CORE FORMATION MEMORY OF SIDEROPHILE ELEMENTS IN EARTH AND MARS Gang Yu[1] and Stein B. Jacobsen[1], [1]Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138 (gyu@fas.harvard.edu; jacobsen@neodymium.harvard.edu)

Introduction: The siderophile elements depletion in planetary mantles is by definition due to core formation [1]. Therefore such elements have long been used to constrain the conditions of formation of planetary cores [2-8]. Planetary cores are likely to form through a series of events over a long time period (1-100 million years) [e.g.10], and we only know the information at the endpoint- the observed siderophile element contents in the current planetary mantles. This makes it difficult to unravel the whole core formation process. The similar depletion of Ni and Co in Earth's mantle has been suggested to result from a high pressure core formation process with estimates of ~28 or 40-55 GPa [3, 6, 11]. An important question left out in previous studies is what range of the core formation history do the inferred core formation conditions apply to? To investigate this problem, we used a simple continuous geochemical accretion and core formation model for planets to constrain how far back in the core formation history of a planet a particular siderophile element in its mantle can record? We define a new concept – "core formation memory" of siderophile elements, and quantified the "memory" for 23 and 8 siderophile elements in the mantles of Earth and Mars, respectively. The result should provide a basis to interpret core formation conditions inferred from siderophile elements and facilitate the application of siderophile elements in modeling multi-stage core formation processes. To illustrate our results, a simple three-stage core formation model for Earth divided in terms of three groups of siderophile elements with different memories was investigated and indicates that core formation processes of the Earth do occur with increasing pressure, temperature and oxygen fugacity.

Model for Core Formation Memory: Based on the continuous accretion and core formation model from [12], the variation of the mantle concentration of a siderophile element i with respect to the mass fraction of the growing planet ($M_p \in [0,1]$) can be obtained from equation 37 in [12] and given as

$$\frac{dC_{i2}}{dM_p} = \frac{C_{i1} - (1 - \gamma + \gamma d_{i23})C_{i2}}{(1-\gamma)M_p}$$

where C_{i1}, C_{i2} represent concentrations of siderophile element i in the bulk planet and the planet's mantle; d_{i23} is the metal-silicate partition coefficient of siderophile element i; γ is the core mass fraction. Here we define a critical point on the accretion and core formation history of a planet as $M_{i,x}$ for a siderophile element i. The core formation processes prior to $M_{i,x}$ have no significant effect on the current mantle concentration of the element i. In another word, the element i has effectively no memory of the accretion and core formation processes prior to $M_{i,x}$. By assuming a constant metal-silicate partition coefficient for the accreting planet as [12] did, we derived a simple equation for "core formation memory" of siderophile element i as

$$CFM_i = 1 - \max(M_{i,x}) = 1 - (SE_i)^{DF_i}$$

where the memory technically is the mass fraction of a planet corresponding to the accretion and core formation history memorized by element i; DF_i is the depletion factor of the siderophile element i in planet's mantle ($DF_i = C_{i2}(1-\gamma)/C_{i1}$); SE_i is the relative uncertainty of the current mantle concentration of the siderophile element i ($SE_i = \Delta C_{i2}/C_{i2}$). Thus, the core formation memory of a siderophile is determined by both how well we know its mantle concentration and its siderophility (DF_i).

Results: Core formation memories of 23 siderophile elements in Earth are illustrated by Fig. 1. We obtained two sets of memories based on two sets of input parameters for the bulk Earth concentrations taken from [13] and [14]. The offsets of the two sets of memories are significant only for Sn, Pb, Cr, Mn, Nb and V (Fig. 1). The reason is that [13] and [14] corrected the volatile loss of those elements in different ways and then obtained different values for their bulk Earth concentrations.

As we expected, the highly siderophile elements (HSEs) have very short memories only covering the last 0.5%-0.8% of Earth's accretion and core formation. We defined them as the ultra short-term memory group. The moderately siderophile elements – notably Mo, W, P, Cu, Ge, Ni, and Co – have memories that span the last ~20% of Earth's accretion and core formation history, defining the short-term memory group. Thus, we can say that the last 20% of Earth's accretion and core formation occurred at a high pressure as suggested by Ni and Co. But the conditions of the first 80% of Earth's core formation cannot be constrained by Ni and Co data.

The Earth-Moon system has been suggested to form from the last giant impact between the proto-Earth and a Mars-sized impactor [15]. The widely accepted mass ratio of the proto-Earth and the impactor is 0.87:0.13 [15]. Based on the memory results, the siderophile elements, which would only be affected by core formation during the Moon-forming giant impact are Mo, W, P, Cu and Ge. Other siderophile elements with longer memory (>13%) likely reflect combined effects of core formation during the Moon-forming giant impact and in the earlier stage.

