2024 Ada Lovelace Workshop on
Modelling Mantle and Lithosphere Dynamics

1-6 September 2024, Sète, France

Workshop booklet

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Welcome to the 2024 Ada Lovelace Workshop on Numerical Modelling of Mantle and Lithosphere Dynamics!

The workshop series was initiated in 1987 in Neustadt an der Weinstrasse, Germany, and workshops usually take place every two years. The last workshops were held in Hévíz, Hungary (2022), Sienna, Italy (2019), and Putten, the Netherlands (2017).
The workshops, previously known as International Workshops on Mantle and Lithosphere Dynamics, were renamed in 2018 by the EGU Topical Events Committee in honour of the 19th century English mathematician Ada Lovelace.

The 2024 workshop will take place at Domaine du Lazaret in Sète, France on the mediterranean sea, 40 km from Montpellier.

The meeting is co-sponsored by European Geosciences Union (EGU), Université de Montpellier, Centre National pour la Recherche Scientifique (CNRS), ANR project Rheobreak (PI Fanny Garel), Géosciences Montpellier and Computational Infrastructure for Geodynamics (CIG).

The scientific committee consists of the following members

- Fabio Capitanio (Monash University, Australia)
- Julianne Dannberg (University of Florida, USA)
- Thibault Duretz (Goethe University Frankfurt, Germany/ Géosciences Rennes, France)
- Fanny Garel (Géosciences Montpellier, France)
- Zhong-Hai Li (University of Chinese Academy of Sciences, Beijing, China)
- Paul Tackley (ETH Zurich, Switzerland)
- Catherine Thoraval (Géosciences Montpellier, France)

This workshop is organized by Catherine Thoraval and Fanny Garel (main organizers), Diane Arcay, Nicolas Berlie, Nestor Cerpa, Buchanan Kerswell, Felipe Saez-Leiva, Andrea Tommasi, Étienne Van Broeck from the research laboratory Géosciences Montpellier.

You can contact the organizers at alw24@sciencesconf.org

Please find hereafter the detailed workshop program, as well as the abstracts of **16 invited oral presentations and 112 poster presentations**. We have about 135 participants in total, with about 2/3 of early-career scientists

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Program overview

2024 Ada Lovelace Workshop on
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Monday, September 2nd 2024

8h30-8h45 Welcome and foreword

Mantle dynamics & evolution in Earth and Planets

8h45-9h30 Denis Andrault - *Insights from Mineral Physics on the dynamics of the primitive Mantle: from Hadean to plate tectonics*

9h30-10h15 Stéphane Labrosse - *Deep mantle structure, dynamics and evolution*

10h15-10h45 1-min (1-slide) poster presentations by Early Career Scientists

10h45-11h45 Coffee break + POSTERS

11h45-12h30 Zhensheng Wang - *The Delamination-Relamination Cycle of the Cratonic Lithospheric Mantle*

12h30-14h Lunch break + POSTERS

14h-14h45 Anna Gülcher - *The perils and promises of geodynamic modeling of planets: a case study of Venus tectonics*

14h45-15h30 Hana Čížková - *Deformation of subducting plates in the mantle and implications for deep seismicity*

15h30-16h Meeting of ECS with speakers

16h-17h Coffee break + POSTERS

17h-18h45 Round tables + Plenary discussion

Tuesday, September 3rd 2024

Deformation Localization & Rheology

8h30-9h15 Maurine Montagnat - *Rheology of ice. Small scale processes and large scale flow simulations*

9h15-10h Dave Bercovici - *Upscaling from Mineral Microstructures to Tectonic Macrostructures*

10h-10h45 1-min (1-slide) poster presentations by Early Career Scientists

10h45-11h45 Coffee break + POSTERS

11h45-12h30 Lukas Fuchs - *Rheological Memory in Plate-Like Mantle Convection including Continents*

12h30-14h Lunch break + POSTERS

14h-14h45 Nestor Cerpa - *Using machine learning to simulate sub-mesh processes in geodynamic modeling: example for the prediction of texture-induced anisotropy in the upper mantle*

INTERNATIONAL LITHOSPHERE PROGRAM

14h45-15h30 Richard Katz - *Models of elastic--viscoplastic unbending to explain sea-level control on fault pacing at fast-spreading mid-ocean ridges*

15h30-16h Meeting of ECS with speakers

16h-17h Coffee break + POSTERS

17h-18h45 - Round tables + Plenary discussion

Wednesday, September 4th 2024

Computational morning

8h30-9h15 Rhodri Davies - *Automating Forward and Adjoint Models for Geodynamics via the Geoscientific ADjoint Optimisation PlaTform (G-ADOPT)*

9h15-10h30 Practical part 1

10h30-11h15 Coffee break + POSTERS

11h15-12h30 Practical part 2

12h30-14h Lunch break + POSTERS

Afternoon : recreational activities (to be announced)

Thursday, September 5th 2024

Lithosphere & Crust Dynamics, Surface Processes, Numerical Methods

8h30-9h15 Anne Glerum - *Geodynamic controls on georesource formation*

9h15-10h Attila Ballazs - *The links between tectonics, surface processes and melting in basin-orogen systems*

10h-10h45 1-min (1-slide) poster presentations by Early Career Scientists

10h45-11h45 Coffee break + POSTERS

11h45-12h30 Luca Dal Zilio - *Poromechanics of Fluid-Induced Earthquakes: Theory, Modeling, and Case Studies*

12h30-14h Lunch break + POSTERS

14h-14h45 Muriel Gerbault - *Partial melting of the continental crust with a VOF method : three little tales*

14h45-15h30 Marta Pérez-Gussinyé - *Spatio-temporal Dynamics of Hydrothermal Circulation over 10 million years of Ultraslow- Rifting and Spreading*

15h30-16h Meeting of ECS with speakers

16h-17h Coffee break + POSTERS

17h-18h45 Round tables + Plenary discussion

Gala dinner and farewell party

Friday, September 6th 2024

Breakfast and departure

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Computational practicals

Part of Wednesday morning (September 4th) will be dedicated to various practical training sessions chosen by participants, either

- **LaMEM & Julia**, instructor: Boris Kaus

  Using LaMEM (through its Julia interface) to run geodynamic models, e.g. falling sphere, 3-D subduction, thermomechanical rifting etc. It will also be demonstrated how recently developed Julia packages can be used to write new nonlinear geodynamic solvers with only a few lines of code.

- **ASPECT**, instructors: Julianne Dannberg & Menno Fraters

  Using ASPECT to run both simple and more complex dynamic models, e.g. a few examples from the classical cookbooks set-ups

- **Firedrake & G-ADOPT**, instructor Rhodri Davies

  Using G-ADOPT(underpinned by Firedrake) to set up and execute forward and adjoint geodynamical models. We will consider: (i) a base case — simple isoviscous convection inside a 2-D square box; (ii) incorporating different physical approximations and boundary conditions; (iii) running in different geometries (e.g. spherical); (iv) automated adjoint cases.

- **pseudo-transient & Just Relax**, instructor Albert de Montserrat

  We will develop simple iterative pseudo-transient solvers for elliptic equations and learn how to port the resulting code to GPUs using the Julia programming language. We will also present some examples of how to use and set up JustRelax.jl to solve simple geodynamic problems on one or more GPUs.

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2024 Ada Lovelace Workshop on Modelling Mantle and Lithosphere Dynamics

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Poster Session - September 2-3

Adams Andrea[1]
Arcay Diane
Arnould Maëlis[2]
Ballmer Maxim
Bao Xiyuan[1]
Chassé Thibaut[2]
Dannberg Juliane
Desiderio Matteo[1]
Duan Wenyong[1]
Fedeli Valeria[2]
Garel Fanny
Gerardi Gianluca[2]
Grima Antoniette Greta[2]
Hernlund John
Jain Charitra[2]
Janin Alexandre[2]
Johnston Gabriel[2]
Kar Prachi[1]
Kerr Madeleine[1]
Kim Hyunseong[1]
Király Ágnes[2]
Krauss Heidi[1]
Labrosse Stephane
Li Kai[2]
Li Ranpeng[2]
Li Yida[2]
Li Yingying[1]
Lim Kang Wei
Lim Kang Wei
Lourenco Diogo
Lu Qianyi[1]
Ma Ziqi[1]
Manjon Cabeza Cordoba Antonio[1]
Marzotto Enrico[2]
Moccetti Bardi Nickolas[1]
Morgan Gwynfor[1]
Panton James[1]
Patocka Vojtech[2]
Pons Michael[2]
Pusok Adina
Récalde Nicolas[1]
Ricard Yanick
Ritter Sandrine[2]
Roy Poulami[2]
Ruh Jonas[2]
Saxena Arushi[1]
Saez-Leiva Felipe[2]
Sim Shi[1]
Sobolev Stephan
Spang Arne[2]
Stegman Dave
Steinberger Bernhard
Stoner Ryan[2]
Tackley Paul
Thibault Duretz
Thielmann Marcel
Tian Jiacheng[1]
Tommasi Andrea
Tuikka Leevi[1]
Van Broeck Etienne[2]
Van Driel Jack
Yamato Philippe
Zhou Xin[2]
Zhu Xiaoxi[2]

[1] 1-min presentation scheduled on Monday 2nd September 10:15-10:45
[2] 1-min presentation scheduled on Tuesday 3rd September 10:00-10:45

Poster Session - September 4-5

Aellig Pascal[3]
Arnould Maëlis[3]
Bergogne Mathis[3]
Billen Magali
Brune Sascha
Cochet Anaïs[3]
Cui Ronghua[3]
De Montserrat Navarro Albert[3]
Frasunkiewicz Jacob[3]
Fraters Menno[3]
Gassmoeller Rene
Gauthier Alexis[3]
Glink Arne[3]
Gray Timothy[3]
Jadamec Margarete
Katz Richard
Kaus Boris
Kerswell Buchanan[3]
Kuhasubpasin Boontigan[3]
Larvet Tiphaine[3]
Le Pourhiet Laetitia
Li Zhong-Hai/ Wang Yang
Lin Jia Xun[3]
Liu Sibiao[3]
Lohani Mohit[3]
Maierová Petra
Mcmillan Mitchell[3]
Neuharth Derek[3]
Olive Jean-Arthur
Plimmer Abigail[3]
Popov Anton
Puckett Elbridge Gerry
Pusok Adina
Qing Jiarong[3]
Regorda Alessandro
Ribe Neil
Rudolph Maxwell
Schuler Christian[3]
Silva Kuruvitage[3]
Smith Robert[3]
Sun Huiwen[3]
Thieulot Cedric
Van Agtmaal Luuk[3]
Wang Yang[3]
Wang Yijun[3]
Weiler Tatjana[3]
Werner Niklas[3]
Whipp David
Xu Chong[3]
Zhang Yinuo[3]

[3] 1-min presentation scheduled on Thursday 4th September 10:00-10:45

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Invited speakers

The links between tectonics, surface processes and melting in basin-orogen systems

Attila Balazs[1, *]
[1] *ETH Zurich, Institute of Geophysics, Zurich, Switzerland*
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Keywords — continental rifting, subduction, erosion and sedimentation

In this study, I analyze the surface fingerprints of distinct crustal and mantle processes that are linked to rifting, subduction and collision, and I will particularly focus on the drivers of subsidence and uplift patterns at different scales. I aim to better understand the feedback mechanisms between tectonics, surface processes and mantle melting. First, I discuss different thermo-mechanical and coupled surface processes implementations that are widely used to study the links between erosion, sediment transportation and deposition in various tectonic settings.

Our model results are conducted by the coupled I3ELVIS-FDSPM code assuming visco-plastic rheologies and diffusion-based surface processes. Sedimentation contributes to increased confining pressure leading to brittle strengthening of the crust, at same time it increases the crustal thermal gradients driven by sediment blanketing leading to ductile weakening effects. Depending on the rate of tectonic processes and different mantle thermo-rheolgoical properties, different surface processes rates alter the timing and flux of mantle melting (Fig. 1) and modify the style of deformation, fault spacing and the timing of break-up.

The topographic evolution of subduction zones is also governed by the links between surface and deep Earth processes. Enhanced sediment subduction lubricates the subduction interface and by water release weakens the overlying mantle. Forearc and back-arc sedimentary basins are sensitive proxies for variable plate and interface rheologies. Lower surface processes rates enable a more efficient stress transfer between the plates facilitating back-arc extension. Whereas higher sediment subduction fluxes contribute to enhanced melting leading to arc rifting. The competition between the slab-pull force, upper plate strength variations and melt-induced weakening are all linked to variations of the subduction velocity and topography.

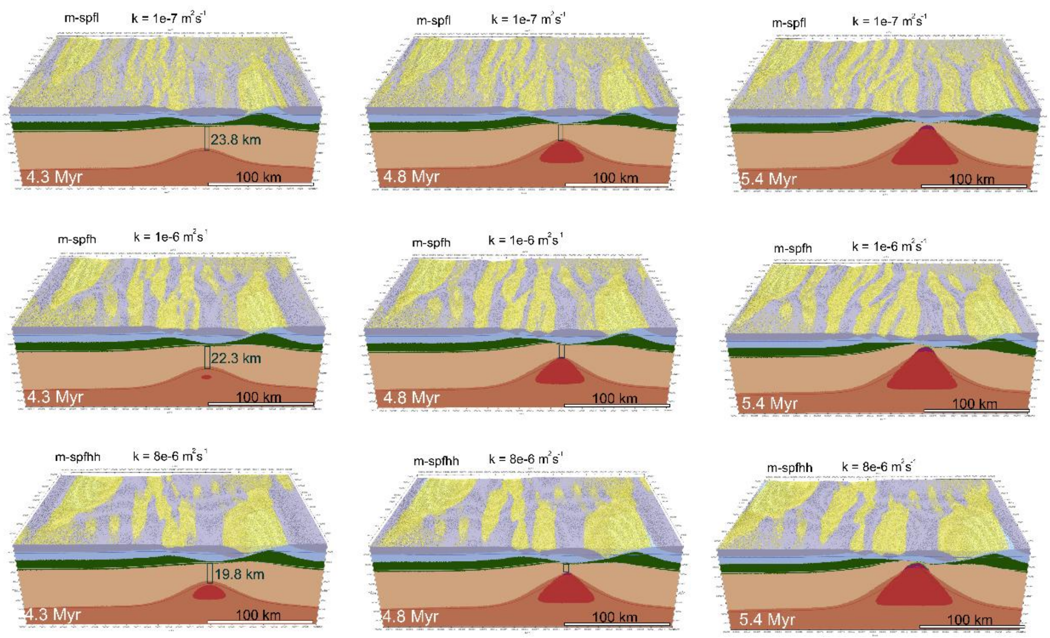

Figure 1: Models assessing the role of different diffusion coefficients assuming a constant 1.8 cm/yr plate divergence velocity. Note that a higher diffusion coefficient and thus higher erosion and sedimentation rates lead to a more localized deformation and an earlier and enhanced mantle melting.

Upscaling from Mineral Microstructures to Tectonic Macrostructures

David Bercovici[1, *]

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Keywords — microstructure, lithosphere deformation, upscaling

Ductile flow in the lithosphere and mantle is not like that of simple viscous fluids in a liquid state. Stress release and deformation in crystalline materials involve transport of defects such as atomic vacancies (point defects), dislocations (1-D defects), and grain boundaries (2-D defects) [1]. Experiments and theories on defect evolution are at millimeter to sub-micron scales, and how to account for this behavior at the tectonic scale is a significant challenge, especially in extrapolating lab experiments over orders of magnitude in time and space. The standard approach is usually to ignore defect evolution, treat only one characteristic defect density or size, and assume a balance between defect sources and sinks, leading to steady state creep laws. But the defect adjustment time scale may not be any shorter than mantle and lithosphere deformation time scales. How point, line and plane defects evolve, survive, and interact are important for time-dependent processes from transient creep to annealing [1, 2].

How defect evolution governs the formation and longevity of weak zones is especially important for understanding the formation of plate tectonics. Anisotropic weakening from CPO involves finite adjustment and annealing times and the preserved fabric influences the formation and durability of weak zones [3]. Brittle behavior plays an important role in weakening the shallow lithosphere, as well as ingestion of water to depth [4], which may help nucleate and preserve deep lithospheric weak zones.

Weakening from the interaction of point, line and plane defects leading to grain-size reduction is also important for generating plate boundaries, but mostly in polyminerallic media where mineral phases mix, as evident in peridotitic mylonites at lithospheric shear zones. Mixed phases promote Zener pinning, which impedes healing (grain growth) and enhances damage (DRX) [5]. Polyphase assemblages also develop shape-preferred anisotropic strength when mineral units are sheared to the percolation limit [6].

The scale of petrological heteogeneity, at which phase mixing occurs, introduces an intermediate "mesoscale" between the micro- and macroscales [7]. Mixing at the mesoscale influences microscale processes, which govern the strength of the lithosphere at the macroscale. I outline an upscaling framework that efficiently couples micro-, meso- and macroscale processes for geodynamic models. The upscaling steps involve modeling diffusive phase mixing at a small mesoscopic volume within the macroscopic grid with a fast analytical solution facilitated by two simple coordinate transformations. The grain-size and viscosity within mixed zones are determined by two-phase grain-damage theory; the unmixed zone properties by mono-phase grain damage. The orientation of phases and mixed-phase bands are defined by a simple fabric tensor, which is used to infer an anisotropic viscosity field that can be incorporated into a macroscale lithosphere flow model. This scheme is demonstrated for a simple model of a lithospheric Rayleigh-Taylor drip driven by ridge-push compressive stress, as a proxy for subduction initiation during passive margin collapse.

References

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Using machine learning to simulate sub-mesh processes in geodynamic modeling: example for the prediction of texture-induced anisotropy in the upper mantle

Nestor Cerpa[1,*], Andrea Tommasi[1], Fernando D. Carazo[1,2], Javier Signorelli[3], Buchanan Kerswell[1], Jose Alberto Padrón-Navarta[4]

[1] *CNRS, University of Montpellier, Montpellier, France*

[2] *Universidad Nacional de San Juan, San Juan, Argentina*

[3] *Instituto de Fisica de Rosario, CONICET, Rosario, Argentina*

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Keywords — Geodynamics, Artificial Intelligence, Mantle Anisotropy

Plate tectonics and mantle convection occur as a result of a variety of micro-scale physico-chemical processes, including solid-solid phase transformations, fluid-rock interactions, and crystal plasticity. Quantitative tools to predict the evolution of such processes with Pressure-Temperature-Composition-Stress (P-T-X-σ) at the small scale exists: thermodynamic codes for prediction of phase assemblages or micro-mechanical models for deformation of polycrystalline materials. Yet, in large-scale geodynamic modeling, it is common to approximate them through parameterized functions of, for instance, mantle density and rheology. That is because coupling codes often requires prohibitive computational costs.

Inspired by state-of-the-art methods used in other fields, such as climate modeling, in our group, we explore the alternative idea of developing artificial-intelligence based surrogates for submesh processes in geodynamical modeling. We currently develop these ideas for 1) the evolution of mantle-rock bulk physical properties (e.g. density) with P-T-C and 2) the evolution of mantle mechanical anisotropy due to texture evolution. In this presentation, I will briefly describe our recent proof-of-concept [1] with machine-learning algorithms trained on predictions of density evolution with P-T-X by Perple_X [2] and will present in more detail our efforts to predict both elastic and viscous anisotropy in the upper mantle.

Both elastic and viscoplastic behaviors of the Earth's upper mantle are highly anisotropic, because olivine, the orthorhombic phase composing 60-80% of the mantle, has a strong intrinsic viscoplastic anisotropy and develops strong textures (or crystal preferred orientations) in response to deformation. To speed up the prediction of elastic anisotropy in the mantle, we develop deep-learning (DL) surrogates trained on a synthetic database built with viscoplastic self-consistent simulations of texture evolution of olivine polycrystals [3,4] in typical 2D geodynamical flows. A first challenge was the choice of memory-saving representations of the texture. Training the DL models on the evolution of the 21 elastic tensor components avoided the need of saving the texture itself (number of grains × 3 Euler angles). We implemented multilayer feed-forward (FFNN), and ensemble neural networks obtaining the best efficiency/accuracy ratio for the FFNN. The results highlight the importance of the standardization of the outputs in the training stage to avoid overfitting in predictions, the statistical characteristics of the strain histories in the training database, and the influence of non-monotonic strain histories on error propagation. One-step predictions have errors <1% and the surrogates are much more time-efficient and less memory-costly than the traditional micro-mechanical models. However, the main challenge has been to keep the errors within reasonable bounds in a recursive-prediction scheme – where a model prediction at a given time step becomes the input for the next one – which is required to evaluate the anisotropy evolution along a flow line. Predictions for unseen strain histories of the analytical corner flow remain accurate for finite strains of up to 3-4, but start to diverge thereafter. To improve the accuracy of the recursive predictions we are currently working on reducing the model space by establishing more condensed descriptions of the problem.

This work was supported by the European Research Council (ERC) under the European Union Horizon 2020 Research and Innovation programme [grant agreement No 882450 – ERC RhEoVOLUTION].

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Deformation of subducting plates in the mantle and implications for deep seismicity

Hana Čížková[1, *], Arie P. van den Berg[2], Craig R. Bina[3], Mohit Lohani[1], Jakub Pokorný[1], and Jiří Zahradník[1]
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[2] *Utrecht University, Department of Earth Sciences, Utrecht, The Netherlands*
[3] *Northwestern University, Department of Earth and Planetary Sciences, Evanston, IL, U.S.A.*
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Keywords — subduction, numerical modeling, deep earthquakes

Processes within subduction zones have a major influence on the plate dynamics and mantle convection. Subduction is controlled by a combination of parameters and there is no simple global relationship between the resulting slab geometry and deformation and any specific subduction parameter. Deformation of the subducted lithosphere in the mantle reflects the thermo-compositional structure of individual subducting plates as well as the mineralogical properties and rheological stratification of mantle material. Constructing the geodynamic models of subduction thus critically depends on our knowledge of mantle composition, phase transitions, water content and rheology.

Most of the world seismicity is associated with the subducting lithosphere. While earthquakes occur on very short time scales, they reflect thermal conditions and stress state attained in the subducted slab during its long-term evolution. Analysis of deep seismicity in subduction zones thus provides invaluable information that helps to constrain geodynamic subduction models. Spatial distribution of deep-focus earthquakes may delineate slab geometry, seismogenic stresses indicate the directions of tectonic stress that developed in the subducting plate due to the thermal and petrological buoyancy and viscous resistance of the mantle. On the other hand, geodynamic models allow to illuminate a possible seismogenic mechanism – dehydrational embrittlement, transformational faulting or thermal runaway.

Here we will present subduction models tailored to several subduction zones including South America (Fig. 1), Japan Sea, Tonga and Aegean. The pressure-temperature conditions and stress orientations in the subducting plates will be used to interpret observed earthquake source mechanisms and shed some light on possible seismogenic mechanism of intermediate and deep-focus seismicity.

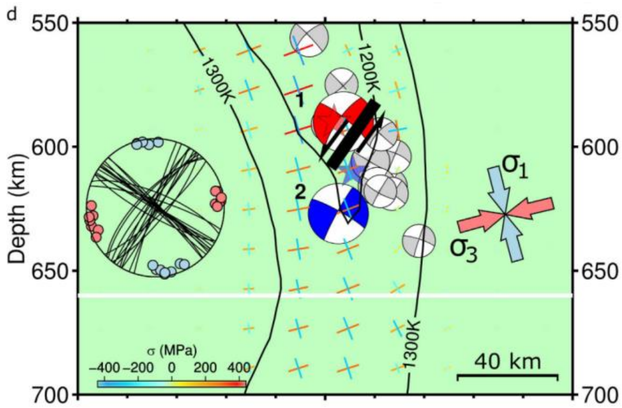

Figure 1: Seismogenic and tectonic stress in the subducted Nazca plate [1]. Seismic data are illustrated by beachballs, nodal planes, P-T axes and principal stress axes in the insets. Geodynamic model stresses are plotted by color-coded crosses.

