Fast accretion of the Earth with a late Moon-forming giant impact

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Constraints on the formation history of the Earth are critical for understanding of planet formation processes. ^{182}Hf-^{182}W chronometry of terrestrial rocks points to accretion of Earth in approximately 30 Myr after the formation of the solar system, immediately followed by the Moon-forming giant impact (MGI). Nevertheless, some N-body simulations and ^{182}Hf-^{182}W and ^{87}Rb-^{87}Sr chronology of some lunar rocks have been used to argue for a later formation of the Moon at 52 to >100 Myr. This discrepancy is often explained by metal-silicate disequilibrium during giant impacts. Here we describe a model of the ^{182}W isotopic evolution of the accreting Earth, including constraints from partitioning of refractory siderophile elements (Ni, Co, W, V, and Nb) during core formation, which can explain the discrepancy. Our modeling shows that the concentrations of the siderophile elements of the mantle are consistent with high-pressure metal-silicate equilibration in a terrestrial magma ocean. Our analysis shows that the timing of the MGI is inversely correlated with the time scale of the main accretion stage of the Earth. Specifically, the earliest time the MGI could have taken place right at approximately 30 Myr, corresponds to the end of main-stage accretion at approximately 30 Myr. A late MGI (>52 Myr) requires the main stage of the Earth's accretion to be completed rapidly in <10.7 ± 2.5 Myr. These are the two end member solutions and a continuum of solutions exists in between these extremes.

Hf-W chronometry | planet formation

Current theories and numerical simulations argue that the Earth grew by numerous collisions between small objects to form larger ones and the last collision with a Mars-sized impactor probably gave rise to the Moon (1–3). Because the core formation processes are thought to have been occurring continuously during the accretion, the time scale of core formation in the growing Earth provides a basis for determining the time scale of formation of the Earth–Moon system (4–7). So far, the best constraint on the time scale of formation of the Earth–Moon system is derived from a combination of ^{182}Hf-^{182}W chronology and core formation models (cf. 4, 5, 8). A two-stage model with a single core formation event gives the time of Earth's formation of 28–35 Myr after the onset of the solar system (9–11). A model with a continuous accretion and core formation process and an exponentially decreasing accretion rate leads to a mean time of the Earth's formation of 11 ± 1 Myr (9). This is the time needed to accumulate approximately 63% of the present Earth's mass (4). A model with an early continuous accretion and core formation immediately followed by a Moon-forming giant impact (5) yielded a mean time of Earth's formation of approximately 11.5 Myr and a time of the Moon-forming giant impact of approximately 32 Myr (5). Overall, all such models consistently show that the major mass of the Earth has a mean time of formation of approximately 11 Myr with the complete formation time of Earth, including the Moon-forming giant impact, being 30–35 Myr (cf. 8). In contrast, both relatively recent ^{182}Hf-^{182}W isotope results and a recent reevaluation of ^{87}Rb-^{87}Sr isotope results for lunar rocks have been used to argue for a later formation of the Moon at 50–152 Myr or 70–110 Myr, respectively (12, 13). This conclusion is also consistent with some old N-body simulations of accretion of the terrestrial planets predicting a late time (100–200 Myr) for the last giant impact on Earth (14). One explanation for the apparent discrepancy between the ^{182}Hf-^{182}W time scale of the Earth's formation and the late time of Moon formation is an Earth core formation model assuming only partial metal-silicate equilibration (cf. 12, 13). Unfortunately, such a model introduces an additional and completely unconstrained parameter, the degree of equilibration. While this may be possible, an addition of a new unconstrained parameter would be justified only if the equilibrium models fail completely.

Here we developed and explored an equilibrium model of metal-silicate differentiation in the growing proto-Earth parameterized specifically to allow a simple evaluation of the conditions and timing of the Moon-forming giant impact relative to the main growth stage of the Earth. We show that this model can explain the discrepancy between the time scale of Earth's formation deduced from the ^{182}Hf-^{182}W isotopic composition of the Earth and the recent estimates of late formation of the Moon without invoking metal-silicate disequilibrium.

By fitting the best and most reliable tungsten isotopic data and concentrations of the five refractory siderophile elements (W, Ni, Co, V, and Nb) in the Earth's mantle, we found that:

i. the siderophile element pattern is consistent with the metal-silicate equilibration in a terrestrial magma ocean and cannot be a remnant of equilibration in Mars-sized or smaller impactors;
ii. a late Moon formation at approximately 50–110 Myr, if real, requires the main stage of Earth's accretion to be completed in 8 to 12 Myr, much faster than previously recognized.

