CORE FORMATION CONDITION THAT SATISFIES THE Ni ABUNDANCE AND W ISOTOPIC RATIO.

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Introduction: Core-mantle differentiation is one of the most dramatic events in the Earth's history. As a result of core formation, the Earth's mantle is depleted in siderophile elements. Amounts of siderophile elements retained in the mantle give important clues for estimation of core formation condition.

It is well known that the observed mantle abundance of Ni is larger than that predicted from low-pressure partitioning experiments [1]. Recent high-pressure experimental studies show that the high-pressure partitioning can resolve this problem. It is proposed that the observed Ni abundance is consistent with the equilibration of mantle with iron at 43-59 GPa (e.g., [2]). In other words, the lowermost part of the mantle is not equilibrated with iron.

Hf-W chronometer is used to determine the age of core formation. Hafnium and tungsten are both highly refractory elements; hafnium is a lithophile element, whereas tungsten is a moderately siderophile element. Assuming the complete equilibration between the mantle and iron at the last giant impact, Yin et al. [3] estimated the age of core formation at 30 Myr after the formation of iron meteorites. However, as noted before, mantle abundance of Ni suggests relatively shallow magma ocean, which is apparently inconsistent with the assumption adopted in the Hf-W chronometry. Moreover, recent planetary formation suggests multiple occurrences of giant impacts [4, 5].

Here, we consider the effect of multiple giant impacts and investigate core formation condition and timing that satisfies both of the element abundance (Ni) and W isotope composition.

Assumptions and model: We consider the two different stages: the protoplanet formation stage and the giant impact stage. In the protoplanet formation stage, we assume that the whole mantle of the protoplanet is molten (= magma ocean) and therefore accreting material completely equilibrates with the mantle. In the magma ocean, iron was divided into small droplets and their settling can achieve chemical equilibration between iron and molten silicate [6]. In the giant impact stage, we assume that a part of the target's mantle melts by each impact and equilibrates with iron in the impactor. In this stage we consider the possibility that only some fraction of impactor's core and target's mantle are involved in equilibration.

Numerical simulations: Here, we represented the condition of giant impacts by four parameters: a, b, n, and dt. Fraction a of the impactor's iron is equilibrated with the molten mantle, which is the mixture of the impactor's mantle and part of target's mantle with b times of the impactor's mass. n is the number of giant impacts. dt denotes the time interval between giant impacts. We define $n \times dt$ as the core formation age. The protoplanets are assumed to be formed in 1 Myr with mass $M_E/(n+1)$ (M_E is the mass of the present Earth). Linear growth in mass is assumed for protoplanets. The giant impact stage starts at 10 Myr and first impact occurs dt. Considering the equilibration in the magma ocean, we take into account the pressure dependence of distribution coefficient between iron and silicate. We extrapolate the experimental data for Ni distribution coefficient [7, 8]. For W, we adopt constant value 25, which is consistent with estimated Hf/W ratio of the mantle [9].

Results: Figure 1 shows the result of the Ni concentration for $n = 9$. The observed Ni concentration in the mantle is obtained when $b = 4.0$ with $a > 0.2$, or $b > 4.5$ with $a = 0.1$. This means that observed Ni concentration is satisfied by equilibration in the shallow magma ocean with wide range of a. When magma ocean is deep (large b), however, most of iron must directly enter the core without equilibrating with mantle silicate so that Ni content does not exceed the observed value.

Figure 2 shows the core formation age satisfying the observed W isotope ratio for $n = 9$. The estimated age increases with the decrease in a or b. We cannot obtain the value of the core formation age if a or b falls below a limit ($a \sim 0.4$, and $b \sim 0.5$). These indicates that at low equilibration rate (small a, or b), high isotope ratio in the target's mantle cannot be lowered by mixing with the impactor at each giant impact. Slow core formation lowers the isotopic ratio to the observed value by weakening the contribution of ^{182}Hf. At moderately low rate of equilibration ($a < 0.4$), however, isotopic ratio of the target's mantle remains higher than the observed value in spite of considering the slow core formation.

These trends for Ni abundance and W isotope ratio are not affected by n. But, the absolute core formation age is slightly delayed when n is small.

Combining the results of Ni and W isotope, observed values can be explained when the shallow magma ocean formed and at least half amount of impactor's iron equilibrates the Earth's mantle. At that

case, the age of the core formation ranges from 30 Myr to 70 Myr.

Discussion: The model presented above rules out the equilibration in the deep magma ocean. However, it seems rather strange from the view point of the recent physical approach [10]. The dynamical simulation of the giant impact shows that the center of the proto-Earth reaches high temperature (2000 - 4000K) after the giant impact. This suggests the formation of the deep magma ocean. Thus, if a deep magma ocean was not formed, it would give really strong constraint on the nature of giant impacts.

