[S2-P01] Double diffusive convection and Layer Formation in Planetary Mantles

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Abstract

The thermal history of the Earth, its chemical differentiation and also the reaction of the interior with the atmosphere is largely determined by convective processes within the Earth's mantle. A simple physical model, resembling the situation,shortly after core formation, consists of a compositional stably stratified mantle, as resulting from fractional crystallization of the magma ocean. The early mantle is subject to heating from below by the Earth's core and cooling from the top through the atmosphere. Additionally internal heat sources will serve to power the mantle dynamics. Under such circumstances double diffusive convection will eventually lead to self organized layer formation, even without the preexisting jumps is material properties. We have conducted 2D and 3D numerical experiments in Cartesian and spherical geometry, taking into account mantle realistic values, especially a strong temperature dependent viscosity and a pressure dependent thermal expansivity . The experiments show that in a wide parameter range. distinct convective layers evolve in this scenario. The layering strongly controls the heat loss from the core and decouples the dynamics in the lower mantle from the upper part. With time, individual layers grow on the expense of others and merging of layers does occur. We observe several events of intermittent breakdown of individual layers. Altogether an evolution emerges, characterized by continuous but also spontaneous changes in the mantle structure, ranging from multiple to single layer flow. Such an evolutionary path of mantle convection allows to interpret phenomena ranging from stagnation of slabs at various depth to variations in the chemical signature of mantle upwellings in a new framework.

*Speaker

[S2-P02] On the effects of planetary rotation on early Earth differentiation

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Abstract

Several giant impacts during the later stage of the Earth's accretion caused one or more deep terrestrial magma oceans of global extent. At that time, the Earth rotated very fast with a rotation period between two and five hours. Owing to the small magma viscosity of the vigorously convecting magma ocean, planetary rotation probably had a profound effect on the magma ocean solidification and the early differentiation of the Earth. Accordingly, the effect of planetary rotation is not only of key importance for the chemical structure and the development of chemical heterogeneities on Earth but also sets the stage for the onset of plate tectonics.
In this work, we numerically investigate the influence of planetary rotation on the early magma ocean crystallization using a spherical shell model. Our results show that without and at slow planetary rotation, crystals are kept in suspension everywhere in the spherical shell. In contrast, at moderate rotation rate clear dependencies on latitude do arise. Here, crystals settle at the poles and are kept in suspension at mid-latitude but accumulate in the bottom half at the equator. All in all, our numerical experiments demonstrate the possibility of a latitudinal inhomogeneous solidification of a terrestrial magma ocean.

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[S2-P03] Timescale of destabilization of a magma ocean cumulate with phase change boundary conditions

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Abstract

It is commonly accepted that the mantle of terrestrial planets has been formed by crystallization of a magma ocean from the bottom-up. The crystallization of the surface magma ocean is expected to occur on a timescale of the order of 1 Myr. This rather short time has lead several authors to assume convection in the solid part takes place only after the complete solidification of the magma ocean. As the crystallization progresses, due to fractional crystallization, the magma and resulting solid are more and more enriched in FeO, leading to an unstable chemical stratification. This unstable configuration triggers an overturn after which the resulting solid mantle is strongly compositionally stratified.

The present study tests the assumption that solid-state mantle overturn only occurs after complete crystallization of the surface magma ocean. We model convection in the solid part of the mantle and parametrize the presence of a magma ocean with phase change boundary conditions. These boundary conditions allow the matter to cross the boundary between the solid and the magma ocean by melting and freezing.

We performed a linear stability analysis with respect to the temperature and compositional profiles obtained in a growing magma ocean cumulate to assess the destabilization timescale of such profiles as a function of the crystallized thickness. By comparing this timescale with a model of surface magma ocean crystallization, we deduce the time and crystallized thickness at which the convection timescale is comparable to the age of the solid crystallizing mantle. This time is found to be much shorter (_˜1 kyr) compared to the time needed to crystallize the entire surface magma ocean (_˜1 Myr).