Accretion and Planetary Differentiation

The accretion of the terrestrial planets is now thought to include three main stages with different accretion regimes (stages II, III, and IV in Fig. 1) (cf. 15). At the first stage, the dust that settled to the mid-plane of the solar nebula coagulates to form a large population of small bodies (planetesimals). Then, within approximately 10^5 years, mutual collisions and runaway accretion of planetesimals produced larger objects with the size distribution being skewed toward Moon- to Mars-sized planetary embryos, some of which eventually became terrestrial planets. At the third and final stage, some of the embryos sweep up the smaller ones by giant impact collisions to form the terrestrial planets. At some time, one of the embryos that became dominant at 1 AU could be identified as proto-Earth. The last major Earth-forming collision, the Moon-forming giant impact (MGI), is commonly thought to involve the proto-Earth and a Mars-sized impactor. At the end of accretion, only the Earth remained at approximately 1 AU, and the accretion process was effectively complete. It is important to

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realize that many larger bodies will be differentiated because of the extensive melting that is caused by giant collisions (16). It is also widely believed that during the third stage the nebular gas has dissipated as indicated in Fig. 1 (based on evidence from proto-stars) (17). This astrophysical scenario for the Earth's accretion is now considered as the standard (cf. 3, 6, 15, 18, 19). An approximate schematic time scale of the Earth's accretion is shown in Fig. 1, with the lower part of the figure illustrating the ideas about mass accretion of the Earth discussed here.

The initial stage of planetesimal accretion yields numerous embryos weighing up to approximately 10% of the Earth's mass, with one of them eventually becoming the Earth. The MGI adds the last approximately 13% of Earth's present mass. In between, the mass accreted to the Earth's embryo and then the proto-Earth was probably delivered in a series of giant impacts (GIs) involving approximately six Mars-sized objects or more, if the impactors were smaller. Previous work on the ^{182}W evolution of the Earth (5) shows that giant impacts always erase most of the ^{182}W excess (compared to the chondritic W) in the silicate Earth. In the first approximately 30 Myr, the ongoing decay of the remaining ^{182}Hf (half-life = 9 Myr) can build up the ^{182}W excess again, so the observed ^{182}W excess in the Earth's mantle allows many giant impacts to occur during this period. After approximately 50 Myr, the recovery of the ^{182}W excess in the silicate Earth after a giant impact is insignificant, so only one such late giant impact can be allowed as described quantitatively later in the paper. Two or more late (>50 Myr) giant impacts would yield the Earth's mantle with essentially chondritic W, that is clearly inconsistent with the observed ^{182}W excess in the mantle (see *SI Appendix*) (9).

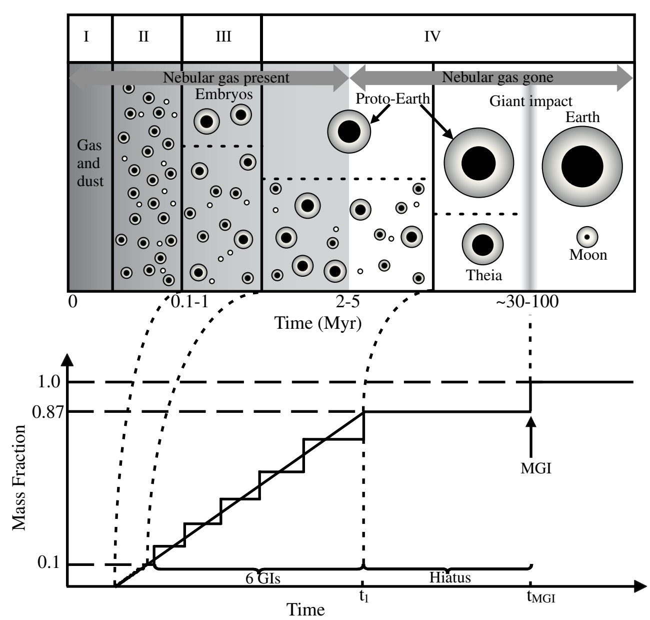

Fig. 1. The upper part is a schematic illustration of the formation of the Earth with a possible late giant moon-forming impact. There are four accretion stages: I (dust settling), II (planetesimal formation), III (embryo formation), and IV (accretion of terrestrial planets by giant impact). The bodies below the dotted lines represent the left material in Earth's feeding zone. The shaded zone represents the presence of solar nebula that was dissipated at 2–5 million years. An approximate time scale is shown and the lower part of this figure shows schematically the mass accretion history of the Earth. Initially (up to about 10%) the accretion is of planetesimals forming embryos. The main phase of accretion is by giant impacts (approximately six Mars-sized giant impacts or more if some are smaller) and is shown as ending at time t_{PE}. Then, there may have been a significant hiatus, before a potentially late MGI adds the last approximately 13% of the mass of the Earth at time t_{MGI}. The figure is not to scale.

In this paper we focus on evaluating how the duration of a "hiatus" between the end of the main stage of Earth accretion and a late MGI (Fig. 1) affects the timing of these events. For the sake of analytical simplicity, the step function of the Earth's main growth stage during accretion was approximated by a smooth function of exponential growth (illustrated by straight line in Fig. 1). This allows a simple parameterization of the timing of the MGI relative to the time scale of the main growth stage of the Earth (up to 87%), as discussed in the next section.

