The Earth's Greatest Natural Disaster

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The rocks of the earth and moon have such similar mineral composition that it is generally thought that the moon was created in the aftermath of a giant impact between Earth and a smaller planet about the size of Mars named Theia. However, no trace of Theia has ever been discovered in the asteroid belt or in meteorites. Wang et al. (2016) showed that a low-energy impact cannot explain small isotopic differences between lunar and terrestrial rocks; instead, a much more violent impact is needed to vaporise Theia and most of the proto-Earth, expanding to form an enormous superfluid disk out of which the Moon eventually crystallized.

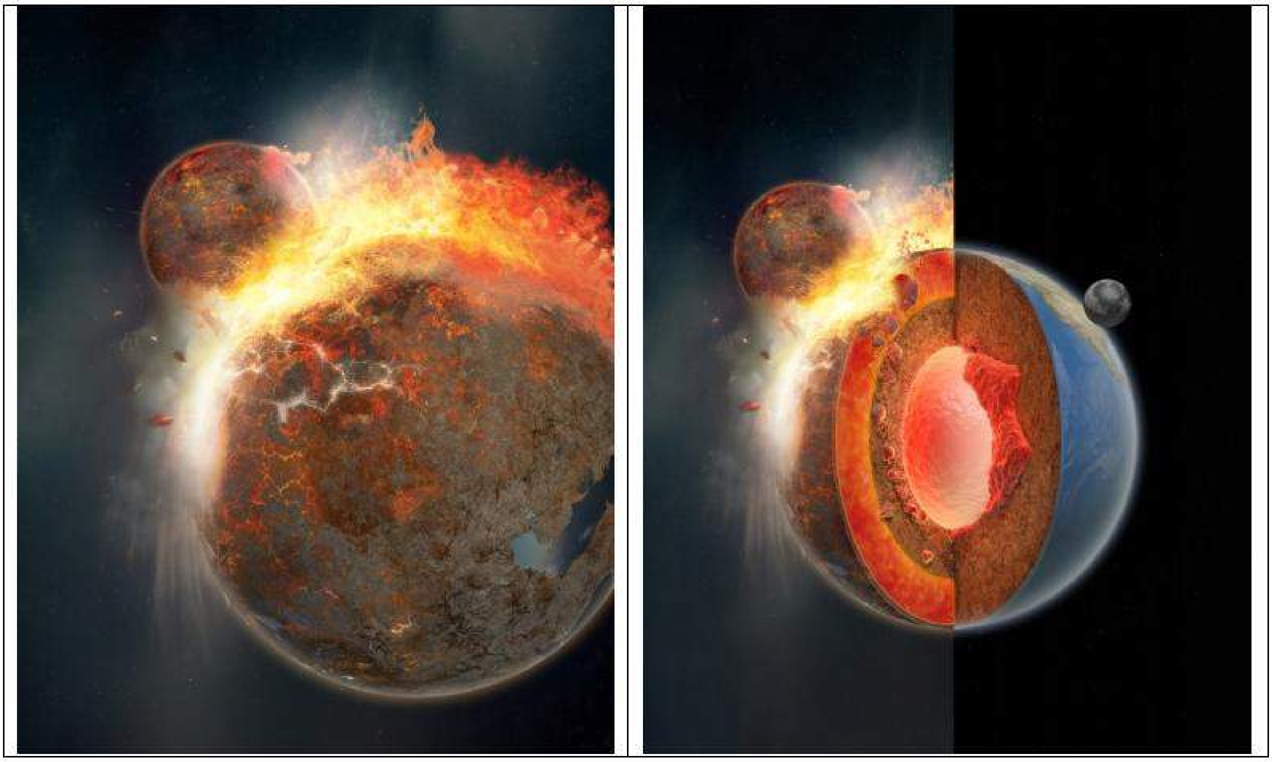

Figure 1. *Left panel: Artist's impression of the collision of Theia (top left) with Earth (centre). Right panel: Artist's impression of the early structure of the Earth (left half) and current structure of the Earth (right half), showing the liquid iron and nickel outer core at the centre (pink), the solid but convecting mantle (brown) with an exaggerated red blob, and the solid earth's crust (the thin outer shell). The moon is shown in the upper right. Artwork by Hernan Canellas/image courtesy of Arizona State University.*

In the 1980s, seismologists discovered two continent-sized blobs of unusual material, known as large low-velocity provinces (LLVPs), located at the base of the Earth's mantle at the core-mantle boundary, one beneath the African continent and one beneath the Pacific Ocean. They are interpreted to be regions with unusually high iron content, whose increased density and temperature reduce the velocities of seismic waves that pass through them (Garnero et al., 2016).