References
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Poromechanics of Fluid-Induced Earthquakes: Theory, Modeling, and Case Studies

Luca Dal Zilio[1, 2 *]

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[2]*Asian School of the Environment, Nanyang Technological University, Singapore*
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Keywords — Poromechanics, Fluid-Induced Earthquakes, Aseismic and Seismic Slip

Fluids in the Earth's crust have the potential to destabilize faults through various styles of slow (aseismic) and fast (seismic) slip spanning a wide range of spatiotemporal scales. Understanding the mechanics and interplay between solid and fluid interactions, and how these interactions control seismic and aseismic slip, is central to seismotectonics as it determines the seismic potential of faults. To better understand solid-fluid interactions in earthquake source processes, we present `H-MEC` (Hydro-Mechanical Earthquake Cycles), a newly-developed two-phase flow numerical framework [1]. This model couples solid rock deformation and pervasive fluid flow to simulate how crustal stress and fluid pressure evolve during the earthquake cycle. This unified, continuum-based model incorporates a staggered finite difference–marker-in-cell method and accounts for inertial wave-mediated dynamics and fluid flow in a poro-visco-elasto-plastic compressible medium. Global Picard-iterations and adaptive time stepping allow the correct resolution of both long- and short-time scales, ranging from years to milliseconds.

We present a comprehensive overview of the theory and modeling, as well as case studies on coupled poromechanics modeling in earthquake and faulting phenomena, including fluid flow, the evolution of porosity and permeability, and frictional slip. Analytical approaches of strain localization and shear-induced dilation and compaction are integrated with numerical simulations that span the spectrum of aseismic to seismic fault slip. We then discuss case studies on fluid-induced earthquake nucleation on frictionally stable faults, seismic and aseismic slip controlled by fault valving of transient fluid pressure pulses, and how permeability barriers control the distribution of creeping patches and locked seismic asperities on seismogenic faults.

Our modeling results demonstrate that fault failure can occur due to poroelastic coupling within a finite-width shear zone, thus highlighting the importance of considering the realistic hydro-mechanical structure of faults to investigate fluid-driven seismic and aseismic slip, either as a natural process or induced by human activities. This work underscores the critical need for advanced models to unravel the complexities of fault mechanics and improve our understanding of earthquake hazards.

References

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Automating Forward and Adjoint Models for Geodynamics via the Geoscientific ADjoint Optiomisation PlaTform (G-ADOPT)

D. Rhodri Davies[1*], Sia Ghelichkhan[1], William Scott[1], Thomas Duvernay[1], Angus Gibson[1] and Stephan Kramer[2]
[1] *Research School of Earth Sciences, The Australian National University, Canberra, Australia.*
[2] *Department of Earth Science and Engineering, Imperial College London, London, UK.*
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Keywords: Geodynamic Software; Adjoints; Finite Element Methods; Mantle Convection; Glacial Isostatic Adjustment.

The **G**eoscientific **AD**joint **O**ptimisation **P**laTform (G-ADOPT - https://gadopt.org) is a next-generation computational framework for simulating geoscientific flows. Building on composable abstraction and automatic code generation techniques, G-ADOPT provides an accurate, efficient, flexible, extensible, scalable, transparent, and reproducible open-source research software. In addition, G-ADOPT overcomes the significant theoretical and practical challenges of generating adjoint models, allowing the community to move from idealised forward models to data-driven simulations (relying on an inverse approach) that rigorously account for observational constraints and their uncertainties.

G-ADOPT is underpinned by four state-of-the-art software libraries:

1. *Firedrake*, an automated system for solving Partial Differential Equations (PDEs) using the finite element method.
2. *Dolfin-adjoint*, an algorithmic differentiation framework that automatically derives the corresponding representation of discrete adjoint equations in a form compatible with Firedrake.
3. *The Portable Extensible Toolkit for Scientific Computation (PETSc),* for the scalable (parallel) solution of scientific applications modelled by PDEs.
4. *The Rapid Optimisation Library (ROL),* a highly efficient package enabling advanced, large-scale optimization.

When combined, they provide a high-performance geoscientific modelling framework with forward and adjoint capabilities that achieve theoretical computational efficiency.

Areas of current application include: (i) Geodynamics, with a particular emphasis on simulating mantle dynamics and its diverse surface manifestations; (ii) Glacial Isostatic Adjustment (GIA), the ongoing response of Earth's surface and sea level to changes in ice and water loading as Earth moves into and out of periods of glaciation; and (iii) Groundwater, focussing on predicting the evolution of water storage in Australia and its sensitivities.

In this presentation, I will demonstrate the applicability of G-ADOPT for a range of forward and inverse geoscientific problems. I will cover the accuracy and efficiency of the approach, alongside parallel scalability. In addition, G-ADOPT's flexibility will be highlighted via straightforward application to different physical and geometrical scenarios. Representative forward and adjoint simulations of global mantle convection and glacial isostatic adjustment will be examined, confirming the framework's suitability for tackling research problems from the frontiers of geoscientific research. A workshop, incorporating tutorials on how to use G-ADOPT, will be convened at the meeting.

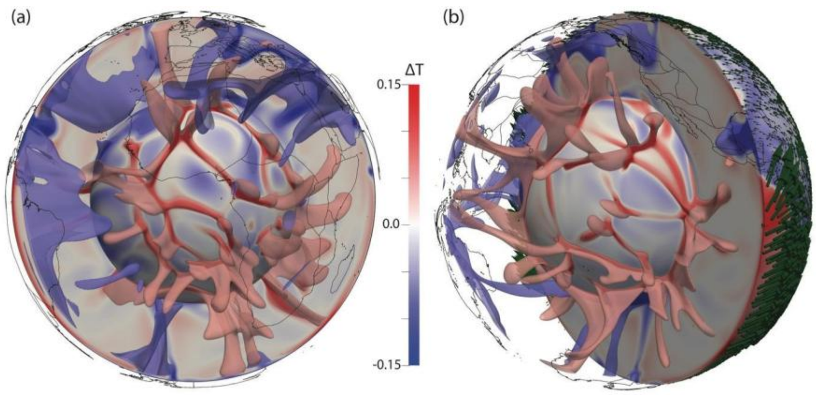

Figure 1: *Present-day thermal structure, predicted from a global mantle convection simulation in G-ADOPT, where the geographic distribution of heterogeneity is dictated by 230 Myr of imposed plate motion history. Each image includes a radial surface immediately above the core-mantle boundary, a cross-section, and transparent isosurfaces at temperature anomalies (i.e. away from the radial average) of T=-0.075 (blue) and T=0.075 (red), highlighting the location of downwelling slabs and upwelling mantle plumes, respectively. Continental boundaries provide geographic reference. Panel a provides an Africa-centered view, with panel b centered on the Pacific Ocean, and including (green) glyphs at the surface highlighting the imposed plate velocities.*

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Rheological Memory in Plate-Like Mantle Convection including Continents

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Keywords — deformation localization, mantle convection, plate tectonics

The creation and maintenance of narrow plate boundaries and their role in the thermo-chemical evolution of Earth remain major problems in geodynamics. Strain-localization and plate boundary evolution are affected by weakening in ductile shear zones, and a change from dislocation to diffusion creep caused by grain-size reduction is one of the weakening mechanisms that has been discussed. However, the causes and consequences of strain localization remain debated, even though strain localization and tectonic inheritance, i.e., the ability to preserve and reactivate weak zones over geological time, appear to be critical features in plate tectonics.

Here, we explore such issues using 3D spherical numerical convection models applying a parameterized, strain-dependent weakening and hardening (SDWH) rheology. This SDWH rheology shows similar transient behavior as grain-size sensitive composite rheology, one of the major candidates for weakening in the ductile lithosphere. Such parameterized rheologies can mimic more complex transient weakening and hardening processes, akin to a grain-size-sensitive composite rheology. In addition, the SDWH rheology allows for memory of deformation, which enables self-consistent formation and reactivation of inherited weak zones within the lithosphere and sustains those weak zones over an extended period.

We analyze how such a SDWH rheology affects the surface dynamics and the time-dependence of plate reorganization and heat transport in 3-D spherical, visco-plastic, thermo-mechanical models using the well benchmarked community code CitcomS. We focus on the evolution of supercontinental assemblies and the effect of SDWH rheologies on strain localization, tectonic reactivation of inherited weak zones, continental break up and assemblage, and their long-term evolution. The results show the importance of a rheological memory for the reorganization of plates, potentially even for the Wilson cycle.

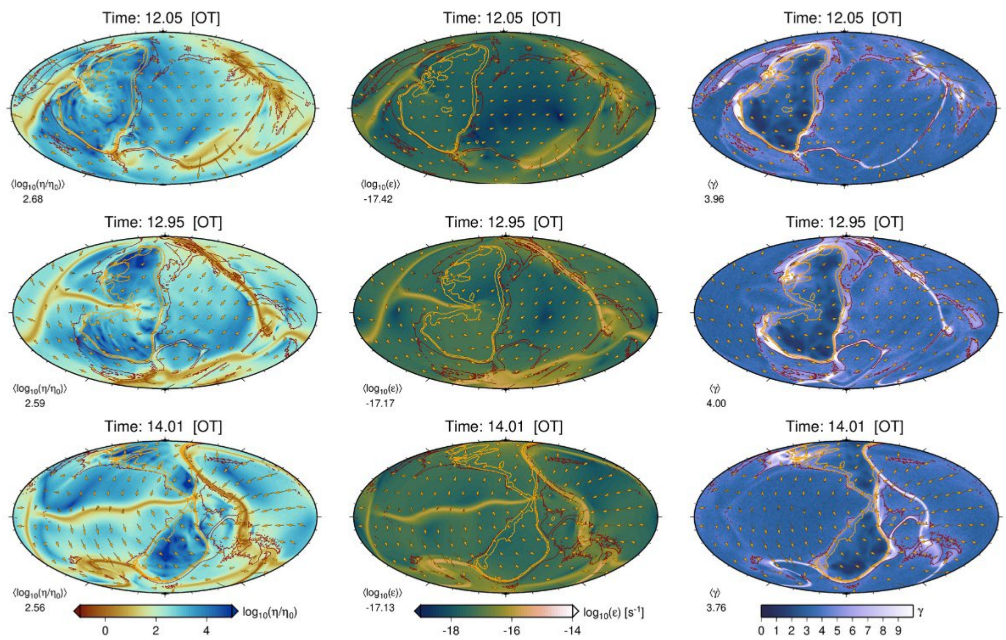

Figure 1: Breakup of a weak continental float. Surface maps of the effective viscosity (left), the second invariant of the strain rate tensor (middle), and the accumulated strain (right) for three consecutive time steps. The maps show the lateral propagation of a divergent plate boundary through the continental material.

Partial melting of the continental crust with a VOF method : three little tales

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Keywords — partial melting, melt segregation, gravity instabilities, VOF method

Partial melting of the continental crust is often a primary condition for the concentration of mineral deposits and geothermal exploration. However continental felsic crust displays a broad variety of heterogeneities, and the mechanisms by which its components differentiate and segregate remains debated. I will first recall the geodynamic context in which gravitational destabilization of partially molten rock can dominate over lateral tectonics, at a tens of million years scale. The specific case of Naxos's (Greece) metamorphic domes is interesting because it appears to display a double mechanism of convection and diapirism. Using cross-scale assumptions allowed us to model this mechanism with an original numerical solver based on the open source OpenFoam's VOF method. This method is adequate to track heterogeneous domains and led to identify criteria for large scale, gravity driven melt segregation [1, 2] (Fig. 1), that may be applicable to broader heterogeneous contexts.

A second tale that this VOF method allows us to tell is the development of partially molten rhyolite under Krafla's volcanic complex (Island, [3]); now at scales of few hundred meters and few decades, and despite large viscosity contrasts, we can track the progressive development of secondary convection in this rhyolite layer, induced by a basaltic injection from underneath. This provides useful thermal constraints for geothermal exploration.

Finally, I will share our state of progress in dealing with partial melting at decimetric scale, by coupling fluid flow and reactive transport equations, aiming to better understand the dominant processes of melt transport in specific metamorphic contexts.

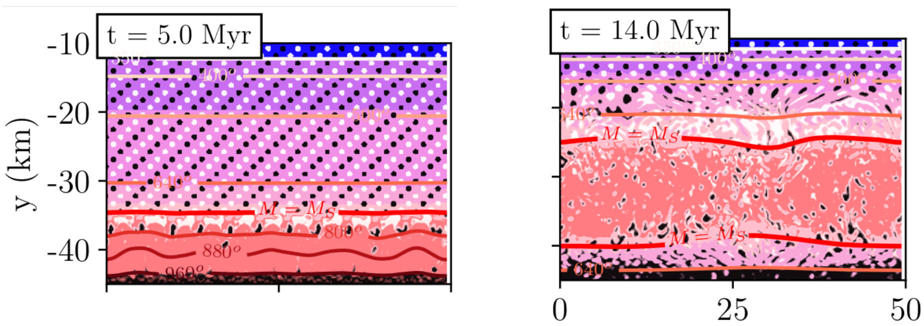

Figure 1: *Snapshots of vertical sections of destabilizing melting heterogeneous crust, after [2]. Convection develops in a 3D crustal domain heated from below. The buoyant partially molten, white material progressively forms domes at 20 km depth.*

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Geodynamic controls on georesource formation

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Keywords — lithospheric deformation, sediment-hosted ore deposits, hydrogen formation

The transition to net-zero CO_2 emissions requires new renewable energy sources; this in turn will lead to a high demand for metal resources. Geosciences play a crucial role in exploring for such resources, requiring a cross-scale understanding of georesource systems. Through geodynamic modelling, we here unravel the large-scale geodynamic controls on the formation of naturally occurring hydrogen gas (H_2) and zinc-lead (Zn-Pb) minerals.

Natural H_2, a potential green energy source, can be generated in large volumes through serpentinization of mantle material as it is exhumed into the right temperature window and reacts with water. Serpentinization is an efficient process along rifted margins, and sediment-hosted clastic-dominated deposits, the largest source of Zn and Pb, are found in failed rifts and rifted margins. We therefore numerically model 2D rift systems from inception to break-up or inversion with the geodynamic code ASPECT [1,2]. ASPECT is coupled to the landscape evolution model FastScape [3,4] to track the transport and type of sediments.

Through post-processing of the modelled fault geometries, rock types and temperatures, we determine when favourable conditions for H_2 accumulation or Zn-Pb ore deposit formation occur. We find that although mantle material in the right temperature window is penetrated by large active faults that could supply the necessary water for serpentinization and H_2 generation during rifting, the H_2 volumes generated during subsequent rift inversion may be up to 20 times higher [5]. Exploration for natural H_2 could thus focus on rift-inversion orogens, such as the Pyrenees.

The formation of clastic-dominated Zn-Pb deposits requires the optimal alignment of metal source and host rock domains, where metals are respectively leached and deposited, with faulting providing fluid pathways between these domains [6]. We show that this optimal alignment occurs most often in narrow asymmetric rifts [7] as opposed to wide and symmetric rifts. On the thinned narrow margin generated by rift migration (see Fig. 1), the long-lived border fault accommodates a thick submarine package of sediments, including permeable continental sediments (source) and shallower organic-rich sedimentary units (host). Both the border fault and later synthetic faults can provide fluid pathways in potential short-lived mineralisation events. Based on our insights, exploration programs should identify exhumed ancient narrow margins formed in asymmetric rift systems.

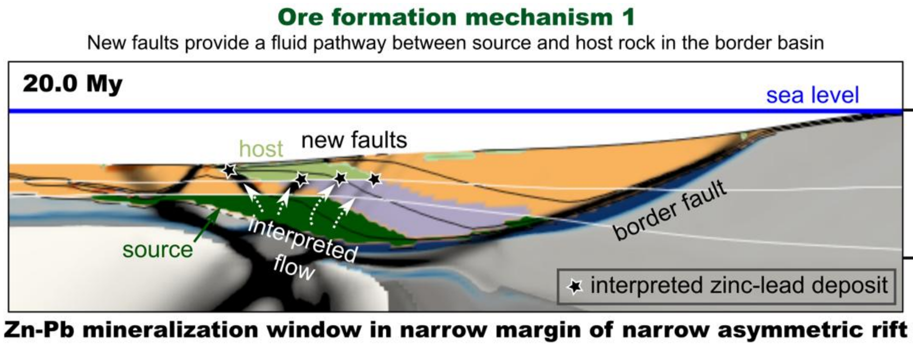

Figure 1: Most promising predicted ore formation mechanism in which for ~3 My new smaller faults in the border basin connect metal source to host rock, allowing for fluid flow (white arrows). Metals would be deposited when the fluids reach the host rock (stars).

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The perils and promises of geodynamic modeling of planets: a case study of Venus tectonics

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Keywords — rocky planets, Venus, mantle and lithosphere dynamics, tectonics, magmatism, data, missions

Solar system science is continually advancing, with frequent, and often significant revisions to prevailing models of atmosphere, surface, and interior dynamics. As we will never have in-situ data for any exoplanet, surface conditions will always be inferred from models based on solar system data. In turn, even within solar system sciences, we largely rely on applying geoscience's wealth of Earth observations and knowledge to fill in the blanks left by minimal planetary data. This also extends to geodynamic modeling, where Earth-centric geodynamic tools are adapted to explore the geodynamics of other rocky planets. Thus, geodynamic studies of planets present unique challenges alongside excitment of the unknown. In this talk, I will examine several perils and promises associated with this approach, with a particular focus on the case study of Venus tectonics and missions.

Venus and Earth share numerous similarities, including size, mass, and chemical makeup. The two planets were formed under comparable conditions, but their environments today are vastly different. While Earth's environment is habitable, Venus has a harsh, crushingly thick atmosphere over an extremely hot, rocky surface. A fundamental question in Earth, planetary, and exoplanetary sciences is why Earth and Venus have evolved so differently. Several upcoming space missions to Venus, such as NASA's VERITAS and ESA's EnVision, aim to shed light on this mystery. Unlike Earth, Venus lacks a mosaic of mobile tectonic plates at the present day. Instead, the planet's global tectonics are primarily driven by mantle upwellings, intrusive magmatism, and lithospheric deformation (Fig. 1). Consequently, the surface of Venus is scarred by numerous tectonic and volcanic structures, both of familiar and exotic forms. Unraveling the origin of these features holds clues for the evolution of Venus and the early Earth, which may have operated in a similar regime.

I will showcase geodynamic models of various tectonic settings on Venus, offering valuable insights into the planet's long-term evolution and current state. I'll demonstrate the integration with current Venus datasets such as radar imagery, topography, and gravity, and what tectonic processes on Venus are inferred by these data and geodynamic models. With several missions to Venus in preparation, we can use predicted dataset resolutions to anticipate what future datasets, such as significantly improved gravity data, can reveal about the geodynamics and tectonics of Venus. I will present our predictions of future VERITAS gravity data abilities and what key hypotheses regarding Venus' tectonics and volcanism can be tested with this data combined with geodynamic models, emphasizing the crucial role of geodynamic modeling tools in **paving the way for the 'Decade(s) of Venus'**.

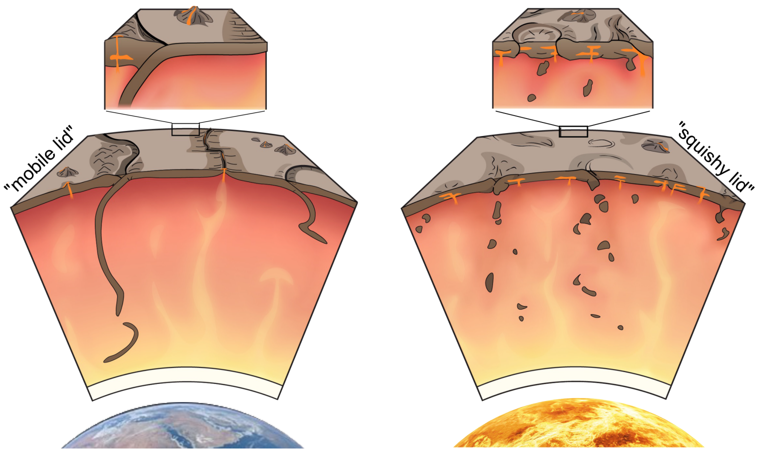

Figure 1: *Conceptual illustration of mantle dynamics and tectonic regimes on present-day Earth (left) and commonly proposed for Venus (right). Illustration from [1] and also available on https://s-ink.org/tectonic-and-mantle-convection-regimes.*

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Granular dilatancy and non-local fluidity of partially molten rock

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Keywords — dilatancy, partial melting, instability

Partially molten rock is a densely packed, melt-saturated, granular medium, but it has seldom been considered in these terms. Here [1] we extend the continuum theory of partially molten rock to incorporate the physics of granular media. Our formulation includes dilatancy in a viscous constitutive law and introduces a non-local fluidity. We analyse the resulting poro-viscous–granular theory in terms of two modes of liquid–solid segregation that are observed in published torsion experiments: localisation of liquid into high-porosity sheets and radially inward liquid flow. We show that the newly incorporated granular physics brings the theory into agreement with experiments. We discuss these results in the context of grain-scale physics across the nominal jamming fraction at the high homologous temperatures relevant in geological systems.

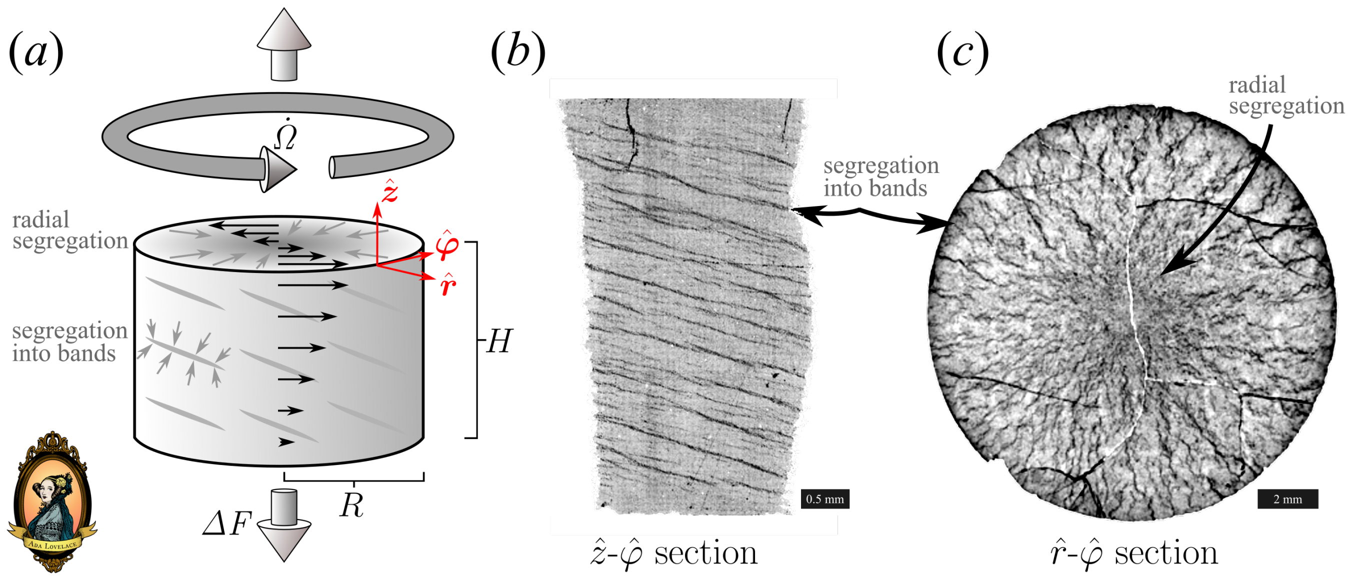

Figure 1: *Configuration and results of published experiments. (a) Schematic diagram of a deforming experimental sample and the emergent patterns of melt segregation. Experiments are conducted at high confining pressure and high temperature. After achieving a specified twist, the sample is quenched, sectioned and polished to reveal the distribution of melt (solidified to glass) and crystalline, granular solid. (b) A tangential section showing high-porosity bands (black) at low angle to the shear plane [2]. (c) A transverse section showing radially inward migration of melt [3]. Cracks visible in (b) and (c) are a consequence of the rapid quench and decompression after deformation.*

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Deep mantle structure, dynamics and evolution

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Keywords — Deep mantle, Large low velocity provinces, Ultra low velocity zones, basal magma ocean

Physical and chemical contrasts across the core-mantle boundary is unequaled in the Earth, as important as the one observed between the Earth interior and the hydrosphere. It is therefore not surprising that seismological constraints on the bottom of the mantle have been uncovering more and more complexities regarding the deepest mantle. At the large scale, two large low velocity provinces (LLVP, a few percents velocity reduction) have been imaged under the Pacific ocean and under South Africa. At the small scale (~ 100 km), ultra low velocity zones (ULVZ, $\delta V_S \sim -30\,\%, \delta V_P \sim -10\,\%$) have been observed in many regions and can be explained by the presence of dense partial melt or highly Fe-enriched solid silicate. Both options require some amount of compositional variations in the deep mantle. A weak geographical correlation between LLVPs and ULVZs has been used to argue for a common origin although recent findings of ULVZs far from any LLVP blur that picture. Several scenarios have been proposed to get to the present situation. In the first scenario, a layered mantle could be the result of the accretion and differentiation in the magma ocean stage of the early Earth. Gradual entrainment of compositional differences by solid mantle convection could lead to the present situation with the remnants of the early lower layer as LLVPs. In the other end-member scenario, the mantle starts with a uniform composition and crustal extraction at mid-ocean ridges creates heterogeneties that are recycled at subduction zones. In this scenario, the oceanic crust, which becomes denser than the average mantle at high pressure, separates from the harzburgitic mantle and accumulate to form LLVPs. Some of the crustal material could remelt and produce ULVZs in the process. A third scenario posits that a few hundreds of km of the lowermost mantle started molten, the basal magma ocean (BMO), and fractionally crystallised with time, forming LLVPs and leaving the last very enriched melts in the form of ULVZs (Fig. 1). These different scenarios are not necessarily mutually exclusive and depend on several mineralogical parameters like the density dependence of solid and melts on temperature, pressure and composition, the partition coefficients between solid and liquid silicates, the rheology of crystal agregates in the deep mantle. The goal of this presentation is to sum up the observations of the deep Earth, the current models regarding its present day dynamics and discuss the possible scenarios for long term evolution of the Earth to its present situation.