Mars-sized giant impactors supply sufficient energy to melt the entire Earth and support a deep magma ocean over the accretion history of the Earth. Also, during the main stage of the Earth's accretion and during the Moon-forming giant impact, the impactors are likely to be completely differentiated (16). Therefore, it is crucial to develop a model that can address both the metal-silicate equilibration at different temperatures and pressures in a magma ocean and the accretion time scale based on the ^{182}Hf-^{182}W system.

Our approach to modeling core-mantle differentiation during the Earth's accretion is sketched in Fig. 2. The box model includes three reservoirs. The Earth is considered to grow by accreting objects from the solar nebula (reservoir 1). As the Earth grows, the accreted material is added to the silicate mantle (reservoir 2). The metallic core (reservoir 3) is segregated (no back reaction) from the mantle, therefore during accretion small metal parcels (equilibrated at some P and T in the magma ocean) are considered isolated as soon as these join the core.

Following (5), we use a system of transport equations for the Hf-W system and other siderophile elements to describe evolving chemical and isotopic compositions of the Earth's mantle and core. The partitioning of elements between the silicate and metallic liquids is calculated based on the experimental partition coefficients that vary with pressure (P) and temperature (T) during core formation. Numerical solution of these equations allows determination of P, T conditions during core formation and the time scale of the process. This model essentially combines the approaches of refs. 5 and 20.

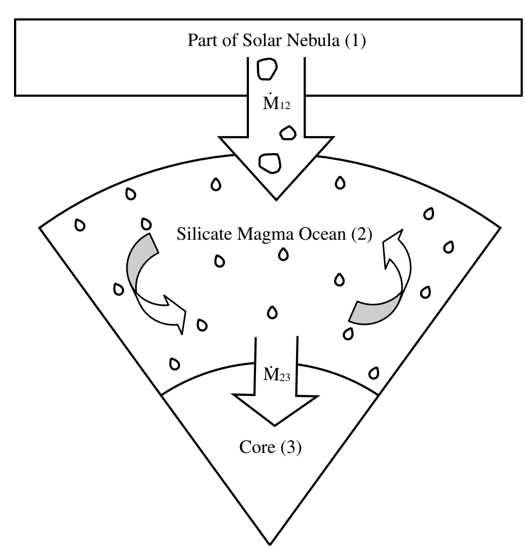

Fig. 2. Sketch of the box model for the accretion and core formation model used in this work. The Earth is considered to grow by accreting objects from the solar nebula (reservoir 1) with a mass flux $\dot{M}_{12}(t)$. As the Earth grows, the accreted material is added to the silicate mantle (reservoir 2). The metallic core reservoir (3) is segregated as small metal parcels (equilibrated at some P and T in the magma ocean) from the mantle during accretion (with a mass flux $\dot{M}_{23}(t)$) and once in the core the metal is considered isolated (no back reaction) from the mantle. There is no direct mass transport flux from the solar nebula to the metallic core ($\dot{M}_{13}(t) = 0$). The whole mantle maintains homogeneity by rapid convection.

The previous studies show that the metal-silicate equilibrium in the terrestrial magma-ocean was attained at pressures in excess of 30–50 GPa (20–22) implying that at each giant impact event the target and impactor materials must have been reequilibrated in the Earth's mantle but not in the impactors, which have core-mantle boundary pressures of less than approximately 20 GPa. The mechanisms of metal-silicate equilibration in the terrestrial magma ocean have been discussed in ref. 23. Their results show that large metal blobs (hundreds of km in size) will be reduced to cm-sized droplets while sinking through the magma ocean. Such metal droplets reach equilibrium with the surrounding silicate melt very quickly (23).

Parameterization of the Mass Accretion History of the Earth

The mass of the Earth (M_E) is considered to grow from a primitive solar nebular reservoir with a growth rate proportional to the available mass $[M_E(\infty) - M_E(t)]$ at any time t, where $M_E(\infty)$ is the mass of the Earth at infinite time when the accretion of the Earth ends and α is the growth constant:

$$\frac{dM_E}{dt} = \alpha[M_E(\infty) - M_E(t)] \qquad [1]$$

Integrating from $t = 0$ to t results in an exponentially decreasing accretion rate expressed as: $M_E(t)/M_E(\infty) = 1 - e^{-\alpha t}$. Because the present mass of Earth $M_E(\tau_0) \approx M_E(\infty)$, and τ_0 is the age of the solar system [approximately 4,567 Myr (24)], the growth rate equation can be simplified to yield: $\mathrm{d}M_E/\mathrm{d}t = \alpha M_E(\tau_0)e^{-\alpha t}$. Then the mean time of formation needed to accumulate approximately 63% of the Earth's present mass is $t_m(\tau_0) \approx 1/\alpha$. This equation closely reproduces the Earth's growth histories predicted by stochastic accretion simulations (e.g., 14, 18, 25) and is a good approximation of the Earth's growth history, perhaps with the exception that there may be one very late giant impact that deviates to a substantially later time compared to the exponential growth approximation.

