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ORIGINAL ARTICLE

The core-merging giant impact in Earth's accretion history and its implications

You Zhou[1,3] · Yun Liu[1,2,3] · Christian Reinhardt[4] · Hongping Deng[5]

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Abstract The Earth's accretion process is accompanied by a large number of collisions. It is widely accepted that collisions dominate the Earth's late accretion stage. Among all these collisions, there is a special type of collision called Core-merging giant impact (CMGI), in which much or most the impactor's core merges directly with the proto-Earth's core. This core-merging scenario plays an important role in the Earth's accretion process and deeply affects the formation of the Earth's core and mantle. However, because CMGI is a small probability event, it has not been fully studied. Here we use the SPH method to comprehensively study all possible CMGIs in the Earth's accretion history. We find that CMGI only occurs in the initial conditions with small impact angle, small impact velocity and big impactor. We further discuss the implications of CMGI. We are confident that CMGI inevitably causes the chemical disequilibrium of the Earth's core and mantle. The CMGI process also brings many light elements into the Earth's core. In particular, if the Moon-forming giant impact is a CMGI, then CMGI can also explain the abnormal content of HSEs in the Earth's current mantle.

Keywords Giant impact · Core-merging process · Disequilibrium of the Earth's core and mantle

✉ Yun Liu
liuyun@vip.gyig.ac.cn

1 International Research Center for Planetary Sciences, College of Earth Sciences, Chengdu University of Technology, Chengdu 610059, China

2 State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China

3 CAS Center for Excellence in Comparative Planetology, Hefei, China

4 Center for Theoretical Astrophysics and Cosmology, Institute for Computational Science, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland

5 Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK

1 Introduction

The Earth experienced a large number of giant impacts or large impacts during its accretion history. These collisions had a profound influence on the formation of the Earth–Moon system. For example, the Moon is thought to be formed in a giant impact event, and it is also thought to be the last one of these Earth-building impacts. Many giant impact simulations have carried out in-depth studies on the Moon-forming giant impact (Canup and Asphaug 2001; Canup 2012; Ćuk and Stewart 2012; Rufu et al. 2017; Hosono et al. 2019). But quite many common giant impacts or large impacts still have happened before the Moon-forming giant impact. Some N-body simulations suggested that the total mass of embryos is equal or greater than the planetesimals in the late stage the Earth's accretion (Brien et al. 2006; Jacobson and Morbidelli 2014). In N-body simulations studying the formation of the terrestrial planets, Quintana et al. (2016) found that the proto-Earth may have experienced several giant impacts and hundreds of large impacts.

Among all these collisions, there is a special class of collisions, in which the impactor's core plunge through the proto-Earth's mantle and merges with the core directly. Here we call this kind of collision core-merging giant

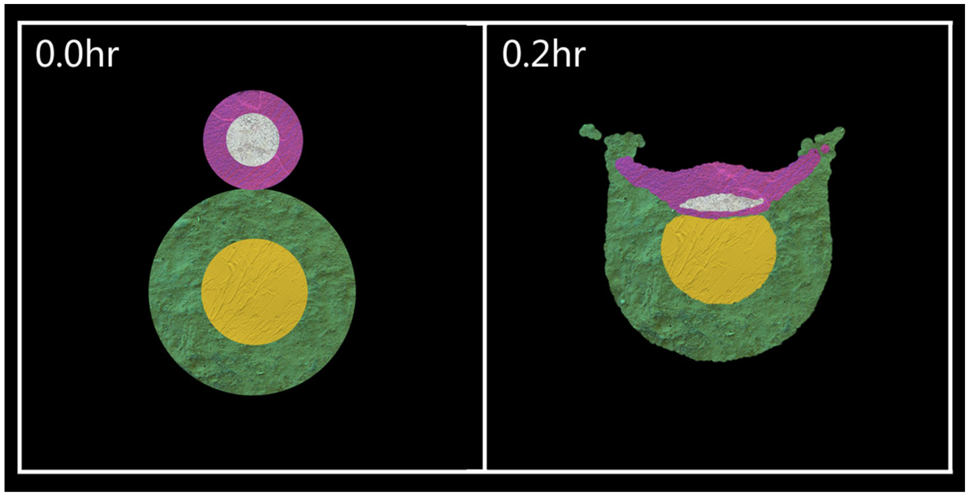

Fig. 1 A cartoon of core-merging giant impact (CMGI) process base on SPH simulation

impact (CMGI), as shown in Fig. 1. The CMGI process obviously has a very direct influence on the proto-Earth's core and mantle, but it was generally considered that CMGI was a small probability event, so its importance was not given enough attention. The CMGI scenario has been discussed in some previous studies. Rubie et al. (2011a, b) presented that the core-merging process should cause the incomplete emulsification of impactor's metallic core in a magma ocean and result the chemical disequilibrium of the Earth's core and mantle. Landeau et al. (2016) proposed that the merged core material of the impactor can induce a stratified layer at the top of the Earth's core, and this stratified layer can even be preserved up to now. Dahl and Stevenson (2010) investigated the turbulent mixing of metallic core and surrounded silicate. They suggested that the blobs which their diameter are larger than 10 km could not be emulsified. Nevertheless, other work showed that fragments with diameters up to 200 km can also be well mixed, because the large metallic fragments will be stretched into smaller pieces when they plunge through the magma ocean (Kendall and Melosh 2016). These works main focus on the Earth's core–mantle differentiation and core–mantle chemical equilibrium, but they have not performed giant impact simulations to investigate the details of CMGI. This makes them ignore some other important effects. The core-merging scenario can be observed in previous giant impact simulations, but the authors did not notice this important process, so they didn't explore this process in depth (Cameron 1997; Genda et al. 2017; Reinhardt et al. 2020).

CMGI has the highest accretion efficiency in all the Earth-building collisions. The minimum accretion efficiency of CMGI exceeds 60%, which means the pro-Earth's mass increased by at least 60% of the impactor's mass after each CMGI (Cambioni et al. 2019). Moreover, CMGI is also important to the Earth's core-formation, because a large fraction of the impactor's core was also merged into the proto-Earth's core directly. Therefore, we believe that CMGI has affected many aspects of the Earth's accretion and core–mantle differentiation process, and these affections have not been thoroughly investigated. This study will investigate the details of CMGI using the Smoothed Particle Hydrodynamics (SPH) method, exploring a large range of different initial conditions and how they affect the collision outcome.

2 Method

We use the Smoothed Particle Hydrodynamics (SPH) method to carry out the giant impact simulation. SPH method is a kind of meshless particle method with Lagrangian form, which is eminently suitable for simulating systems which have large deformation and allows to track the origin and history of the material during and after the collision. The two key steps of the SPH method are the kernel approximation and the particle approximation.

2.1 Kernel approximation

For any function, the integral expression defined as follows can be used:

$$f(x) = \int_{\Omega} f(x')\delta(x - x')dx' \tag{1}$$

f is any function of variable x, Ω is the integral domain containing x, and δ is the Dirac function. If the function $W(x - x', h)$ is used to replace the Dirac function δ in Eq. (1), the integral expression of can be written as:

$$f(x_i) = \int_{\Omega} f(x')W(x - x', h)dx' \tag{2}$$

In this formula, $W(x-x',h)$ is called the smoothing function or the kernel function; h is the smoothing length that defines the influence area of the smoothing function. Since the kernel function is not a Dirac function, the integral expression of Eq. (2) is an approximate expression.

2.2 Particle approximation

Using the particle volume ΔV_j to replace the infinitesimal volume element dx' at the particle j in Eq. (2), then the kernel function approximate expression can be further written as a discretized particle approximate expression:

$$\begin{aligned} f(x_i) &= \int_\Omega f(x')W(x-x')dx' \\ &= \sum_{j=1}^{N} f(x_j)W(x-x_j,h)\Delta V_j \\ &= \sum_{j=1}^{N} f(x_j)W(x-x_j,h)\frac{m_j}{\rho_j} \end{aligned} \tag{3}$$

Therefore, the SPH particle approximate formula of the function value at particle i is:

$$f(x_i) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W_{ij} \tag{4}$$

Equation (4) shows that the function value of particle i can be obtained by multiplying the function values of all particles in the neighborhood of particle i by their mass and dividing by their density, and then summing the weighted kernel function.