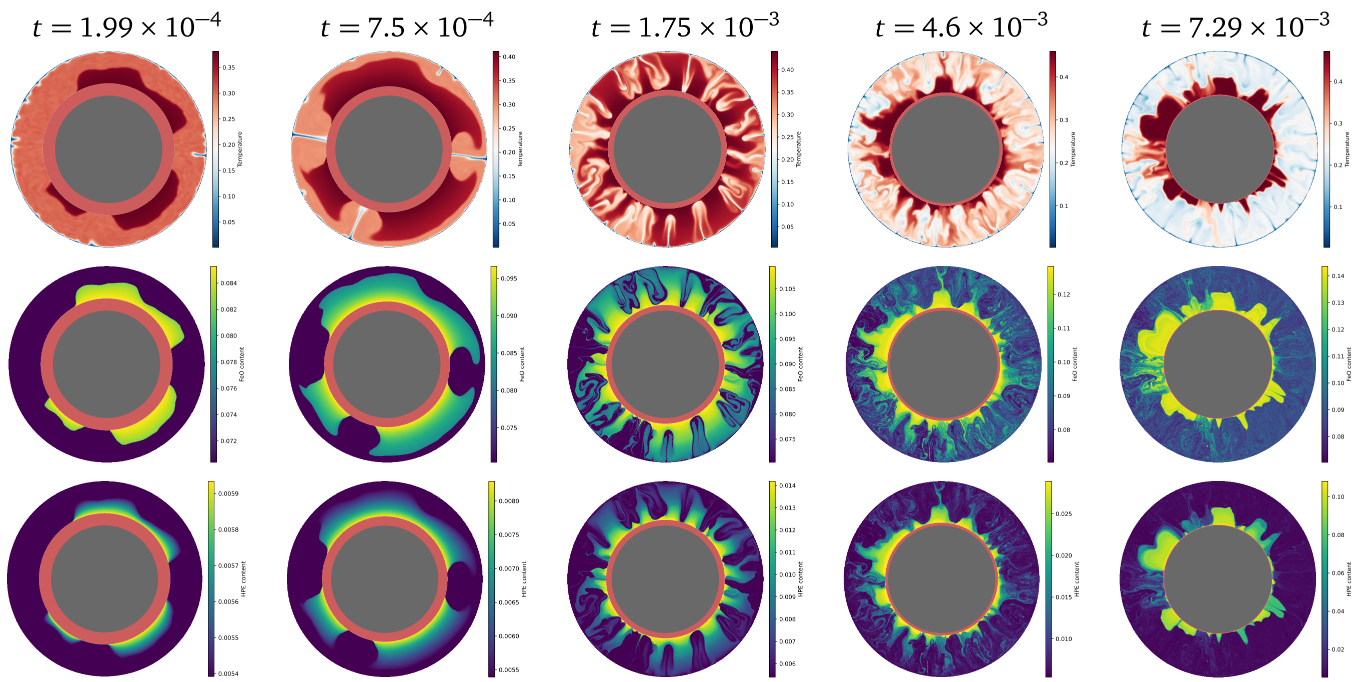

Figure 1: *Evolution of the temperature (top row), the Fe number (middle row) and concentration in heat producing elements (arbitrary unit) in a model of mantle convection evolution with a crystallising basal magma ocean (pink layer).*

Spatio-temporal Dynamics of Hydrothermal Circulation over 10 million years of Ultraslow- Rifting and Spreading

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Keywords — tectonics, magmatism, hydrothermal flow

Hydrothermal fluid circulation across the oceanic crust plays a major role in regulating the Earth's energy budget by extracting 30% of the oceanic lithospheric heat output [1], and contributes to element exchange between the hydrosphere and the geosphere through fluid-rock interactions, resulting in carbonation processes that sequester CO_2 [2], as well as in the accumulation of important mineral resources on the seafloor that are instrumental for the energy transition (e.g., [3]). In addition, fluid interaction with low-silica ultramafic rocks leads to natural abiotic production of H_2 and CH_4, which enable microbial communities to exist in surface and subsurface environments, sustaining a deep biosphere that thrives under extreme conditions (e.g. [4]). Despite the importance of submarine hydrothermal systems, much remains to be understood about how geological factors, such as faulting and magma intrusion at mid-ocean ridges, control their dynamics and spatio-temporal variability. As a result, historical and current mass, energy and element fluxes across the ocean floor remain largely unconstrained.

Coupled tectonic-hydrothermal models can support the understanding of feedbacks between tectonics, magmatism and the life cycle of hydrothermal systems and the quantification of heat and element budgets. Here, we discuss the mechanical, fluid flow and heat flux patterns in a coupled thermo-hydro-mechanical, Rift2Ridge-Hydro, model at the ocean basin scale (Figure 1). The case study is an ultra-slow spreading basin, evolving from the initial rifting stages up to the ridge formation. Heat release by plastic deformation at fractures and faults, exothermic serpentinization reactions, sensible and latent crystallization heat from magmatic emplacement and radiogenic heat provide different energy-source signatures promoting hydrothermal activity. The large basin-scale domain allows us to navigate through the evolution of the modelled concurrent hydrothermal systems, emerging and decaying in consonance with the tectonics and the energy-sources. We discuss how the evolving permeability field in crust and sediments exerts a strong control on the hydrothermal circulation, and describe the dynamics of reorganization patterns in fluid flow in response to the mechanical strains and heat sources.

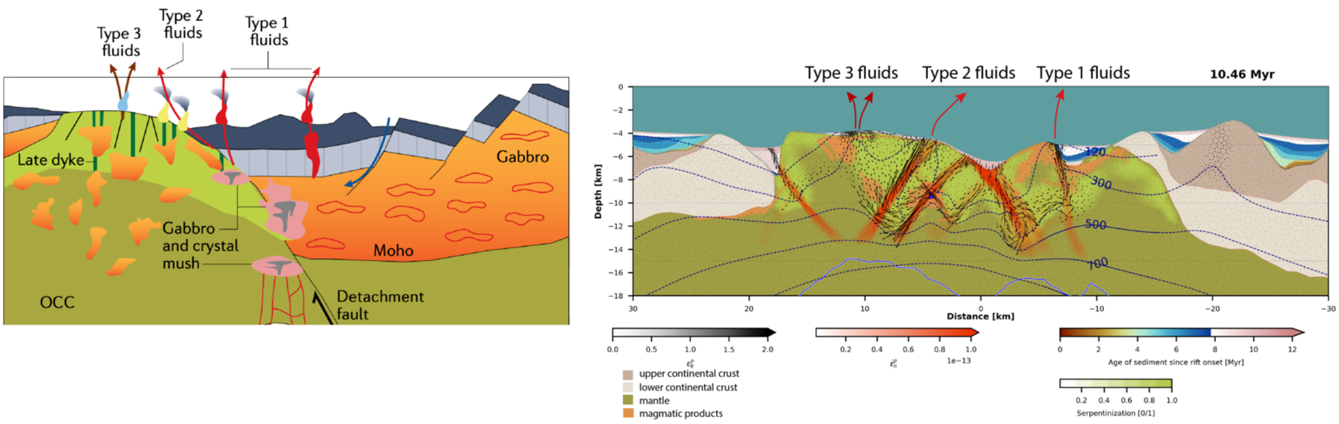

Figure 1. Left: Conceptual illustration of types of hydrothermal systems at slow and ultra-slow environments (modified from [4]). Right: a step through a Rift2ridge-Hydro simulation at 10 mm/yr full spreading. Vectors are fluid velocities.

The Delamination-Relamination Cycle of the Cratonic Lithospheric Mantle

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The existing ancient continental mantle lithosphere roots are predominantly composed of refractory peridotite, which remains after experiencing significant partial melting. Compared to fertile peridotite, which is undepleted in melt components, these refractory peridotites possess higher chemical buoyancy. This higher buoyancy facilitates their gradual accumulation in the Earth's shallow regions, integrating them into the low-temperature thermal boundary layer and forming the main component of the lithospheric mantle. As the lithosphere cools, these refractory peridotites undergo sufficient negative buoyancy due to thermal contraction, which eventually surpasses their chemical buoyancy. Concurrently, the base of the lithosphere undergoes

long-term modification and refertilization, reducing its chemical buoyancy and making it more susceptible to being counterbalanced by temperature-induced negative buoyancy. During subsequent geological processes such as subduction, collision, or mantle plume activity, the lithospheric mantle can become decoupled at the depth of the lower crust or the Mid-Lithosphere Discontinuity. This decoupling allows parts of the continental lithospheric mantle to undergo delamination driven by negative buoyancy.

When the delaminated lithosphere enters the convective mantle, some portions fully mix with the convective mantle, contributing to the formation of the depleted mantle and the chemical stratification of the mantle. However, other portions may be reheated by the convective mantle, reducing the negative buoyancy induced by low temperatures. As the chemical buoyancy once again exceeds the negative buoyancy, these portions ascend back to shallower depths in the form of small diapiric bodies. The spatial and temporal scales, along with the specific evolutionary processes of this phenomenon, are influenced by the size, temperature anomaly, and refractory nature of the delaminated lithospheric mantle, as well as the cooling processes and temperatures of the ambient mantle.

Due to the relative motion of plates and the mantle, when the recycled lithospheric mantle returns to shallow depths, it is often horizontally displaced for hundreds to thousands of kilometers from its original delamination location. This displacement results in the delaminated ancient continental lithosphere relaminating beneath young orogenic belts, oceanic basins, or even emerging at mid-ocean ridges and becoming embedded into oceanic basins as they expand. Eventually, as oceans close and continents collide, these materials may once again be stacked beneath newly formed continents. Subsequent delamination could trigger new cycles of delamination and relamination, causing the continuous exchange of depleted lithospheric mantle components between ancient continents, young orogenic belts, and oceanic lithosphere through the convective mantle.

Although the scale of the refractory lithospheric mantle currently involved in the delamination and relamination cycle may not be particularly large, this cycle was likely very common before the stabilization of the early cratonic lithosphere. This process intermixes materials from different continental units and even from different mantle depths, creating a mosaic-like composition, source, and age structure in the lithosphere. This provides a theoretical basis for explaining some complex and puzzling observations of the lithosphere.

Insights from Mineral Physics on the dynamics of the primitive Mantle; from Hadean to plate tectonics

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High-pressure tools like diamond anvil cell and multi-anvil press can be combined with *in situ* measurements to study the melting properties of the deep Earth's mantle. We developed strategies to refine the melting diagram and the composition of the melts as function of mantle depths and temperatures [1,2]. A major feature is a gap of 250 to 500 K between solidus and liquidus temperatures, which has spread the progressive crystallization of the hot early mantle over long geological times. As a result, significant amounts of melt could have persisted at mid-mantle depth up to the Archean-Proterozoic transition [3].

Composition of experimental melts are compared with those of natural komatiites of all ages and large igneous provinces. Composition of early lavas are well explained by a simple model of gradual mantle cooling starting from a highly super-adiabatic temperature gradient in the early mantle. Onset of large-scale mantle convection induced upwelling of hot diapirs, which underwent partial melting in the first ~1000 km of the young Archean mantle. With secular cooling, progressive flattening of the temperature profile made the mantle diapirs cooler. Then, they encountered melting at shallower depths, in agreement with the komatiites inventory. The cooling model also provides insights into the mechanism of the geodynamic Archean-Proterozoic transition.

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Rheology of ice. Small scale processes and large scale flow simulations.

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Simulation of ice flow in large-scale modeling approaches is essential for predicting the response of glaciers and ice sheets to climate, and in particular their future in a warming climate. It is also of use to date the ice cores extracted from deep ice sheets and access to the Earth climate history.
Although ice sheet and glacier flow modeling now integrates a wide range of complexity in terms of physics and mechanisms accounted for (interactions with the atmosphere, the ocean, calving processes, mechanisms at bedrock, etc.) or in terms of spatial resolution (tens of meter), the ice rheology remains, in most cases, poorly represented by a linear and isotropic flow law, the Glen's law.
This law originates from laboratory experiments and is a simplification of the relation between the strain rate at secondary (or minimum) creep and the imposed compressive stress, for a sample with an isotropic crystallographic texture at start.
This law therefore drastically reduces the complexity of the mechanisms at play during deformation of ice that are, for instance, the strong viscoplastic anisotropy of the single crystal of ice that results into strong strain heterogeneities between grains in the polycrystal. But also the dynamic recrystallization mechanisms that take place to accommodate theses heterogeneities, and the specific texture they induce. Textures that, in turn, result into an anisotropic mechanical response at the macroscopic scale that is rarely accounted for.
During this presentation we will travel through some of the complexity of the deformation of ice evidenced by laboratory and field measurements. We will clarify the assumptions and simplifications made for large-scale flow modeling and try to estimate some of their likely impacts on the modeling of the glacier and ice sheet flow. At the end, we will visit the requirements to account for the minimum complexity of the deformation of ice and in particular the viscoplastic anisotropy and its evolution with flow.

Poster presentations

Congratulations to the best student poster awardees :

(by alphabetical order)

- Anaïs Cochet,
- Matteo Desiderio,
- Arne Glink,
- Kai Li,
- Ziqi Ma,
- Abigail Plimmer,
- Sandrine Ritter,
- Poulami Roy,
- Tatjana Weiler,
- Niklas Werner.

The role of silicate weathering of intra-oceanic subductions on the atmospheric CO_2 budget through geological time

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Keywords — intra-oceanic arcs, silicate weathering, mantle convection

The evolution of the atmospheric CO_2 budget of our planet over 10-100 Ma time scales is notably controlled by both internal (including plate tectonics, volcanism and mantle convection) and surface processes (including weathering and sedimentation). However, the relative contribution of each of these processes is still debated. One efficient driver for atmospheric CO_2 removal is silicate-rich rock weathering, which is notably favored in the context of arc magmatism [1]. The modeling of the past evolution of the atmospheric CO_2 content therefore requires to finely reconstruct the evolution of past subduction zones. However, our knowledge of past subduction zones is incomplete due to the permanent recycling of oceanic lithosphere. One difficulty notably resides in the reconstruction of the spatiotemporal extent of intra-oceanic arcs, which leave almost no direct imprints in the geological record, although they could significantly contribute to the atmospheric CO2 removal through silicate weathering, especially in the tropics [2].

In this contribution, we propose to test how the variability of intra-oceanic arcs extent can affect the amount of CO_2 removed from the atmosphere through supercontinent cycles. To do so, we propose to use 3D numerical models of whole-mantle convection self-generating Earth-like plate tectonics [3,4] in order to quantify the temporal evolution of the number and length of intra-oceanic arcs, in a fully-dynamic context, independent of any plate reconstructions. In order to detect subduction arcs, we use the automatic plate tessellation algorithm $MAPT^3$ developed by A. Janin [5] which is based on the open-source library Topology ToolKit (TTK, [6]). Using this method, we show that the total length of intra-oceanic arcs varies significantly depending on the continental configuration in the models. We then test the sensitivity of atmospheric CO_2 absorption level through silicate weathering to the latitudinal distribution of the intra-oceanic arcs, their width and fraction above sea-level, and the potential effect of True Polar Wander on the temporal evolution of the position of the poles. Finally, we compare the amount of weathering produced in our geodynamic models with Earth's estimates deduced from a one-billion-years plate reconstruction [7] using the climate-enabled biogeochemistry box model SCION [8]. We show that in a fully-dynamic model, it is possible to reach the amount of extra-weathering required to possibly explain the atmospheric CO_2 and temperature drops observed, especially during periods of continental aggregation. Nevertheless, the amount of intra-oceanic subduction zones in the geodynamic models varies over longer timescales than in the plate reconstruction, and cannot explain alone, rapid periods of Earth's atmospheric cooling, such as during the Hirnantian [9].

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Geodynamica: slinging Earth and (exo)planets' structure and dynamics into Diamond Open Access

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Keywords — Diamond Open Access, community-led, peer-reviewed

The past decade has seen the consolidation of open access practices in scientific publishing, with funding bodies, international agencies and academic institutions requiring free access to not only scientific papers but also other output such as datasets and computer codes. While mostly embraced by the scientific community, the transition to open access practices has led multiple academic publishers to offer Gold Open Access schemes, under which scientific papers are free-to-read. Compared to the traditional publication models, Gold Open Access comes at a much higher cost for the authors, normally of thousands of US Dollars for a single paper. These practices have had a documented negative impact on the scientific publishing landscape, from the rise of predatory journals to the broadening of the economic divide between academic institutions.

Partly in response to the negative impact of Gold Open Access practices, different fields of Earth Sciences have recently seen the rise of several community-led, Diamond Open Access journals (e.g., Volcanica, Tektonika, Seismica). These journals are free-to-publish and free-to-read. The aim is to remove financial barriers to scientific publishing by publishing peer-reviewed articles at no cost to both authors and readers, thus offering a platform for true open science. Diamond Open Access journals are created and maintained by the very same scientific community they aim to serve, thus removing economical and business considerations that drive a large fraction of the modern publishing landscape. Therefore, community-led journals offer a high-quality alternative to classical for-profit scientific journals.

We are pleased to announce a new Diamond Open Access journal initiative called **Geodynamica**, with the aim of promoting free-to-publish and free-to-read research on the dynamics of the Earth's and (exo)planets' interior. The project of creating Geodynamica was initiated in 2023 thanks to the effort of six scientists, who form the core committee that coordinate the efforts of the various teams. The target launch date for the journal is autumn 2024. Geodynamica aims at promoting academic discourse and disseminating research pertaining to the quantitative study of Earth and (exo-)planetary internal structure, dynamics, and evolution from observational to modelling perspectives.

Geodynamica enjoys the support of eScholarship (University of California), and hugely benefits from the experience of existing community-led journals within the geosciences community, namely Volcanica, Tektonika and Seismica.

In this contribution, we will provide the vision behind this initiative, report on the structure of this journal, its scope, and the remarkable community effort that will make this new diamond open access journal a reality.

Modeling Peel-Back Delamination at Artemis Corona and Derceto Plateau on Venus

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Keywords — Venus, peel-back delamination, StagYY

The tectonic framework which currently governs Venus is not well understood. Thousands of kilometers of possible subduction sites have been identified on Venus as having a narrow, arcuate trench with a large outer rise curvature comparable to certain subduction zones on Earth [1, 2]. However, subduction on Venus is inhibited by the presence of positively buoyant lithosphere that in some locations is thick and resistant to forming instabilities. Recently, a new tectonic regime called peel-back delamination was shown to be a viable mechanism of recycling thick, positively buoyant near chasma rift zones on Venus [3, 4]. Rather than recycling the entire lithosphere like in subduction, peel-back delamination (PBD) occurs when dense lithospheric mantle is destabilized at a pre-existing chasma weak zone and decouples and peels away from a layer of positively buoyant crust at the surface. Though this mechanism was shown to be viable in 2D, the 3D surface expression of this tectonic process remained unclear.

This work aims to understand the 3D surface expressions of PBD by linking models to two proposed subduction sites on Venus: Artemis Corona and Derceto Plateau. A series of StagYY models with 3D spherical patch geometry will investigate the effect of chasma geometry, lithospheric thickness, and lithospheric strength on the surface expression of PBD. Observed surface feature geometry and flexural topography at Artemis Corona and Derceto Plateau will be used as constraints to link models to observations. We find that the initial length of the chasma weak zone controls the length of the delamination zone parallel to the chasma. A short chasma segment will produce a more circular surface expression like Artemis Corona (Figure 1), whereas a long, continuous chasma segment will produce an elliptical surface feature like Derceto Plateau. We predict that the width of the delamination zone perpendicular to the chasma segment is affected by the thickness and strength of the lithosphere. For example, a trench-outer rise structure is expected to form close to the initial chasma (e.g. Derceto Plateau) when the lithosphere is thin and/or weak.

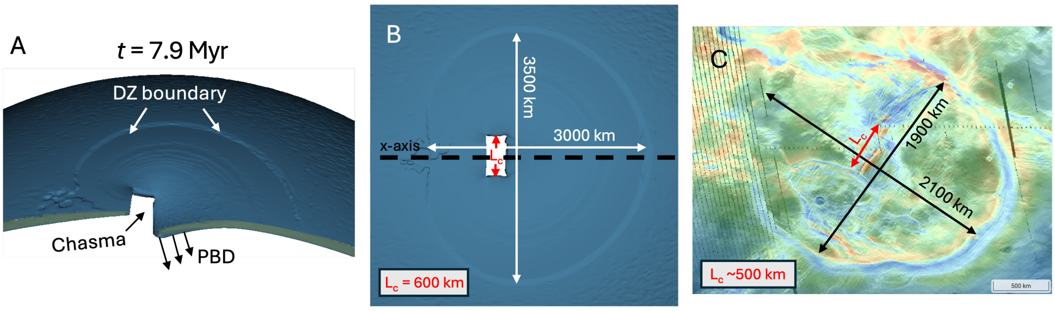

Figure 1: *A preliminary numerical model of Artemis Corona (A-B) compared to observed stereo topography (C). (A) An cut-away view of the $\eta = 10^{22}$ Pa*s isoviscous surface at $t = 7.9$ Myr shows PBD of the lithospheric mantle initiated at the chasma rift segment (crust not shown). The boundary of the delamination zone (DZ) shows where decoupling has initiated between the crust and the lithospheric mantle. (B) A top-down view of the delamination zone mirrored across the x-axis shows the full extent of the expected DZ geometry due to PBD. A 600 km chasma produces a circular delamination zone. (C) The modeled chasma length is comparable to an uplifted rift segment ($L_c \approx 500$ km) in the interior of Artemis Corona.*

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Towards dynamic modelling of caldera collapse

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Keywords — Magmatic Systems, Lithosphere Deformation, Caldera collapse

Understanding the driving forces behind large scale caldera forming eruptions is crucial as millions of people live near an active volcano. Even though the volcanology community has a good understanding about the geochemical cycles of magmatic system and their eruption triggers, none of the current numerical models have produced caldera like structures while coupling nonlinear rheologies and magma dynamics within the same framework.

In this study, we apply a multi-physical numerical modelling approach to investigate the onset of caldera collapse and its implications on the surrounding lithosphere. To achieve this, we use the pseudo-transient relaxation method with a finite-difference discretization on a staggered grid. The open-source software is written in Julia and, through the seamless integration of various other packages, is able to model magmatic systems with non-linear visco-elasto-plastic rheologies in 2D and 3D. The corresponding lithosphere deformation and the propagation of shear zones and fractures enables us to assess the potential to form a collapse caldera while taking the thermal effects on the lithosphere into account.

Our approach is also applicable to assess the evolution of current magmatic systems. We apply the model to the well-studied area of the Toba caldera (Indonesia) by taking into account the topography, rheological constraints and magma distribution. By placing the magma where seismic inversion studies have identified a melt phase, the systems evolution and ability to produce another caldera forming eruption is assessed.