Now let's develop an analytical formulation that helps in evaluating the relationship between the time scale of the main stage of Earth's accretion and the timing of the MGI. The main stage of accretion (which likely includes numerous giant impacts), assumed to follow exponential growth, ends at time t_{PE} when the proto-Earth's mass (PE) reaches $M_E(t_{\mathrm{PE}})$. Then, the mass of the proto-Earth before the Moon-forming giant impact (Fig. 3*A*) is given by:

$$\frac{M_E(t_{\mathrm{PE}})}{M_E(\tau_0)} = 1 - e^{-\alpha t_{\mathrm{PE}}}. \qquad [2]$$

The mean time of the main accretion stage of the Earth, t_m, is related to the end time of main-stage accretion, t_{PE}, by (see *SI Appendix* for details):

$$t_m = \frac{-t_{\mathrm{PE}}\left[1 + \frac{M_E(\tau_0)}{M_E(t_{\mathrm{PE}})}\left(1 - \frac{M_E(t_{\mathrm{PE}})}{M_E(\tau_0)}\right)\ln\left[1 - \frac{M_E(t_{\mathrm{PE}})}{M_E(\tau_0)}\right]\right]}{\ln\left[1 - \frac{M_E(t_{\mathrm{PE}})}{M_E(\tau_0)}\right]} \qquad [3]$$

The Moon-forming giant impact always occurs later than t_{PE} at time t_{MGI}, so $t_{\mathrm{MGI}} \geq t_{\mathrm{PE}}$. Simulations of the Moon-forming impact require the mass fraction of the impactor to be ∼0.13 of the final Earth–Moon system in order to match its astronomical characteristics (26). Neglecting the small mass of the Moon, the mass ratio of the preimpact Earth to the Earth is $M_E(t_{\mathrm{PE}})/M_E(\tau_0) = 0.87$. This results in $t_{\mathrm{PE}} = 2.93t_m$. Fig. 3*A* shows an example of an accretion history of the Earth assuming $M_E(t_{\mathrm{PE}})/M_E(\tau_0) = 0.87$ and an MGI at $t_{\mathrm{MGI}} = 45$ Myr. In this case, in order to match the Hf/W ratio and the W isotopic composition of the present Earth's mantle, 87% of Earth's mass has to be accreted in $t_{\mathrm{PE}} = 10.2$ Myr, corresponding to a mean time for the main accretion stage of $t_m = 3.5$ Myr.

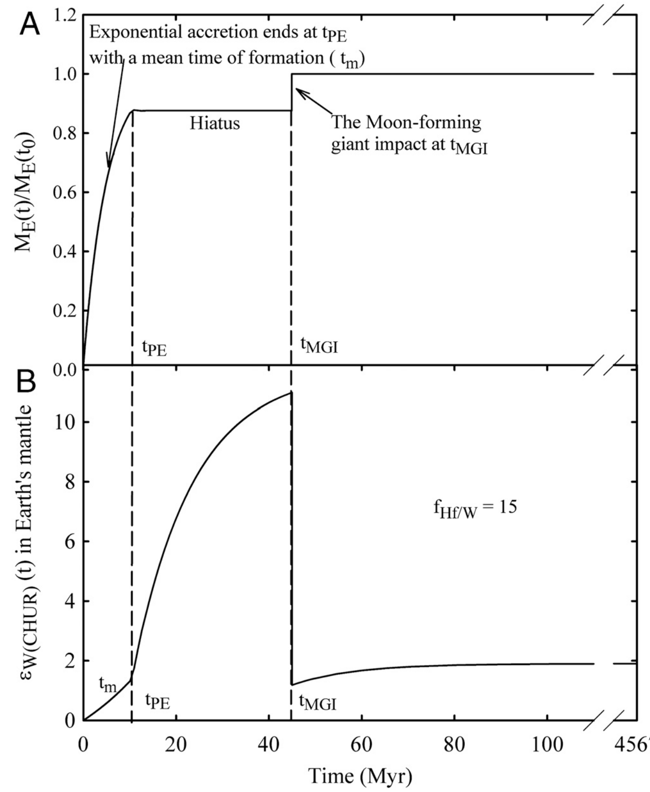

Fig. 3. (*A*) The fractional mass of Earth as a function of time in our model, which is composed of an early continuous accretion and core formation stage and a later Moon-forming giant impact. The growth curve shows an early continuous accretion and core formation process with a mean time of 3.5 Myr ($t_m = 3.5$ Myr) and the Moon-forming giant impact occurs at $t_{\mathrm{MGI}} = 45$ Myr. The mean time of formation of the proto-Earth in this model is defined as the time taken to build approximately 63% of Earth's present mass. (*B*) The calculated W isotope evolution in the silicate Earth corresponding to the accretion scenario (*A*) and match the present W isotopic composition of the Earth's mantle ($\epsilon_{\mathrm{W(CHUR)}} = 1.9 \pm 0.2$ and $f^{\mathrm{Hf/W}} = 15$).