The SPH particle approximation of the function derivative $\nabla \cdot f(x)$ at particle i can be written as:

$$\nabla \cdot f(x_i) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) \cdot \nabla_i W_{ij} \tag{5}$$

The significance of Eqs. (4) and (5) is to transform the continuous integral expression of the field function and its derivatives into a discrete summation expression on arbitrarily distributed particles, so that the SPH method does not need any grid.

Using SPH method to discretize the Navier Stokes equation in space domain, we can get the SPH formula of Navier Stokes equation as follows:

$$\begin{cases} \dfrac{d\rho_i}{dt} = \displaystyle\sum_{j=1}^{N} m_j v_{ij}^{\beta} \cdot \frac{\partial W_{ij}}{\partial x_i^{\beta}} \\ \dfrac{dv_i^{\alpha}}{dt} = -\displaystyle\sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2}\right) \cdot \frac{\partial W_{ij}}{\partial x_i^{\alpha}} \\ \dfrac{de_i}{dt} = \dfrac{1}{2}\displaystyle\sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2}\right) v_{ij}^{\beta} \cdot \frac{\partial W_{ij}}{\partial x_i^{\beta}} \end{cases} \tag{6}$$

where p is the hydrostatic pressure, x is the spatial position vector, v is the velocity vector, Superscript α and β are the directions of spatial coordinates, ρ is density, e is internal energy, t is time, and m is particle mass, N is the number of particles in the neighborhood and W is the kernel function.

We adopted the modified Gadget2 as our computational hydrodynamics code (Springel 2005). Gadget2 has been widely used to simulate giant impacts in general (e.g., Marcus et al. 2009) and specifically the Moon-forming impact (Ćuk and Stewart 2012; Rufu et al. 2017; Lock et al. 2018), making it a reliable tool for this study. In all our simulations, both the impactors and the targets are set to have 30% core and 70% mantle in mass. The materials are modelled using the M-ANEOS equation of state (EOS) (Thompson & Lauson 1974; Melosh 2007). We use the forsterite M-ANEOS table from (Marcus et al. 2009; Ćuk and Stewart 2012) to represent the mantle and the iron M-ANEOS table to represent the core. Our simulations use the number of particles on the order of 10^5 to 10^6, and few special examples use the number of particles on the order of 10^7. These settings are similar with previous studies (Canup and Asphaug 2001; Canup 2012; Ćuk and Stewart 2012; Reufer et al. 2012; Rufu et al. 2017; Hosono et al. 2019).

Before we carry out giant impact simulation, all SPH particles need to go through a relaxation process to achieve hydrostatic pressure equilibrium (Monaghan 1994). As in prior work, we use a velocity damper to reduce relaxation time after the relaxation process, the velocity of each particle must be less than 1% of the typical impact velocity (approximately 10 km/s in the case of Moon-forming giant impact). The proto-Earth in hydrostatic equilibrium is shown in Figs. 2 and 3.

3 SPH simulation results

We divide the proto-Earth's accretion history into three stages, which the proto-Earth's size is $0.01M_\oplus$, $0.1M_\oplus$, and $1M_\oplus$ ($M_\oplus$ is the mass of current Earth). They represent the proto-Earth growing to the size of the Moon, the Mars and the current Earth respectively. In order to understand the consequences of the CMGI event more clearly, we studied

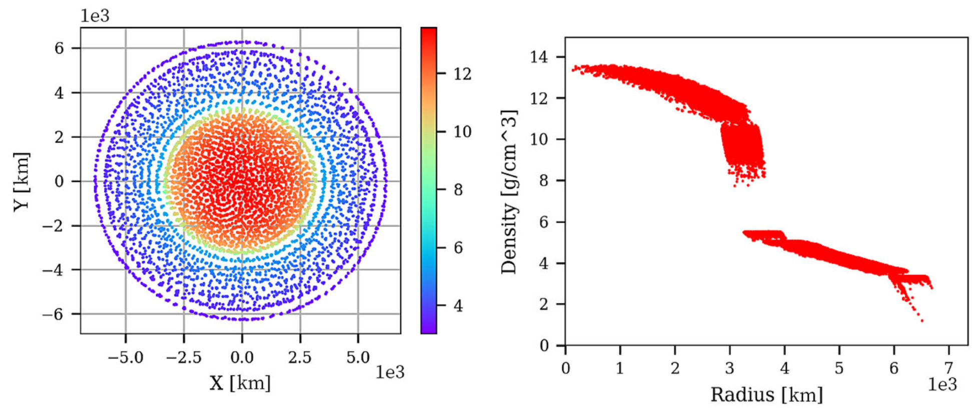

Fig. 2 Radial profiles of the mass and the density of the pro-Earth ($1M_{\oplus}$)

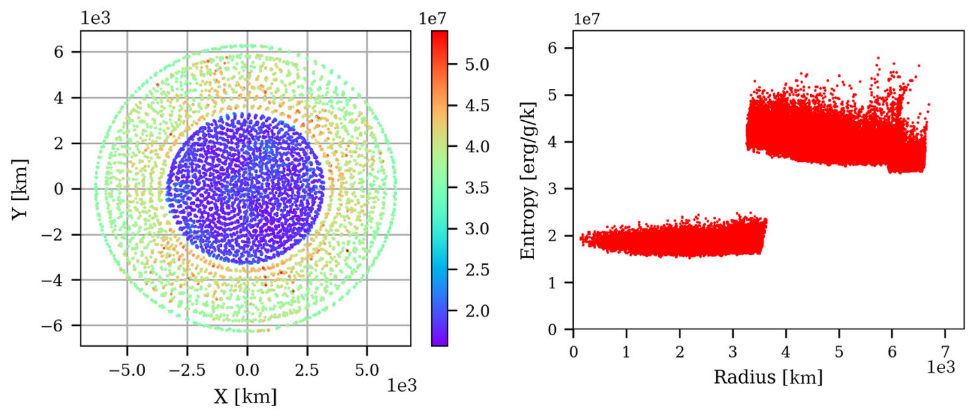

Fig. 3 Radial profiles of the mass and the entropy of the pro-Earth ($1M_{\oplus}$)

all the possible initial conditions of CMGI in these three stages.

We first study the giant impact events in the final stage of Earth's accretion history. Because at this stage, the mutual gravitational interaction between embryos or pro-planets is relatively simple, the initial conditions for a giant impact have been thoroughly investigated (Agnor et al. 1999). We set the target's mass to $1M_{\oplus}$ ($M_{\oplus}$ is current Earth's mass) at this stage. We have performed 240 smoothed particle hydrodynamics (SPH) simulations with impact angle varied from 0° to 90°, impactor's mass varied from $0.05M_{\oplus}$ to $0.5M_{\oplus}$ and impact velocity varied from 1 to 4Vesc (Vesc is mutual escape velocity). Under these impact conditions, most of giant impact's possibilities have been included (Agnor et al. 1999). Figure 4 shows a part of our simulation results at this stage with different impact angles (0°–45°).

It is noteworthy that the target and the impactor will be strongly eroded or even disrupted under high-velocity impact conditions, as shown in Fig. 5. In these cases, both the mantle and the core are collided into fragments, and they should experience a chemical re-equilibrium process.

We summarize all the results of CMGIs under the condition of the Earth's mass is $1M_{\oplus}$, as shown in Fig. 6. Giant impacts are classified as the perfect, the good, the bad and the worst CMGIs as shown in Fig. 4. The examples of the perfect, the good, the bad and the worst CMGI are shown in Fig. 4a, b, d, e, respectively.

