GIANT IMPACT ORIGIN FOR THE LARGE LOW SHEAR VELOCITY PROVINCES

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Introduction: The Moon is widely recognized as formed from the "Giant Impact": when at least a Mars-sized planetary embryo Theia collided with the proto-Earth during the last stage of terrestrial planet formation [1]–[4]. Such a model is well aligned with some key physical aspects of Earth-Moon system, including anomalous high angular momentum of Earth-Moon system, small iron core of the Moon and its high mass ratio compared to the Earth [2], [4]. However, one of the most critical issues related to this scenario is that no evidence has been found for the existence of the hypothesized planetary embryo Theia. This is in part because of its widely debated size ranging from 0.1~0.45 Earth mass ($M_\oplus$) [5] and enstatite to carbonaceous chondrite composition [6]–[9]. Moreover, whereas it is mostly agreed that the core of Theia promptly merged with the proto-Earth core shortly after the impact [3], what fraction of and how the Theia mantle was preserved into the Earth mantle remain elusive. This post-impact process is not only responsible for the initial thermal and compositional structures of the Earth, but also significantly affects Earth's long-term chemical evolution.

In the meantime, the continent-sized Large Low Shear Velocity provinces (LLSVPs) above the core-mantle boundary has been seismically identified [10], [11], which play an important role to understand the structure and thermochemical evolution in the deep mantle [10], [12]. Although purely thermal origin of the LLSVPs are not completely ruled out [13], growing evidences relate them to chemically dense thermochemical piles [14], [15] as the LLSVPs show anti-correlation between shear-wave and bulk-sound velocity [16], [17] and sharp side boundaries [18]–[20]. The correlation between LLSVP margins and surface hotspots together with reconstructed locations of large igneous provinces [21], [22] is better satisfied with a chemically denser component which is more likely to be stable for at least 250 Ma [23]. In this scenario, the dense materials have been proposed to origin from the remnants of ancient differentiation process [24]–[26], the subducted oceanic crust [27]. All these different hypothetic origins of the dense materials in the lowermost mantle are due to the Earth's internal differentiation. However, increasing studies of noble gases, such as neon, xenon and helium, show less degassed primordial characters of some oceanic island basalts (OIBs) than the middle ocean ridge basalt (MORB) established by 4.45 Gyr ago [28]. If the OIB rocks were indeed derived from the LLSVPs as suggested [23], these noble gas isotopes suggest LLSVPs should exist since the formation of the Earth and was preserved even after the Moon-forming impact [28].

Simulations of the Giant Impact suggest that at least some intact pieces of Theia's mantle may have persisted in the Earth's mantle throughout Earth's history (e.g., [5]). In this study, we hypothesize that, due to its possible enrichment in iron [29], [30], the left-over Theia mantle materials may sink to the bottom of Earth's mantle and cause the LLSVPs (Fig. 1). We provide several lines of evidence and perform numerical modeling experiments to support this hypothesis.

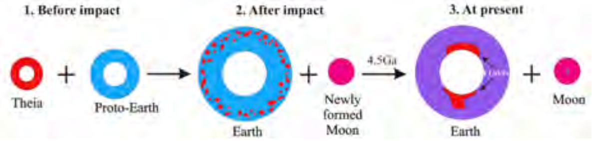

***Fig. 1** The Giant Impact hypothesis for the origin of the LLSVPs.*

Geodynamic modelling: We perform numerical calculations to explore the dynamics of the left-over Theia mantle in the Earth mantle. The conservation equations of mass, momentum and energy were solved under the Boussinesq approximation with the Citcom code in a 2D Cartesian geometry [31]. Our models contain 2 compositional components: the Theia mantle materials (TMM) and the background Earth's mantle materials. Theia mantle materials were introduced at the surface of the model at the beginning of each calculation. So far, the initial distribution of TMMs within Earth's mantle after the Giant Impact is unclear [32]. We therefore explored two end scenarios with one being global homogenous layer and the other one being random ball mixed with Earth's mantle, with the assumption that they are not completely molten [33].

We define successful models in which the TMMs sink to the lowermost mantle, accumulate on the CMB, and form into spatially isolated thermochemical piles that occupy 3-15% area of the 2D model domain after 4.5 Gyr, similar to the present-day LLSVPs which occupy ~3-9 vol% of the Earth's mantle [21], [34]. Our geodynamic numerical experiments consistently show that the Theia mantle will sink down to the CMB and survive mixing due to mantle convection throughout the Earth's history if it is denser than Earth's mantle. The favored density anomaly is 1.5–3.5% with the initial thickness of TMM in the range of 350 km and 500 km.

Density of Theia mantle: Meier et al. (2014) [29] systematically explored the FeO contents of Theia mantle in all different kinds of giant impact models including Canonical, Hit-and-run and high angular momentum models and found FeO needs to be between 11%-40 wt% to reconcile the isotopic similarity and FeO dissimilarity between Moon and Earth. All of them are significantly higher than that in enstatite chondrite, which is accepted as the building materials of Proto-Earth [35]. In order to explain the very low-D/H (δD ≈ -750‰) content of some lunar samples [36], Desch and Robinson (2019) [30] propose the FeO content of Theia mantle should large than 13 wt%, but also less than 18 wt% so as to be compatible with impact models.

Following Desch and Robinson (2019) [30], we calculate the densities of Theia's mantle assuming its minerals are a mixture of oxides FeO, MgO and SiO2 with a fixed molar ratio of Mg/Si = 1, and a variable FeO content of 13, 15, or 17 wt%. We adopt the bulk silicate Earth composition [37] for the mantle of the Earth after the giant impact. We calculate the mineralogy and density for Theia's mantle and Earth's mantle using the thermodynamic modelling program Perple_X [38], [39], the thermodynamic dataset from [40], and two different geotherms ([41], [42]). Since Fe is the heaviest of the major elements, the FeO-rich Theia mantle compositions are systematically denser than the bulk silicate Earth throughout the mantle. At most mantle depths, the Theia mantle compositions are ~2.0 – 3.5% denser than the BSE, which is consistent with the required density anomaly of ~1.5 – 3.5% as constrained by geodynamic simulations.

Discussion: The Giant Impact hypothesis is one of the most examined model for the formation of Moon, but direct evidence indicating the existence of the impactor Theia remains elusive. First-principles modeling and predictions are complicated by the uncertainty in the size and composition of Theia itself. Here, we demonstrate that Theia's mantle may be several percent intrinsically denser than Earth's mantle, which enables the Theia mantle materials to sink to the Earth's lowermost mantle and accumulate into thermochemical piles that may cause the seismically-observed LLSVPs.

Our hypothesis is also consistent with the isotope geochemistry of OIBs and lunar samples. Mukhopadhyay (2012) [28] found that the OIBs have a lower isotopic ratio of ^{129}Xe/^{130}Xe than MORB, indicating that the source of OIBs contains primitive materials that are have not been mixed by the Moon-forming Giant Impact and the ~4.5 Gyr history of mantle convection. Williams et al. (2019) [43] also found that OIBs above the LLSVPs preferentially have primitive, low ^{4}He/^{3}He ratios. It is suggested that the OIB sources contain materials brought up by mantle plumes from the LLSVPs. Therefore, the primitive materials may origin from the LLSVPs, which is well explained if the LLSVPs preserve Theia mantle materials that are older than the Giant Impact.

References:

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