Yuan et al. (2021, 2023) suggest that the blobs are remnants of the ancient planet Theia that violently collided with Earth 4.5 billion years ago, in the same giant impact that created our moon. They conclude that most of Theia was absorbed into the young Earth, forming the LLVP blobs, while residual debris from the impact coalesced into the moon. It is thought that Theia struck the Earth with a glancing blow, resulting in the 23.5° tilted axis of the Earth, thus causing the seasons.

The moon appears to have materials within it that are representative of both the pre-impact Earth and Theia, but it was initially thought that any remnants of Theia in the Earth would have been erased and homogenized by billions of years of dynamics, such as mantle convection, within the Earth. However, Yuan et al. (2023) make the case that distinct pieces of Theia still reside within the Earth, at its core-mantle boundary.

Given such a violent impact, why would Theia's material clump into the two distinct blobs instead of mixing together with the rest of the forming planet? Yuan et al.'s (2023) simulations showed that much of the energy delivered by Theia's impact remained in the upper half of the mantle. Because the impact did not completely melt the lower mantle, the blobs of iron-rich material from Theia stayed largely intact. It was found that the dense, iron-rich materials from Theia could sink to and accumulate at the base of Earth's mantle and remain there through Earth's history.

It is also thought that the collision may have initiated plate tectonics (Yuan et al., 2016). Of all the planets, Earth is the only one known to have plate tectonics, in which plates diverge at ocean ridges and converge in subduction zones, causing the earthquake and volcanic activity of the Earth, driven by convention currents caused by heat generated by radioactive decay in the mantle. Yuan et al. (2023) found that once these hot blobs had sunk to the bottom of the mantle, they could have caused the upwelling of large plumes of warm mantle material, initiating and driving plate motion. It is thought that subduction began about 200 million years after the collision of Theia with Earth.

I was an observer of the crucible in which these ideas took form: weekly seminars at 4pm on Friday afternoons at the Seismological Laboratory at Caltech in Pasadena, California, sometimes also attended by researchers at Caltech's Division of Geological and Planetary Sciences. The extraordinarily high level of rigorous questioning of speakers from a wide range of areas of expertise in the audience provided an efficient way of fostering creative thinking and eliminating invalid assumptions and concepts. Ed Garnero, a graduate student in seismology at the time I was working as an engineering seismologist in Pasadena, had Don Helmberger as PhD supervisor, and I followed their discovery of the blobs while I interacted with Helmberger in areas closer to my field, the modeling of strong ground motions from earthquakes. The first author of the key papers on the collision, Qian Yuan, was Garnero's graduate student at Arizona State University before becoming a postdoctoral fellow at Caltech, completing a circle sustaining the high level of productivity in research at Caltech.

REFERENCES

Garnero, E. J., McNamara, A. K. & Shim, S. H. (2016). Continent-sized anomalous zones with low seismic velocity at the base of Earth's mantle. Nat. Geosci. 9, 481–489 (2016).

Ogasa, Nick (2023). A moon-forming cataclysm could have also triggered Earth's plate tectonics. https://www.sciencenews.org/article/moon-planet-collision-earth-plate-tectonics.

Wang, K. et al., (2016). Potassium isotopic evidence for a high-energy giant impact origin of the Moon, *Nature* (2016). DOI: 10.1038/nature19341

Yuan, Q., M. Gurnis, and P.D. Asimow (2023). A Giant Impact Origin for the First Subduction on Earth. 54th Lunar and Planetary Science Conference 2023 (LPI Contrib. No. 2806)

Yuan, Q., Li, M., Desch, S.J. et al. (2023). Moon-forming impactor as a source of Earth's basal mantle anomalies. Nature 623, 95–99 (2023). https://doi.org/10.1038/s41586-023-06589-1

Yuan, Q., Li, M. M., Desch, S. J. & Ko, B. (2021). Giant Impact Origin for the Large Low Shear Velocity Provinces. 52nd Lunar and Planetary Science Conference LPI Contrib. No. 2548 (2021).

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