According to the above results, we figure that the impact angle is the most important factor for producing a CMGI. Impact angle determines the relative spatial position and move direction of the impactor and the target. Therefore, a small impact angle is necessary for CMGI to occur. Because the cases with larger impact angles are very quickly transit from core-merging collisions to hit-and-run collisions at higher impact velocities (e.g., Asphaug et al. 2006). The sweet spot of impact angle should be at least less than 30°, and preferably less than 20°. A low impact velocity is also important. Because even at the lowest impact velocity (i.e., $1V_{esc}$), the impactor still has enough energy to allow its core to plunge through the pro-Earth's mantle and merge into pro-Earth's core. While at high impact velocity cases (i.e., $\geq 3V_{esc}$), impactors and targets are generally disrupted (Fig. 5). Therefore, a low impact velocity is also required for CMGI, which the impact velocity should be less than $3V_{esc}$, preferably less than $2V_{esc}$. Impactor's total mass controls the thickness of its mantle, which needs to be preserved before impactor's core has been merged into the pro-Earth's core. Such as in perfect CMGI, the impactor's mantle needs to be thick

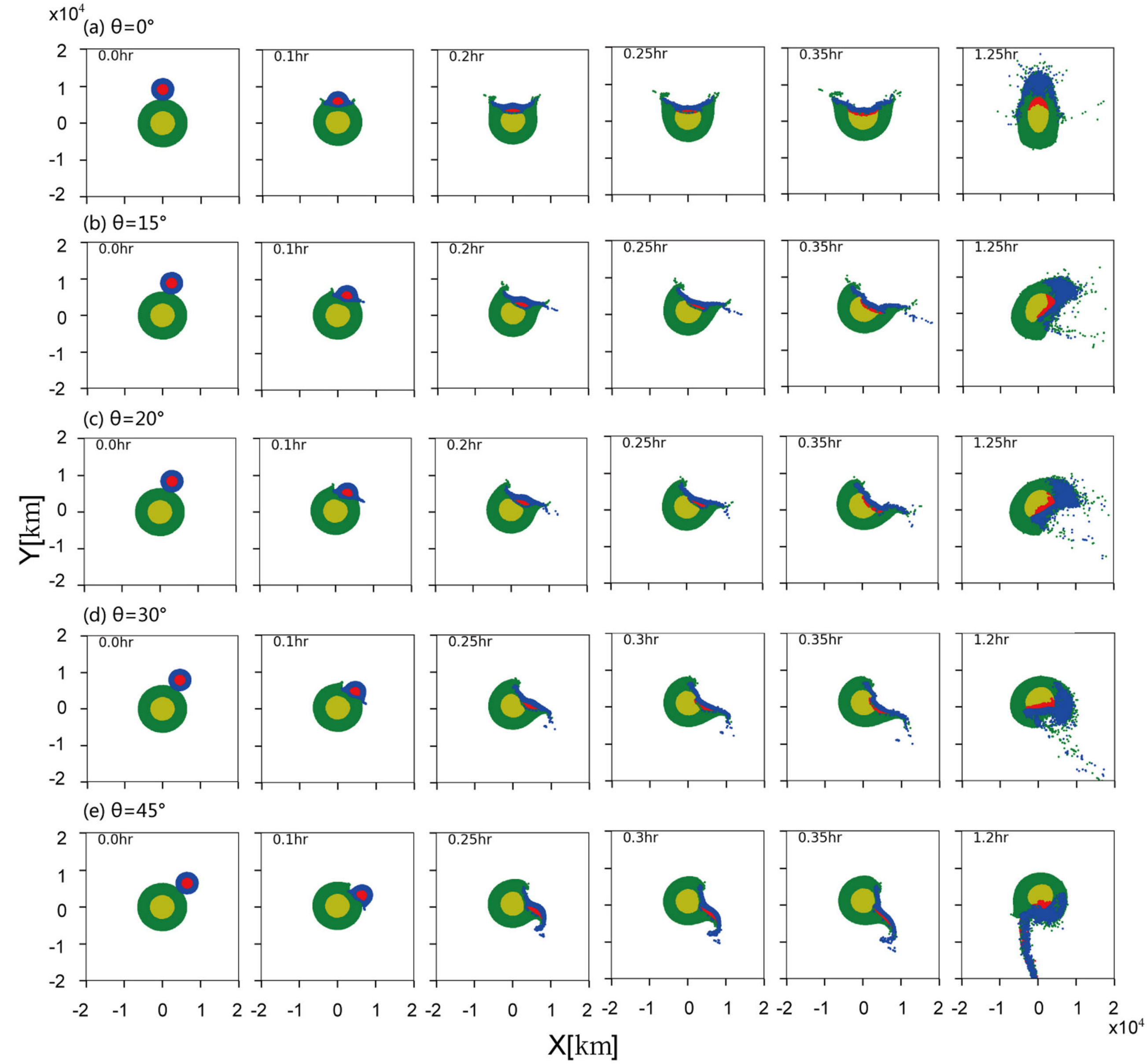

Fig. 4 Snapshots of a CMGI with M_{tar} (mass of target) is $1M_{\oplus}$ (the showed slices are cut between $-0.1R < Z < 0.1R$ from a 3D simulation, where R is radius of target). The X and Y axis are in unit of 10^4 km. The impact velocity is 2Vesc, and impactor's mass is $0.07M_{\oplus}$. Different colors represent different materials (i.e., forsterite for mantle and iron for core). Impactor's move direction is from the top to the bottom

enough to against the turbulence erosion and let impactor' core merge into Earth's core intactly. If the impactor's mantle is too thin, the mantle will be completely eroded and let the impactor's core exposed to pro-Earth's mantle. Therefore, the impactor cannot be too small. Overall, at the Earth's latest accretion stage, small impact angle (< 30°, but < 20° is better), low impact velocity ($< 3V_{esc}$, but $< 2V_{esc}$ is better) and big impactor's mass ($> 0.07M_{\oplus}$) can usually produce a perfect or a good CMGI.

We further test smaller targets with mass at $0.01M_{\oplus}$ and $0.1M_{\oplus}$, in order to find out the happening conditions of CMGI at the other accretion stages. They represent the pro-Earth accrete to the size of the Moon or the Mars, respectively. We also perform hundreds of SPH simulations in this stage. We find that CMGI can still occur in these stages by some chances, as shown in Figs. 7 and 8.

From all the above results, we find that the happening conditions of CMGI at early stages are similar to those at the final stage. We also need small impact angles (< 30°, but < 20° is better), lower impact velocity ($< 2V_{esc}$,-$\sim 1V_{esc}$ is better) and big impactor ($> 0.07M_{tar}$, where M_{tar} is target's mass) to produce a good or perfect CMGI. The difference is that the CMGI in the early stage requires a lower impact velocity compared to the final stage. For

