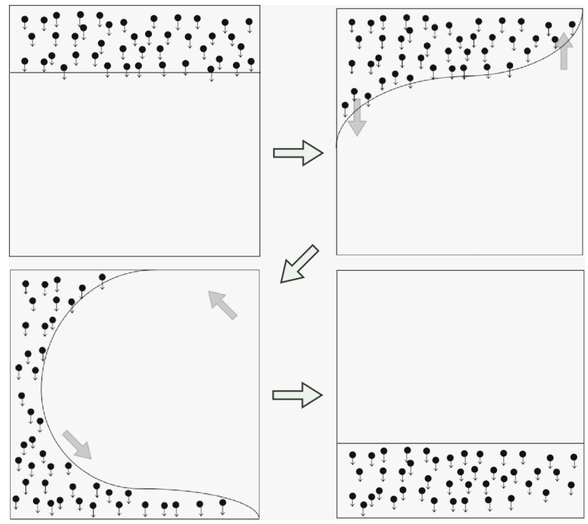

Fig. 1 Sketch of metal droplets' behavior in the silicate melt layer, which is supposed to be fully molten. After a giant impact, the ejecta and broken impactor are mixed each other and accrete to the protoearh as a mixture. Accreted mixture is separated into silicate and centimeter-scale metal droplets, then these droplets sink in well mixed metal-silicate layer (first sketch). If these droplets is small enough to achieve perfect equilibration, the layer that holds small metal droplets, upper layer in first sketch, is equilibrated of Hf-W system. Then next, the Rayleigh-Taylor instability between the silicate melt layer with metal droplets and that of metal free occurs immediately because the growth of the Rayleigh-Taylor instability is by far faster than the Stokes sedimentation of metal droplets (second sketch). Once the Rayleigh-Taylor instability has grown, the layer with metal droplets sink into the core as a cluster, thus the equilibrated layer and non-equilibrated layer overturn immediately (third sketch). On this occasion, metal droplets in mixture layer cannot interact with silicate outside the cluster. Thus, there exist two regions in the mantle such as equilibrated region (last sketch, lower layer) and non-equilibrated region (last sketch, upper layer).