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ÉCOLE DOCTORALE
SCIENCES DE LA TERRE ET DE L'ENVIRONNEMENT ET PHYSIQUE DE L'UNIVERS, PARIS

Titre du sujet : Mixing, stratification & chemical heterogeneities following giant impacts

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Equipe d'accueil : **IPGP- Equipe de Dynamique des Fluides Géologiques – UMR7154**

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Motivations & open questions:
The formation of the Earth and other planets involved **giant impacts** between planetary embryos. Each impact lasted only a few hours, yet it was decisive: it set the initial temperature & composition for the planet evolution.

During each giant impact, shock waves melted the colliding embryos (Nakajima et al. 2021). The core and mantle of the impacting body were then released in a fully-molten silicate magma ocean. In this ocean, the impactor core quickly fragmented into metal drops (Landeau et al. 2014, Maller et al. 2024), which equilibrated with a fraction of the magma ocean silicates (Deguen et al. 2014, Wacheul & Le Bars 2018, Landeau et al. 2021). Accretion models predict that the metal and silicates added by each impact likely had a different composition from that of the proto-core and mantle (Rubie et al. 2011, 2015, Jacobson et al. 2017). As a result of this heterogeneous accretion, the core and the mantle of the Earth were likely partially stratified in composition after their formation (Rubie et al. 2015, Jacobson et al. 2017, Landeau et al. 2016).

An early stratification of the core is problematic: it could have impeded the initiation of the geodynamo. Yet, we know that the geodynamo started within the first billion years of the Earth (Tarduno et al. 2014). It is unlikely that convection eroded this stratification in less than 1 Gyrs (Bouffard et al. 2020). Another mechanism must therefore have destroyed it. **Did the last giant impacts that formed the Earth mix the early core?**
On the mantle side, in addition to heterogeneities inherited from accretion, the solidification of magma oceans likely generated mantle heterogeneities (Boukaré et al. 2025). Isotopic anomalies in Nd and W support the presence of distinct chemical reservoirs during the first 150 million years of our planet (Boyet et al. 2003, Touboul et al. 2012, Mundl et al. 2017). It is therefore likely that the magma pond generated by each giant impact was at least partially stratified in composition. However, current models of the cooling, mixing and degassing of a fully-liquid magma ocean assume that the ocean was initially well-mixed and hence unstratified (Lebrun et al. 2013, Monteux et al. 2016, Thomas et al. 2024, Salvador & Samuel 2023). This assumption implies that each giant impact efficiently mixed its own magma pond. **Yet, the mixing efficiency by an impact is poorly known. Did giant impacts fully homogenized Earth's magma ocean?**

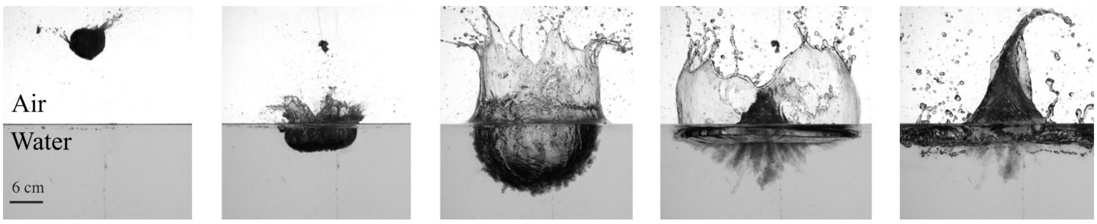

Figure 1: Liquid impact experiment (Landeau et al. 2021). Time = 0.3 s in last image.

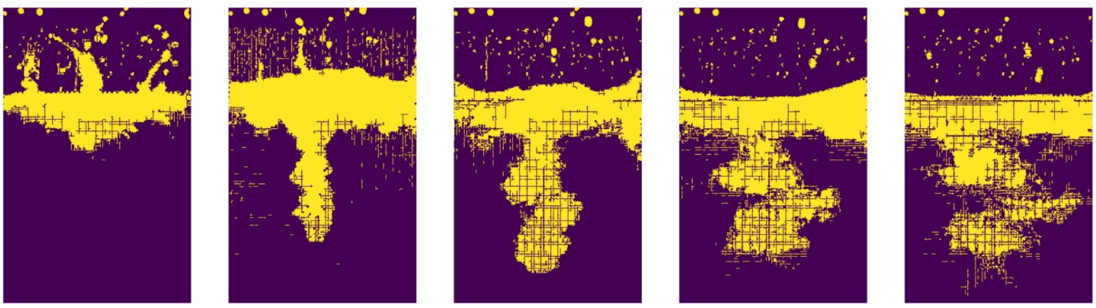

Figure 2: Impact of a liquid onto a linearly stratified liquid (Maller, PhD thesis). Image width = 15 cm, time = 10 s in last image.

Objectives & methods:

In this project, the PhD student will assess whether giant impacts fully mixed the core and the mantle of the Earth, thereby erasing pre-existing chemical heterogeneities, or whether some early heterogeneities could have survived giant impacts. The student will use laboratory experiments, extending previous impact experiments on the fluid dynamics of giant impacts (figure 1) (Landeau et al. 2021, Maller et al. 2024).

To model the mixing of an initially stratified magma ocean, the PhD student will conduct a first series of experiments on the impact of a liquid volume onto a pool of a linearly stratified salt solution, representing the magma ocean (figure 2). In a second series of experiments, he/she will model the mixing of an initially stratified core. The target liquid will then be formed of two layers: an upper layer of silicone oil, representing the magma ocean, and a lower layer of a linearly stratified salt solution, representing the early stratified core.

In both experiments, the PhD student will record the flow on a high-speed camera and characterize the turbulent mixing using laser-induced fluorescence and synthetic Schlieren techniques. He/she will measure the mixing efficiency and obtain scaling law for this efficiency as a function of the ratio of the stratification strength to the impact speed. He/she will then apply these scalings to Earth's formation and determine whether some impact scenarios (in terms of impactor size and speed) were able to fully mix and homogenize the magma ocean and the core of the Earth. We will then evaluate the likeliness of these impact scenarios in global models of planetary accretion.

Depending on the student's interest, several directions can be explored in the longer term. One could use impact simulations to quantify the effect of the impact angle. This would involve collaborations with M. Nakajima (Univ. of Rochester, USA). Alternatively, one could apply the above experiments to Earth's water oceans: as rain drops of fresh water fall onto the salty upper ocean, they induce transfers of heat, momentum and mass between the atmosphere and the ocean (Bellenger et al. 2016). Our experiments could be used to refine the parametrization of these exchanges in global climate models.

Primary collaborations: Angela LIMARE (IPGP, DFG), Simon CABANES (IPGP, DFG), Laëtitia ALLIBERT (*Museum für Naturkunde*).

Other potential collaborations : Cinzia Farnetani (IPGP, DFG). Miki NAKAJIMA (Univ. of Rochester), James BADRO (IPGP, CAGE).

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