New insights into deep mantle dynamics from seismic observations and other constraints

Maureen D. Long, Yale University

In this talk I will highlight recent advances in our understanding of the patterns, drivers, and consequences of flow in the deep mantle. In particular, the past 5-10 years has seen major advances in our ability to measure and interpret seismic anisotropy, or the directional dependence of seismic wavespeeds, at the base of the mantle. This progress has been spurred by innovations in observational strategies, the increasing availability of high-quality, dense seismic instrumentation, advances in geodynamical modeling capabilities, and tighter constraints on the elasticity and deformation of lowermost mantle materials from mineral physics. New observations and interpretations of seismic anisotropy are shedding new light on flow patterns at the base of the mantle and how flow interacts with structures such as large low velocity provinces (LLVPs) and ultra-low velocity zones (ULVZs). In tandem with constraints from geodynamical modeling and mineral physics, seismic observations are shedding new light on the dynamics of the deep mantle and the role that processes at the base of the mantle play in controlling Earth evolution.

Magmatic processes in planetary bodies: a modelling perspective

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Magmatic processes in planetary bodies include disparate phenomena ranging from first melting and differentiation of early planetesimals, to whole-mantle magma oceans in young terrestrial planets to ongoing magmatism and volcanism coupled to mantle and lithosphere dynamics of evolving planets including today's Earth. These diverse manifestations of magmatic processes range from melt-poor partially molten rock, to mush bodies at intermediate melt fractions, and melt-rich magma suspensions. What they have in common is that access for direct observation is limited to modern surface to shallow subsurface phenomena, while indirect observations (geochemistry, field geology, geophysical imaging, meteorites and space probes) suffer from incompleteness, poor resolution, and non-uniqueness of interpretation. Forward modelling offers a complementary perspective to help unravel underlying processes across disparate scales in space and time.

Previous process-based models have represented magmatic systems as either porous flows at low melt fractions (<20%) or suspension flows at high melt fractions (>60%). A lack of theoretical basis to represent mush flows at intermediate phase fractions has thus far hindered investigations into the dynamics of crustal mush bodies crucial to understanding long-term, large-volume volcanic activity. Previous theories were formulated specifically for two-phase flows of melt-solid mixtures, hence not allowing for the inclusion of a third, volatile or other fluid phase. My contribution addresses this gap by presenting a comprehensive theoretical model [1] of inertial, compressible, reactive multi-phase flows across all phase fractions at the system scale, rooted in mixture theory. I substantiate its applicability with a numerical implementation utilising a finite-difference staggered-grid approach [2] and a flexibly calibrated multi-component melting model [3].

Numerical experiments replicate expected behaviours for two-phase flows including rank-ordered porosity wave trains in 1D, and porosity wave breakup in 2D in the porous flow regime, as well as particle concentration waves in 1D, and mixture convection in 2D in the suspension flow regime. In the mush regime, numerical experiments show strong melt localisation into lenses and stress-aligned melt-shear bands. Further application including the thermo-chemical-mechanical evolution of magma bodies from metre-scale crustal sills to 1000 km-size magma oceans demonstrates the versatility of the theoretical model and its numerical implementation. Model codes are available open source at github.com/kellertobs/pantarhei and github.com/kellertobs/nakhla.

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Dynamics and structure of the lowermost mantle beneath North America and the surrounding regions