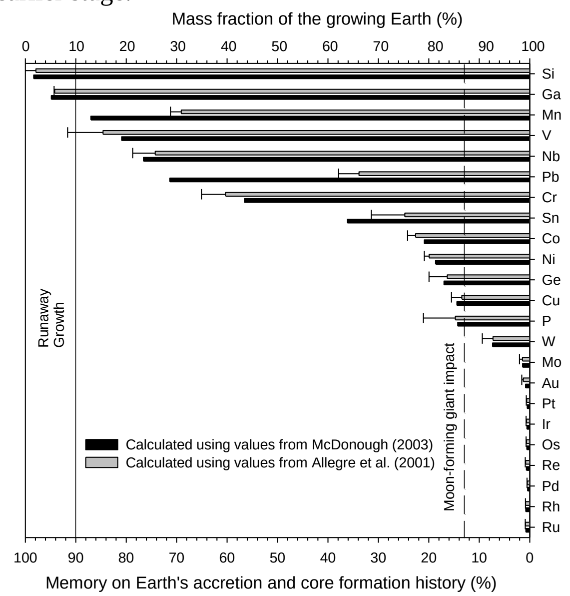

Fig. 1 Memories of 23 siderophile elements of the Earth's accretion and core formation history

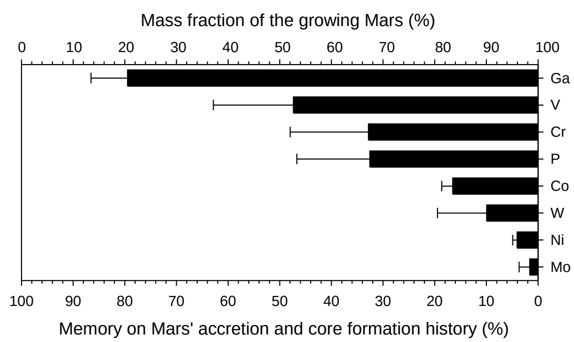

Fig. 2 Memories of 8 siderophile elements of the Mars' accretion and core formation history

Four slightly siderophile and volatile elements Sn, Pb, Cr and Mn have memories of the last 20%-70% of Earth's accretion and core formation history and are defined as the intermediate-term memory group. Four slightly siderophile and refractory elements V, Nb, Ga, and Si have memories that span nearly the whole accretion history of the Earth, defining the long-term memory group. [3] suggests a reduced condition for the first 20% of the accretion and core formation process based on the depletion of Nb, V, Mn and Si in Earth's mantle. However, Nb, V and Mn are not able to memorize the effect of that early core formation history because their small depletions in Earth's mantle and moderate mantle content uncertainties. Only Si and Ga have the ability. So the early reduced core formation stage needs to be confirmed by Ga.

We also calculate the core formation memories of siderophile elements in Mars (Fig. 2). However, compared with Earth, precise estimates for siderophile elements concentrations in the martian mantle and bulk Mars are sparse [e.g. 16]. We only obtain the memories of 8 elements for Mars. Similarly, Mo, Ni, Co and W in the martian mantle have short memories less than 20% of accretion and core formation history of Mars while Ga, V, Cr and P have longer memories.

Application to multi-stage core formation modeling: We can divide the core formation of the Earth into three stages corresponding to the three sub-groups of siderophile elements, except the ultra short-term memory group. Within each stage, we model the conditions of core formation only using the siderophile elements with significant memory for the particular stage. As illustrated by Fig. 3, the result shows that core formation processes in the early Earth have experienced increasing pressures (12→32→40 GPa), temperatures (2316→2887→3116 K) and oxygen fugacity (represented by mantle Fe content of 0.5→2→6.46 %). This is consistent with previous results [3, 7].

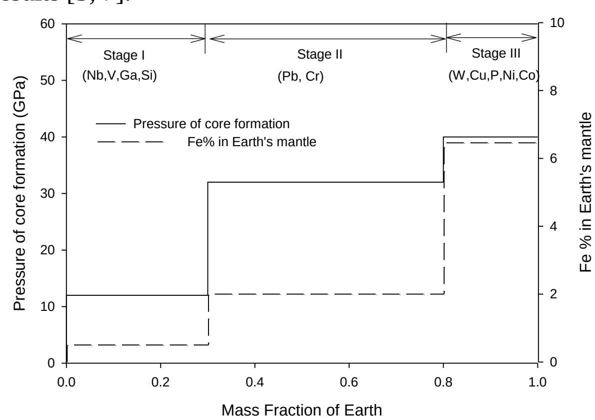

Fig. 3 A three-stage core formation model for Earth

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