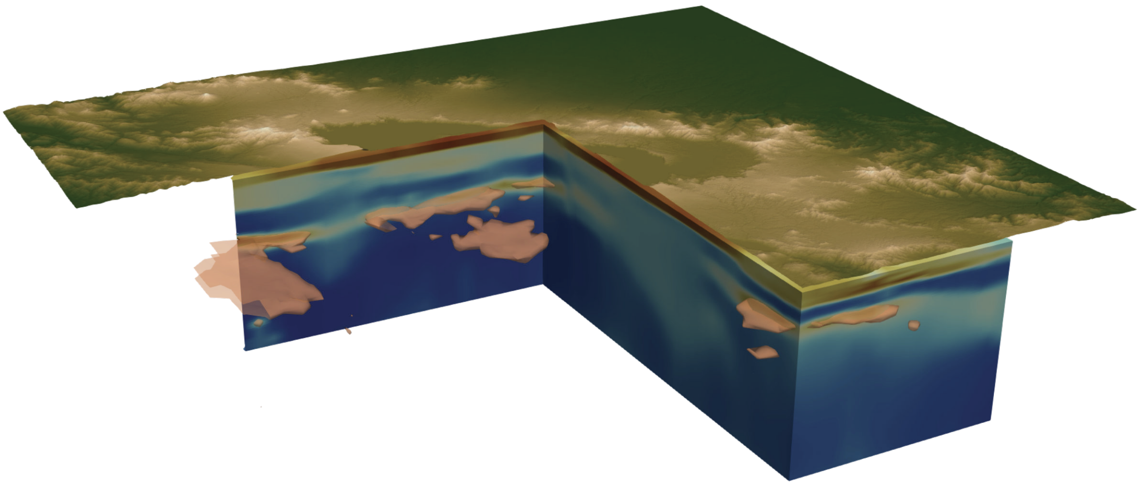

Figure 1: *Toba has experienced a caldera-forming eruption 74 Ka ago. Through seismic inversion studies, the current location of melt pockets can be visualised. This inversion enables us to model the emplacement of magma by applying the coupled model to this site and assess its convective behaviour and magma accumulation.*

How does subduction initiation proceed at a transform fault, and how does a rheological heterogeneity can affect this process? Insights from 2D numerical modeling

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Keywords — subduction initiation, lithologic raft, oceanic transform fault, numerical simulation.

A recent study has shown that among the subduction zones initiated in the Cenozoic era, the subducting oceanic lithosphere could have any age, and was as often older than the overriding plate as younger than it [1]. To understand this unexpected observation, we consider the simple setup of an oceanic transform fault (TF) and perform 2D thermomechanical experiments where a constant convergence velocity (1 cm/yr) is applied, by combining a non-Newtonian ductile and a pseudo-brittle rheologies. We first observe that the success and polarity of the incipient subduction zone are mainly dependent on the initial depth of the transform fault when convergence is applied. The initiation of the younger plate subduction always occurs for active transform faults supposed to be characterized by weak fault zones cutting through the lithosphere, whatever the plate age offset, while subduction of the older plate is restricted to moderately shallow fault gouges characterizing fracture zones and small age offsets. The subduction zone polarity can be predicted by comparing the initial gouge depth to the depth of the brittle-ductile transition in the new overriding plate, where the lithosphere strength is maximum [2]. Our results agree with the records of incipient subduction at the Mussau and Hjort trenches, and at the Gagua Ridge in the West Pacific.

However, while we forecast that significant plate age offsets prevent the old plate subduction at a classical oceanic transform fault, this disagrees with a number of geological records, such as observed at Izu-Bonin-Mariana, Matthew & Hunter or Palau. We note that, in these cases, a thicker crust made of continental or oceanic slivers (fossil arc or plateau) was always present in the vicinity of the inter-plate domain at the convergence onset. We investigate how this kind of lithologic heterogeneity could affect subduction initiation when the plate age offset is high (25 to 76 Myr), by varying the raft dimensions, location, and initial shape (rectangular vs. 'keel' shape). Simulations show that the lithological raft always eases subduction initiation. We find that the raft shape and size (width, bottom depth) are key parameters controlling the under-thrusting of the older and thicker plate. The subduction of the older lithosphere is promoted for rafts less than ~22 km thick, and less than 50 km wide, and is easier for keel-shape rafts. At last, our results suggest that the raft must partly overlap the old plate at convergence onset to allow the old plate subduction. Finally, adequate combinations of raft geometry and location can be identified, leading to the old plate subduction, for all investigated plate age offsets. We are currently comparing the critical dimensions and locations of the lithologic raft derived from our experiments to geological records.

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Dissecting the puzzle of tectonic lid modes in terrestrial planets

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Keywords — mantle convection, tectonic regimes, planetary evolution

The dynamics of the coupled plate-mantle system control planetary dynamo action, mantle thermal evolution, crustal geology and geo-morphology, as well as atmospheric evolution and habitability. Rocky planets within our solar system display a diverse array of tectonic regimes, despite their similar origins. Among them, Earth is unique in exhibiting plate tectonics. Deciphering the conditions that give rise to these regimes and their transitions throughout planetary evolution poses a challenge due to the hysteresis of the complex plate-mantle system. In this study, we employ 2D hemispheric-scale thermochemical mantle convection simulations, reaching a quasi-steady state, to overcome these obstacles and examine the influence of core-mantle boundary temperature, internal heating rate, upper-mantle activation energy, and effective yield stress on planetary thermal conditions and upper-mantle rheology. Our results identify six distinct tectonic regimes, including a previously unrecognized episodic-squishy lid regime characterized by alternating episodes of plutonic-squishy lid and mobile-lid behavior. By systematically exploring the parameter space, we develop a regime diagram that predicts the tectonic evolution of terrestrial planets as they cool over time. Our findings offer a comprehensive framework for understanding the tectonic history of Earth, Venus, and other terrestrial bodies, shedding light on their surface conditions and interior evolution.

Illuminating Mantle Convection: Unraveling Plume Dynamics over LLSVPs in the Laboratory

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Keywords — plume, LLSVP, fluid experiment

Hotspots have geochemical fingerprints distinct from mid-ocean ridges. Approximately half of catalogued hotspots are obviously hotter than the ambient mantle. This is compatible with buoyant plumes rising from the lowermost mantle, entraining a distinct geochemical reservoir, perhaps housed in the Low Shear Velocity Provinces (LLSVPs). However, the nature of LLSVPs themselves and the dynamical relationship between plumes and LLSVPs remain hotly debated. In the spectrum of LLSVPs, two end-members exist: purely thermal plume clusters and fixed, rigid, thermochemical piles. Given the complexity of faithfully resolving large-scale flow alongside small-scale plumes in numerical simulations, we take a different approach: laboratory analogs using very viscous fluids and 3-D optical visualization, leveraging real-word physics and infinite resolution. We perform a series of experiments in a 40.5cm x 40.5 cm x 27.5 cm plexiglass tank, heated from below. We use scanning Stereoscopic Particle Image Velocity (SPIV) to image the fluid. We start with the purely thermal end-member experiments and then proceed to experiments with 3-D printed obstacles, simulating non-deformable thermochemical LLSVPs. We use Lagrangian analysis (Eulerian FTLE), cluster analysis (DBSCAN) and velocity peak analysis (K-D Tree) to track individual plumes and analyze their morphology. Using automatic adjoints, we further reconstruct the full 3-D velocity and temperature in space and time with unprecedented detail. Ray tracing is also used to determine the size of plumes *in situ* from particle images.

We will show how plumes source the thermal boundary layer and identify, even with only temperature-dependent viscosity, extremely varied and rich plume morphology, including shifting, merging/splitting, branching, deflection, and dying plumes. We will also compare the two end-member in terms of plume distribution, strength, source material in and around LLSVP, with respect to surface observations, and implications for interpreting seismic observations.

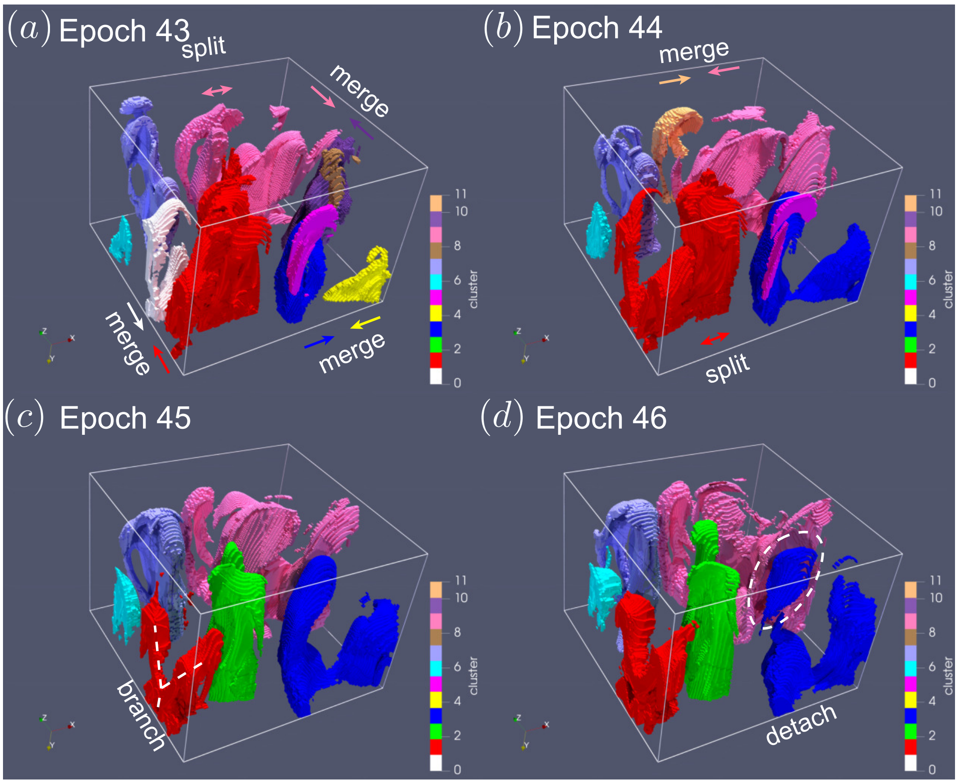

Figure 1: *The dynamics of plume clusters from the purely thermal experiment (no 3-D printed LLSVP), including splitting, merging, branching and detachment. Cluster numbers are consistent across panels.*

1D modelling of pegmatites migration

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Keywords — Thermal two phase flow, Pegmatites, Lithium

Pegmatites (and rare metal granites) are igneous rocks with a granitic composition, characterised by crystal growth dominated texture. They can be valuable deposits of economic interest enriched in rare elements (such as Li, Cs, Be, Nb, Ta...) that belong to the list of critical raw materials defined by the European commission. The aim is to use modeling to understand the formation of pegmatite, and especially the parameters that control the migration distance between their sources (granite, migmatites) and their level of emplacement.

We use a 1D two phase flow in finite difference code, written in Julia, based on the porosity waves with compressible fluid, where the porosity is interpreted as melt [1, 2], to model the magma migration inside migmatitic domes. To improve the yet existing codes, we implement temperature in our two phase flow formulation, it will be calculated from energy conservation. This allows a thermal coupling with the viscosity.

As we want to understand pegmatite melt migration the model is with a constant geothermal gradient except in the bottom where we consider a constant temperature due to partial melting. In this area we set a preexisting porosity of 10%, the other part has a background porosity (1%).

A first version, without temperature, shows that increasing the ratio of matrix permeability over the fluid viscosity results in a greater distance travelled by the melt, for a constant number of time steps. For a fluid viscosity of 10^4 Pa.s the increase of matrix (dynamic) permeability from 10^{-13} to $10^{-11} m^{-2}$ accelerates the migration of the melt by a factor 2 and increases the travelled distance by a factor 1. This is explained by the dependence of the characteristic length on viscosities as well as the permeability of the medium. Thus, a higher characteristic length mean a slower magma migation

Then, when the temperature is added, with a linear coupling with viscosities, the travelled distance of the melt is highly affected because viscosities increase near the surface due to temperature decrease. When the melt is travelling, its characteristic length is increases so the melt slows down until it cristalizes due to thermal diffusion.

We are also realizing 3D numerical model of metamorphic core complex with pTatin to have geologicaly coherent viscosities, permeability and temperature for the melt migration.

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Advances in Subduction Modeling using ASPECT: From Time-dependent Evolution to Deep Earthquakes

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Keywords — subduction, rheology, phase transitions

Geodynamics simulations of subduction provide an important tool for determining the material properties of the mantle, by comparing how variations in properties affect observables related to the subduction process, such as tectonic plate motion, trench motion, shape of subducted lithosphere, the orientation of stress in slabs and the spatial distribution of slab seismicity. Building on extensive community and developer investment in the ASPECT geodynamic modeling software, we have made contributions to ASPECT and developed workflows to support modeling the impacts of compositional variations, rheology and mineral phase transitions on slab evolution in two and three dimensions. These developments allow us to build on the recent related work (Billen & Arredondo, 2018) but using the additional capabilities of ASPECT. We have also developed methods and a workflow for comparing the present-day state of deformation in a slab to regional observations of seismicity (Fildes & Billen, in review). All of the methods development for these models are incorporated in the main branch of ASPECT, enabling other researchers to build on these developments to test new and competing hypothesis about the relationship between mantle material properties and slab evolution.

Here, we will focus on new 2D and 3D models of slab evolution aimed at disentangling the various factors contributing to slab evolution and trench motion. We find that the first order control on trench motion is the size of the numerical domain. In 2D cylindrical geometry models with a model depth equal to that of the Earth's mantle, a box width of less than 80 degrees exhibits a dependence of trench motion on the box width, while for box widths greater than 80 degrees the trench motion no longer depends on domain size (Li & Billen, in prep). For box widths less than 40 degrees, trench motion oscillates between trench advance and retreat. Similar behavior is found for 2D models using cartesian geometry. In 3D models, the effect of model domain size is similar but the transition to steady trench roll-back occurs at a smaller domain width (see Fig. 1). These results reconcile the different modes of subduction behavior and trench motion observed by research groups using different model domain sizes. For example, a shorter domain box tends to result in trench advance motion, similar to that found in models with multiple slabs (Cizkova & Bina, 2015; Pusok & Stegman, 2019). The results also suggest that in the Earth the tendency of slabs to evolve into a trench retreating mode is strongly influenced by flow restrictions imposed by the surrounding mantle, including proximity to other slabs.

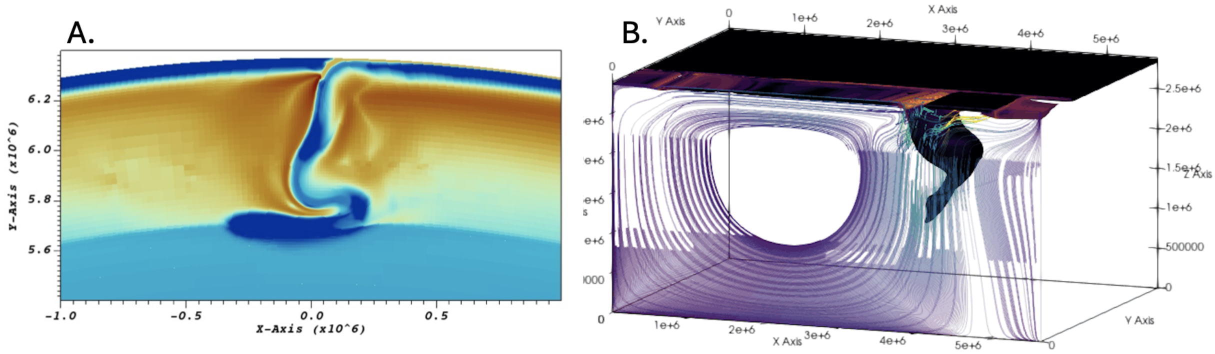

Figure 1: *Subduction models in* ASPECT. *A. Snap-shot of 2D slab evolution with low temperature plasticity. B. Snap-shot of 3D slab evolution with streamlines. Model domain size impacts slab evolution, but less so in 3D than in 2D models.*

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Linking continental breakup, kimberlite formation and craton denudation: migrating Rayleigh–Taylor instabilities at the base of cratons

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Keywords —Small-scale convection, Cratons, Rifting

Kimberlites are volatile-rich magmas, sometimes containing diamonds, that have explosively erupted at Earth's surface in the geologic past. Originating from depths greater than 150 km within Earth's mantle, these magmas typically occur within cratons and exhibit eruption pulses that broadly coincide with the fragmentation of supercontinents. The exact mechanism behind their mobilization is debated, with hypotheses suggesting either mantle plumes or mechanical weakening of the cratonic lithosphere as potential drivers. Kimberlite diatremes are often deeply eroded, which requires significant uplift to post-date kimberlite emplacement [1].

Here we combine geodynamic modelling with geological observations, geochemical data and statistical analysis to propose a geodynamic driver for both kimberlite formation [2] and exhumation [3]. In particular, we explore the process of delamination at the base of cratonic lithosphere that is facilitated by the existence of weakened, metasomatized continental roots, as evidenced by kimberlitic xenocrysts [1].

We employ analytical models and numerical simulations using ASPECT. Both modelling approaches support the occurrence of sequential Rayleigh–Taylor instabilities that feature characteristic wavelengths of 50-100 km and that migrate cratonward at a rate of ~15-20 km per million years (Fig. 1). These instabilities are kicked-off by continental rifting and associated lithospheric thinning. They progressively remove the thermal boundary layer and thereby drive adiabatic upwelling of the asthenosphere, which ultimately causes kimberlite volcanism. At the same time, removal of dense lithosphere causes isostatic uplift of craton interiors, which occurs more slowly and leads to the formation of stable, elevated plateaus. Sequential delamination can explain the observed surface denudation, which postdates kimberlite volcanism and persists for tens of millions of years as it migrates across the craton.

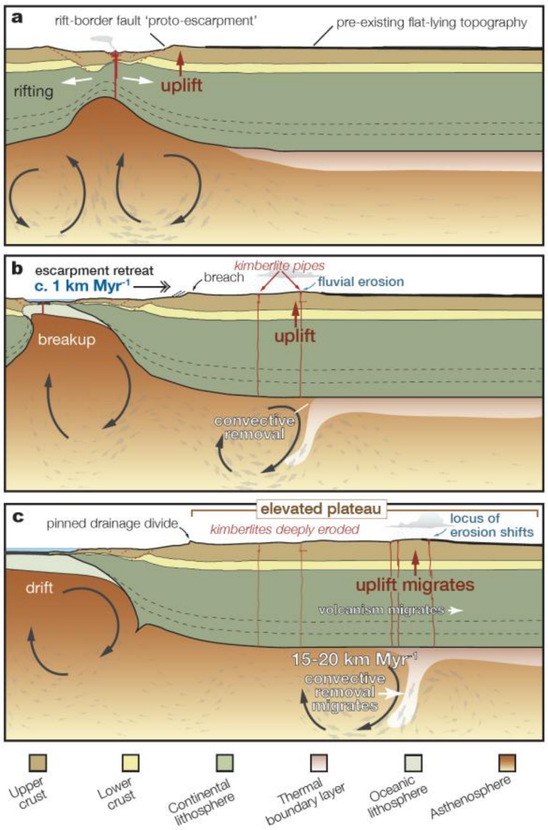

Fig. 1: Conceptual sequence of events: rifting, edge convection, sequential delamination, kimberlite formation and exhumation of craton interiors (from Ref. 3).

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Thermal Plumes in Complex Fluids

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Keywords — Mantle convection, Rheology

Mantle convection has a key role in the evolution of planets. A few years ago, [1] has shown with a combination of computation and data analysis that some plumes in the mantle are broader than expected. Among the different explanations for this feature, [2] suggest a visco-plastic rheology for the mantle, instead of a pure shear-thinning one. We therefore investigated the influence of rheology on the process of thermal convection.

We performed numerical simulations using the code LaMEM (Lithosphere and Mantle Evolution Model [3]), varying systematically the type of rheology (shear-thinning, visco-plastic, visco-elastic and visco-elasto-plastic) and the associated parameters. The set-up and the materials are close to the laboratory experiment [4], for future work will include comparison between numerical modelling and experimental measurements.

First results suggest a great influence of rheology on the time scales on which a plume evolves, the thermal structure of the plume once it has risen, and its shape. Plasticity and elasticity reduce the onset time of a plume, and imply episodicity, while shear-thinning (or newtonian) fluids reach a permanent regime after the first plume rise. Elasticity leads to small heads with winding wakes behind them, whereas plasticity is associated with a regularly shaped head with a straight stem. We exhibit correlations between plume size and rheological parameters for different rheologies, though no scaling law has been identified yet.

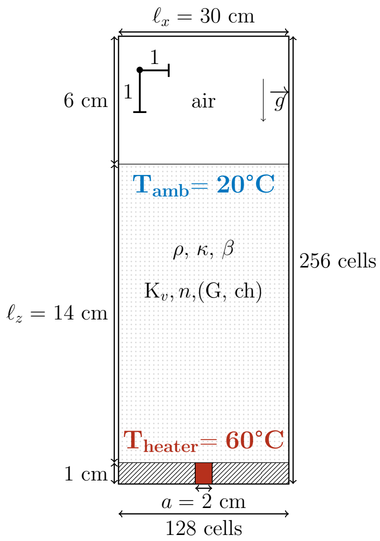

Fig.1 Schema

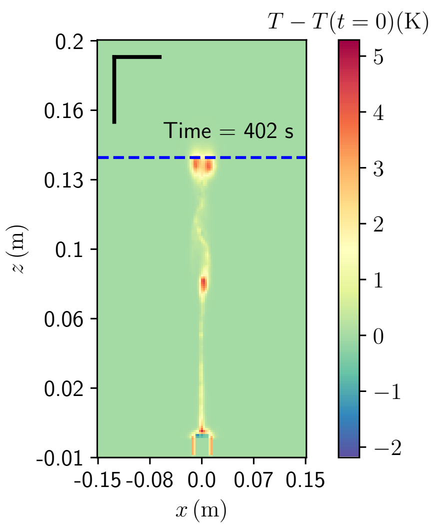

Fig.2 Visco-elastic rheology

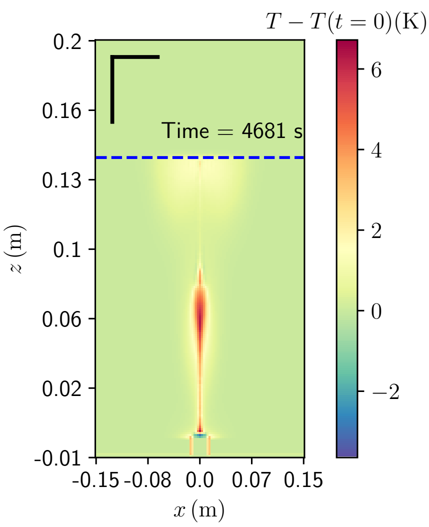

Fig.3 Visco-plastic rheology

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3D geodynamic model to understand Lesser Antilles Arc subduction history

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Keywords — Geodynamic, Lesser Antilles Arc, Mechanical model

The tectonic evolution of the Lesser Antilles Arc (LAA), where the North American and South American Plates subduct beneath the Caribbean Plate, has been extensively studied using geophysical, geological, and geochemical methods, providing constraints on the subduction history and the distribution and styles of regional seismicity and volcanism. Most previous studies focused on using observational data to infer the geological history of LAA, leading to various proposed mechanisms for the shape, evolution and productivity of its arc and its unusual style of seismicity. Geodynamic modelling could help understand: (i) What factors have led to today's highly curved LAA where subduction is limited to a relatively narrow area? (ii) What is the current state of stress of this subduction zone? (iii) How would tears in the downgoing plate affect mantle flow, volcanism and seismicity? (iv) How has convergence between North and South America affected the evolution? To address these questions, we will use the adaptive open-source Finite-Element code Fluidity which helps capture and track layered visco-plastic plate rheology. We are building a set of 2D and 3D mechanical subduction models including subducting plate, upper plate and side plates to systematically analyse different proposed mechanisms and driving factors of the LAA subduction process. In our study we will focus on the subduction history of past 50 Ma of LAA which previous work has shown has left a continuous slab in the upper mantle below the region. .

Modelling propagation of eclogite fingers: the case study of Holnøy (Norway)

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Keywords — Eclogite propagation, pressure variation, anisotropy, numerical modelling

Metamorphic reactions that occur in the lower crust in response to pressure and temperature changes can strongly modify the mechanical properties of the rocks. In this study, we model eclogitization of continental granulites, a key transformation for understanding the rheology of the subducting lithosphere. Indeed, this transformation that is responsible for a significant densification and weakening has been associated with seismicity. While eclogitization associated with shear zones has been widely studied, propagation of static eclogitization along finger-like structure remains poorly understood. We here present the results of novel thermo-mechanical models that consist in the deformation of an inclusion within a reactive matrix whose physical properties differ from those of the inclusion. A parametric study is performed to investigate the role of mechanical heterogeneities in the initiation and propagation of the transformation in response to local pressure variations.