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We present results from three studies that focus on the lowermost mantle beneath North America and the surrounding regions. First, we apply beamforming to enhance seismic signals, which enables us to measure seismic anisotropy beneath in a large geographic region. In this process, we use rarely analyzed seismic waves such as S3KS. We find that measured splitting due to lowermost mantle anisotropy is sufficiently strong to be non-negligible in interpretations of SKS splitting due to upper mantle anisotropy in certain regions, which may prompt future re-evaluations of upper mantle anisotropy beneath North and Central America. Second, we perform the first simultaneous analysis of SPdKS waves to characterize low-velocity heterogeneity and anisotropy at the base of the mantle beneath northeastern Pacific Ocean, parts of the Unites States, and Canada. Through geodynamic modeling simulations, we find that the sinking of subducted slabs to the lowermost mantle can trigger formation of hot thermal anomalies near subducted slabs, where chemical heterogeneities can accumulate. The thermochemical anomalies can cause reduction of seismic velocity while the slab-induced flow can cause seismic anisotropy, potentially explaining our seismic observations. Third, we show that the proposed location of the Yellowstone plume at the base of the mantle is strongly seismically anisotropic. This finding is complemented by geodynamic modeling results showing upwelling flow and high strains in the lowermost mantle beneath the Yellowstone region. Our results support the idea that the Yellowstone volcanism is caused by a plume rooted in the deepest mantle beneath Baja California, connecting dynamics in the deepest mantle with phenomena at Earth's surface.

Numerical Study on the Stability of Thermochemical Piles and Plumes: Effect of Rheological Parameters

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Large low shear velocity provinces at the core-mantle boundary beneath Africa and the Pacific have been observed. These several hundreds of kilometers high structures are considered to have been stable the last hundred million years. However, their origin and nature is still an open question. One idea is that these provinces originate from a primordial layer at the base of Earth's mantle which is thermally and chemically distinct from the bulk of the mantle. In our study, we numerically investigate the temporal and spatial stability of thermochemical piles depending on a viscosity varying with the stress, composition, and depth. We find that an increase of the viscosity at the top or bottom of the system increases the stability of piles. A larger yield stress increases the rigidity of the surface layer, thus preventing the formation of large downwellings. Therefore, the deep dense material is hardly affected. For a viscosity with composition or depth dependence, the deep dense material moves more sluggish, increasing the lifetime of a pile. While the composition-dependent viscosity only acts locally within a pile and decreases with time due to entrainment, a global increase of viscosity with depth strongly stabilizes piles spatially and temporally. Additionally, we find that a thermal expansivity decreasing with depth has a similar effect on the stability of the piles as the depth-dependent viscosity. Furthermore, we investigate the location of thermal plumes with respect to the thermochemical piles. While plumes occur at the edges of piles when the latter are merged or split up, they strive towards the center of the piles.

Influences of glacial forcing on seafloor spreading and plate motions in the last glacial cycle

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Glacial cycles have significantly influenced Earth's surface processes throughout the Quaternary period, impacting the climate, sea level, and seismic and magmatic activities. However, the effects of glacial cycles on plate tectonic processes remain largely unknown. Using a computationally efficient, accurate, and recently updated open-source modeling code CitcomSVE-3.0, we formulate high-resolution global glacial isostatic adjustment (GIA) models to explore the effects of GIA on plate tectonics during the last glacial cycle. Our models use ICE-6G and ANU ice models as ice history models for the last glacial cycle and incorporate mantle compressibility, viscoelasticity, 3D crustal structures based on CRUST1.0, and realistic lithospheric structures with varying elastic thickness and weak plate margins. The horizontal resolution of our models is ~30 km at the surface, which resolves the 100 km wide plate margins. The mantle viscosity structure is based on VM5a with an additional weak asthenosphere. Our modeling demonstrates that the interaction between lithospheric structures and glacial forcing causes significant plate rotation and changes in the spreading rates of mid-ocean ridges, especially for plates and slow-spreading ridges situated near major ice sheets during and following deglaciation. We found that the rotation rate of the North American plate can be altered by ~25% over 10,000 years timescales in the last glacial cycle. Due to the effects of both plate rotation and ice melting in Greenland and Fennoscandia, the spreading rates of Iceland Ridge may experience up to 40% fluctuations that may explain the Holocene volcanism in Iceland. Our modeling also indicates increased rates of seafloor production and degassing, including that of CO_2 from mid-ocean ridges during the deglaciation periods, leading to net increases in seafloor production and CO_2 for the last glacial cycle. These results underscore the critical dynamical interplay between glacial cycles, plate tectonics, and climate during ice ages.