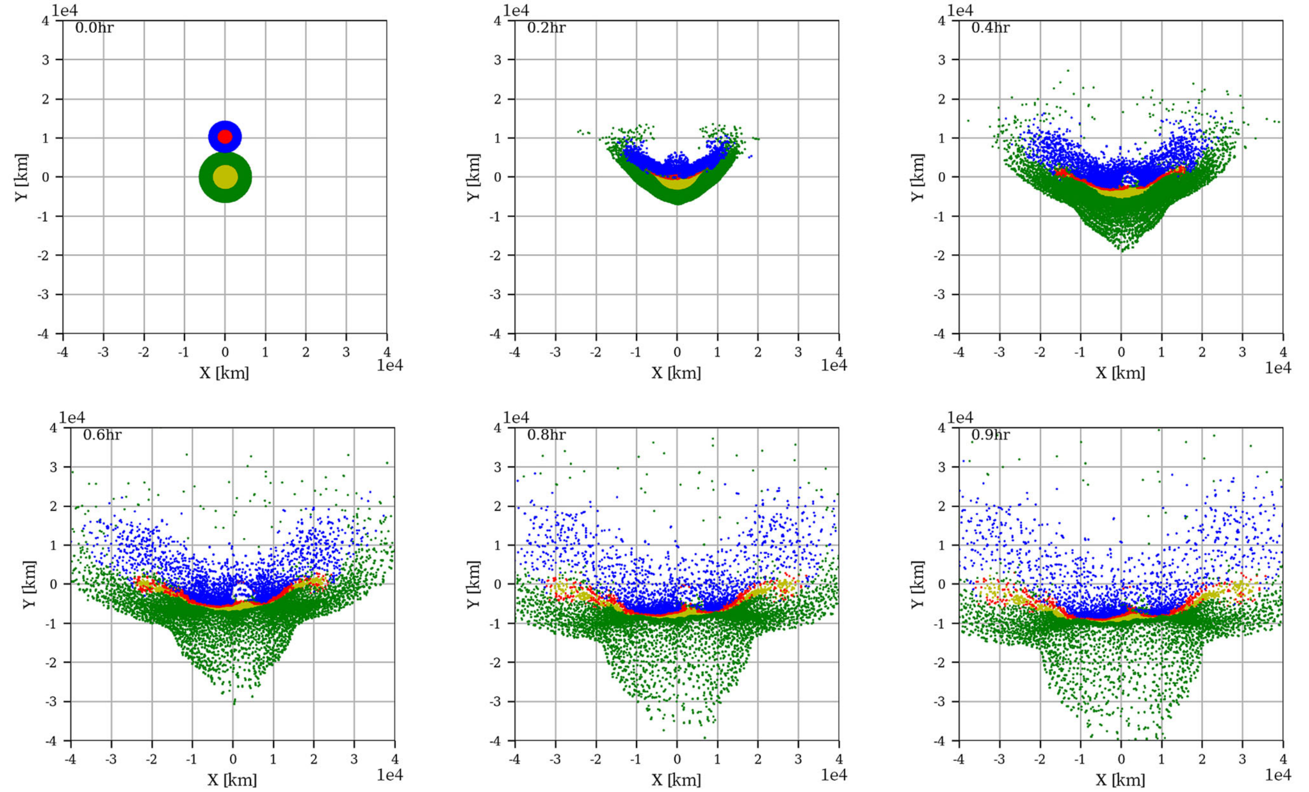

Fig. 5 Example of target and impactor are broken up. The initial conditions are as follows: Impact angle is 0°, Impact velocity is 3Vesc, Impactor's mass is 0.17$M_{\oplus}$ and target's mass is 0.85$M_{\oplus}$ (Mimpactor/Mtarget = 0.2), resolution is 600,000 particles

example, in the final stage, CMGI has many chances to occur when the impact velocity is 2Vesc, while in the early stage, CMGI occurs at the impact velocity around 1Vesc. The early stage needs lower impact velocity is because the sizes of target and impactor will be closer at early accretion stages, which makes targets and impactors are easier to disrupt. Therefore, CMGI is more likely to occur in the late stage of the Earth's accretion history than in its earlier stages. CMGI will undoubtedly cause the Earth's core and mantle to become more disequilibrium, because there is no metal-silicate differentiation in this process. There, we can further speculate that the smaller planetary embryos may be closer to core–mantle chemical equilibrium than larger embryos and proto-Earth, due to lesser chance of CMGIs for small planetary embryos.

4 The influence of different methods and resolutions on the results

In the SPH method, in order to prevent these particles from penetrating the boundary unphysically, we apply artificial tension to the particles adjacent to the boundary. In CMGI scenario, the artificial tension tends to damp the turbulent erosion, so that the impactor's core can more easily maintain its own shape. But for an impactor plunge through Earth's mantle, the total time of this process is very short ($\sim$ 0.2 h). At the same time, the turbulence velocity is much small comparing to the shock wave. Therefore, in theory, the turbulence cannot make significant changes for such quick process. We further use the meshless finite mass (MFM) codes GIZMO (Deng et al. 2019; Hopkins 2015) to examine the influence of turbulence on the erosion of the merging core. We obtained almost identical results, which means that an improved treatment of turbulence and material interfaces does not substantially affect the outcome of CMGI, except for some subtle changes at the Earth's core–mantle boundary.

We further investigated the effect of resolution by carrying out simulations with different resolutions and comparing their results. Different resolutions have no significant impact within the resolution range in this study. (Figs. 10, 11). From our simulations, different resolution scenarios are almost the same when the impactor plunge through the interior of the proto-Earth, including the erosion effect on the core mantle boundary (CMB). But for the particles that sputtered outside of the proto-Earth, there were some differences. This shows that in the SPH simulation, the resolution can affect the simulation of the free

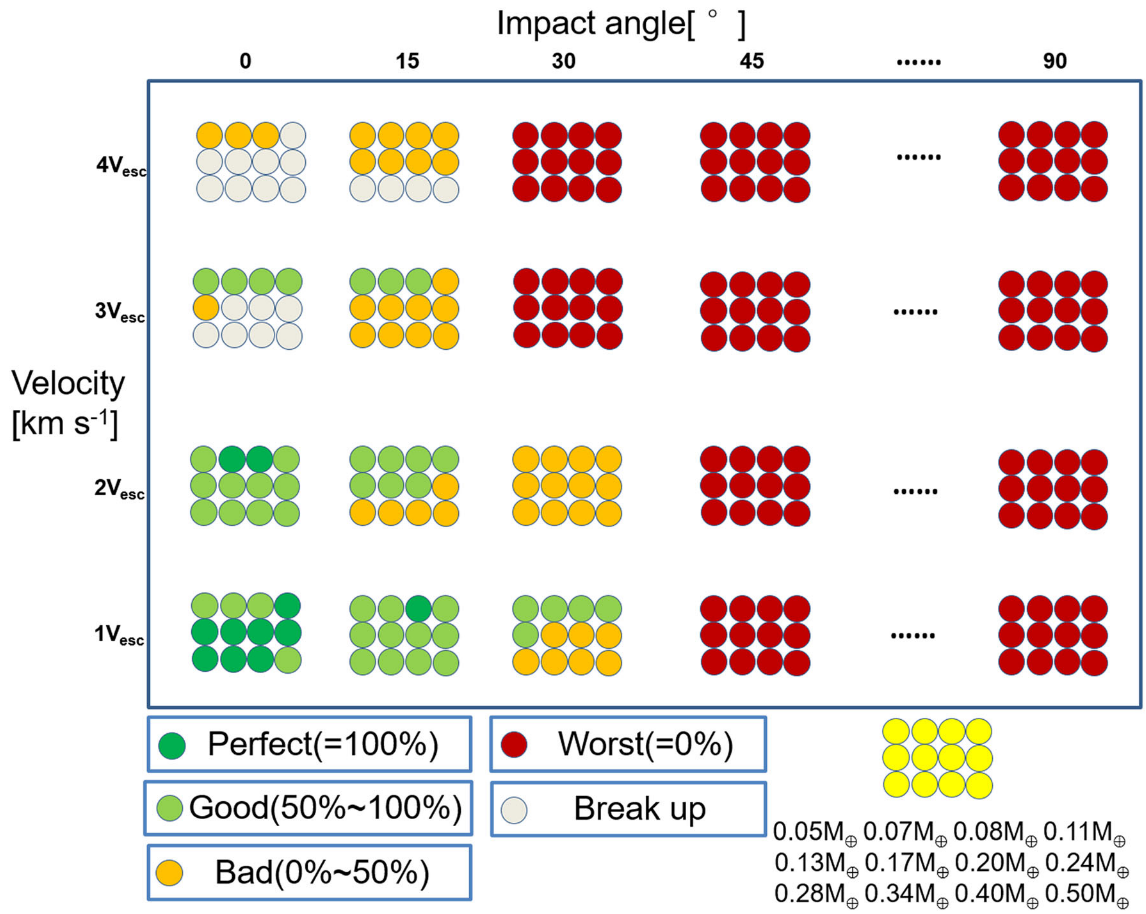

Fig. 6 Results of possible CMGIs at the latest stage of the Earth's accretion. Each circle represents a specific simulation performed in this study. The abscissa is the impact angle, and the ordinate is the impact velocity. Twelve impactors with masses from $0.05M_{\oplus}$ to $0.5M_{\oplus}$ are used for different impact angles and impact velocities as shown at the lower right corner. The dark green circles represent the perfect CMGI. The percentage is the mass of impactor's core that merge to Earth's core directly, e.g., 100% impactor's core has been directly merged to the target's core for the perfect CMGI cases. The pale green circles represent the good CMGI (50%–100% merged). The orange color circles represent the bad CMGI (0%–50% merged). The brown circles represent the worst CMGI (0% merged). The gray circles represent the targets and impactors are totally broken up or largely deformed

surface, but it cannot affect the simulation of the pro-Earth's interior.

5 What is the probability of CMGI happening?

During the Earth's accretion history, considering numerous large or giant impacts happened, the CMGI would undoubtedly have happened for many times (Quintana et al. 2016). But what is the probability of CMGI happening? We can't get an accurate answer to this question, but we can get a statistical result by investigating the initial conditions of CMGI.

