Numerical modeling of Earth (and planetary) mantle dynamics, evolution and compositional structure

The Dept. of Earth Sciences at UCL can offer one PhD studentship in the field of geodynamics. The start date is not fixed, but the preferred start date will be in autumn 2020. There is some freedom in the choice of research topics, but the main theme should overlap with the research interests of the main advisor, Dr. Maxim Ballmer (also see his website http://jupiter.ethz.ch/~ballmerm/index.html). Three example projects are explained in detail below, but Maxim's research interests also involve, e.g., the long-term evolution of terrestrial planets (e.g. Mars, Moon, Exoplanets), and the Earth's asthenospheric dynamics (and its geophysical signals). Maxim is particularly keen to quantitatively compare geodynamic model predictions with geophysical and geochemical data. In any project, including the three examples below, there will be at least one co-advisor from UCL, and several collaborators UK- and worldwide.

Contact: Dr. Maxim Ballmer, m.ballmer <at> ucl.ac.uk

The seismic signals of the heterogeneous Earth mantle

Geophysical imaging of the Earth's deep interior, and hence our understanding of present-day mantle structure and long-term evolution, is subject to fundamental limitations. For example, the deep mantle is interrogated by Earthquake-generated sound waves through seismic tomography, but the true resolution of any releated tomography model is limited to 10s-100s km. On the other hand, geochemical data has little-to-no spatial resolution power. Based on such limited information, the mantle has been suggested to be anything between a rather well-mixed "marble cake" of recycled mafic (basaltic) and ultramafic (harzburgitic) heterogeneities, or a poorly-mixed "plum pudding" with prevalent blobs of ancient material [Ballmer et al., 2015, 2017]. Within uncertainties in terms of mantle material properties and initial condition, both these scenarios are viable and can be reproduced by numerical models of mantle convection.

In this project, we will quantitatively test the predictions of such godynamic models by comparison with seismic data. While comparison of geodynamic model predictions with seismic tomography models is performed routinely (but subject to intrinsic limitations), we will focus on direct comparison with data. This approach will involve forward-modeling of a huge dataset of synthetic waveforms [Nissen-Meyer et al., 2014], and application of a machine-learning technique (to be newly developed) in order to compare these synthetic waveforms with real seismograms. Such an integrated geodynamic-seismological effort will serve to quantify, and potentially distinguish, the geophysical signals of the marble-cake vs. plum-pudding mantles.

The PhD candidate will be trained in geodynamic and seismic modeling, as well as machine-learning techniques. The candidate will also have the opportunity to develop their teaching and programming skills, as well as various soft skills. This project is fully funded for UK/EU applicants for three years at the normal RCUK rate (£17,428 in 2020/21). Tuition will be covered for at least three years (for UK/EU applicants). Applicants require to have (by the time of starting) a Masters level degree (either undergraduate or postgraduate) in Geology, Geophysics, Physics, or a closely related field and an enthusiasm to work in computational geophysics. Good programming skills in Matlab/Python/C/Fortran or a similar language, as well as familiarity with LINUX operating systems, are highly beneficial.

citations: doi.org/10.1126/sciadv.1500815, doi.org/10.1038/ngeo2898, doi.org/10.5194/se-5-425-2014

Potential collaborators: Ana Ferreira, CSML, John Brodholt (UCL), Tarje Nissen-Meyer (Univ. Oxford), Paula Koelemeijer (RHUL), Paul Tackley (ETH)

The initial condition for the long-term evolution of terrestrial planets

Terrestrial planets evolve through stages of large-scale melting, or magma oceans, due to the energy release during accretion and differentiation. Any magma ocean is thought to become progressively enriched in FeO and incompatible elements upon freezing due to fractional crystallization. The resulting upwards enrichment of the cumulate (=crystal) package(s) drives gravitational over-turn(s) of the incipient mantle [Ballmer et al., 2017a], and ultimately stabilizes a FeO-enriched molten layer at the core-mantle boundary (CMB), or “basal magma ocean” (BMO) [Labrosse et al., 2007]. The BMO itself is expected to freeze by fractional crystallization, ultimately stabilizing a thick FeO-enriched layer at the CMB. Such a layer, however, would be too dense to be entrained by mantle convection, a scenario that is ruled out by geophysical observations, at least for Earth.