Modeling Siderophile Element and W Isotopic Evolution of the Growing Earth

During accretion and core formation of the Earth, the conditions of the metal-silicate equilibration, such as temperature, pressure, redox conditions are changing with time as the Earth grows. To model this effect explicitly, we adopted the "deep magma ocean" core formation model of ref. 5, developed for the ^{182}Hf-^{182}W system. We added to this model transport equations describing partitioning (maintaining system mass balance) of the siderophile elements Ni, Co, V, and Nb (in addition to W) between metal and silicate liquids using metal/silicate partition coefficients that are allowed to vary as Earth grows in response to changing pressures and temperatures and redox conditions. To reflect the physical conditions in the mantle up to the values at the core–mantle boundary as Earth grows, we used available thermodynamic fits (to P, T, and f_{O2}) of experimentally determined metal-silicate partition coefficients (20, 27–29) (see *SI Appendix*).

Because the partition coefficients depend upon redox conditions, we use the Fe content in the mantle as a proxy for redox conditions at each step, thus cancelling out the f_{O2} dependence. During the early continuous accretion (mass fraction of the Earth is <0.2) the Fe content in the mantle is assumed equal to 14%, close to the average Fe contents in mantles of Mars and Vesta

(30). After the MGI (mass fraction of the Earth is >0.87), the Fe content is assumed to be 6.26%, which is the average Fe content in Earth's mantle today (31). In the intermediate stage, the Fe content is 1.01%, corresponding to a reduced accretion stage that is required to make the observed core–mantle concentration ratio of V consistent with that calculated using experimental partition coefficient of V (20).

At each step before the MGI, after adding a parcel of new material (with chondritic average composition) to the growing Earth, we calculate new concentrations of trace elements and the W isotope composition of the mantle. The core–mantle boundary is assumed to be on the peridotite liquidus (Eq. 7 in *SI Appendix*), with the pressure being calculated for a given value of the Earth's mass using Eq. 6 in *SI Appendix* and temperature from the peridotite liquidus. Then we calculate the partition coefficients at these conditions, the amount of newly formed metallic liquid assuming constant core mass fraction in the Earth of 0.325, the concentrations of trace elements in the metallic liquid. Finally, after segregating the newly formed metal into the core, the concentrations of trace elements in the mantle and the core, the concentration ratios in the core relative to the mantle ($C_{\mathrm{core}}/C_{\mathrm{mantle}}$), and W isotopic composition of the mantle are calculated.

At the last step, after the addition of the final 13% of the Earth mass by the MGI we calculate the pressure and temperature of the metal-silicate equilibration in an iterative procedure that involves (*i*) initial assumption on the value of equilibration pressure, (*ii*) calculation of the corresponding temperature from the peridotite liqidus curve, (*iii*) calculation of partition coefficients and values of $C_{\mathrm{core}}/C_{\mathrm{mantle}}$, (*iv*) comparison of the calculated ($C_{\mathrm{core}}/C_{\mathrm{mantle}}$) values with the "observed" ones in the present-day Earth using a least square fitting technique, and (*v*) changing the pressure and repeating steps *ii* through *iv* until the best fit between the modeled and observed ratios is obtained for all five elements (see Fig. 4). Finally, the Hf/W ratio and the W isotopic composition in the mantle are calculated.

The "observed" concentration ratios of the refractory siderophile elements Ni, Co, W, V, and Nb in the core relative to the mantle ($C_{\mathrm{core}}/C_{\mathrm{mantle}}$) can be estimated with some certainty from bulk silicate Earth and chondritic abundances (31; Table 1 of *SI Appendix*), because no correction for the volatile loss during Earth's formation is needed.

To be considered successful, a model of Earth's accretion must satisfy the present isotopic composition of the Earth's mantle ($\epsilon_{\mathrm{W(CHUR)}=}1.9 \pm 0.2$) (9) and a Hf/W weight ratio of 18 ± 3 (5, 32, 33). This corresponds to a Hf/W fractionation factor relative to chondrites of $f^{\mathrm{Hf/W}} = (^{180}\mathrm{Hf}/^{183}\mathrm{W})_{\mathrm{mantle}}/(^{180}\mathrm{Hf}/^{183}\mathrm{W})_{\mathrm{CHUR}} - 1 = 15 \pm 3$.