However, the deep magma ocean and siderophile partitioning can be reconciled, if either of the following two conditions are satisfied: (i) Ni abundance changes to a lower value or (ii) W isotope ratio at small *a* and large *b* changes to a lower value than our estimate. Both Ni abundance and W isotopic ratio are significantly affected by the formation condition of protoplanets, which we do not investigate here. In addition, if the distribution coefficient of Ni at very high pressure is higher than the value extrapolated from experimental data at ~ 50 Gpa, range of appropriate *a* value is significantly affected. Thus, it will be not adequate to rule out the deep magma ocean at giant impacts at this moment, Further investigation on the protoplanet formation is definitely required.

References: [1] Ringwood, A. E. (1966) *Geochim. Cosmochim. Acta 30*, 41-104. [2] Li J. and Agee C. B. (2001) *Geochim. Cosmochim. Acta 65*, 1821-1832. [3] Yin, Q.-Z. et al. (2002) *Nature 418*, 949-952. [4] Kokubo, E., and Ida, S. (1998) *Icarus 131*, 171-178. [5] Wetherill, G. W. and Stewart, G. R. (1989) *Icarus 77*, 330-357. [6] Rubie, D. C. et al. (2003) *Earth Planet. Sci. Lett. 205*, 115-134. [7] Bouhifd, M. A. and Jephcoat, A. P. (2003) *Earth Planet. Sci. Lett. 209*, 245-255. [8] Righter, K. (2003) *Annu. Rev. Earth Planet. Sci. 31*, 135-174. [9] Newsom, H. et al. (1996) *Geochim. Cosmochim. Acta 66*, 1155-1169. [10] Cameron, A. G. W. (2000) in *R. M. Canup, K. Righter (Eds.), Origin of the Earth and Moon, The University of Arizona Press*, pp.133-144. [11] McDonough, W. and Sun, S.-S. (1995) *Chem. Geol. 120*, 223-253. [12] Palme, H. and Beer, H. (1993) in *H. Voigt (Ed.), Landolt-Bornstein Group VI, Astronomy and Astrophysics, Instruments; Methods; Solar System, vol.3a, Springer*, pp. 198-221. [13] Klein. T. et al. (2004) *Geochim. Cosmochim. Acta 68*, 2935-2946. [14] Newsom, H. E. (1995) in *T. J. Ahrens (Ed.), Global Earth Physics, American Geophysical Union*, pp.159-189.

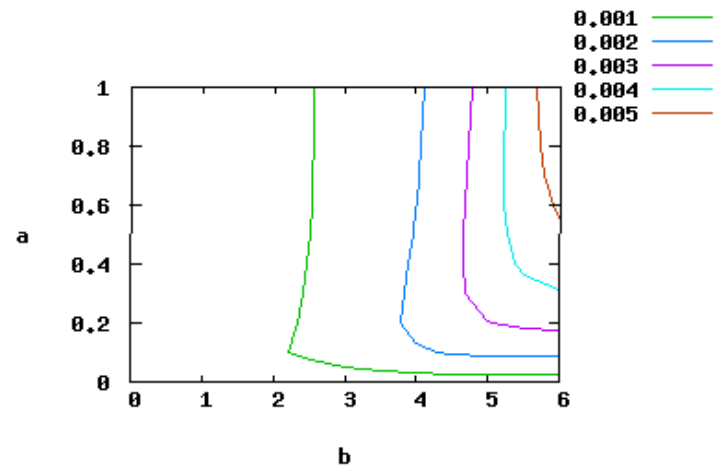

Fig. 1 The estimated Ni concentration (kg/kg) in the Earth's mantle for n = 9. See the text for definition of *a* and *b*. When *b* = 6, the whole mantle are molten. We adopt the experimental data [7] and the formulation [8] of the distribution coefficient. The temperature and the fugacity are fixed (T = 2500K, f_{O2} = -1.5ΔIW). Ni concentration of the Earth's mantle (0.002), and the bulk Earth (0.018) are from [11].

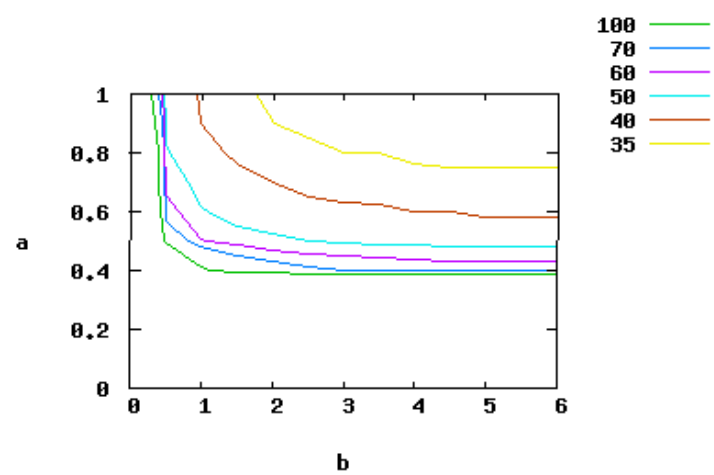

Fig. 2 The estimated core formation age (Myr) which satisfies the observed W isotope ratio for n = 9. Using the isotopic data from [3, 9, 12, 13, 14].