Compositional changes in the lower mantle and surface mobility in the early Earth

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Abstract

Numerical models of mantle convection are often constrained by present-day observations. However, mantle behaviour before plate tectonics initiated is less certain. The early Earth may have possessed a large hot magma ocean trapped near the core-mantle boundary after formation during differentiation, and likely containing different elements from the surrounding mantle. We examine the impact of composition-dependent properties in the deep mantle on the surface mobility of the early Earth using high Rayleigh number mantle convection models. Our models indicate that increased conductivity or decreased viscosity flattens basal topography while also increasing the potential for surface yielding. We vary the viscosity, thermal conductivity, and internal heating in a compositionally distinct basal magma ocean and explore the compositional topography, insulation effects and surface stresses for non-Newtonian rheology. Models are run using a variety of crustal compositions, such as the inclusion of primordial continental material before the onset of plate tectonics. We monitor the surface for plate-like behavior. Since convective vigour is very strong in the early Earth, specialized tracer methods are employed for increased accuracy. In our models, Stokes flow solutions are obtained using a multigrid method specifically designed to handle large viscosity contrasts and non-Newtonian rheology.

Keywords: early Earth, basal magma ocean, plate tectonics, high Rayleigh number

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The persisting conundrum of mantle viscosity inferred from mantle convection and glacial isostatic adjustment processes

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Mantle viscosity exerts important controls on the long-term (i.e., $>10^6$ years) dynamics of the mantle and lithosphere and the short-term (i.e., 10 to 10^4 years) crustal deformation induced by loading forces including ice melting, sea-level changes, and earthquakes. However, mantle viscosity structures inferred from modeling observations associated with mantle dynamic and loading processes may differ significantly, remaining as a hotly debated topic for recent decades. In this study, we consider mantle viscosity structure constrained by the observed geoid and seismic structure from mantle convection and by GPS and GRACE observations of GIA-induced present-day crust motion and gravity change in North America. We show using mantle convection models with the plate motion history for the last 130 Myrs that the immediate wavelength geoid (from degrees 4 to 12) and seismic mantle structure can be best explained by mantle viscosity structure with an asthenospheric viscosity of $3\text{x}10^{19}$ Pas to 300 km depth, upper mantle viscosity of $6\text{x}10^{20}$ Pas between 300 km and 670 km depth, and a lower mantle viscosity of $2\text{x}10^{22}$ Pas. However, mantle viscosity structure VM5 inferred from GIA studies with ICE-6G ice model fails to explain the geoid and seismic structure. The conundrum is that the mantle viscosity with a weaker asthenosphere and upper mantle than the lower mantle that is required by the geoid and seismic structure greatly reduces the fit to GPS and GRACE observations of GIA-induced signals, compared with VM5a. This conclusion holds true for the ANU ice model by Lambeck's group, thus appearing to be independent of ice models. We discuss several possible mechanisms to resolve this conundrum, from transient rheology, non-Newtonian rheology, to ice history models. It is important to note that our time-dependent mantle convection models for the geoid differ significantly from the conventional instantaneous mantle flow models for the geoid. The present-day mantle buoyancy from our convection models is determined by mantle dynamics with 130 Myrs plate motion history, while the conventional flow models derive the buoyancy from seismic structures. Therefore, our geoid models constrain not only relative mantle viscosity structure but also its magnitude that the conventional mantle flow models cannot.

On the impact of true polar wander on heat flux patterns at the core-mantle boundary

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Abstract

The heat flux across the core-mantle boundary (CMB) is a fundamental variable for Earth evolution and internal dynamics. Seismic tomography provides access to seismic heterogeneities in the lower mantle, which can be related to present-day thermal heterogeneities. Alternatively, mantle convection models can be used to either infer past CMB heat flux or to produce statistically realistic CMB heat flux patterns in self-consistent models. Mantle dynamics modifies the inertia tensor of the Earth, which implies a rotation of the Earth with respect to its spin axis, a phenomenon called true polar wander (TPW). This rotation must be taken into account to link the dynamics of the mantle to the dynamics of the core.