Our results show that some of the parameters studied, such as (i) the difference in pressure between the pressure of the transformation and the initial pressure of the model, or (ii) the viscosity of the protolith, play an important role in the initiation of the transformation. In contrast, the other parameters studied help enhancing or inhibiting the propagation, but do not play a major role on the initiation of the reaction. These parameters are (i) the density variations between the protolith and its reaction products, (ii) the difference in viscosity between the protolith and the heterogeneity, and (iii) the morphology and the orientation of the heterogeneity. Our results also show that the presence of an anisotropy, as observed in the field, greatly hinders the eclogitic propagation (fig.1), and that an optimum configuration exist for the propagation, when the foliation is oriented at 90° from the shortening direction. These results are in agreement with previous field observations and measurements of the finger-shaped eclogitic structures observed in the island of Holsnøy (Norway).

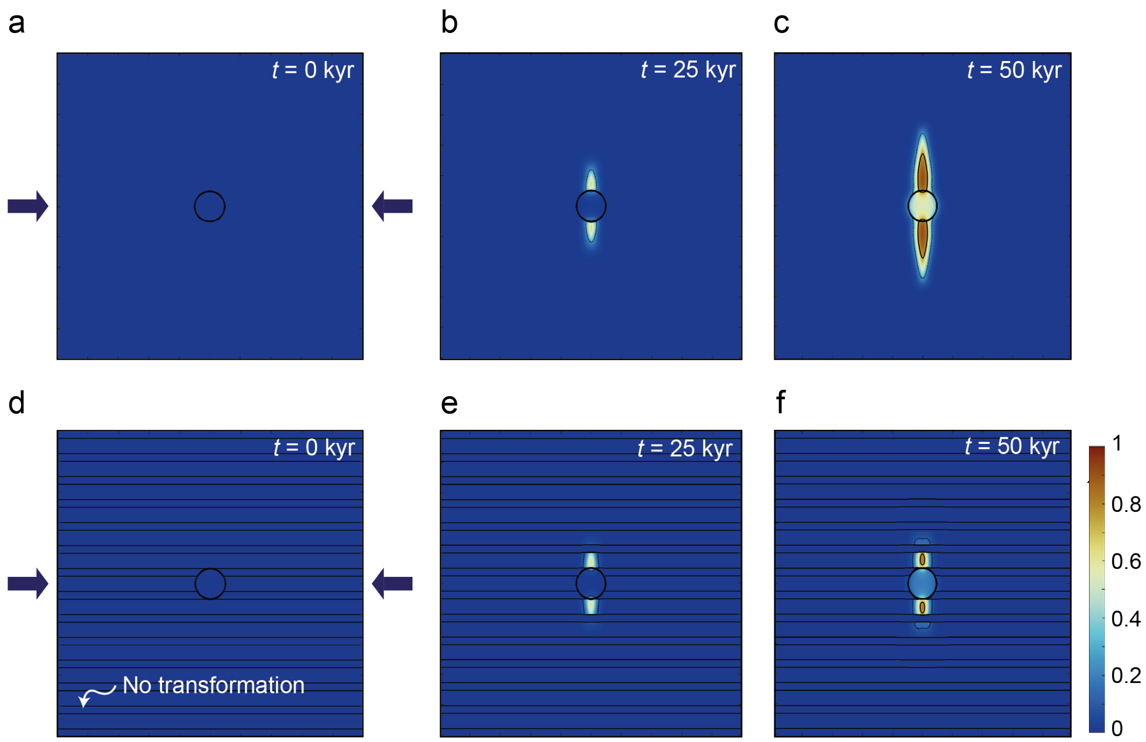

Figure 1: *Propagation of eclogite transformation with time without (a to c) and with (d to f) anisotropy.*

Degree-one convection pattern during the lunar magma ocean solidification

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Keywords — Lunar magma ocean, Lunar dichotomy, convective overturn

The classical scenario for the solidification of the lunar magma ocean (LMO) explains the formation of the crust by flotation of anorthite crystals. This model explains many geological features specific to the lunar crust, including its composition, highly enriched in anorthite minerals, and the presence of the Procellarum KREEP terrane, which concentrate incompatible elements. But it does not explain the degree-one variation in thickness of the lunar crust. The lunar crust is indeed significantly thinner on the near side (∼ 23–30 km) than on the far side (∼50-60 km). One proposed hypothesis is that degree-one convection can set up in the solid cumulates before the end of LMO crystallization. The phase-change boundary between the magma ocean and the solid cumulates allows material to flow through the solid-liquid interface by crystallization or melting, and favour the appearance of a degree-one convection pattern in the solid cumulates [1].

Here, we develop a model for the solidification of the Moon in its magma ocean stage. This model is based on a simple olivine-pyroxene/anorthite phase diagram with a eutectic. Two stages of crystallization result from this phase diagram. (1) In the first stage, olivine-pyroxene crystallize and settle at the bottom in about a thousand years, forming cumulates. (2) At the eutectic, simultaneous crystallization of anorthite and olivine-pyroxene leads to cumulate growth and to the formation of a flotation crust which insulates the LMO. This insulating crust considerably increases the crystallization time of the magma ocean to about 100 million years. Using a linear stability study accounting for a phase change boundary conditions at the interface between the solid cumulates and the magma ocean [2], we show that convection can take place in the cumulates before complete solidification of the LMO and that a spherical harmonics of degree one is the preferred mode of convection at onset. This provides a plausible explanation for the observed contrast in crustal thickness between the near and far side of the Moon.

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Modeling geoid and dynamic topography from mantle convection with chemical density anomalies in some continental areas of the lithosphere

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Keywords — dynamic topography, geoid, mantle convection

Mantle convection causes the most important contribution to the geoid and dynamic topography. With high resolution tomography models and numerical simulation methods solving the governing equations of mantle convection, the modeled geoid can fit well compared to observation. However, if seismic velocity variations are converted to density variations assuming both are due to temperature variation in the entire mantle, there is still a large discrepancy between present dynamic topography predicted by mantle flow and that induced from observations: Especially large negative topography is predicted in cratons, contrary to observations.

In this study, in order to improve the fit of model dynamic topography compared to observations, we include different chemical density anomalies in earth's lithosphere while modeling with three tomography models: SEMUCB_WM1, SAVANI and a combined model Sl_Gra10, which combines the upper part of SL2013SV and lower part of Grand10 model. We combine these lithospheric chemical density anomalies with lateral viscosity structure and study the effect on model dynamic topography and geoid.

From the modeling cases we have conducted, we find that for these three tomography models, with adding chemical density anomalies, we could improve a bit of the fit of the model dynamic topography to its observation but not too much. It means that there are some other reasons we should seek to improve the fit between the dynamic topography and its observation.

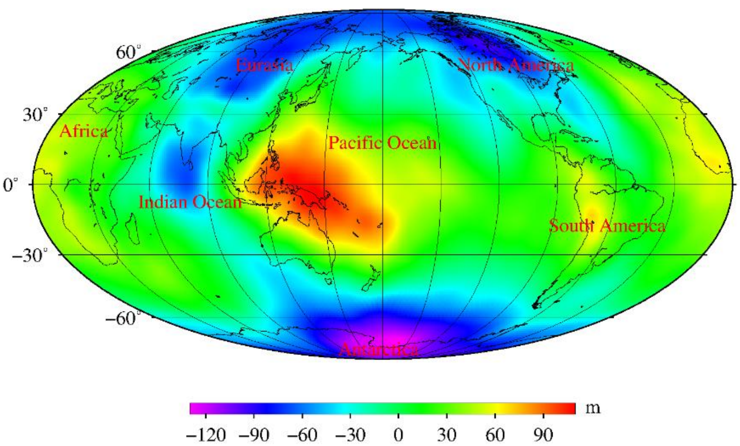

Figure1 hydrastatic geoid from Chambat et al. (2010)

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Dynamics of Sub-Lithospheric Small-Scale Convection as a Key to Constraining Asthenosphere Rheology

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Keywords — oceanic plates, asthenosphere, mantle dynamics

Understanding how oceanic plates and the underlying asthenosphere interact is essential for explaining surface heat flux, plate motions, and mantle convection patterns. While sub-lithospheric small-scale convection provides an explanation for why oceanic plates do not continue to thicken after a certain age, there are still many open questions about this process. Here, we link dynamic models of mantle flow, grain-scale processes, seismic imaging, and surface observations to gain new insights into the mechanisms of asthenospheric small-scale convection and its surface expressions.

We present a series of high-resolution 3D numerical models of the evolution of oceanic plates and the development of thermal instabilities at their base using the community geodynamic modeling software ASPECT (see Figure 1). These simulations use an Earth-like rheology that includes coupled diffusion and dislocation creep as well as their interplay with an evolving olivine grain size. Our models quantify how the effective asthenospheric viscosity and the balance between diffusion and dislocation creep affect the morphology and temporal stability of small-scale sub-lithospheric convection, including the age of its onset, the average depth and wavelength of the small-scale convection rolls, and the amplitude of the temperature and grain size anomalies within the rolls.

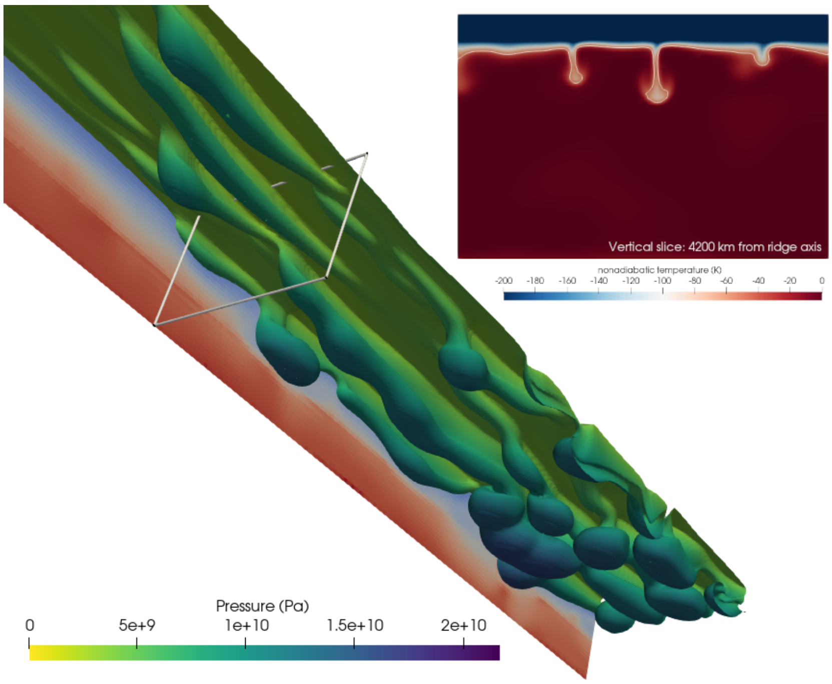

Figure 1: *Sublithospheric small-scale convection in our geodynamic models, seen from below the plate, represented by a temperature contour 20 K below the initial adiabatic temperature with colors illustrating pressure. The inset shows the temperature in a vertical slice at 4200 km from the ridge axis.*

All of these quantities predicted by the dynamic models can be directly related to geophysical observables through laboratory-derived constitutive relations. To accurately compare our model outputs to these geophysical data, we convert them to seismic velocity and attenuation, taking into account variations in temperature, pressure, grain size, water content and calculated stable melt fraction. We then create synthetic seismic tomography models of different dynamic scenarios and analyze their fit to observations from the Pacific OBS Research into Convecting Asthenosphere (ORCA) experiment. Comparison with both seismic imaging and surface expressions allows us to determine the parameter range in which geodynamic models fit these observations, providing new constraints on the convection patterns and the rheology of the oceanic asthenosphere beneath the Pacific Plate.

Advances in GPU-accelerated geodynamics modelling

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Keywords — numerical methods, lithosphere dynamics

Computational Earth Sciences often requires of extremely large simulations which are typically executed on High-Performance Computing (HPC) machines because of the substantial computational power required. Despite the latest advances in Graphics Processing Unit (GPU) cards and the investment of HPC institutions in large multi-GPU systems, large-scale geodynamic computations are run by legacy codes that exclusively execute on multiple Central Processing Unit (CPU) systems. Transitioning these fairly large legacy codes, that were originally designed and optimized for CPUs, to GPU-based systems is a time-consuming and complex task for two primary reasons: (i) GPU kernels require different compilers and vendor-specific syntax, necessitating extensive code rewriting; (ii) not every algorithms scales efficiently on GPUs, thus developing or implementing new GPU-friendly algorithms may be needed.

We present JustRelax.jl, an open source and highly portable Stokes solver for geodynamic modeling that operates seamlessly on shared and distributed memory CPU and GPU systems. To fully leverage the parallelism provided by GPUs, Stokes equations are solved using the accelerated Pseudo-Transient method, a matrix-free iterative solver known for its high scalability on GPUs [1]. While JustRelax.jl offers a high-level API, it is designed to be highly modular, building upon other packages developed by the GPU4GEO project: (i) we can use GeophysicalModelGenerator.jl to easily generate fairly comple two and three dimensional model setups; (ii) local solver- and discretization-agnostic rheology-related calculations are implemented in GeoParams.jl; (iii) advection is handled by JustPIC.jl, a multi-XPU Particles-in-Cell package specialized in staggered grids; (iv) ParallelStencil.jl abstracts the architecture's backend, allowing the user to write backend-agnostic kernels, hence significantly reducing boilerplate code; and (v) MPI communication is managed by ImplicitGlobalGrid.jl.

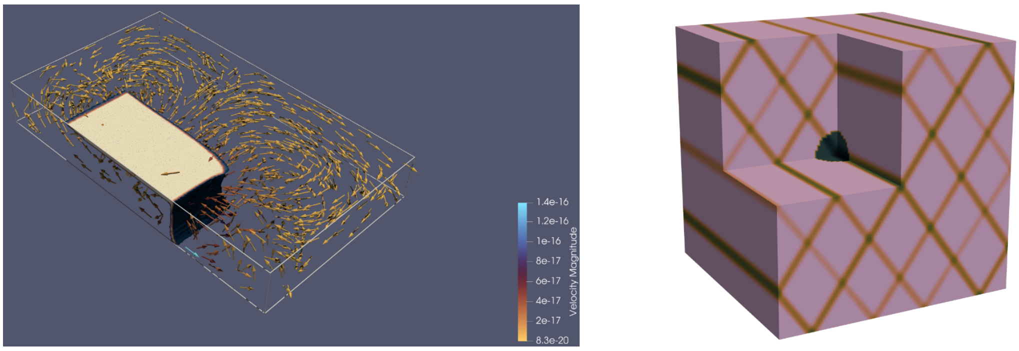

Figure 1: *Three-dimensional toy models produced by JustRelax.jl. Left: subduction of oceanic lithosphere. Right: shear band localisation with a visco-elasto-viscoplastic rheology*

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Hunting for Mantle Heterogeneities: Insights from Geodynamic and Seismic Models

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Keywords — Mantle Heterogeneity, Seismic Filtering, Basal Magma Ocean

As the Earth lower mantle accounts for half of our planet's mass, accurately understanding its dynamics is crucial to constrain the evolution of the system Earth as a whole. Several models of magma-ocean crystallization predict a layered compositional structure in the early Earth, characterized by bridgmanite- (Bm) enriched domains in the Lower Mantle (LM). As the intrinsic strength of Bm is much larger than that of all other LM phases, numerical models of mantle convection predict that Bridgmanite Enriched Ancient Mantle Structures (BEAMS) may survive in the present-day Earth. However, a quantitative comparison between such predictions and seismic observations is still missing.

Here, we model mantle convection in 2D spherical-annulus geometry with the code StagYY. We investigate the style of heterogeneity preservation as a function of the intrinsic density and viscosity of Recycled Oceanic Crust (ROC) at LM conditions.

We find that the physical properties of ROC strongly affect the extent of Bm preservation in the convecting mantle. Namely, ROC intrinsic density and viscosity enhance preservation, as they promote the formation of stratified thermochemical piles that insulate the mantle from the core and reduce global convective vigor. BEAMS are predicted for realistic ROC density contrasts of 2% $\sim$ 3%, but only if ROC viscosity is very large (relative to the ambient mantle). Then, we use the Gibbs energy minimization code Perple_X to map the temperature and compositional fields here predicted to seismic velocities. We investigate the signal of BEAMS on a range of indicators, including maps of seismic velocity, also quantifying the effect of the limited resolution of seismic tomography imaging techniques. We discriminate the different mantle convection regimes obtained here based on their respective synthetic seismic signature. By modeling the seismic signature of BEAMS, we outline a strategy of detection in the real Earth, thus shedding light on the earliest stages of our planet's evolution.

Global subduction redox cycle reveals plate tectonics driving long-term mantle oxidation

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Abstract

Geochemical and petrological evidence suggests the mantle has undergone long-term oxidation throughout Earth's history, potentially driving significant oxidation events (O'Neill and Aulbach 2022). However, the related oxidation mechanisms remain unclear. Subduction zones transport substantial quantities of oxidized materials into the deep Earth (Wood et al. 1990), yet the specific fluxes and release mechanisms are still not well understood. Understanding these processes is crucial for elucidating whether plate tectonics can drive long-term mantle oxidation. In this study, we estimate the oxidation inputs and outputs of 56 subduction zones worldwide using a new two-dimensional thermodynamic-geodynamic redox numerical model. Across four simulation settings with 224 iterative calculations, we consistently find an oxidation input of 49.9-51.7 x 10^12 mol/yr. Mass balance analysis indicates that 25-29% of this oxidation flux can be released into the sub-arc mantle with fluid, far exceeding the contribution into arc magmas. Our modeling and geochemical data suggest subduction fluid desulfurization could be a key mechanism for global sub-arc mantle and arc magma oxidation. Removing oxidation output to the surface, subduction zones can contribute an annual oxidation flux of 29.7-40.6 x 10^12 mol/yr to the mantle, sufficient to oxidize the entire mantle to modern levels within 2.2 (+0.5/-0.3) billion years, a timeframe potentially shortened by additional observations. Given that plate tectonics likely began before 2.5-3.2 billion years ago, our calculations indicate that plate tectonics are sufficient to drive long-term mantle oxidation, promoting the birth of an oxygen-rich habitable Earth. Precambrian mantle convection simulations (Perchuk et al., 2020) suggest that during Neoarchean-Paleoproterozoic plate tectonics initiation, a substantial oxidized flux carried by

subducted plates could trigger rapid oxidation of the upper mantle and subsequent Great Oxidation Event.

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Gravity rate of change at convergent margins

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Keywords — subduction, numerical methods, gravity rate of change

The presented work is part of the ASI founded project NGGM-MAGIC - a breakthrough in understanding the dynamics of the Earth, of which the University of Milan is Prime Contractor, and which involves 6 teams of experts in the different sectors of Solid and Fluid Earth (°). One of the main objectives of the project is to determine the advances that the ESA-planned NGGM/MAGIC (Next Generation Gravity Mission/Mass change And Geosciences International Constellation) mission will allow to achieve in understanding the dynamics of the physical processes that occur in the compartments of the solid and fluid Earth, thanks to the high accuracy that NGGM/MAGIC will allow to achieve regarding the knowledge of the gravity field, both in spatial and temporal resolution, compared to previous missions.

Every physical process that occurs in every compartment of the Earth, either solid and fluid, involves a redistribution of mass in space and time and therefore a disturbance of the Earth's gravity field. One of the expected results of the project will be the determination of the detectability by the NGGM/MAGIC mission of the gravity anomalies associated with the different dynamic processes of the solid and fluid Earth, therefore to verify whether the gravity signal from the dynamic processes can be detected by the mission based on the definition of the mission itself and the measurement performance of the instrumentation.

In particular, the presented work contributes to the analysis of the detectability of slow tectonic processes.

Slow tectonics, as well as its gravitational signature, is widely seen as static. In more recent years, however, greater attention has been paid to the analysis of the rate of variation of gravity induced by slow dynamic processes and it has been shown how the important lateral variations in density that occur in areas characterized by extension to rifting can induce significant gravity rate of change, up to 0.1 μgal/yr [1]. The gravity rate of change remains much lower when associated only with the vertical movements of the masses that occur during subduction [2].

As part of the project, we have deepened this topic and, using the FE algorithm FALCON [3], we developed a set of 2D subduction models differing for different convergence velocities. From the output time series of the density, we calculated the gravity and the gravity rate of change for the different settings and discuss the impact that the subduction kinematics has on the perturbation of the gravity field at convergent margins.

(°) University of Milano (Prime Contractor, ** PI A.M.Marotta)
University of Trieste (Partner 1)
University of Naples Federico II (Partner 2)
University of Padua (Partner 3)
CNR-IRPI Perugia (Partner 4)
Politecnico of Milano (Partner 5)

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~~Automated Forward and Adjoint Modelling Techniques~~ for Geothermal Reservoirs with Julia

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Keywords — numerical methods

Exploration of geothermal reservoirs has gained significant interest due to their potential for sustainable energy production, leading to advancements in the forward modeling of nonlinear Darcy-flow problems in confined aquifers. To effectively use these simulations as predictive tools, understanding the sensitivity of simulation parameters is crucial. Traditional inversion approaches are inherently computationally expensive, as solving the Jacobian of the entire parameter space scales linearly to the number of independent parameters. Utilization of the adjoint method reduces the complexity of the inversion to an additional system of linear equations that is the same size as the forward problem. The automatic differentiation framework within the Julia programming language allows for efficient calculation of the Jacobian matrix, needed for both the forward simulation and the inverse problem. We demonstrate how one can use automatic differentiation tools in Julia to automatically compute the adjoint of nonlinear equations and utilize that to compute the sensitivity of the solution to input and material parameters. Initial sensitivities are calculated for the Darcy-flow equations, but the same framework can be seamlessly applied to the Stokes equations. Here, the *GeoParams.jl* package enables the usage of visco-elasto-plastic rheologies using direct implicit finite-difference solvers in the automatic differentiation framework. Future research will focus on extending these methodologies to more complex coupled fluid-solid systems.

Exploring the structure of the Cascadia Subduction Zone by coupling 3D thermomechanical modeling and CPO evolution with observations.

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Keywords — Cascadia, Subduction, CPO

The Cascadia Subduction Zone is characterized by young subducting lithosphere, its isolation from other subducting systems, and its ability to produce megathrust earthquakes (M>9.0) and devastating tsunamis. Due to its high potential hazard and risk, it is also a well-studied subduction zone where modern, diverse and detailed observational datasets are available through the USGS and initiatives like GeoPrisms and EarthScope. These datasets include high quality GPS, onshore and offshore geophysical imaging, geochemical and seismic anisotropy data. Integrating these data sets with geodynamic modeling presents an opportunity to gain insight into outstanding questions regarding slab structure, tectonic evolution, seismic hazards, and the physical processes that can self-consistently explain all these observations. For example, geologic and geophysical data suggest that there may be one or two prominent slab gaps or tears, while tomographic data does not fully constrain the depth extent of the slab. Furthermore, the overriding plate is composed of different terranes and contains numerous active and slowly moving faults, complicating efforts to accurately constrain variations in present-day stress and deformation rates.

In this study we test whether comparison of observations to geodynamic model predictions can distinguish between different slab geometries for the Cascadia Subduction Zone. To this end, we have created regional 3D geodynamic models of Cascadia including the slab based on the Slab 2.0 dataset. The model setup is built with the Geodynamic World Builder, and the models are run with the geodynamics code ASPECT. We present results which compare the Juan de Fuca plate velocities against the present day Euler poles. We have found that matching the plate velocity magnitude and direction is sensitive to the rheological model overall, while at the same time being insensitive to certain aspects of the plate boundary rheologies. We will also show some preliminary results of the evolution of these models we track the development of the CPO (Crystal Preferred Orientation) with an implementation of the DREX algorithm, so we can compare it against observations of seismic anisotropy in the region. Our presentation will focus on the importance of the geometry of the slab and the strength of different sections of the interface. Furthermore, these models and demonstrate workflows for linking the model results to surface tectonics.