In this project, we will investigate the consequences of an alternative mechanism that has not yet been considered, BMO reactive crystallization, on the initial condition of solid-state mantle convection and long-term planetary evolution. First results indicate that entrainment of reactive cumulates should be efficient such that reaction (driven by chemical disequilibrium between the mantle and BMO) proceeds swiftly. The related BMO reactive cumulates are expected to range from Mg-enriched bridgmanite (MgSiO3) to FeO-enriched pyrolite, but the detailed compositions as a function of BMO initial chemistry and volume will be calculated in this project using available thermodynamic models [e.g., Boukare et al., 2015]. The long-term thermochemical evolution and entrainment of the cumulate package will be addressed by geodynamic modeling [e.g., Ballmer et al., 2016, 2017b; Nakagawa and Tackley, 2014]. The predicted thermochemical mantle structures will be compared to the seismic signature of the Earth’s lower mantle, using available constraints for physical properties of mantle materials at high pressures and temperatures [e.g., Thomson et al., 2019]. There will be also an opportunity to generate new constraints on these properties using computational mineral physics in a side project (depending on interest of the PhD candidate). Finally, results will be applied to terrestrial planets in general. Such an effort is expected to yield systematic predictions in terms of planetary deep-mantle structure (with important implications for long-term thermal evolution), since the stabilization of a BMO depends on the pressure at the core-mantle boundary, and hence on planet mass/composition.

The PhD candidate will be trained in geodynamic modeling and computational mineral physics, as well as numerical modeling in general. The candidate will also have the opportunity to develop their teaching and programming skills, as well as various soft skills. This project is fully funded for UK/EU applicants for three years at the normal RCUK rate (£17,428 in 2020/21). Tuition will be covered for at least three years (for UK/EU applicants). Applicants require to have (by the time of starting) a Masters level degree (either undergraduate or postgraduate) in Geology, Geophysics, Physics, or a closely related field and an enthusiasm to work in computational geophysics. Good programming skills in Matlab/Python/C/Fortran or a similar language, as well as familiarity with LINUX operating systems, are highly beneficial.

citations: doi.org/10.1002/2016GC006605, doi.org/10.1002/2017GC006917, doi.org/10.1038/ngeo2898, doi.org/10.1002/2013GC005128, doi.org/10.1002/2015JB011929, doi.org/10.1038/nature06355, doi.org/10.1038/s41586-019-1483-x

Potential collaborators: Ana Ferreira, John Brodholt, Dave Dobson, Andy Thomson (UCL); Oliver Shorttle (Cambridge); George Helffrich, John Hernlund, Christine Hernlund (ELSI, Tokyo Tech); Kei Hirose (ELSI, Tokyo Tech; Univ. Tokyo); Razvan Caracas (ENS Lyon)

The dynamics of mantle plumes, and their geophysical and geochemical expressions

While magmatic activity along plate boundaries is well explained by plate-tectonic theory, the expressions of intraplate volcanism may inform about deep-mantle processes. Mantle upwellings, or "plumes", are thought to sustain major intraplate volcanism at oceanic hotspots, but the explicit upwelling dynamics as well as the chemistry of materials carried that are by plumes remain poorly understood. For example, a range of plume parameters can account for geophysical observations such as hotspot swell geometry or distribution of volcanism [Ribe and Christensen, 1999; Asaadi et al., 2011; Ballmer et al., 2011, 2013].

In this project, we will explore the dynamics of plumes as a function of the composition and properties of these materials using 3D numerical models of mantle convection. Model predictions in terms of the geophysical expression of plumes (seismic tomography, dynamic topography, …) and geochemical signatures of ocean-island basalts (major-element and trace-element signatures) will be compared to observations such as for the Hawaiian Islands or Iceland hotspots. Incorporation of multiple datasets, including those from geochemistry, is critical to put constraints on plume upwelling dynamics [Ballmer et al., 2011; Poore et al., 2011]. Such an integrated approach will exploit the coupled controls of plume composition on both upwelling dynamics and lava chemistry, and hence provide new quantitative constraints on the structure of mantle plumes, and thus on the make-up of the plume-source region near the core-mantle boundary [Weis et al., 2011].

The PhD candidate will be trained in geodynamic and geochemical modeling, as well as numerical modeling in general. The candidate will also have the opportunity to develop their teaching and programming skills, as well as various soft skills. This project is fully funded for UK/EU applicants for three years at the normal RCUK rate (£17,428 in 2020/21). Tuition will be covered for at least three years (for UK/EU applicants). Applicants require to have (by the time of starting) a Masters level degree (either undergraduate or postgraduate) in Geology, Geophysics, Physics, or a closely related field and an enthusiasm to work in computational geophysics. Good programming skills in Matlab/Python/C/Fortran or a similar language, as well as familiarity with LINUX operating systems, are highly beneficial.

citations: doi.org/10.1038/ngeo1187, doi.org/10.1016/j.epsl.2013.06.022, doi.org/10.1038/ngeo1161, doi.org/10.1038/nature09993, doi.org/10.1016/S0012-821X(99)00179-X, doi.org/10.1038/ngeo1328

Potential collaborators: Ana Ferreira, John Brodholt, Dave Dobson, Andy Thomson (UCL); Kate Rychert (Univ. Southampton); Lara Kalnins (Univ. Edinburgh); Oliver Shorttle (Cambridge); Mark Hoggard (Harvard); Antonio M.-C. Cordoba (ETH)