The probability of CMGI happening depends on its initial conditions. For giant impacts at pro-Earth's latest accretion stage, their probability distributions of impact angle between θ and $\theta + d\theta$ follow the formula $dP = 2 \sin\theta\cos\theta d\theta$, where P is the probability of impact angle and θ is the impact angle (Shoemaker 1962; Pierazzo and Melosh 2000). The leftovers median of their impactor velocity is about $\sim$ 16 km/s ($\sim$ 1.7Vesc) and the width is $\sim$ 3–4 km/sec (Raymond et al. 2013). The impactor's mass distribution is still very controversial. We adopt the distribution of the impactor's masses by the plots of Agnor et al. (1999).

Based on the above initial conditions, we can discuss the probability of CMGI happening. When the impact angle is less than 30°, the probability of CMGI happening is 25%. When the impact velocity needs to be less than 3Vesc, the probability of CMGI happening is 90% to 95%. When the impactor's mass (Mimp/Mtar) needs to be greater than 0.07, the probability of CMGI happening is 60% to 70%. Overall, in all of the giant impact events, the probability of CMGI happening is 13.5% to 16.625%. This percentage is more accurate in the late stage of Earth's accretion, which is when the proto-Earth grows from $0.1M_{\oplus}$ to $1M_{\oplus}$. But in

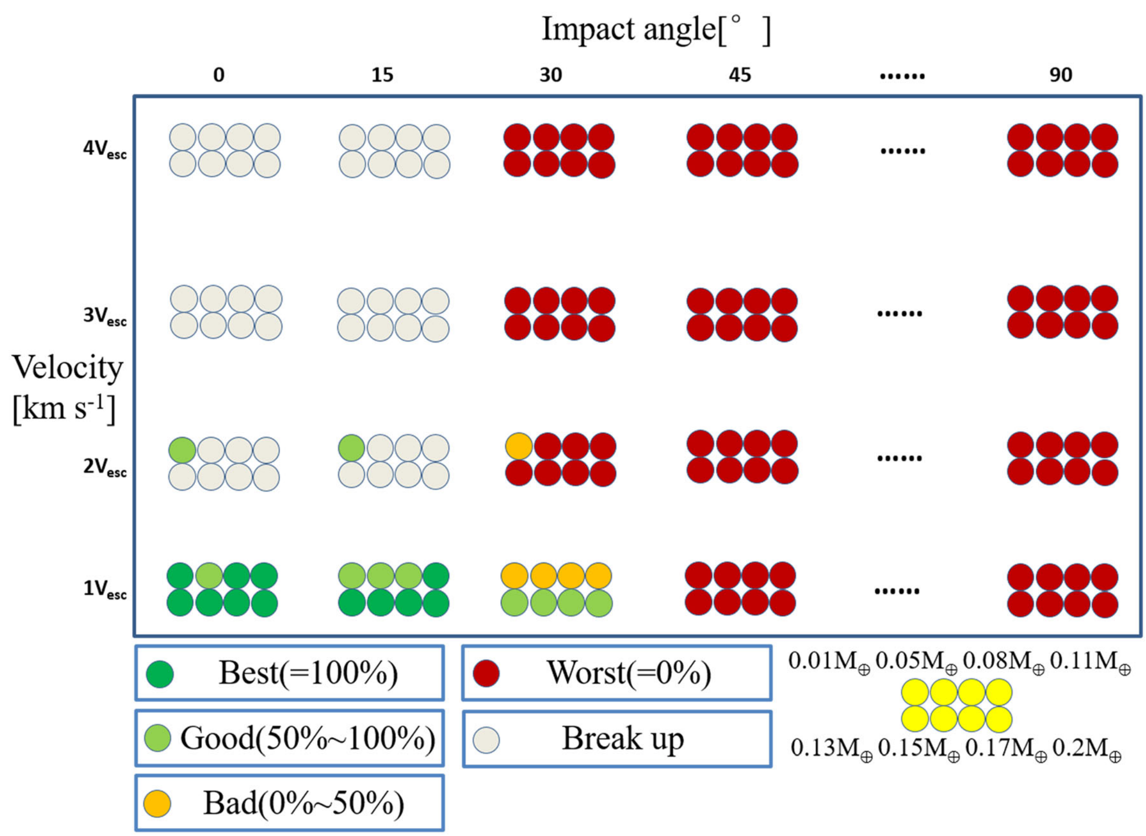

Fig. 7 The simulation results with target mass as 0.1M$_\oplus$. The abscissa is the impact angle, and the ordinate is the impact velocity. The dark green circles represent the perfect CMGI. The pale green circles represent the good CMGI. The pale red circles represent the bad CMGI. The brown circles represent the worst CMGI. The gray circles represent total break up or large deformation

the early accretion stage, which is before the Earth grows to 0.1M$_\oplus$, this percentage cannot be applied, because the gravitational interaction between planetesimals is too complicated at that time.

6 How CMGI affects the Earth's core–mantle element partition?

Earth's core contains a lot of light elements, such as C, S, Si, H, O, etc., which are responsible for lowering the density about 5%–12% for the outer core and 3%–5% for the inner core. However, how these light elements to enter Earth's core is still an unsolved issue (Li and Fei 2014). This study shows that the CMGI can directly bring silicates into the center of Earth's core by trapping them in front of the impactor's core (Fig. 2). These silicates will react with Earth's core, leaving some light elements in the core. For some light elements (e.g., Mg), it is very difficult to bring them into Earth's core if only by chemical differentiation at low pressures. Traditionally, people think core–mantle element partitions were happened at the bottom of a shallow magma ocean (Rubie et al. 2003). However, if some silicates can be brought into the center of the core, the partition coefficients under extremely high temperature and pressure are hence desperately needed. Foreseeably, the element partition at core will be quite different from those at much lower pressures.

Furthermore, if the impactor's core has been enriched with elements such as C and S, etc., these elements will be brought into the Earth's core directly without experience a partition in magma ocean (Fig. 12). Therefore, a terrestrial planet with S-rich core could also enrich C in its core, although the presence of C and S in a terrestrial planet's core is considered to be mutually exclusive under high temperature and pressure experiments. For example, during the accretion of Mars, although it has an S-rich core (Fei and Bertka 2005), some C-rich materials could also be brought into the Mars's core by a CMGI.