Predicting slab temperature and strain rate in the transition zone by taking into account slab folding throughout subduction history

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Keywords — subducion, slab folding, transition zone, deep-focus eartquakes

The thermal structures of subducted slabs is often derived from the thermal parameter "phi", associated to the downward advection of isotherms and approximated as slab age x sinking velocity (McKenzie 1969, Kirby+ 1996). This “instantaneous” thermal parameter is relevant to predict shallow slab temperatures (< 200 km depth) to infer e.g. slab dehydration (Syracuse+ 2010, van Keken+ 2011), and has also been used to predict slab core temperature in the transition zone (King+ 2015). However, we expect that the first-order relationship derived from steady-state kinematic models (“distance = age x velocity”) will not hold for actual slabs deforming in the mantle transition zone, as imaged by seismic tomography, that do not sink at a constant dip and velocity.

We analyze in this study various models of free-subduction zone with upper plate and a mobile trench featuring

- different initial plates’ ages,
- different viscosity at the subduction interface,
- different viscosity profiles (viscosity jump between upper and lower mantle, possible subplate weak layer),
- presence or absence of olivine phase transitions at 410 and 660 km,

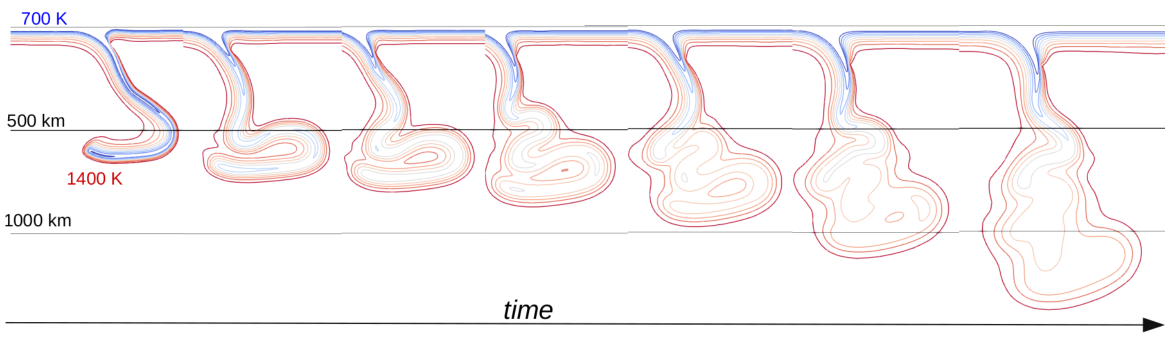
resulting in a large range of slab morphologies (Garel+ 2014, Pokorný+ 2021, Cerpa+ 2022).

We show that slab temperatures between 400 and 700 km depth vary through time in response to both folding amplitude and thermal state of the previously subducted material. The variation of slab core temperature with depth cannot be predicted using a single “phi” parameter, hence the evaluation of present-day slab temperatures in the mantle deeper than 400 km cannot rely on present-day subduction zone parameters.

Our results also highlights the enormous temporal variations of strain rates (up to $10^{-13}\,s^{-1}$) witin the cold slab in response to folding - as already shown by Billen (2020).

We propose first-order regime diagrams linking slab morphology & folding amplitude to slab temperature and peak strain rates within the transition zone, that could help to explain deep-focus earthquakes occuring in subduction zones.

This work is part of ANR project RheoBreak (ANR-21-CE49-0009).



Evolution of slab thermal structure during subduction (model from Cerpa+ JGR 2022).

ASPECT 3.0: The Advanced Solver for Planetary Evolution, Convection, and Tectonics

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***Keywords* —** Numerical methods, Research software, Lithosphere modeling

Modern geodynamic models have become increasingly complex, coupling detailed approximations to many physical processes with large observational datasets in the same model. This coupling creates unique challenges for modern research software such as how to combine complex rheologies utilizing multiple flow mechanisms with the simultaneous modeling of mineral microstructure; how to model realistic geometries and evolving surface topography while simultaneously including large observational datasets; and how to utilize highly-optimized and scalable numerical solvers while keeping up with changing high-performance computing architectures.

We here present our approach to reconciling these challenges: The next major release of ASPECT - The Advanced Solver for Planetary Evolution, Convection, and Tectonics. During the six years since our last major release, we have implemented many new features and improvements. Here we report on a new major release that highlights ASPECT's increased flexibility in modeling complex tectonic and convection problems. New features we will present at the workshop are in particular:

- A new default Stokes solver utilizing a matrix-free geometric multigrid preconditioner
- Complex rheologies like visco-elasto-plasticity including Peierls-, dislocation-, and diffusion-creep
- Modeling of pinned grain-size evolution in a two-mineral assemblage
- Evolution of crystal-preferred orientation using DREX like algorithms
- Utilizing modern external libraries for the accurate solution of ordinary differential equations
- Extended support for efficiently including large-scale datasets in parallel models
- Interfaces to surface evolution modeling software like Fastscape and other surface deformation
- Optimizing finite element type, degree, and advection method for different compositions
- Major improvements to the structure of the code base, plugin system, and user interface

As usual the release is open-source and freely available at `aspect.geodynamics.org`. We hope that providing well-documented, flexible, and tested geodynamic research software provides the community with the necessary tools to tackle the next generation of geodynamic research questions.

Deformation of the accretionary prism associated with seamounts subduction

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Keywords — accretionary prism, seamounts, subduction

We conducted thermomechanical simulations using pTatin2d [1] [2] to investigate the deformation of accretionary prisms in subduction zones associated with seamount subduction. We varied the size of the seamounts, their frequency, and basal friction. The objectives of these simulations are twofold: 1) To highlight certain tectonic structures and correlate them with geological parameters, providing geologists with tools to interpret seismic lines, and 2) To understand the mechanical behavior driving deformations within the prism.

Our numerical simulations are similar to analog experiments. We consider sediment with some oceanic crust seamounts accreting against a backstop at a constant velocity. Basal temperature boundary conditions are given as flux, allowing the temperature of the model to evolve as the accretionary prism grows. Flexural deformation of the basement in response to the thickening of the accretionary prism is also considered.

Our results show that depending on the size of the seamounts, the destabilization of the prism associated with their subduction can induce gravitational collapse. The burial of seamounts leaves behind a distinctive imprint called a 'slice' at the base of the prism [3], delineating an undeformed, hence more resistant, zone. This zone subsequently functions as a new backstop, against which sediments accrete. Finally, smaller seamounts, being less resistant, are cut off within their own slice. Larger seamounts, which are more resistant, can only be sheared by the backstop and destroy the slices left by previous seamounts as they pass through.

The size of the seamounts and the friction at the base of the décollement modify the mechanical response to the perturbation caused by the subduction of a seamount. These different mechanical responses result in various structures (basin, slice, underplating, chaotic zone) that we have identified and associated with geological parameters. The different behaviors of the prism and the various structures can impact coupling and the seismic cycle of the subduction zone.

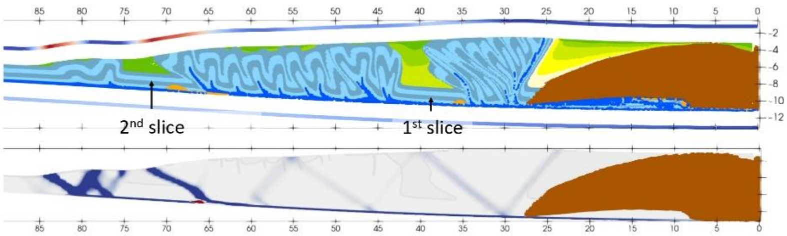

Figure 1: Accretionary prism with a basal friction of 5° after two seamounts burial. Deformation is mainly accommodated at the front of the 2nd slice.

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~~Microstrucural and rheological analysis of silica~~ colloids: a DEM study

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Keywords — Rheological & mechanical properties, Numerical methods, Mantle convection

Colloidal dispersions of silica nanoparticles have proven to be excellent materials for setting up laboratory mantle convection experiments. Indeed, thanks to their particular rheology, these fluids can reproduce some of the fundamental features underlying the complex dynamics of mantle convection (e.g. plate tectonics). However, the relationship between colloidal properties (particle size, salt concentration, pH, etc.), nanoparticle spatial organization and macroscopic rheological behavior remains poorly understood.

To shed light on this problem, we use dynamic particle-scale numerical simulations to model our colloidal silica dispersions. The evolution of the system is driven by the Langevin equations of motion where the conservative potential accounts for both DLVO interactions (non-touching particles) and granular interactions (particles in contact). Using the experimental data in our possession, we first characterize the microstructural organization of the colloidal dispersions (e.g. void distributions, particle network connectivity, locally favored structures) at different particle volume fractions (ϕ). The computer simulations nicely reproduce the phase diagram obtained experimentally in terms of sol-gel and gel-glass transitions. They show how the competition between electrostatic repulsion and particle concentration fully controls the phase transitions that characterize this colloidal system. Second, we focus on the rheological characterization of our numerical configurations. This part of the study (still in progress) will lead us to a better understanding of the micro-macro/scale relationship behind our colloidal dispersions and, thus, to a better control of their rheological behavior. This result will allow us to improve the design of laboratory experiments on mantle convection.

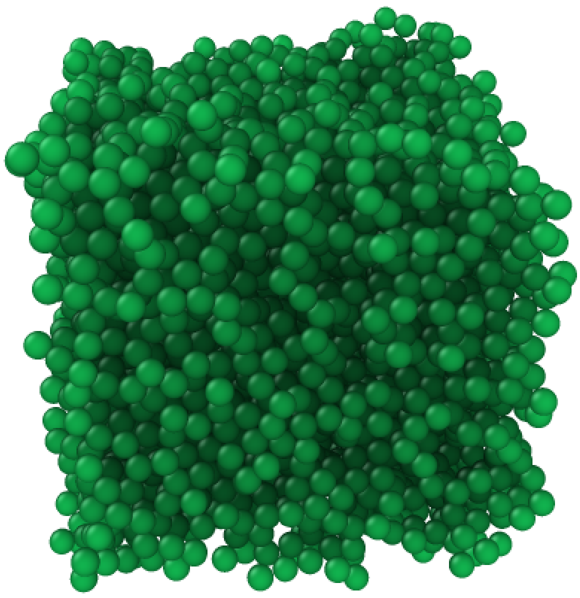

Figure 1: *Equilibrium gel structure of a colloidal silica system (particle volume fraction $\phi = 0.42$).*

Formation of exceptionally large hydrothermal deposits in the vicinity of detachment faults, investigated using coupled hydro-thermo-mechanical modeling

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Keywords — mid-ocean ridges, detachment faulting , hydrothermal activity, hydro-thermo-mechanical model

The young oceanic lithosphere created at mid-ocean spreading centers is subject to complex magmatic, tectonic and hydrothermal processes. Observations of, among others, bathymetry, rock samples, fault structures, microearthquake distribution, and hydrothermal activity reflect the interplay of these processes, especially in regions of widespread detachment faulting. Permeable fault zones may channel hydrothermal fluids, which would in turn affect the strength of the faulted rock. To put this to the test, we develop a custom 2D numerical model coupling mechanical deformation and hydrothermal fluid flow to study the relationship between tectonic detachment faulting and fluid circulation.

The Mid-Atlantic Ridge (MAR) around 13°N hosts various detachment faults at different stages of their life cycle. Multiple active and inactive vent fields have been mapped on and around the resulting oceanic core complexes (OCC). Here, we focus on the OCC at 13°30'N (Fig. 1 a,b), which is suspected to be in its terminating stage as an adjacent volcanic ridge segment propagates into the OCC from the north. The OCC hosts the active Semenov-2 vent field as well as four inactive vent fields identified by sulfide deposits. The largest of theses sulfide mounds is Semenov-4, which is located on the hanging wall of the dying detachment right above its shallowest portion and has an exceptional size on the order of 10 Mt.

We test whether fluid flow along the detachment can lead to sulfide accumulation of this extent, or whether alternative explanations need to be considered. First, we set up a baseline visco-elasto-plastic model [1] for the evolution of the 13°30'N OCC (Fig. 1 c). Detachment faulting is initiated by prescribing a diking region that accounts for 50 % of plate divergence. After footwall rotation and exhumation of the OCC establish, the diking region is shifted into the footwall of the detachment fault, leading to its cessation and dissection by normal faults. The resulting history of tectonic deformation including mantle upwelling, footwall rotation and localized plastic strain is subsequently used as transient framework to model porous flow in the presence of active faulting and a self-consistent topography (Fig. 1 d). We investigate the influence of different permeability structures and heat sources on the formation of hydrothermal deposits. Our results show that the ability of the detachment to guide hydrothermal fluids all the way through the lithosphere depends sensitively on detachment geometry, background permeability and permeability increase within the fault zone. Further processes that can lead to significant redirection of plumes are plume interactions, topography effects and additional shallow heat sources.

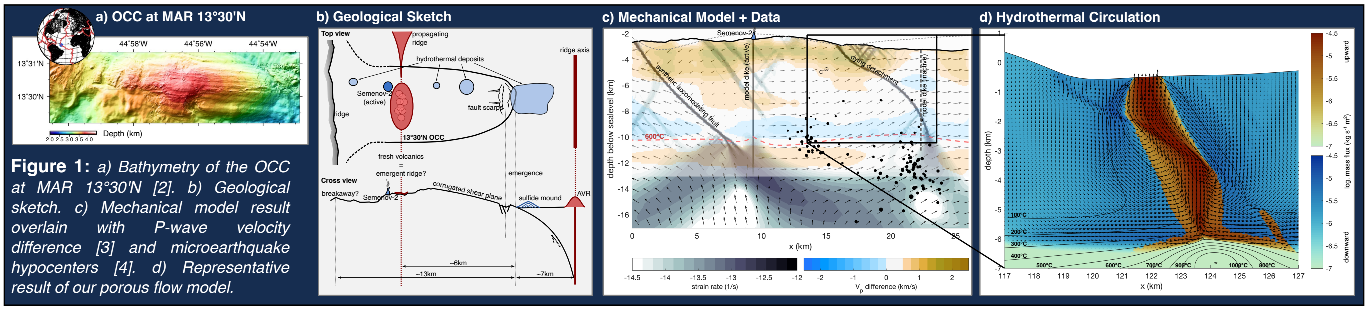

Figure 1: *a) Bathymetry of the OCC at MAR 13°30'N [2]. b) Geological sketch. c) Mechanical model result overlain with P-wave velocity difference [3] and microearthquake hypocenters [4]. d) Representative result of our porous flow model.*

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Free surface methods applied to global scale numerical geodynamic models

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Keywords — numerical modelling, surface processes,

Coupled planetary systems, particularly the coupling of geodynamic processes with climate and biological processes, have received greater interest in recent times. These couplings primarily occur at planetary surfaces, motivating the need to understand topographic evolution of planets over time on a global scale. The natural tools for studying global scale geodynamic processes, numerical mantle convection codes, often struggle to resolve surface topography to a sufficient resolution without significantly increasing computational costs, especially in 3D models. There are two main reasons for this. First, models often lack a free-surface boundary condition, opting instead for a more simple free-slip boundary condition which can result in reduced accuracy, particularly around convergent or divergent features [1]. Second, models that do feature free surfaces often do so using the sticky air method, which when combined with a typical marker-in-cell approach, can lead to reduced surface tracking accuracy [2].

We present several methods for improving the treatment of free surfaces in the finite-volume global scale mantle convection code StagYY [3]. In the first method, Lagrangian markers are used to directly track and manipulate the surface in conjunction with an appropriate free-surface solver such as the existing sticky air method. In the second method, a volume of fluid method is used to track the surface in a volume conservative way, also in conjunction with an appropriate solver [4]. In the third method, the work of these first two methods is extended through the use of an alternative Stokes solver, which supersedes the sticky air method by implementing alternative boundary conditions near the surface [5]. Together, these methods provide a useful set of tools for investigating planetary topographic evolution.

The methods presented have a number of applications, for example sea level modelling. Either of the two surface tracking methods may be used to model the distribution of surface water, while the alternative Stokes solver can be extended to add a traction term approximating the load imposed on the surface. Additionally, coupling of surface topography with surface process models could potentially lead to insights on the origin and nature of Earth's tectonic style. Finally, the models of topographic evolution can be coupled with existing models of climate and biodiversity, giving insights onto the origin and prevalence of life on Earth.

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The Role of the Overriding Plate and Mantle Viscosity Structure on Deep Slab Morphology

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Keywords — subduction dynamics, continental overriding plate, mantle viscosity structure

Using 2D numerical subduction models, we compare deep slab behaviour with oceanic and continental overriding plates and a mantle viscosity structure where the lower mantle viscosity jump occurs either at 660 km or at 1000 km depth as suggested by the latest geoid inversions. We demonstrate that a strong, thick, and buoyant continental plate, combined with a 1000 km depth viscosity increase, promotes slab penetration into the lower mantle. Conversely, the same slab will deflect at 660 km depth if this subducts under an oceanic plate into a mantle where the viscosity increases at the canonical 660 km depth. To quantify these dynamics, we introduce a slab bending ratio, by dividing the deep slab tip angle by the shallow slab angle, reflecting the steepness, and sinking history of the slab. Ocean-ocean convergence models with a viscosity increase coincident with the phase transition at 660 km depth have low ratios and flattened slabs comparable to ocean-ocean cases in nature (e.g., Izu-Bonin). Coupling a continental overriding plate with a 1000 km depth viscosity increase separate from the endothermic phase change results in slabs with high ratio values, and stepped morphologies similar to that observed for the Nazca plate beneath the Southern Peruvian arc. Our results highlight that slab morphologies ultimately express the interaction between the type of overriding plate, slab-induced flow, and phase transitions, modulated by the viscosity structure of the top of the lower mantle and transition zone.

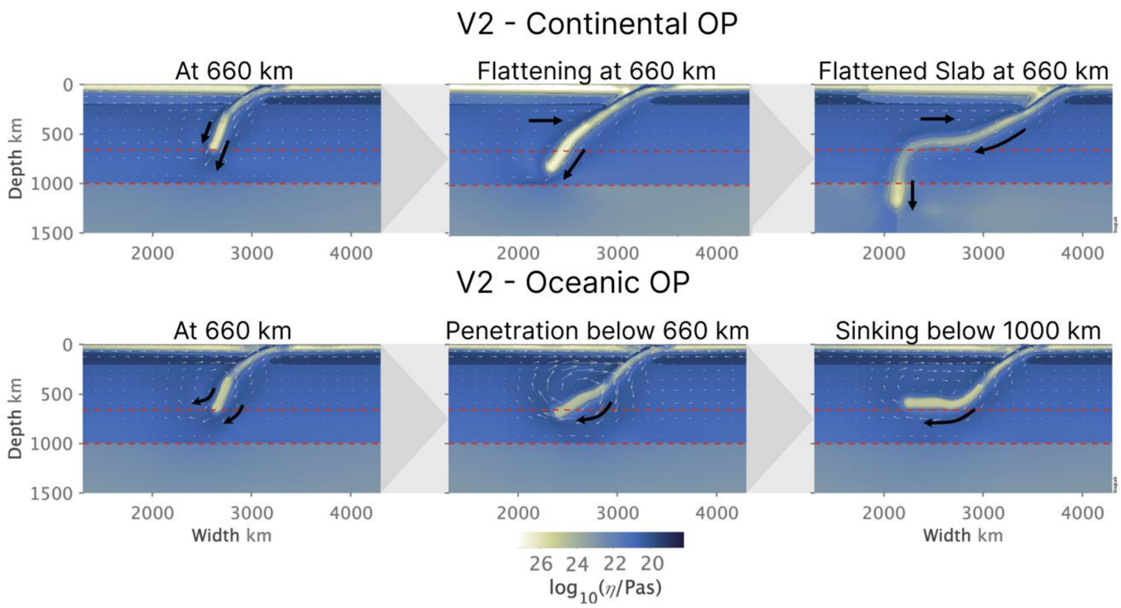

Figure 1: Plots of the viscosity with darker blue shades indicating lower viscosity, for the V1 model with a viscosity increase at 660 km depth, coincident with the bridgmanite phase transition, with continental (a) and oceanic (b) overriding plates. White arrows indicate the magnitude and direction of the induced viscous flow in the models and red dotted lines delineate the 660 km and 1000 km depth. ***Top****: The continental overriding plate drags the shallow upper mantle towards the slab encouraging slab rollback. Vertical flow induced by the steeply sinking slab tip drags the subducting slab below 1000 km depth, resulting in a stepped slab shape.* ***Bottom****: The thinner oceanic overriding plate results in shallow slab dip angles and encourages faster overall surface plate motions resulting in strong horizontal viscous flow in the upper mantle, trench rollback and slab flattening above 660 km depth.*

Dynamics of Iron Disproportionation

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Keywords — Early Earth, Mantle Convection, Oxygen Fugacity, Iron Disproportionation, Oxidation

A variety of theoretical and experimental mineral physics studies propose that the dominant ferrous iron oxide species in the Earth's mantle may undergo a disproportionation reaction to ferric and metallic iron at high pressures [e.g., 1]:

$$3\mathrm{FeO} \rightarrow \mathrm{Fe_2O_3} + \mathrm{Fe}. \tag{1}$$

This reaction is driven by a negative volume change (pressure) and/or crystal chemistry, the latter of which may be moderated by energetically favorable joint Fe^{3+}-Al substitution in bridgmanite. This proposed *chemical* process underpins an entire family of hypotheses regarding the source and nature of material that accreted to form the Earth, and the evolution of mantle oxygen fugacity to its present state. However, the *physical* processes that are invoked to accomodate these chemical changes have not been scrutinized in detail, such that the conditions for– and outcomes of– such hypotheses remain largely unexplored. Furthermore, evidence for secular variations in oxygen fugacity has emerged, suggesting that this was an ongoing process in the solid mantle for more than a billion years after Earth's formation. We aim to fill in this vital missing link, which will both enable further tests of these hypotheses and develop a broader understanding of how iron disproportionation shapes the dynamical evolution and oxidation state of a terrestrial planet.

We are presently conducting Boussinesq numerical models of mantle convection including reaction (1) under a variety of hypothesized circumstances. We are running the models with strong temperature-dependent viscosity and psuedo-plastic yielding in the upper boundary layer in order to mimic plate tectonics-like circulation of cold viscous "lithosphere" into the deep mantle. We include buoyancy due to thermal expansion and iron content variations, and allow for the metallic Fe to undergo melting and percolate downward relative to the rock matrix if the volume fraction exceeds a critical wetting fraction.

We find that regardless of the chemical mechanism or the depth at which it operates, Fe metal produced by reaction (1) is initially frozen in the rock matrix. In the hot lowermost mantle thermal boundary layer this metallic iron may melt and drain out of the rock into the top of the core, leaving behind a rock that is relatively oxidized (higher Fe^{3+}/Fe^{2+}) and buoyant (owing to loss of iron). This increases the buoyancy of upwelling plumes and may be expected to contribute to widespread high temperature (i.e., komatiitic) volcanism at the surface. Core-mantle heat flow is also enhanced during iron loss, possibly providing a "kickstart" to the early geodynamo. The wetting fraction limits the extent to which iron can be removed from the mantle, and this process establishes both the residual iron oxide content and oxygen fugacity of the mantle while providing a reservoir for highly siderophile elements that mitigates the need for a late veneer.

In our models, dense iron-rich piles (DIRPs) do not emerge from this process because percolation is efficient owing to the large metal-rock density difference and small viscosity of liquid iron, such that any excess iron would disproportionate and drain into the core until the residual iron content is the same as the surrounding mantle. We suggest that the existence of DIRPs requires that disproportionation is dominantly driven by crystal chemistry, and that the material comprising DIRPs does not exhibit the requisite mineralogy to undergo the same extent of disproportionation and iron loss as the surrounding mantle. This condition may be satisfied if DIRPs are late cumulates of a basal magma layer which are depleted in silica and alumina (because bridgmanite is on the liquidus, SiO_2+Al_2O_3 are depleted early). This additionally offers an alternate explanation for the inferred iron-enrichment of Mars' mantle, as a result of reduced iron disproportionation over the limited range of pressures, temperatures, and mineralogy. Such a hypothesis also predicts that Venus' mantle will have a similar iron oxide content as the Earth.

We are presently considering the impact of this process on the Earth's ancient surface environment. The world's iron ore supply is dominantly derived from dissolved Fe^{2+} that precipitated from marine waters over billions of years (banded iron formations), which was driven by a large flux of oxidants into the surface environment over more than a billion years. The partial loss of disproportionated iron to the core, and the consequent generation of mantle melting by increasingly oxidized rock, may provide a plausible source of oxidants. The great oxygenation event at 2.2-2.3 Ga, and the rise of photosynthetic cyanobacteria, may have been coupled to exhaustion of the supply of environmental redox buffers. The interactions between biology and the deep Earth during this episode are a key target of ongoing research.