*Speaker

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[S2-P04] The influence of small-scale stretching enhanced diffusion on metal/silicate equilibration and mixing during core formation

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Abstract

During the formation of terrestrial planets, the degree of heat partitioning and chemical fractionation between the impactors' metallic core and the early magma ocean is crucial. The efficiency of metal/silicate equilibration indeed controls the thermal and magnetic evolution of planetary bodies, and the interpretation of geochemical data (including core-formation chronometers). Fluid dynamics experiments suggest that, before its fragmentation, a volume of liquid metal falling into a magma ocean undergoes a strong stretching leading to a change of topology from a compact volume of metal toward a collection of sheets and ligaments. In the context of miscible fluid, the vigorous stretching of a compositional heterogeneity is known to accelerate its homogenization through a mechanism known as stretching enhanced diffusion. We first generalize the formalism of stretching enhanced diffusion to two-phase flows and investigate to what extent the metal/silicate equilibration of sheets and ligaments is accelerated, as a function of a Péclet number based on the stretching rate. At large Péclet, mixing is dramatically enhanced by stretching, with a homogenization time inversely proportional to the stretching rate and depending only weakly (logarithmically) on the diffusivity. We find that during core-formation thermal equilibration is expected to occur before fragmentation, unlike chemical equilibration of siderophile elements. We also carry out numerical simulations of the dynamical and thermal - or chemical - evolution of a planetesimal's core falling into a magma ocean. We identify several regimes depending on the values of the Péclet (Pe), Reynolds (Re) and Bond (Bo) numbers. At large Pe, Re and Bo, a stirring regime in which the metallic phase is vigorously stretched and convoluted develops. We show that thermochemical equilibration is then controlled by the stretching enhanced diffusion process, which develops from the mean flow, as the fall of the metal entrains surrounding silicates. Extrapolating our scaling law in the stirring regime, we find that in terms of temperature, a planetesimal with a core smaller than 56 km will significantly equilibrate in a 3000 km magma ocean.

*Speaker

[S2-P05] Residence Time of Oceanic Crust in the Deep Mantle

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Abstract

There is growing evidence from geophysical and geochemical studies that the Earth's mantle is compositionally heterogeneous. The origin and evolution of heterogeneity is intimately linked with the convective mantle flow: upwelling and subsequent melting of the upper mantle at mid-ocean ridges continuously produces compositional heterogeneity in the form of differentiated mantle material, which is then brought back into the planet's interior by subducting slabs, where vigorous convective flow acts to mechanically stir and homogenize it. In the presented work, we investigate one of the key players in the chemically and dynamically coupled process of mantle convection, namely, segregation and recycling of subducted oceanic crust (OC), its role in the thermal and compositional structure of mantle plumes, and the geochemical signature of their erupted lavas. Mechanical stirring within mantle plumes, as well as within the deep mantle material from which they are sourced (i.e., the hot thermal boundary layer at the core-mantle boundary, as well as the thermochemical piles), contributes to a great diversity of plumes and the lavas they produce, in terms of temperature and composition. In spite of their diversity, one property is strikingly similar across plumes in all of our tested models - the age-distribution of the entrained OC-material. Our results show that segregated OC can be stored in the deep mantle for several billions of years before resurfacing with the mantle plumes. However, a more detailed analysis of plumes' composition reveals that they preferentially sample the OC-material that most recently arrived at the CMB. Specifically, most of the OC material in plumes experienced a time-difference of _˜700-900 Myr from when it was produced at the surface and until it was brought back to the surface with the plume. In addition, plumes contain a smaller fraction of OC-material that was produced from _˜700-3000 Myr prior to resurfacing in plumes. The older material exhibits a different degree of homogenization of the OC-material of different ages. We propose that a single source of compositional heterogeneity, namely subducted oceanic crust, can simultaneously explain both the ancient and the young geochemical signatures observed in plume-derived lavas, such as in ocean island basalts.