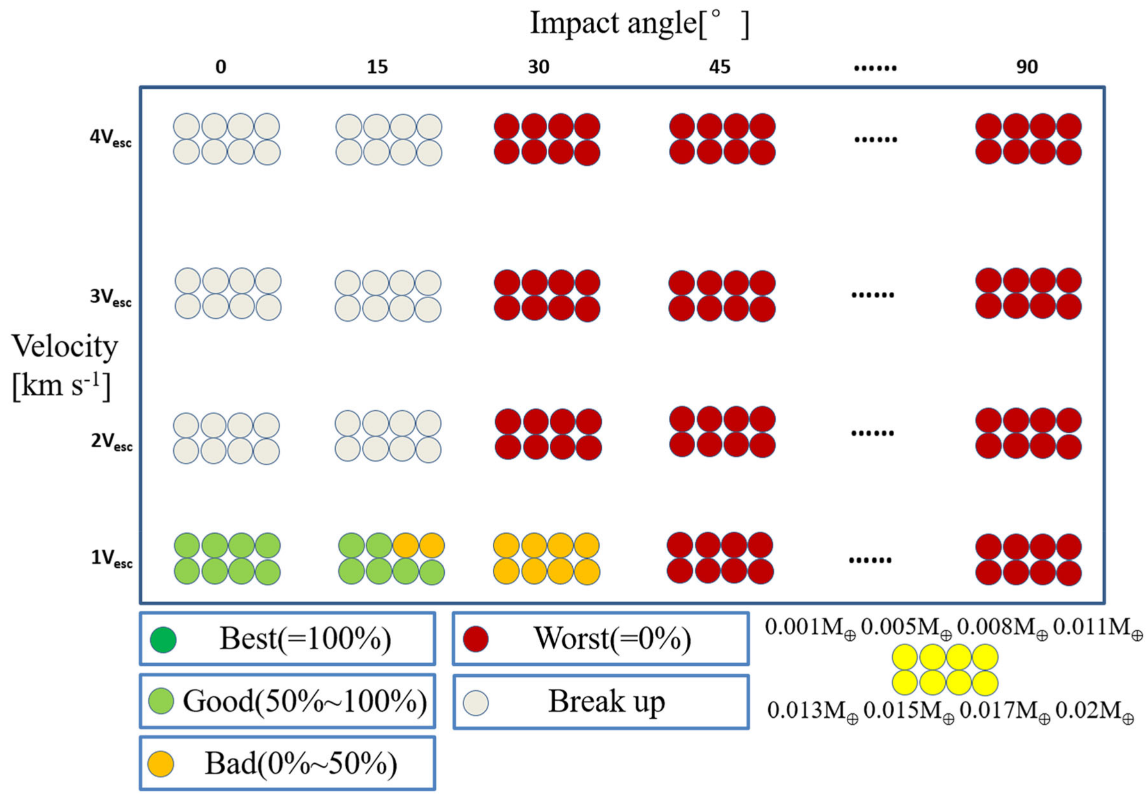

Fig. 8 The simulation results with the target mass as $0.01M_{\oplus}$. The abscissa is the impact angle, and the ordinate is the impact velocity. The dark green circles represent the perfect CMGI. The pale green circles represent the good CMGI. The pale red circles are mostly hit and run scenarios, representing the bad CMGI. The brown circles represent the worst CMIG. The gray circles represent total break up or large deformation cases

7 What if the Moon-forming giant impact was a CMGI?

Statistically, CMGI can certainly occur during the accretion of a terrestrial body. However, the last giant impact, i.e., the Moon-forming giant impact, may or may not be a CMGI. Recently, there are more and more studies suggest that the Moon-forming giant impact may be a CMGI. For explaining the mantle carbon excess paradox, Li et al. (2016) suggests the last giant impact is a core merging giant impact. Wang et al. (2021) also supports that the lighter Ni isotope of the Earth can only be explained when the Moon-forming giant impact is a CMGI.

The first question is whether a CMGI can produce the Earth–Moon system in terms of proper disc mass, angular momentum, etc.? Ćuk and Stewart (2012) have simulated the Moon-forming giant impact and obtained a successful Earth–Moon system by using an impact angle as $\sim$ 17.5°. In such simulation, most of impactor's core have been merged into Earth's core directly. It means there is plenty parameter space to produce the Earth–Moon system with a CMGI-like event. What is the consequence if the Moon-forming giant impact really is a CMGI?

We find that the CMGI can affect the partition of highly siderophile elements (HSEs) (Os, Ir, Ru, Pt, Pd and Re) or moderately siderophile elements (MSEs) (O, C, H, Si, etc.) by affecting the reaction chance or degree between metal and silicate. HSEs have a strong tendency to be partitioned into metal relative to silicate. The contents of HSEs in Earth's mantle are much higher than the values estimated from experiments of equilibrium element partition between metal and silicate. It is generally believed that after the last giant impact (the Moon-forming giant impact), almost all HSEs would go into the Earth's core due to a global magma ocean event and well mixing of metal and silicates. Therefore, excessive HSEs were thought to be delivered by late accretion after the solidification of the mantle. The magnitude of excess of HSEs had been used to constrain the amount of materials delivered in the late accretion, which was estimated about 0.5% of the entire Earth's mass (Mann et al. 2012; Rudge et al. 2010).

However, if the last giant impact is a CMGI, the concentrations of HSEs of mantle will be different from what previously assumed. We use the two-stage model as Earth's growth model to simulate the HSEs content in the mantle (as shown in Fig. 13, the yellow lines), in which Earth's mass have a step up due to the Moon-forming giant

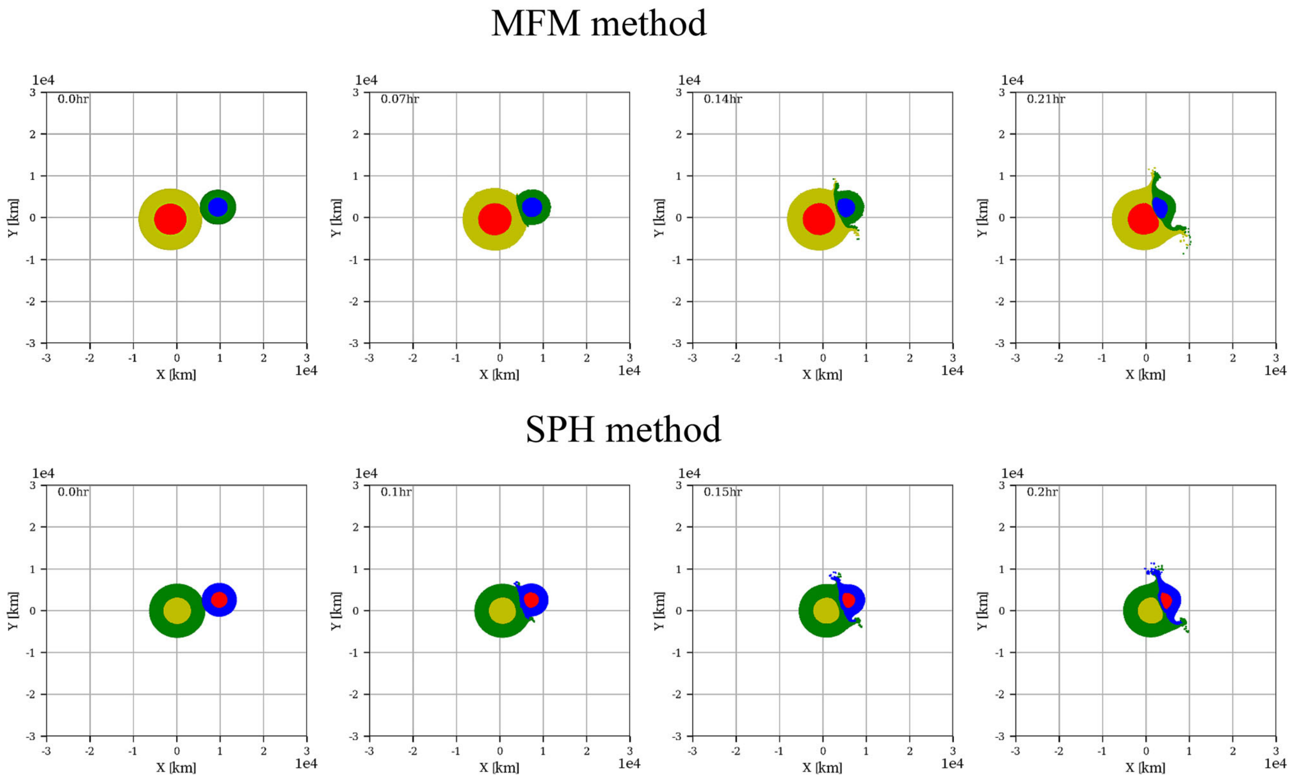

Fig. 9 Comparison of the simulation results of the MFM and SPH method. The core-core merge process simulated by using the MFM method and SPH method. The initial conditions are as follows: Impact angle is 15°, Impact velocity is 1Vesc, Impactor's mass is $0.2M_{\oplus}$ and target's mass is $0.85M_{\oplus}$. Both simulation methods have a resolution of 600,000 particles. Impactor's move direction is from the right to the left

impact in the late stage of Earth's accretion (Raymond et al. 2006; Rudge et al. 2010). Before the first core–mantle differentiation, the black line will stay in the range of chondrite. After the first global magma ocean caused by a large impact, all the HSEs will be carried into Earth's core (Fig. 13a), while the black line declines to zero. As the Earth growing, its HSEs would also be slowly accumulated, and the black lines will rise. The cumulative rate of HSEs is an assumption between the first differentiation event and the giant impact event, because it was great affected by different N-body simulations. But in subsequent global magma oceans, these HSEs would still be brought into the Earth's core, so the black line will rise and fall repeatedly (Fig. 13). We assume that the Moon-forming giant impact occurred at 120 Ma, which is the time of the last global magma ocean (Rudge et al. 2010). In most models, the Moon-forming giant impact would take away all HSEs which were accumulated in the mantle (the black dash line). But if the Moon-forming giant impact is a CMGI, it won't change the HSEs abundances in mantle at all. In a perfect CMGI, the impactor's core will directly merge to Earth's core, to let the mantle have chance to survive some HSEs previously accumulated (Fig. 13b). Therefore, the HSEs might not be reset to zero (as the black dotted line) in this CMGI scenario. Instead, HSEs will keep accumulating and the black line will rise to the green area (current mantle value). Hence, the CMGI may significantly affect the HSEs content and provide another explanation on the excess of HSEs in Earth's mantle.