In this study, we explore the impact of TPW on the CMB heat flux over long timescales ($\sim$ 1 Gyr) using two recently published mantle convection models: one model driven by a plate reconstruction and a second that self-consistently produces a plate-like behaviour. We compute the geoid in both models to correct for TPW. In the plate-driven model, we compute a total geoid and a geoid in which lateral variations of viscosity and density are suppressed above 350 km depth. An alternative to TPW correction is used for the plate-driven model by simply repositioning the model in the original paleomagnetic reference frame of the plate reconstruction. The average TPW rates range between 0.4° Myr^{-1} and 1.8° Myr^{-1}, but peaks up to 10° Myr^{-1} are observed. We find that in the plate-driven mantle convection model used in this study, the maximum inertia axis produced by the model does not show a long-term consistency with the position of the magnetic dipole inferred from paleomagnetism.
TPW plays an important role in redistributing the CMB heat flux, notably at short time scales ($\leq$ 10 Myr). Those rapid variations modify the latitudinal distribution of the CMB heat flux, which is known to affect the stability of the magnetic dipole in geodynamo simulations.

A principal component analysis (PCA) is computed to obtain the dominant CMB heat flux pattern in the different cases. These heat flux patterns are representative of the mantle convection cases studied here and can be used as boundary conditions for geodynamo models.

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Title: On the Lasting Influence of the Moon-forming Giant Impact on Earth's Evolution

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Abstract: Earth's Moon is widely accepted to have been created 4.5 billion years ago through a giant impact between Earth and a hypothetical planet known as Theia. Yet, direct evidence for Theia's existence has remained elusive. Here, we demonstrate that the mantle remnants of Theia may explain fundamentally important features of the largest seismically-imaged anomalies within Earth – the two large low-shear-velocity provinces (LLSVPs) in Earth's deepest mantle. We combine state-of-the-art evidence from theoretical and computational astrophysics, geodynamics, mineral physics, and seismology to demonstrate how Theia's mantle remnants naturally provide an explanation for a compositionally distinct origin for LLSVPs, as well as their age, density, and size. We also show that the thermal and chemical structure set by this impact can give rise to strong mantle plumes that could rise from LLSVPs and induce Earth's earliest subduction events. This work substantially expands the influence of giant-impact planetary processes in shaping Earth's evolution, with implications for understanding the diversity of terrestrial planets and the quest for Earth-like exoplanets.

Influence of Subduction History and Mineral Deformation on Seismic Anisotropy in the Lower Mantle

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Seismic anisotropy, largely absent in the majority of the lower mantle, becomes pronounced in the deepest part of the lower mantle (D"). This anisotropy often arises from deformation processes within the Earth, either through lattice preferred orientation of anisotropic minerals, or shape preferred orientation of materials with distinct elastic properties, such as partial melt. With this link between deformation and anisotropy, the characterization of anisotropic structure can yield important constraints on convective flow and dynamic processes in the mantle. Seismic anisotropy is observed to be more prevalent in the areas surrounding Large Low Shear Velocity Provinces (LLSVPs), and this has spurred our interest of tracking anisotropy in the lower mantle with realistic mineral compositions and the latest deformation mechanisms and slip systems. The potential mineral physics explanations on D" anisotropy, including ferropericlase, bridgmanite, and post-perovskite—the high-pressure polymorph of bridgmanite—are subjects of extensive experimental and first principles work. Post-perovskite is thermodynamically stabilized in cooler regions of D", whereas bridgmanite is favored in warmer regions of D". Therefore, with the thermal field derived from the convective model, it will be possible to distinguish the origins of D" anisotropy and slip models of different minerals by systematically comparing the computed anisotropy pattern with the existing seismic data. We are using a method to track the crystal fabric of an aggregate composed of thousands of grains that represents candidate D" rocks subject to the temperature, stress, and pressure evolution found by tracing that aggregate in the convection model. Additionally, we incorporate multiple lower-mantle phases deformed simultaneously with temperature- and pressure-dependent elastic tensors for the bulk of the lower mantle. The simulated elastic tensors of deformed aggregates will be further post-processed to be directly compared with global anisotropy models and regional S-wave splitting data. Preliminary findings from 2-D models show pronounced seismic anisotropy at the base of slabs near the core-mantle boundary. Strong mineral fabrics are also developed at the edges of LLSVPs.