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On the Role of Anisotropic Viscosity on the Motion of the Pacific Plate

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Keywords — Geodynamics, Pacific Plate, Viscous Anisotropy

Earth's tectonic plates and the underlying convecting mantle are connected at the asthenosphere, which is therefore a key location for studying the interplay between rock deformation and tectonic plate motions. In particular, shear in the asthenosphere causes olivine crystals to align with the direction of deformation. This formation of olivine texture leads to large-scale elastic and viscous and anisotropy beneath the plate. The elastic anisotropy can be detected seismically, and the presence of viscous anisotropy can potentially resist changes in plate motion, as suggested by previous numerical models [1]. It is interesting to consider the motion history of the Pacific Plate in this context. Plate reconstruction models show that the Pacific Plate has experienced rapid direction changes that can be explained by variations in the direction of the slab pull force on the plate [2]. However, the same models also show that a change in slab pull force at 20 Ma did not produce an immediate change in plate motion direction [2], which suggests that the motion of the plate might be locked by anisotropic viscosity.

Here we consider a simple system that assumes deformation of a 200 km thick asthenosphere by simple shear, driven by the motion of a rigid lithosphere. We compute strain rate in the asthenosphere for a hexagonal grid of fixed points on the Pacific plate with surface velocities calculated from a plate reconstruction model [3]. The calculated strain rates were then applied to a micromechanical model of olivine deformation [4] in order to predict the formation of rock textures, and associated anisotropic viscosity, beneath the plate. The anisotropic viscosities were then used to compute the traction needed to produce the estimated strain. We find that between 60 and 50 Ma and from 25 Ma to the present there is a significant difference in the direction (up to 20°) between the velocity of the Pacific Plate and the driving traction that is needed to produce the modeled strain rates in the asthenosphere. This suggests that the evolution of anisotropic textures beneath the tectonic plates can, via anisotropic viscosity, significantly impact the journey of plates on Earth's surface.

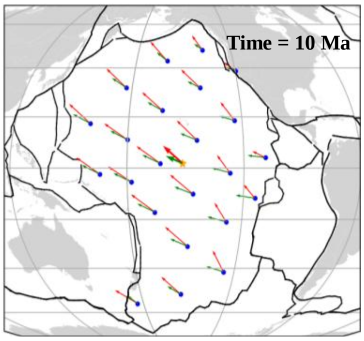

Figure 1: Map of the Pacific plate at 10Ma, the current grid points (blue dots), the centroid of these points (yellow star), the plate velocities (green arrows) and tractions (red arrows) at each grid point and at the centroid. Black lines indicate plate boundaries.

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Revisiting Three-dimensional Subduction Dynamics in the Aleutian-Alaska Subduction Zone

Margarete Jadamec

July 2024

1 Abstract

Seismic observations of modern slab geometries motivate the need for geodynamic models of natural systems that examine the effect of variable slab shapes, and resulting density perturbations, on the three-dimensional lithosphere-asthenosphere dynamics. For example, the Aleutian-Alaska subduction zone is a major subduction zone on Earth, forming the northern boundary of the Pacific Ring of Fire. The Alaska segment of the subduction zone is characterized by flat slab subduction, plateau subduction-collision, and a plate boundary corner geometry that terminates into the Fairweather-Queen Charlotte transform boundary resulting in a lateral slab edge at depth with complex geometry. Results from high-resolution, three-dimensional numerical models of the Aleutian-Alaska subduction zone are presented that examine the relative effect of the flat slab geometry, plateau subduction, and lateral slab edge on the upper plate deformation and lateral slab edge flow dynamics. In addition, and importantly, the role of a composite viscosity structure in the mantle is examined, as it places an important constraint of the rate and intensity of induced mantle flow. The results suggest that slab edge-induced mantle upwelling may be a common phenomenon and provide a physical mechanism to explain observed anomalous slab-edge related volcanics in subduction zones along the Pacific Ring of Fire.

Influence of water and composite rheology on early Earth evolution models

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Keywords — early Earth evolution, water content, continental crust production

Many aspects of solid Earth's evolution such as crustal growth, tectonic regime and the onset of plate tectonics remain enigmatic. Water lowers the melting temperature, density, and viscosity of rocks, however, the estimates of total amount of water (at the surface and in the deep interior) vary from 5-15 ocean masses (OMs) based on magma ocean solidification models to 1.2-3.3 OMs based on petrological models. In this work, we investigate the influence of water and composite rheology on early Earth dynamics in 2D global compressible convection models. Using the code StagYY [1], these models self-consistently generate oceanic (mafic) and continental (felsic) crust while considering both plutonic and volcanic magmatism. Pressure-, temperature-, and composition-dependent water solubility maps calculated with Perple_X are utilised, which control the ingassing and outgassing of water between the mantle and surface [2]. When compared to models with just diffusion creep, the models that incorporate a more realistic composite rheology (diffusion creep and dislocation creep proxy) for the upper mantle show higher production of continental crust, more efficient planetary cooling and higher recycling of denser oceanic crust through subduction, delamination and dripping processes. These models exhibit intermittent episodes of long-lasting mobile-lid regime and short-lived plutonic-squishy-lid regime in the Hadean and the early Archean accompanied by extensive subduction leading to rapid production and recycling of the continental crust. These models also show higher mobilities (ratio of surface to mantle rms velocities), which have been previously shown for diffusion creep models only with low surface yield stress values [3]. By initialising our models with different water content, a strong influence on the felsic melt production is observed. Once the effect of water on the density of rocks is considered, a drop in mobility is also observed and tectonic regimes change (see Fig. 1). For a comparison of these results with geochemical data (Rb-Sr isotopes, Nb, U, Ce and Pb trace elements) obtained from olivine-hosted melt inclusions extracted from komatiites of 3.27 Ga Weltevreden formation in Barberton Greenstone Belt (South Africa), see Sobolev et al. at this workshop.

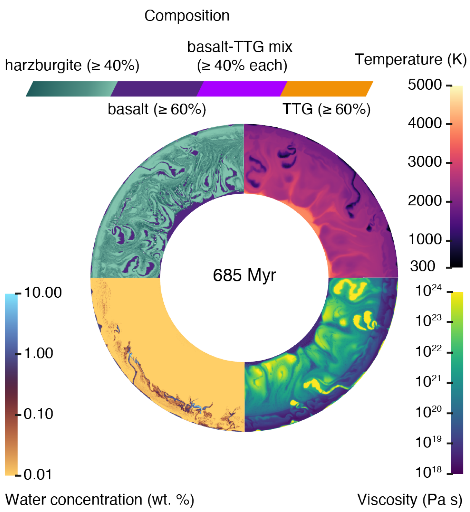

Figure 1: *Evolution of a representative model where four quadrants represent different fields (clockwise from top left: composition, temperature, viscosity, water content).*

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Global plate kinematic changes and reorganisation of mantle dynamics from 3D spherical mantle convection modeling.

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Keywords — Plate tectonics, Mantle convection, Plate motion change, 3D modeling, Computational Topology

Nowadays, the Earth lithosphere is divided into a jigsaw puzzle of about 50 tectonic plates separated by boundaries where much of the surface deformation occurs. Tectonic plates move at the surface of the Earth following a dynamic equilibrium continuously evolving with time. Sporadically, tectonic plates experience abrupt changes during which the norm and/or the direction of their motion change. These events are called kinematic changes or plate reorganisation events and seem to be an essential characteristic of the Earth plate tectonics.

Analyzing plates dynamics requires a precise record of their past motion over several hundred million years. Modern plate reconstruction models propose scenarios for the past 500 Myrs evolution allowing the study of the successive cycles of creation and destruction of oceans and the drift of continents. However, since $\sim 70\%$ of the present-day oceanic lithosphere is younger than 80 Ma, the reconstruction of the plate network in the Paleozoic time or even before becomes a real challenge.

Nowadays, three-dimensional spherical mantle modeling generates successfully self-consistently a stiff surface fragmented into several rigid caps displaying a plate-like behavior. Thus, it becomes possible to analyze the dynamics of these models through the prism of plate tectonics theory and compare it to plate reconstruction models for the Earth. However, to perform this kind of analysis over long times series or between different models and to avoid non-objective and time consuming plate drawing by hand, a methodological breakthrough involving new numerical methods is needed.

For this study, we developed a method to automatically detect and time track plates in three-dimensional spherical mantle convection models, based on a trans-disciplinary approach combining geodynamics and topology. The application of this method on a fully dynamical state-of-the-art mantle convection model on the surface of which an Earth-like plate tectonics emerge shows that similarly to the Earth, (1) the motion of plates at the surface of the model are stable over stages of several tens of million years and (2) change abruptly (< 2 Myrs) during kinematic changes. Furthermore, we show that occasionally, plate kinematic changes can go beyond the local scale of two adjacent plates and have a global impact affecting the motion of the entire plate network. The detection of such global plate reorganisation event (GPRE) shows that global kinematic changes can arise self-consistently from the dynamics of the coupled mantle-lithosphere system, suggesting that GPREs are likely to occur on Earth. Moreover, we show that contrary to a local kinematic change, GPREs affect the entire mantle circulation down to the lower mantle causing a reconfiguration of the mantle flow. Finally, our results give us new arguments to reinterpret the motion of plates at the surface of the Earth during the mid-Eocene event ($\sim 53-40$ Ma, in particular associated to the Hawaii-Emperor bend, Tonga-Kermadec and Izu-Bonin-Mariana subduction initiations etc), showing that this event has the key properties of a GPRE, thus suggesting that its regional sub-events are linked and dynamically interconnected, coinciding with a reconfiguration of the Earth mantle flow around 47 Ma.

Towards a New Geodynamic and Geochemical Reconciliation of the Origin of the DUPAL Geochemical Anomaly in the South Atlantic and Southwest Indian Oceans

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Keywords — mantle convection, petrology & geochemistry, plumes

The question of the origin, structure, and composition of the mantle source of the DUPAL geochemical anomaly (Dupré & Allègre 1983), a southern hemisphere anomaly with high radiogenic Pb and Sr isotopic ratios, continues to generate active debate within the geophysics and geochemistry communities. A range of geochemical hypotheses have been proposed that involve contrasting interpretations or inferences of the geometry, vigor, and temporal evolution of the mantle-convective origin of the DUPAL anomaly. To address this challenge, we employed time-dependent thermal convection models that reconstruct the 3-D evolution of global mantle structure. These reconstructions employ a back-and-forth nudging (BFN) method for time-reversed thermal convection initialized with a present-day tomography model derived by jointly inverting seismic-geodynamic-mineral physical data (Glišović & Forte 2016). Although the African Large Low Shear Velocity Province (LLSVP) is often believed to contribute to the geochemical distinctiveness of these anomalies, our study provides geophysical and geochemical arguments that challenge this common assumption. Reconstructed particle trajectories in the mantle reveal two distinct and far-removed paleo-subduction-zone source regions for the South Atlantic and Southwest Indian Ocean hotspots. In addition, we find that these hotspot-related particle trajectories avoid the high-density core of the African LLSVP, providing compelling evidence that their distinct isotopic signatures reflects an inheritance of deep-sourced subducted material. In summary, this multidisciplinary investigation provides novel insights on paleo-subduction sources for hotspot geochemistry in the South Atlantic and Sothwest Indian Oceans.

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Prolonged Survival of Large Low Velocity Provinces: Internal Stratification is the Key

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Earth's lowermost mantle features two large low-velocity provinces (LLVPs), located beneath Africa and the Pacific Ocean, known for their substantial reduction in seismic wave velocities. These structures are often considered to be intrinsically dense thermochemical piles. Understanding the structure and dynamics of LLVPs are crucial, as they play a critical role in the thermal and compositional evolution of Earth's mantle. However, their internal structure, morphology, composition, and stability remain poorly constrained. Some previous studies suggest that dense material accumulates within the deep-mantle thermochemical piles (Tackley, 1998), and an excess intrinsic density of ~2-4% is required to preserve such heterogeneity (Jones et al., 2020; Tackley, 2012). A study based on GPS data and tidal tomography models by Lau et al., 2017 shows that LLVPs exhibit a higher-than-average density, with a mean excess density of ∼1% within the bottom ∼350km of these structures. On the contrary, Stoneley mode observations indicate that LLVPs are, on average, positively buoyant, although a ∼100 km-thick, anomalously dense basal layer cannot be ruled out (Koelemeijer et al., 2017). Therefore, the density distribution within thermochemical piles remains debated with contradicting observations. In this study, we conduct high-resolution two-dimensional geodynamic modeling experiments to investigate the long-term stability of LLVPs and how it could be influenced by the density structure of thermochemical piles. Our findings indicate that a denser, compositionally distinct root at the base of the thermochemical piles helps anchor LLVPs over the core-mantle boundary (CMB), ensuring their stability over geological time, even if the rest of the pile is buoyant with a much lower intrinsic density. This thin, intrinsically dense basal layer acts as a shield, preventing the buoyant materials on top from being entrained and mixed by mantle convection, for a duration comparable to Earth's history. Thus, our study proposes that the density within LLVPs is not homogeneous, but can be stratified, increasing towards the core-mantle boundary.

Keywords: Large low-velocity provinces (LLVPs); Core-mantle boundary (CMB); Mantle dynamics; Geodynamic modeling

Models of elastic–viscoplastic unbending to explain sea-level control on fault pacing at fast-spreading mid-ocean ridges

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Keywords — mid-ocean ridge, faulting, flexure

Spectral analysis of abyssal-hill topography at fast-spreading mid-ocean ridges has a significant concentration of energy at the 41 ka Milankovitch band [1]. We hypothesise that this spectral signature arises from sea-level variations associated with glacial cycles. These cycles are thought to drive variations in crustal thickness, which can be used to force a model of cylindrical elastic-plate flexure proposed by Buck (2001) [2]. Assuming that elastic thickness of the plate correlates with crustal thickness, we show that deviatoric stress is concentrated where the crust is thin (see figure, below). We then introduce a new theory for elastic–viscoplastic bending that, in the absence of thickness variations, produces regularly spaced plastic kinks representing tectonic faults. Even at very low amplitude of perturbations, these kinks/faults phase-lock with the elastic thickness. This suggests that if unbending is an appropriate model of tectonic stress generation at fast-spreading mid-ocean ridges, the signature of sea-level variation will be readily imparted on abyssal-hill topography. Using temporally aligned bathymetric data from the Juan de Fuca ridge, we show that rapid changes in sea level are associated with large-throw normal faults, consistent with the theory.

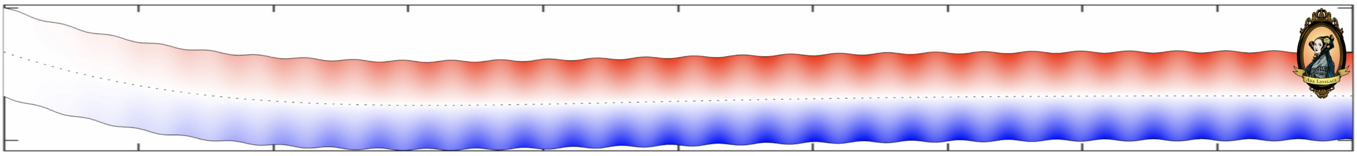

Figure 1: *Unbending stress in an elastic plate with small thickness perturbation. Red colours indicate tensile fibre stress ($\sigma_{xx} > 0$); blue colours indicate compressive fibre stress. The mid-ocean ridge axis is at the left edge. The plate moves with speed U to the right. Each tick in the x-direction represents one half of an elasto-gravitational bending length.*

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How to automatically write nonlinear geodynamics solvers using a few lines of Julia

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Keywords — numerical methods, lithosphere dynamics, keyword3

Developing solvers for computational geodynamics, especially for nonlinear processes like visco-elasto-plastic lithospheric behavior, has historically been complex and time-consuming. However, recent advancements have made this task easier. One notable development is the Julia package GeoParams.jl, which simplifies handling constitutive and material parameters [1]. It offers pointwise computational routines and a comprehensive database of rheological properties. Since all geodynamic codes require these pointwise calculations, any new constitutive relationship added to GeoParams.jl is automatically integrated into all related codes.

GeoParams.jl is utilized in JustRelax.jl, a package that solves governing equations on parallel GPU systems using the pseudotransient solution method, supporting both 2D and 3D computations. By combining GeoParams.jl with automatic differentiation tools in Julia, users can develop a classical implicit staggered finite difference discretization that uses Newton iterations for nonlinearities. With sparsity detection algorithms, users only need to write residual routines for mass and momentum conservation equations, while GeoParams.jl handles nonlinear rheologies. This approach is demonstrated by solving viscoelastoplastic localization problems, and the process for adding new nonlinear rheologies to GeoParams.jl is discussed.

Once a solver is created, the Julia package JustPiC.jl can be used to advect material properties using a particle in cell approach. These tools enable the creation of new geodynamics solvers in Julia with minimal code, making it easier for educational use and experimentation with new equations.

However, challenges remain. This method works best with direct solvers, as multigrid methods need tuning. Additionally, the current sparsity detection algorithms are slow, indicating areas for future improvement.

References

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Mantle avalanches in a Venus-like stagnant lid planet

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Keywords — phase transitions, Venus, numerical modelling

Stagnant lid planets are characterized by a globe-encircling, conducting lid that is thick and strong, which leads to reduced global surface heat flows. Consequently, the mantles of such planets can have warmer interiors than Earth, and interestingly, a pyrolitic mantle composition under warmer conditions is predicted to have a distinctly different mantle transition zone compared to the present-day Earth [1–4]. Instead of olivine primarily transforming into its higher-pressure polymorphs such as Wadsleyite and then Ringwoodite, at pressures corresponding to 410km and 520km depth in Earth, respectively, it instead transforms into a mineral assemblage of Wadsleyite, Majorite, and Ferropericlase (WMF), and then to Majorite + Ferropericlase (MF), before finally transforming into Bridgmanite at pressures corresponding to 660km depth in Earth [2, 3]. Convective motions in stagnant lid planets are dominated by small-scale instabilities (cold drips) forming within the mobile rheological sublayer under the rigid lid. Using ASPECT [5] and a thermodynamic model of a pyrolitic mantle composition generated by HeFESTo, we show that under certain conditions, the small drips can pond atop the WMF-MF mineral phase transition. The barrier to convective flow arises from an exotic property of WMF assemblage having a negative thermal expansivity. In contrast to mobile lid planets that recycle their entire lithosphere via large-scale downwellings which pass through the WMF zone without difficulty [4, 6], the WMF zone in stagnant lid planets is capable of causing an ephemeral layering of the mantle. Our numerical models show that in stagnant lid planets with mantle potential temperatures that exceed 1900K, the smaller, cold drips from the lid continue to pile up until enough of them have coalesced that they collectively avalanche as a larger instability into the deeper interior.

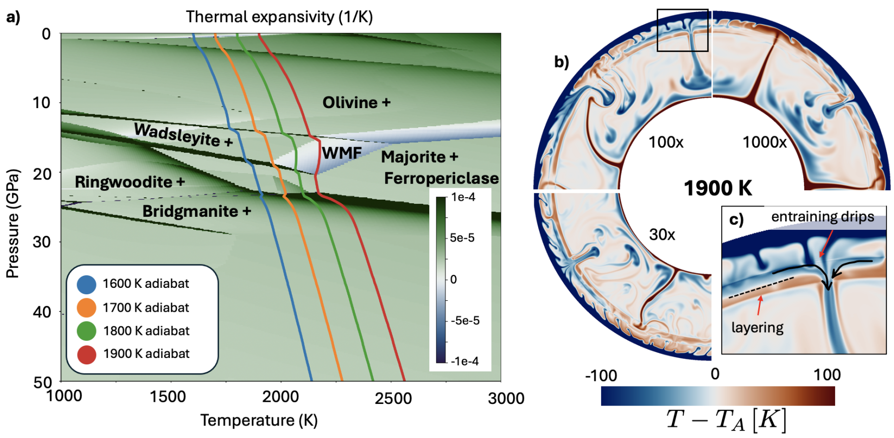

Figure 1: *a) Pressure-temperature maps of thermal expansivity (α) for a pyrolitic composition [4] overlaid with major mineral phases and mantle adiabats for 1600 K, 1700 K, 1800 K, and 1900 K. b) Snapshots of the non-adiabatic temperature field of stagnant lid models with an initial potential temperature of 1900 K and mantle viscosity ratios of 30, 100, and 1000 across the domain. The zoomed-in panel c) shows layering at the base of the WMF region at 600 km depth and cold drips from the lid entrained by the conduit of a mantle avalanche.*

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RocMLMs: Predicting Rock Properties through Machine Learning Models

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Keywords — Mantle Transition Zone, Olivine Phase Transitions, Gibbs Free Energy Minimization, Machine Learning, Numerical Geodynamic Models

Mineral phase transformations significantly alter the bulk density and elastic properties of mantle rocks and consequently have profound effects on mantle dynamics and seismic wave propagation. These changes in the physical properties of mantle rocks result from evolution in the equilibrium mineralogical composition, which can be predicted by the minimization of the Gibbs Free Energy with respect to pressure (P), temperature (T), and chemical composition (X). Thus, numerical models that simulate mantle convection and/or probe the elastic structure of the Earth's mantle must account for varying mineralogical compositions to be self-consistent. Yet coupling Gibbs Free Energy minimization (GFEM) approaches with numerical geodynamic models is currently intractable for high-resolution simulations because execution speeds of widely-used GFEM programs (10^0–10^2 ms) are impractical in many cases. As an alternative, this study introduces machine learning models (RocMLMs) that have been trained to predict thermodynamically self-consistent rock properties at arbitrary PTX conditions between 1–28 GPa, 773–2273 K, and mantle compositions ranging from fertile (lherzolitic) to refractory (harzburgitic) end-members defined with a large dataset of published mantle compositions. RocMLMs are 10^1–10^3 times faster than GFEM calculations or GFEM-based look-up table approaches with equivalent accuracy. Depth profiles of RocMLMs predictions are nearly indistinguishable from reference models PREM and STW105, demonstrating good agreement between thermodynamic-based predictions of density, Vp, and Vs and geophysical observations. RocMLMs are therefore capable, for the first time, of emulating dynamic evolution of density, Vp, and Vs in high-resolution numerical geodynamic models.

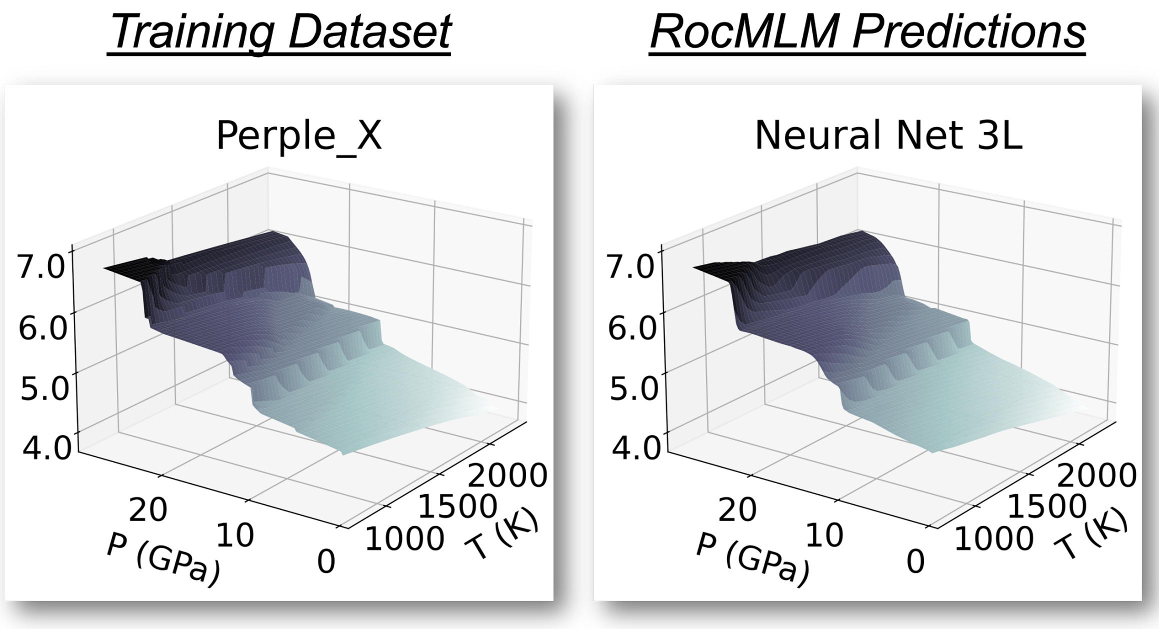

Figure 1: *PT-ρ surfaces showing how the density of a dry peridotite changes with PT. Thermodynamic solutions found by Gibbs Free Energy minimization (left; Perple_X) were used to train machine learning models (right; RocMLM). RocMLM predict density (and other rock properties) up to 10^0–10^3 times faster than Perple_X with equivalent accuracy.*

Hiding in Plain Sight: Searching for Evidence of Subduction on Europa's Icy Shell

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Keywords — Europa, Subduction, Topography

Satellite images from Voyager 1/2 and Galileo indicate that the Jovian moon Europa has a geologically young surface (40-90 Myr) and might host active tectonics within its icy shell. Previous work has interpreted many of the surface features on Europa as evidence of extensional deformation. However, besides the relatively smooth and asymmetric subsumption bands, evidence of compressional topography is very limited. This suggests that compression induced topographic uplift on Europa must be either; a) very diffuse, potentially due to the elastic properties of the ice, b) undetectable in current satellite images due to photoclinometry and resolution limitations, or c) some of the ice mass must subduct below the surface. To investigate this hypothesis, we first calculate the total volume of new ice that is generated at extension bands and rifts for a first order approximation of the expected amount of compressional uplift, assuming icy shell mass conservation and considering isostatic balance. Using the finite element code ASPECT, we will then run numerical models of icy subduction on Europa with visco-elastic-plastic deformation, ice rheology, adaptive mesh refinement and free surface boundary condition. We will also explore the effects of tidal heating and the effects of the Jovian gravitational pull on ice deformation and topography. Our goal is to investigate whether the subduction of ice and its associated (diffuse) compressional deformation at subsumption bands can account for the 'missing' ice mass build-up one would expect in a system entirely dominated by extensional processes. Our results have the potential to unravel the mystery of Europa's topography and provide new insights into the tectonics of icy planetary bodies.