Because people used the concentrations of HSEs in mantle to estimate the amount of materials added to Earth after the solidification of mantle, our CMGI model requires much less materials in the late veneer process. Marchi et al. (2017) suggested 2 to 5 times more materials were delivered compared to that previously estimated amount for the late veneer (0.5 wt%), because large metallic fragments of impactors can easily plunge through the solidified mantle and let lesser HSEs remained in mantle. If the last giant impact is a CMGI, the mass of late accretion estimated by HSEs could be smaller because of the survived excess HSEs in mantle. It will lower what Marchi et al. (2017) suggested by some degree, depending on how many previous HSEs survived since the previous giant impact. Therefore, the previously estimated proportion of late veneer, i.e., 0.5% of total mass of Earth, maybe still can be accounted for.

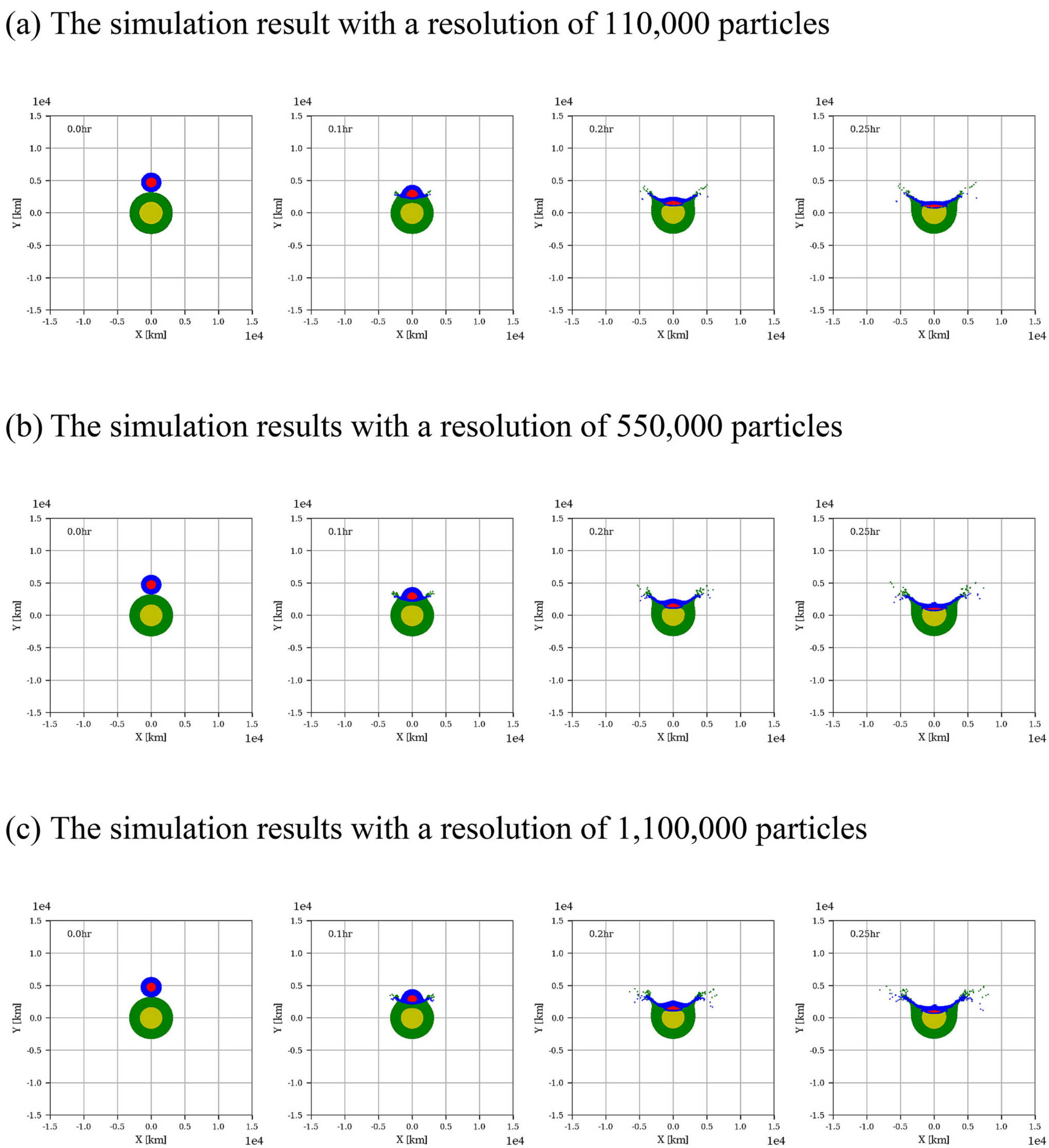

Fig. 10 Comparison of simulation results with different resolutions. The initial conditions are as follows: Impact angle is 15°, Impact velocity is 1Vesc, Impactor's mass is $0.01M_{\oplus}$ and target's mass is $0.1M_{\oplus}$($M_{impactor}/M_{target}$ = 0.1). These three examples with different resolutions are exactly the same in the core-merging process, but there are some differences in the simulation of free surface