Thermal transport properties of MgO Periclase and Ferropericlase at High Pressures-Temperatures using X-ray diffraction.

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Large scale dynamics within the Earth are the result of cooling. Heat is transported towards the surface by large scale convection in the mantle and in the core, and by conduction across the thermal boundary layers at the core–mantle boundary (CMB) and the lithosphere. Thermophysical properties of lower mantle minerals, such as periclase and Ferropericlase are important to determine as they are needed to understand the thermal history of the Earth. There is a range of estimates for the thermal transport properties, e.g. thermal conductivity (k) in the lower mantle ranges between 4 and 16 W/m K, resulting from a lack of consensus on how to represent the pressure (and temperature) dependence of k; different models yield very different extrapolations. A novel approach is established to study thermal conductivity of deep earth minerals at CMB conditions using time resolved MHz X-ray diffraction and heating in a diamond anvil cell. The hard Xray beam at the European XFEL (18.08 keV) couples with MHz pulse trains to perform time resolved measurements of heat flow in high pressure samples heated by XFEL pulse trains. Finite element modelling is carried out utilising volume change with temperature in a sample, extracted from the diffraction data. Temperature dependent thermal conductivity is fitted to the data. We report thermal conductivity values of polycrystalline MgO and $Mg_{0.9}(FeO)_{0.1}$ at pressures of 9-55 GPa and temperatures of 300K – 4000 K.

Electrical and Thermal Conductivity of Iron-enriched Basal Magma Oceans in Early Earth and Super-Earths

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The Earth's earliest magnetic field may have originated in a basal magma ocean, a layer of silicate melt surrounding the core that could have persisted for billions of years. Recent studies show that the electrical conductivity of liquid with a bulk silicate Earth composition exceeds 10,000 S/m at basal magma ocean conditions, surpassing the threshold for dynamo activity. Over most of its history, the basal magma ocean is more enriched in iron than the bulk silicate Earth, due to iron's incompatibility in the mineral assemblages of the lower mantle. Using ab-initio molecular dynamics calculations, we examine how iron content affects the silicate dynamo hypothesis. We investigate how the electrical conductivity of silicate liquid changes with increasing iron fraction Fe/(Fe+Mg), up to Super-Earth pressures and temperatures. We compute the electronic contribution to the thermal conductivity, to evaluate convective instability of basal magma oceans. We find that silicate dynamos are likely to have operated in the early Earth and in super Earths.

Deep Earth-Moon Tidal Coupling and its influence of the hadean mantle heterogeneity.

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Several tens of million years after the beginning of its accretion, the Earth experienced a giant impact that formed the Earth-Moon system. This event is expected to have induced the formation of a deep Earth magma ocean (MO) and generated a debris disk around the proto-Earth that rapidly reaccreted to form the Moon. At this time, the Moon was closer to the Earth than today, which may have had severe consequences on the interplay between the two objects. In particular the tidal interactions following the Moon formation controlled the evolution of the rotation and potentially influenced the cooling of the early Earth and Moon and their internal chemical differentiation. However, the influence of the early Moon on the thermal and melt evolution of the early Earth still remains unexplored.

In the proposed presentation, we will discuss our novel numerical models developed to monitor the influence of tides on the crystal content evolution of the Hadean Earth during the crystallization of the MO. From these models, we monitor the influence of mechanical (density contrast between the crystal fraction and the surrounding magma, magma viscosity, partially molten layer thickness) and orbital parameters (Earth-Moon distance and Earth’s rotation period) on the ability of tidal forces to favor heterogeneities within the deep Earth mantle before its final stages of solidification. In particular, we aim at understanding if strong tidal interactions with the young Moon can influence the chemical differentiation within the early Earth's mantle and contribute to the geochemical signature we measure today from the isotopic heterogeneities observed within the deep Earth.