

PhD Project Description

What Lies Above the Core

Supervisors

Lead Supervisor: Asst. Prof. Doyeon Kim

Research Group

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Project Summary

The Earth's lower mantle hosts a fascinating variety of enigmatic structures that remain among the least understood features of our planet's interior. At the largest scale, two continent-sized anomalies—known as Large Low-Velocity Provinces (LLVPs)—stand out consistently across global tomographic models. At smaller scales, ultralow-velocity zones (ULVZs) and mega-ULVZs mark regions of extreme seismic heterogeneity along the core–mantle boundary.

These structures may hold fundamental clues to how Earth formed and evolved. Geochemical and geodynamic studies suggest that parts of the lowermost mantle could preserve ancient reservoirs dating back to the earliest history of the planet, while also interacting with the core, feeding mantle plumes, and influencing large-scale mantle circulation. Yet their origin, composition, geometry, and long-term stability remain intensely debated.

Seismology provides one of the only ways to observe these regions directly. Global tomography reveals the broad outlines of LLVPs, but many of the most diagnostic features remain unresolved: How sharp are their margins? How rough are their upper surfaces? Are they coherent thermochemical piles, networks of upwellings, or something more complex? At smaller scales, ULVZs can produce subtle but distinctive waveform effects through multipathing, scattering, waveform broadening, and travel-time shifts. These signatures contain information about structures far below the resolution of conventional tomography.

This project aims to push seismic imaging into this hidden frontier by combining global waveform mining, machine learning, 3-D numerical simulations, adjoint methods, and seismic inversion. The goal is to detect previously overlooked seismic phases, identify the waveform fingerprints of deep-mantle structures, and reconstruct their geometry with far greater resolution than is currently possible.

The project also extends beyond Earth. The Moon and Mars may host their own forms of deep mantle layering or basal structures, shaped by very different thermal and tectonic histories. Comparing these worlds offers a powerful way to ask broader questions: How do rocky planets differentiate? Why does mantle layering persist on some worlds? What controls the initiation—and long-term survival—of plate tectonics?

By connecting observations from Earth, the Moon, and Mars, this project will use seismology to investigate some of the deepest and oldest structures preserved inside rocky planets.

Research Context and Objectives

Please contact Asst. Prof. Doyeon Kim (doyeon.kim@imperial.ac.uk) for details on specific objectives of each PhD project. Projects within this theme may include, but are not limited to, the following: (i) Data-driven discovery – Mine global seismic waveform archives to uncover

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previously unrecognized, “exotic” seismic phases associated with ULVZs and LLVPs, expanding our observational understanding of deep mantle heterogeneity; (ii) Numerical exploration – Perform systematic 3-D wavefield simulations informed by geodynamic models to predict the seismic signatures and waveform features of realistic deep-mantle structures; (iii) Seismic imaging and inversion – Apply adjoint methods and compute 3-D sensitivity kernels to invert for velocity perturbations, reconstructing the detailed 3-D morphology of ULVZs and LLVPs with unprecedented resolution; (iv) searching for analogous structures inside other planets -- Investigate whether the Moon, Mars, and other rocky bodies contain comparable deep-mantle heterogeneity or layering, and determine which structures can be constrained using existing and forthcoming planetary seismic datasets.

Collaborators and partners on the project:

Collaborations and partnerships will be determined flexibly for each PhD project, depending on the specific research focus and objectives.

Further reading:

For applicants interested in learning more about the scientific background and recent developments related to this research theme, the following publications provide valuable insight:

Kim, et al. (2025). Seismic and Mineralogical Evidence for an Iron-Rich Mega-ULVZ Beneath Hawaii. *Science Advances*, <http://doi.org/10.1126/sciadv.adz1962>

Dannberg, et al. (2021). The morphology, evolution and seismic visibility of partial melt at the core–mantle boundary: Implications for ULVZs. *Geophysical Journal International*, 227(2), 1028-1059. <https://doi.org/10.1093/gji/ggab242>

Samuel, et al. (2023). Geophysical evidence for an enriched molten silicate layer above Mars's core, *Nature*. <https://doi.org/10.1038/s41586-023-06601-8>

Russell, et al. (2023). Evidence for a kilometer-scale seismically slow layer atop the core-mantle boundary from normal modes, *Geophysical Research Letters*. <https://doi.org/10.1029/2023GL105684>

Kim, et al. (2020). Sequencing seismograms: A panoptic view of scattering in the core-mantle boundary region. *Science*, 368(6496), 1223-1228. <http://doi.org/10.1126/science.aba8972>

Li, M. et al. (2017). Compositionally-distinct ultra-low velocity zones on Earth's core-mantle boundary. *Nature Communications*, 8(1), 177. <https://doi.org/10.1038/s41467-017-00219-x>

Mundl, A., et al. (2017). Tungsten-182 heterogeneity in modern ocean island basalts. *Science*, 356(6333), 66-69. <http://doi.org/10.1126/science.aal4179>

Lekic, V., et al. (2012). Cluster analysis of global lower mantle tomography: A new class of structure and implications for chemical heterogeneity. *Earth and Planetary Science Letters*, 357, 68-77. <https://doi.org/10.1016/j.epsl.2012.09.014>

Weber, R., et al. (2011). Seismic detection of the lunar core. *Science*, <http://doi.org/10.1126/science.1199375>

Who are we looking for?

We are looking for motivated hard hard-working students with a strong background in earth and planetary sciences, seismology, physics, mathematics, or engineering, and a curiosity to

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explore how planets work from the inside out. A willingness to learn computational methods as needed. A willingness to learn and apply computational and numerical methods is essential.

Through these projects, candidates will develop advanced numerical modeling and data analysis skills, gain hands-on experience with cutting-edge planetary science tools, and build expertise at the intersection of geophysics and space exploration.

Candidates will be encouraged and supported to present their work at international conferences and publish in high-impact journals, fostering both scientific and professional growth. The projects also offer opportunities for collaboration with other research groups within and beyond ESE, creating a dynamic, interdisciplinary research environment.