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[S2-P06] Dynamics of a subducted slab with grain-damage

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Abstract

A model for dynamic weakening and detachment of a stagnant, subducted slab is developed to include the coupling between grainsize-dependent rheology and grainsize evolution due to damage. Abrupt tectonic events such as precipitous changes in plate motion may be the result of detachment of a downgoing slab. In this study, simulations of dynamic weakening produce a necking instability which allows the slab to detach and sink in the ambient mantle. Deformation and shearing impart damage to grains, reduce grainsize and dynamically weaken the neck to produce the detachment process. We study dynamic weakening over a broad range of rheological parameters using convection calculations with a tracer method to understand how and on what timescale slab detachment occurs for different formulations of deformation and damage. We show how the rheology governs the rate of damage, the characteristic weakening timescale, and the timescale on which the slab decouples from the overlying lithosphere with reference to specific rheological parameters. The decoupling timescale is broadly consistent with observations of abrupt tectonic events, which helps to validate the physics governing dynamic weakening and decoupling of a stagnant slab from the overlying lithosphere. We also present a new numerical method for solving the evolution and advection of grainsize.

*Speaker

[S2-P07] The cause of slab stagnation in mantle transition zone and its effects on the dynamics of the mantle

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Abstract

The linear structures of seismically fast anomalies, often interpreted as subducted slabs, in the southern Asia and circum-Pacific lower mantle, provided strong evidence for the whole mantle convection model. However, recent seismic studies have consistently shown that subducted slabs are deflected horizontally for large distances in mantle transition zone in the western Pacific and other subduction zones, suggesting that the slabs meet significant resistance to their descending motion and become stagnant in the transition zone. This poses challenges to the whole mantle convection model and also raises the question about the origin of stagnant slabs. Here, using a global mantle convection model with realistic spinel-post-spinel phase change (-2 MPa/K Clapeyron slope) and plate motion history, we demonstrate that the observed stagnant slabs in the transition zone and other slab structures in the lower mantle can be explained by the presence of a thin, weak layer at the phase change boundary that was suggested from mineral physics and geoid modeling studies. Our studies suggest that while the phase change may affect slab and plume dynamics on time scales of tens of millions of years, it does not alter long-term mass exchange between the upper and lower mantles.

*Speaker

[S2-P08] Influence of flat slab in sublithospheric mantle on inboard continental deformation: Numerical modelling of Farallon Plate subduction

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Abstract

The subducted Farallon plate is believed to have evolved to a flat geometry underneath North America plate during Late Cretaceous, triggering Laramide deformation. The Laramide Orogeny was a period of thick-skinned lithosphere shortening and surface uplift in the western United States that occurred more than 700 km inboard of the Farallon Plate subduction zone. However, mechanisms that cause slab flattening and factors that control inboard deformation remain uncertain. Here we use 2D thermal-mechanical models using the SOPALE code to study the dynamics of Farallon flat-slab subduction and deformation of the continental lithosphere. Models correspond to a geological time of _˜90 Ma to _˜50 Ma, during which an oceanic plateau (conjugate Shatsky Rise) is inferred to have subducted beneath western North America, initiating flat-slab subduction. We test the idea that interactions between the flat-slab and the presence of a pre-existing continental weak zone resulted in inboard deformation. Models examine the influence of the structure and rheology of the weak zone on triggering lithosphere deformation, focusing on two factors: (1) continental mantle lithosphere strength (approximating conditions from wet olivine to dry olivine) and (2) lower crustal strength. Models show that the development of thick-skinned deformation and shortening require a relatively weak continental lithosphere and is enhanced by a weak crust. Future work will focus on how stress transfer from the flat-slab induces continental deformation and on the topographic record of flat-slab subduction and shortening.