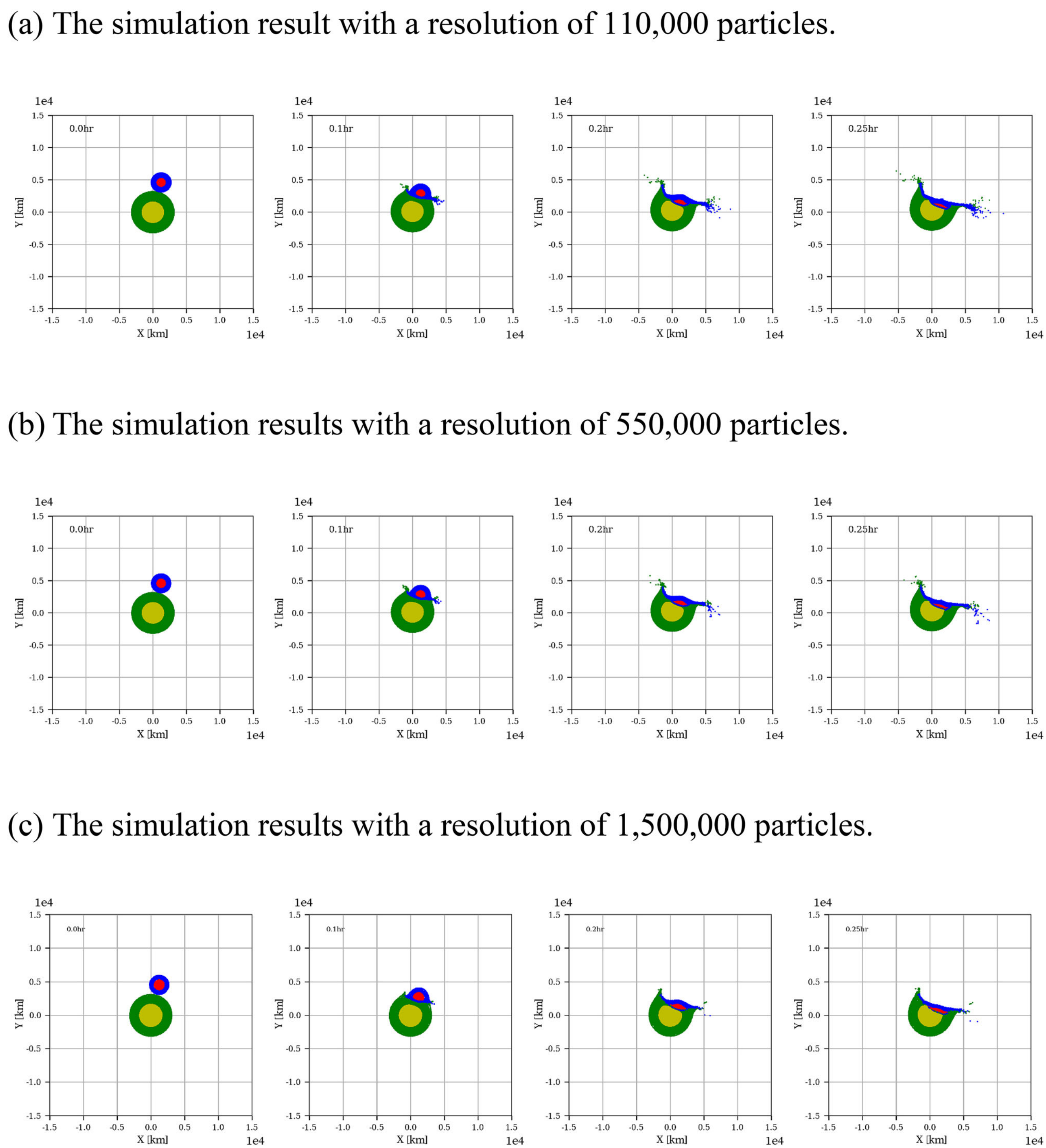

Fig. 11 Comparison of simulation results with different resolutions. The initial conditions are as follows: Impact angle is 0°, Impact velocity is 1Vesc, Impactor's mass is $0.01M_{\oplus}$ and target's mass is $0.1M_{\oplus}(M_{impactor}/M_{target} = 0.1)$

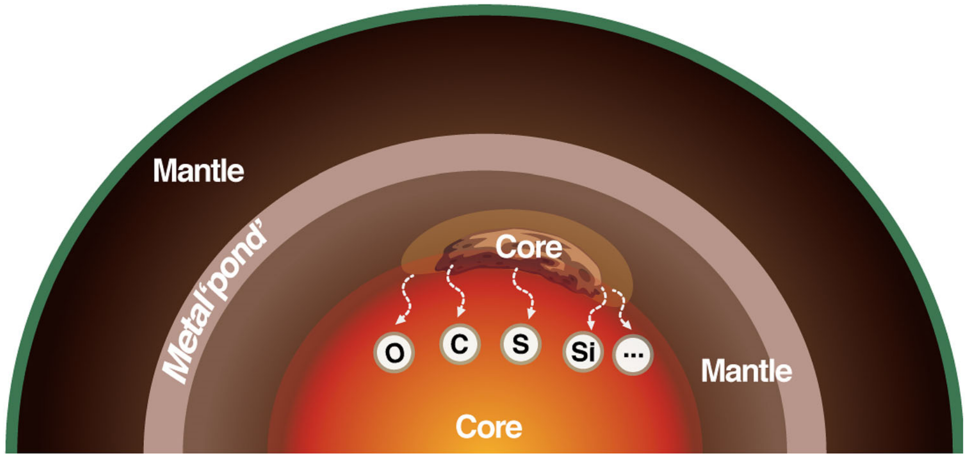

Fig. 12 A possible model of light elements entering Earth's core caused by CMGI

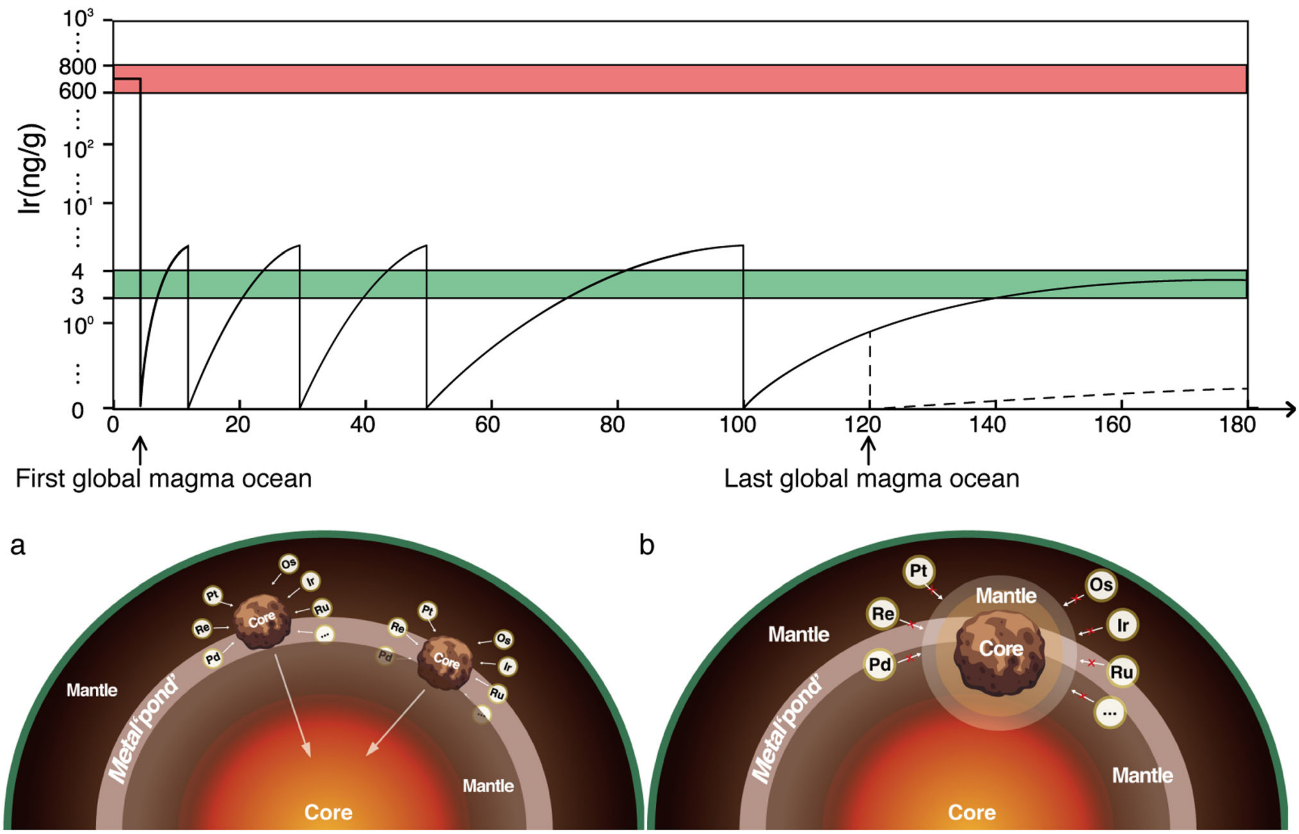

Fig. 13 HSEs contents changed with the process of Earth's accretion. X axis is the time and Y axis is the concentrations of HSEs in mantle. The black line is the HSEs contents change during the Earth's accretion. The red region represents the HSEs content in chondrite (600–800 ng/g). The green range represents HSEs contents in the Earth's primitive upper mantle (3–4 ng/g). **a**, **b** show possible effects of the partition of HSEs between silicate mantle and metallic core in a global magma ocean

8 Conclusions

We have systematically investigated the conditions of a special kind of impact, i.e., the core-merging giant impact, also called as the CMGI. We find that the impactor's core can merge with the target's core directly under appropriate initial conditions. From our simulation results, a small impact angle ($< 30°$, but $< 20°$ is better), a lower impact velocity ($<$ 3Vesc, but $<$ 2Vesc is better) and a big impactor's mass ($>$ 0.07Mtar) can usually make a good or best CMGI.

CMGI can be happened for different targets from planetesimals to planets. But it is much easier in the late stage than the early stage in the Earth's accretion history.

Although the CMGI was not a common phenomenon in the proto-Earth's accretion, but if we consider the total number of impacts that occurred in the accretion of the proto-Earth, the CMGI definitely had chance to bring an influence on the proto-Earth's accretion process.

In essence, CMGI is a new mode of Earth's core formation without experience the sufficient core–mantle differentiation process, which has an important influence on the Earth's deep core and mantle. The influence of CMGI on the Earth includes (1) causing disequilibrium of the Earth's core and mantle; (2) bringing light elements to the Earth's core; (3) possibly affecting the HSE content in the mantle. The more influence of CMGI still needs to be further explored.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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