Results and Discussion

Metal-Silicate Equilibration Pressure During Earth's Growth. We determine a metal-silicate equilibration pressure history by obtaining an optimal least squares match between the modeled and "observed" concentration ratios for Ni, Co, W, V, and Nb between the core and the mantle. We explored a range of P-T conditions of the metal-silicate equilibration in the growing Earth by assuming the pressure of metal-silicate equilibration to be a fraction of that of the core–mantle boundary at any given Earth mass. Overall, regardless of the assumed equilibration pressure before the MGI, the equilibration pressure after the MGI is always in the range of 40–50 GPa. We also found that a decrease in the pressure of metal-silicate equilibration, relative to the core–mantle boundary pressure, during the Earth's main accretion stage invariably results in an increase, by up to approximately 25 rel. %, in the pressure of the final metal-silicate equilibration after the MGI. Therefore, in order to place lower limits on the pressure of the final metal-silicate equilibration below we discuss only the scenarios assuming equilibration at the core–mantle boundary during the main stage of Earth accretion.

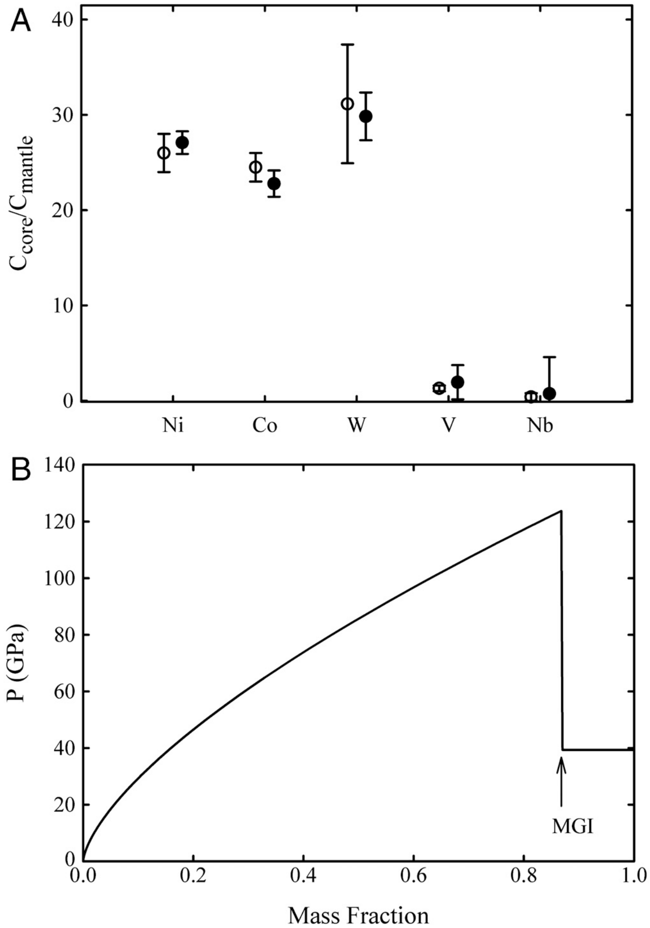

Fig. 4. (*A*) Observed (open symbols) concentration ratios of five siderophile and refractory elements (Ni, Co, W, V, and Nb) between Earth's mantle and core are compared with the corresponding values calculated from our model and experimentally determined partition coefficients (solid symbols). (*B*) The metal-silicate equilibration pressure during the Earth's accretion and core formation history is shown as a function of the fractional mass of the accreting Earth. The equilibration pressure in the magma ocean is fixed to be at the core/mantle boundary except during the Moon-forming giant impact when it is calculated to be approximately 40 GPa to be consistent with observational and experimental constraints.

Fig. 4*A* shows an example of the final concentration ratios calculated for the accretion scenarios like the example shown in Fig. 4*B*. There is excellent agreement between the modeled and observed concentration ratios. The final concentration ratios of W, Ni, and Co are primarily controlled by the MGI stage, because their strongly siderophile behavior has depleted the pre-MGI Earth's mantle in these elements. In contrast, the concentration ratios of the less siderophile V and Nb could potentially provide more information on the physical conditions of metal-silicate equilibration in the pre-MGI Earth's mantle, but their concentration ratios are less well established. The final equilibration pressure (approximately 40 GPa) obtained for this accretion scenario (Fig. 4*B*) is consistent with previous estimates for both static and continuous magma-ocean models that are typically in the range of approximately 30–50 GPa (20, 21, 28, 29).

Thus, both our and previous results show that the siderophile element pattern of the Earth's mantle is consistent with high-pressure metal-silicate equilibration in a terrestrial magma ocean and cannot be inherited from the Mars-sized or smaller impactors. Therefore, there is no need to introduce the degree of equilibration as an additional parameter. The lower than the current core–mantle boundary pressure (approximately 136 GPa) of metal-silicate equilibration estimated by us may indicates either (*i*) a problem with extrapolating the experimental partition coefficients, to core–mantle boundary conditions, beyond their experimentally determined range (typically <25 GPa) or (*ii*) some important contributions from additional factors not included in our model, such as ponding of metal above a crystal cumulate pile filling up the magma ocean with time (cf. 21).