*Speaker

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[S2-P09] From nebular atmosphere to magma ocean: early mantle acquisition of hydrogen and helium

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Abstract

The origin and abundance of mantle volatiles presents major unresolved questions for Earth's evolution and the factors that govern its habitability. Here we quantify volatile acquisition by ingassing, the process by which Earth's mantle absorbed and retained volatiles from a dense, hot hydrogen-helium atmosphere derived from the solar nebula. We model nebular atmosphere-mantle evolution during Earth's accretion by coupling a boundary layer representation of magma ocean dynamics to a one-dimensional stellar atmosphere model modified for terrestrial planet formation. Novel features include (i) nebular atmosphere winds based on scaling laws for rotating fluid convection in deep spherical shells, and (ii) gas transfer between the magma and the nebular atmosphere based on the measured systematics of air-sea CO2 transfer, including effects of wind speed and accretion rate. We identify two key phases of system evolution: (1) nebular atmosphere growth with ingassing of hydrogen and helium into the magma ocean during the first part of accretion, followed by (2) dissipation of the nebular atmosphere with partial degassing of hydrogen and helium during late accretion.

The amounts of hydrogen and helium ingassed and degassed depend on their solubility and diffusivity, the mean age of the planet surface, plus three astrophysics-controlled timescales: the lifetime of the solar nebula, the dissipation timescale of Earth's nebular atmosphere, and the accretion time. Using standard values for these parameters, we find that the surface pressure of Earth's nebular atmosphere may have exceeded 0.5 kb and the surface temperature may have approached 3000 K, maintaining a super-heated magma ocean with turbulence driven by atmospheric winds and impacts. Under these conditions, Earth would have ingassed several ocean equivalents of hydrogen and orders of magnitude more primordial helium-3 than the present-day mantle abundance. Later, partial loss of hydrogen during the degassing phase initiates Fe+3 production and magma oxidation, eventually raising the magma fO2 from IW to FMQ, while leaving enough hydrogen behind in the mantle to produce Earth's full inventory of surface water.

The surface pressure of a nebular atmosphere, and therefore the volatile solubility in a magma ocean, depend very strongly on the planet mass. Whereas an Earth-sized (1 ME) planet stores enough volatiles to produce a wet world, our model predicts that a Mars-sized (0.1 ME) planet would acquire insignificant amounts hydrogen for water production from its nebular atmosphere, while a 4 ME terrestrial planet accreted in the same nebula would absorb 10s to 100s of ocean equivalents of hydrogen, leading to water-world conditions.

*Speaker

[S2-P10] The breakup of liquid iron diapirs within the magma ocean

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Abstract

The latest stages of planetary accretion probably involved large impacts between differentiated bodies and large scale melting events. Due to the enormous amount of kinetic energy dissipated during large impacts, to the radioactive heating caused by the decay of short-lived radio-elements, and to the potential energy dissipated as heat during the core-mantle separation, large impacts could generate large, deep and localized magma oceans. Following the impact, the liquid iron from the impactor core sinks as an immiscible cloud of droplets into the less dense magma ocean, leading to thermo-chemical exchanges between the two phases before merging with the Earth's core. The influence of the viscosity contrast between iron and silicates on the shape and dynamics of the drops, as well as on the efficiency of the thermo-chemical exchanges, has been up to now mostly neglected. In this work, we use COMSOL Multiphysics to model the sinking dynamics of an initially spherical iron liquid diapir within a molten silicate phase. We characterize the shape and maximal stable size of the iron drops, the drag coefficient, the different fragmentation modes, the boundary layer thickness, the characteristic break-up time and distance, as functions of the viscosity ratio, Reynolds number and Weber number. We show that the viscosity ratio strongly influences the shape and the condition for stability of a single structure. Increasing Weber number leads to enhanced thermo-chemical exchanges and rapid breakup into small droplets, thus efficient equilibration between the iron drop and the molten silicates.

*Speaker