The Timing of Moon Formation and the Rate of Main-Stage Accretion for the Earth. To facilitate comparison with earlier work and evaluate the effect of including variations in the Hf/W ratio during accretion on the resulting time scale of the main accretion stage of the Earth (t_{PE}) and the timing of the MGI (t_{MGI}), we explored accretion models with both a constant and variable partition coefficient for W (D_W). The more realistic variable D_W case results in a Hf/W ratio that varies by more than an order of magnitude during accretion.

First, for simplicity, let us discuss a case of constant D_W (and therefore $f^{Hf/W}$). Fig. 3*B* shows the evolution of the W isotopic composition of the silicate Earth calculated for the accretion scenario of Fig. 3*A* with the MGI at 45 Myr and a constant $f^{Hf/W} = 15$. The W isotopic composition during the Earth's main growth stage increases slowly because of the continuing addition of material with the average chondritic W and ongoing segregation of radiogenic W into the core. After the completion of the main stage of Earth accretion (time t_{PE} in Fig. 3*B*), the mantle remains a closed system and retains radiogenic W causing rapid growth of $\varepsilon_{W(CHUR)}$ because of its high Hf/W ratio and that ^{182}Hf is still live. The MGI (time t_{MGI} in Fig. 3*B*) induces the last major episode of metal segregation that removes much of the accumulated radiogenic W isotope signature and results in a sharp drop in the $\varepsilon_{W(CHUR)}$ value. This sharp drop is due to addition of large amounts of W with average chondritic isotopic composition ($\varepsilon_{W(CHUR)} = 0$) (see *SI Appendix*). The final W isotopic composition matches that of the present Earth's mantle.

Fig. 5 shows the relationships between the timing of the MGI (t_{MGI}), the time scale of the main accretion stage of the Earth (t_{PE}), and the mean time of accretion (t_m) for models with constant D_W and $f^{Hf/W} = 15$ (curves with open symbols) and variable D_W (curves with solid symbols). All curves show a clear inverse relationship between the timing of the MGI (t_{MGI}) and the time scale of the main accretion stage (t_{PE}). We note that the inverse relationship between t_{PE} and t_{MGI} is robust and not strongly dependent on the exact evolution of D_W metal-silicate partition coefficient during accretion. For t_{MGI} less than 40 Myr, there is a little difference between the models with constant and variable D_W. However, for $t_{MGI} > 60$ Myr, the model with constant D_W predicts accretion rates (in terms of t_m and t_{PE}) that are a factor of two faster than in the case of variable D_W. For example, the model with constant D_W yields $t_{PE} \sim 5$ Myr, while the more realistic model with variable D_W yields $t_{PE} \sim 10$ Myr (Fig. 5*A*).

The earliest possible time of an MGI is approximately 30 Myr, immediately after the completion of the main accretion (straight line labeled $t_{MGI} = t_{PE}$ in Fig. 5). Such an accretion scenario is broadly consistent with the results from some recent high resolution N-body simulations (15) that give an average time scale of 14^{+11}_{-9} Myr for Earth-sized objects to reach 50% of their final mass and 34^{+42}_{-10} Myr to reach 90% of their final mass.

For late formation of the Moon (>52 Myr) our modeling results (Fig. 5) imply the main stage of the Earth's accretion to be completed rapidly in 10.7 ± 2.5 Myr for a giant impact at 52 Myr and 7.9 ± 3.3 Myr for a giant impact at 100 Myr. In this case, there is a long (>40 Myr) hiatus between the early continuous accretion stage and the Moon-forming giant impact. A late formation of Moon is supported by the W isotopes results on lunar rocks (12). In particular an upper limit to Moon formation is placed by estimates of the time of its magma-ocean crystallization. Equilibration of tungsten isotopes within the lunar magma ocean has been constrained to 62^{+90}_{-10} Myr after solar system formation (12) and is consistent with the ^{146}Sm – ^{142}Nd results on lunar rocks (34) suggesting late (150^{+16}_{-13} Myr with the new ^{146}Sm half-life of 68 Myr) (35) crystallization of the lunar magma ocean. Such fast accretion is broadly consistent with the ^{182}Hf-^{182}W evidence that Mars also accreted very fast in 0–5 Myr (5), 0.9–4.8 Myr (36), or 2–4 Myr (37). Fast accretion of Mars combined with our result for late formation of Moon suggest that the main stage of planetary accretion may have occurred very early, within approximately 10 Myr of solar system formation.

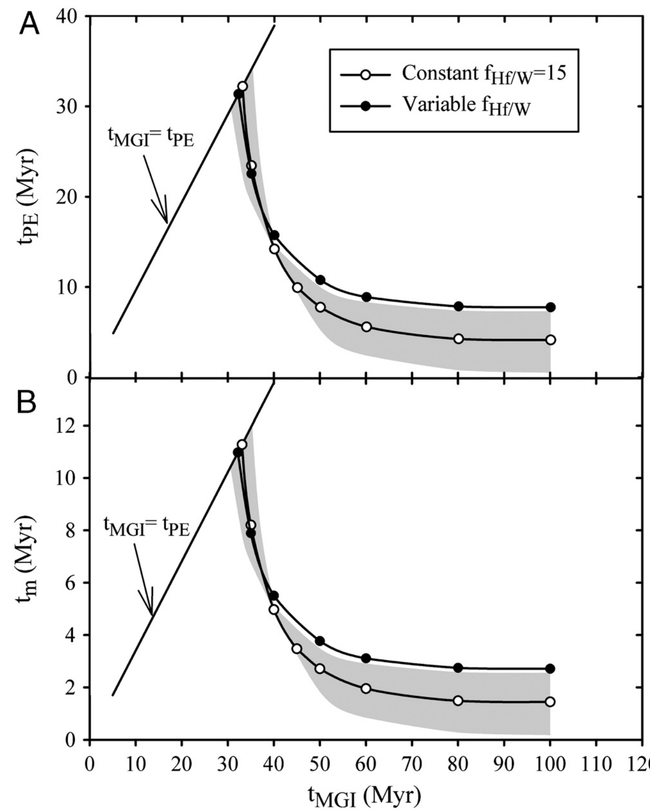

Fig. 5. (*A*) The time scale (t_{PE}) of the main accretion stage of the proto-Earth as a function of the timing of the Moon-forming giant impact (t_{MGI}) inferred from the W isotopic composition in Earth's mantle today. The curve with the solid symbols shows the result that includes using experimentally determined partition coefficients for Ni, Co, W, V, and Nb to determine their partitioning into the core during accretion. This results in $f^{Hf/W}$ of the mantle varying by over an order of magnitude during accretion but being constrained to end with a value of 15. The curve with the open symbols is for the case that $f^{Hf/W}$ of the mantle has the current value of 15 throughout accretion history of Earth. An error band for this curve is shown as the shaded area. The upper limit for $t_{MGI} > 40$ Myr corresponds to $f^{Hf/W} = 12$ and the lower to $f^{Hf/W} = 18$. A similar error band (not shown for clarity) applies to the curve with the solid symbols. The solid straight line shows the case that the Moon-forming giant impact happens right after the early continuous accretion ($t_{MGI} = t_{PE}$). (*B*) The mean time of formation of the proto-Earth (t_m) as a function of the timing of the Moon-forming giant impact (t_{MGI}) for the same case shown in *A*.

Conclusions

We have developed a model for accretion and core formation in the Earth that combines previous models of both ^{182}Hf-^{182}W chronometry (5) and experimental results for refractory siderophile elements (Ni, Co, W, V, and Nb) partitioning (20). Our model also includes a parameterization that allow for a Moon-forming giant impact (MGI) that could be substantially later than the main stage of Earth's accretion. Our results are as follows:

1. The concentrations of the refractory siderophile elements of the Earth's mantle are consistent with high-pressure metal-silicate equilibration in a terrestrial magma ocean during the

Earth's accretion. This feature cannot be inherited from Mars-sized or smaller impactors and the fact that the data are consistent with equilibrium conditions that existed only in the deep Earth and not the impactors shows that introducing disequilibrium into the problem is not necessary.

2. The timing of the MGI is inversely correlated with the time scale of the main accretion stage of the Earth. Specifically, the earliest time of the MGI could have taken place right at approximately 30 Myr, in this case also corresponding to the end of main-stage accretion at approximately 30 Myr. A late MGI (>52 Myr) requires the main stage of the Earth's accretion to be completed rapidly in 10.7 ± 2.5 Myr for a giant impact at 52 Myr and 7.9 ± 3.3 Myr for a giant impact at 100 Myr. These are are the two end member solutions, and a continuum of solutions exists in between these extremes.
3. Only one late (greater than approximately 50 Myr) Mars-sized giant impact is allowed over the accretion history of the Earth; two would completely erase the ε_W-anomaly in the Earth's mantle, which is inconsistent with the observed ε_W anomaly (1.9) (see *SI Appendix*).
4. The apparent conflict between ^{182}Hf-^{182}W chronometry of terrestrial rocks when compared to recent estimates for a late formation of the Moon (>52 to 100 Myr) can be clearly understood in terms of our results. A late formation of the Moon is possible but requires very fast formation of the Earth prior to the late Moon-forming impact.

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