Superpiles: A Low Density Explanation for LLSVPs

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Keywords — Lower Mantle, Thermochemical Convection, Large Low Shear Velocity Provinces

One hypothesis for the formation of Large Low Shear Velocity Provinces (LLSVPs) is that they formed from an intrinsically more dense compositional reservoir in the lower mantle. The possibility of mantle plumes originating from this compositional reservoir could provide an explanation for the observed trace element geochemistry differences between mid ocean ridge basalts (MORBs) and ocean island basalts (OIBs). Our geodynamic models have shown compositional reservoirs tend to form either active superplume, or passive pile morphology. Tomography models indicate the LLSVPs have a morphology which resembles superplumes. The thermal initial condition of a geodynamic model greatly impacts the morphology of these compositional reservoirs. A hot thermal initial condition increases the upwards buoyancy or effective density of the surrounding mantle. This causes the compositional reservoir to form a new type of pile morphology at smaller than expected density differences, a superpile. Superpiles are tall features resembling superplumes, but they are passive features formed by mantle convection the same as a pile morphology. If LLSVPs have a superpile morphology they could have a density similar to the surrounding mantle while explaining the tall LLSVP morphology.

Unraveling the Connection between Subsurface Stress and Geomorphic Features

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Keywords — Lithospheric stress, Active faults, River networks

The stress field within the lithosphere plays an important role in shaping surface features such as the relief of mountains, the direction of active faults, and the course of major rivers [1,2]. These stress fields, at long wavelengths, originate from variations in crust and lithospheric mantle thickness and density, as well as tractions from the convecting mantle acting on the lithosphere's base [3,4]. However, how these stress sources manifest in surface features remains largely unclear. In this study, we investigate the alignment between principal horizontal compressive stress directions, fault traces, and river networks from global databases. We show that the present-day global lithospheric stress field is the primary factor controlling fault trace orientations, as evidenced by a strong correlation with Anderson's fault theory [5] (Fig. 1a). Additionally, we observe that river networks tend to align with fault directions in areas with active faults, particularly high-order rivers. Investigating further, we found that the source of stress (mantle flow or lithospheric heterogeneity) that best predicts fault orientation depends on the fault regime: normal faults correlate with lithospheric heterogeneity, while reverse faults align more with mantle-driven stress (Fig. 1a). This suggests that stresses from mantle flow are essential for breaking rocks under compression. We propose a new metric to quantify the mantle's influence on surface features and use it as a proxy for spatial variations in lithospheric strength (Fig. 1b). This study provides a new approach to understanding interior-surface coupling, the distribution of fault regimes, and long-wavelength geomorphic patterns.

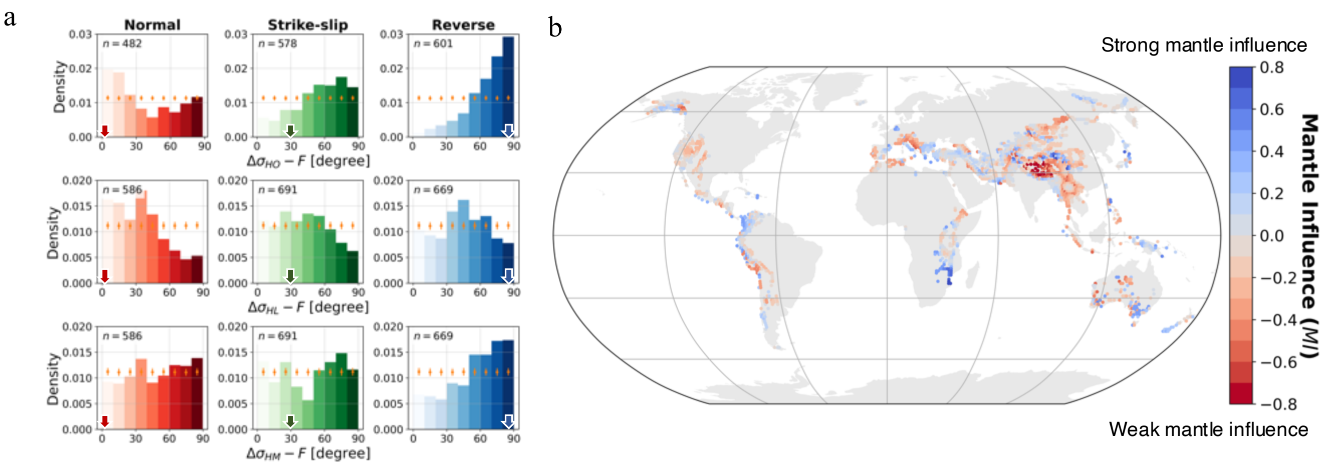

Figure 1: (a) Abundance frequency distribution of the angular differences (Δ) between directions of fault trace (F) and the most compressive stress from observational stress (σ_{HO}), modeled stress from lithospheric heterogeneity (σ_{HL}), and mantle flow (σ_{HM}). The colors represent fault regimes and opacity shows (low) parallel to (high) perpendicular Δ. Yellow dots show the random uniform distribution expected from Monte Carlo simulations. Arrows indicate the expected Δ based on Anderson's fault theory. The n shows the total grid points used in each panel. (b) Global map of the degree of influence of mantle flow (MI) on surface features. Colors represent MI, ranging from strong (blue) to uncertain (gray) to weak (red).

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3D numerical modeling of oblique collision: the Taiwan case study

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Keywords — Transpression, Obliquity, Taiwan

The Taiwan orogeny is well-regarded as a key location for studying the initial stages of collision and the interactions between tectonics and surface processes. Another significant yet relatively less explored aspect of this orogeny is its obliquity. In this region, two distinct types of obliquity can be identified: (1) the oblique convergence between the Eurasian plate and the Philippine Sea plate, which creates a transpressional regime leading to strain partitioning, and (2) the orientation of the inherited margin structure from the South China Sea relative to the direction of convergence.

How do the obliquity of inherited structures and convergence affect the thermal structure and strain localization within the orogen?

To address this question, we develop a 3D thermo-mechanical model of oblique subduction-collision using pTatin3D. This model accounts for erosion-sedimentation processes using diffusion, thermo-dynamically consistent densities, and new Navier-slip type boundary conditions specifically designed for oblique setting. We aim to conduct two parametric studies: one focusing on the obliquity of the convergence, while the other focuses on the obliquity imposed by the structural inheritance. By comparing simulations results with thermo-chronological models and structural observations, we target the development of a framework to help interpreting geological observations and records in the highly 3D Taiwann region.

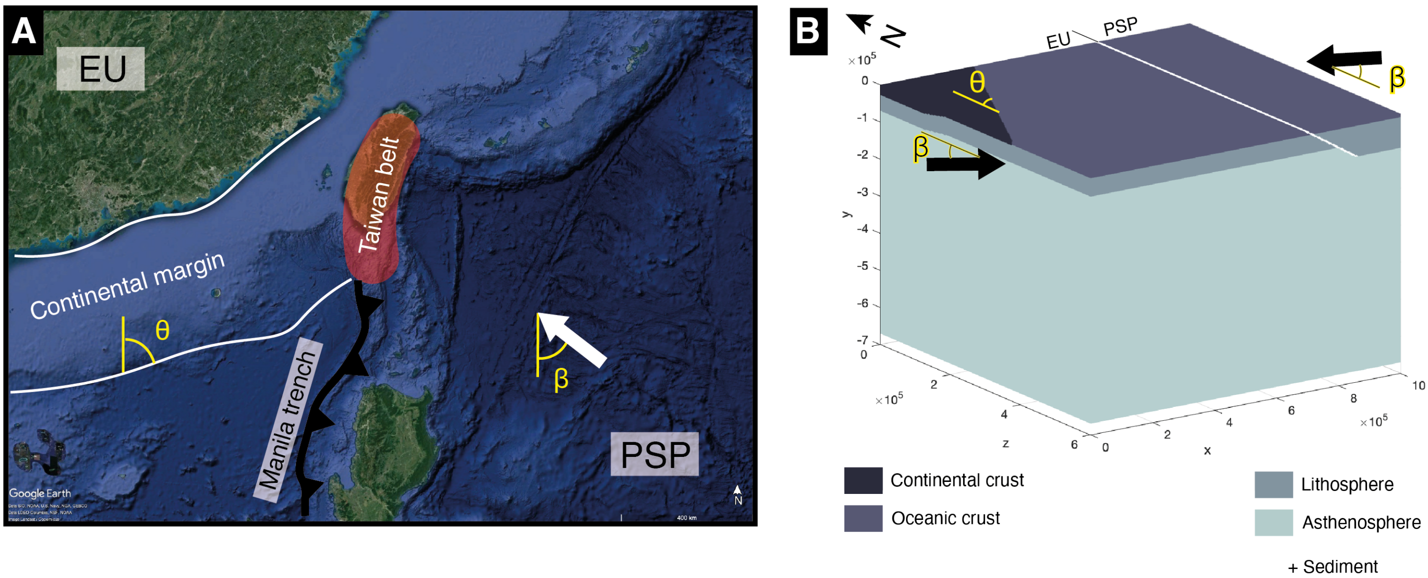

Figure 1: *A. Satellite image of the Taiwan area. The collisional belt is highlighted in red. The arrow indicates the relative velocity between the Eurasian Plate (EU) and the Philippine Sea Plate (PSP). The angle β represents the obliquity of convergence, while α denotes the orientation of inherited margin structures. B. Initial and boundary conditions of the 3D simulations.*

Mantle flow and rifting

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Keywords — rifting, mantle convection,

Rifting is a combination of far-field forces, which leads to boudinage of the lithosphere in a more or less localized manner depending on the rheology of the lower crust and buoyancy forces that contribute to the thinning of the mantle. If buoyancy forces dominate, mantle necking occurs faster than crustal necking, potentially leading to active rifting in the presence of far-field forces [1]. Otherwise, mantle necking occurs first by boudinage, and only at the end of continental rifting do buoyancy forces arising from the passive thinning of the mantle overtake the far-field component, leading to continental breakup and active drifting [2].

In these two end-member models, the mantle dynamics are somewhat fixed relative to the lithosphere. However, large convection cells that act as so-called conveyor belts may induce a relative movement between the lithosphere and the mantle [3]. Moreover, large-scale mono-directional flow may evolve into Richter convective cells [3] in the asthenosphere that align with the direction of shearing causing fingering in the upper mantle. Under these conditions, one might ask how the large-scale direction of flow interacts with the dynamics of rifting.

It has been shown that in 2D mantle flow, shearing at the base of the lithosphere may inhibit continental breakup driven by slab pull forces because the shearing exerted by the flow tends to flatten the mantle necking, reducing the role of buoyancy forces [4]. However, one might wonder what happens when the mantle flow is parallel to the rift, as in the Red Sea or in the East Central Rift System (ECRIS). This contribution reports the results of a parametric study in which we systematically vary the intensity of the flow and the rate of stretching in a direction normal or perpendicular to the imposed mantle flow to test the idea of whether the direction of the large-scale mantle flow matters in the ratio of passive to active rifting/early magmatic margins versus late magmatic margins.

The model setup is a 3D upper mantle scale box of 1500 km by 1500 km, similar to that used in [1], but we fully utilize the new stress boundary conditions that have been implemented in pTatin, which permit imposing a differential pressure in the upper mantle and the asthenosphere to drive a mantle current in the x direction. We then stretch the lithosphere in both the x and z directions and measure how the mantle flow influences the dynamics of rifting and the timing of continental breakup.

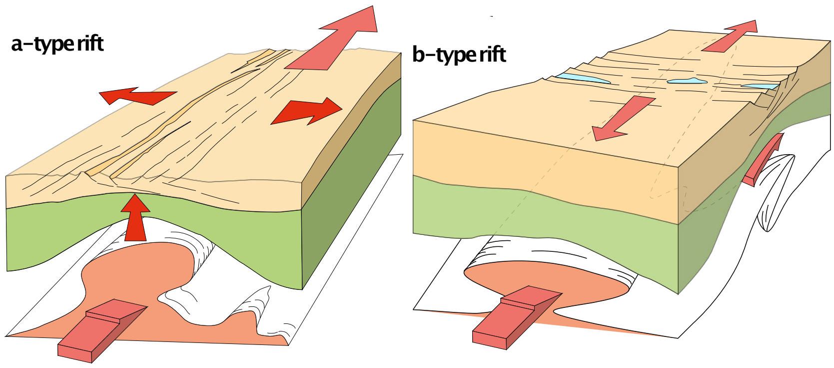

Figure 1: Illustration of the two types of rifting that we tested numerically.

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Quantifying the influence of orogenic inheritance on rifted margin formation through Wilson cycle modelling

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Keywords — Orogenic inheritance, Wilson cycle, rifted margin architecture

The Wilson cycle describes the repeated opening and closure of oceanic basins from continental rifting to continent-continent collision. The correlation between ancient orogenic belts and young rift systems highlights the significance of orogenic inheritance in shaping the complexities of rifted margins, but the actual inversion from orogen to rift remains poorly understood. A fundamental question arises: to what extent should orogenic inheritance be incorporated into numerical models simulating rift evolution? Conversely, are there specific scenarios where the influence of inherited structures can be reasonably neglected?

To address these questions, a numerical forward model was applied that integrates the geodynamic, finite element code ASPECT and the landscape evolution software FastScape. The simulations include continental collision, post-orogenic collapse, continental rifting, and breakup, through velocity boundary conditions that vary from compression to extension over time (Figure 1). Two end-member orogen styles are generated by the adjustment of crustal rheology and erosion efficiency. For comparative analysis, we also simulate the extension of laterally homogeneous lithosphere without orogenic inheritance.

Our results show that neglecting inherited structures in numerical models may overestimate required driving forces for rifting initiation. We find that the reactivation of thrust faults and thermal weakening associated with inherited orogenic structures promote the formation of wider rifted margins. Surface erosion efficiency is also identified as a factor influencing rifted margin complexity, impacting width and lower crust exhumation. Finally, a comparison between models with and without inherited structures reveals that rheologically weak initial lithospheric conditions result in rifted margins more closely resembling those in homogeneous models. This suggests that the impact of inherited structures on rifted margins diminishes for weak crust that is dominated by ductile deformation.

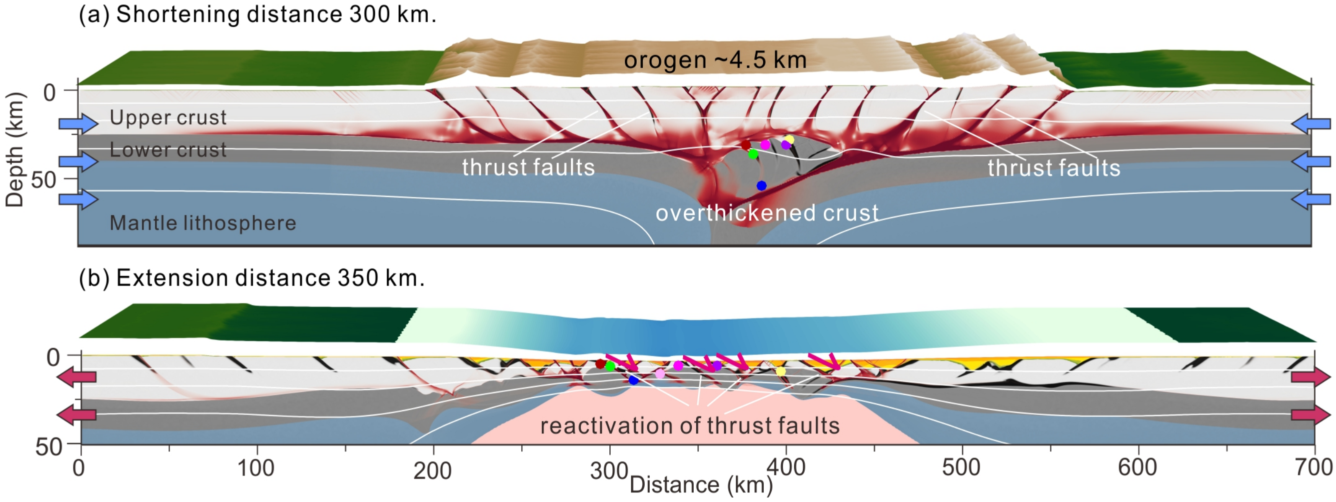

Figure 1: The evolution of the reference model (a) The model results after 300 km shortening distance. (b) The rifted margin architecture after 350 km extension distance.

How Phase Transitions Impact Changes in Mantle Convection Style Throughout Earth's History: From Stalled Plumes to Surface Dynamics

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Keywords — mantle convection, phase transitions, plume dynamics

Mineral phase transitions can either hinder or accelerate mantle flow. In the present day, the formation of the bridgmanite + ferropericlase assemblage from ringwoodite at 660 km depth has been found to cause weak and intermittent layering of mantle convection. However, for the higher temperatures in Earth's past, different phase transitions could have controlled mantle dynamics.

We investigate the potential changes in convection style during Earth's secular cooling using a new numerical technique that reformulates the energy conservation equation in terms of specific entropy instead of temperature. This approach enables us to accurately include the latent heat effect of phase transitions for mantle temperatures different from the average geotherm, and therefore fully incorporate the thermodynamic effects of realistic phase transitions in global-scale mantle convection modeling. We set up 2-D models with the geodynamics software ASPECT, using thermodynamic properties computed by HeFESTo, while applying a viscosity profile constrained by the geoid and mineral physics data and a visco-plastic rheology to reproduce plate-like behavior and Earth-like subduction morphologies.

Our model results highlight the layering of plumes induced by the wadsleyite to garnet (majorite) + ferropericlase endothermic transition (between 420–600 km depth and over the 2000–2500 K temperature range). They show that this phase transition causes a large-scale and long-lasting temperature elevation in a depth range of 500–650 km depth if the potential temperature is higher than 1800 K (Fig. 1), indicating that mantle convection may have been partially layered in Earth's early history. In the future, we plan to extend our approach to account for chemical heterogeneities, and we present a framework that allows it to incorporates multiple components within our entropy formulation as a first step towards this goal.

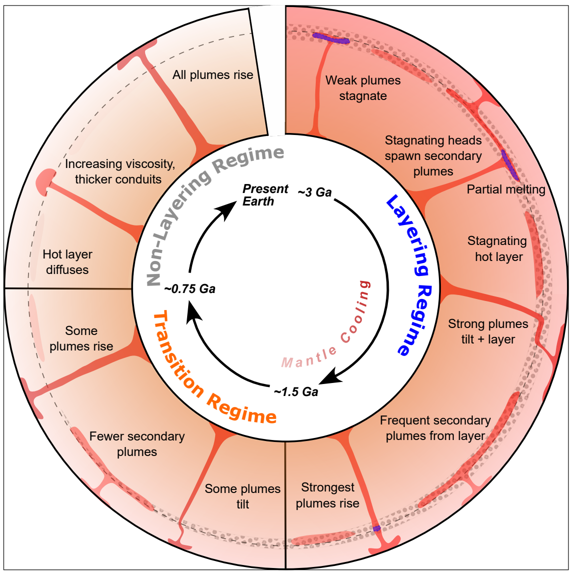

Figure 1: *A schematic diagram summarizing the plume morphologies featured in our models and how they change throughout the Earth's secular cooling. Time evolves in clockwise direction. The dashed line indicates a depth of 500 km. Dotted area shows where the wadsleyite to garnet (majorite) + ferropericlase phase transformation occurs. Purple shading illustrates areas where partial melting occurs. The timeline and corresponding convection regimes assume that the mantle potential temperature was 1900 K at around 3 Ga and that the mantle cools about 100 K per Gyr.*

Subduction zones play a pivotal role in the mechanics of plate tectonics by providing the driving force through slab pull and weak megathrusts that facilitate the relative motion between tectonic plates. The initiation of subduction zones is intricately linked to the accumulation of slab pull and development of weakness at plate boundaries and by consequence the largest changes in the energetics of mantle convection. However, the transient nature of subduction initiation accompanied by intense subsequent tectonic activity, leaves critical evidence poorly preserved and making subduction initiation difficult to constrain. We overcome these limitations through a comprehensive analysis focused on Puysegur, a well-constrained extant example of subduction initiation offshore South Island, New Zealand. Through time-dependent, three-dimensional thermo-mechanical computations and quantitative comparison to new geophysical and geological observations, including topography, stratigraphy, seismicity, and earthquake focal mechanisms, we demonstrate that subduction initiation develops with a fast strain weakening described with a small characteristic displacement ($\Delta_s \approx 4 - 8$ km). Potential physical mechanisms contributing to the strain weakening are explored and we find that the observed fast weakening may arise through a combination of grain-size reduction within the lower lithosphere and fluid pressurization at shallower depths. With the shared commonality in the underlying physics of tectonic processes, the rapid strain weakening constrained at Puysegur offers insights into the formation of the first subduction during early Earth and the onset of plate tectonics.

Intra-plate volcanism generated by slab-plume interaction: Insights from geodynamic modeling

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Keywords — Intraplate volcanism, Slab-plume interaction, Eifel

Intraplate volcanism took place in a number of places around the world, such as the Eifel volcanic area, Massif Central in central Europe and the volcanoes in Indochina, Hainan in South East Asia. The origin of these volcanoes still remains poorly understood, although multiple approaches have been used for the volcanoes' study.

Seismic tomography shows that there are thermal upwellings which are interpreted as mantle plumes beneath the transition zone of these areas [1, 3]. It also shows that these areas are surrounded by or neighboring to subduction zones of different slab geometries. Based on these observations, our hypothesis is that the primary mantle plumes originated from the core mantle boundary are stagnant below the transition zone. The subducted slab then triggers the upper-mantle plumes above the primary plume, which leads to the formation of the intraplate volcanism. Using a finite element code ASPECT [2], we build an upper mantle box model with two slab geometries—slab rollback (trench retreating) and slab rollover (trench fixed). We approximate the influence of lower mantle plumes by imposing a thermal boundary layer at the base of the model. The influence of thermal boundary layer temperature and thickness on the plume strength and melt generation is tested.

Model results show that the slabs of both geometries can trigger upper-mantle plumes (Fig. 1). The strengths of the mantle plumes in the slab rollback setting are largely smaller than in the slab rollover setting. The increase of TBL temperature and TBL heating time leads to the increase of plume strength and the decrease of plume longevity in the slab rollover setting. However, TBL temperature doesn't have much influence on plume strength and it increases the plume longevity in the slab rollback setting. Our models provide a possible mechanism for the origin of intraplate volcanism in central Europe and southeast Asia.

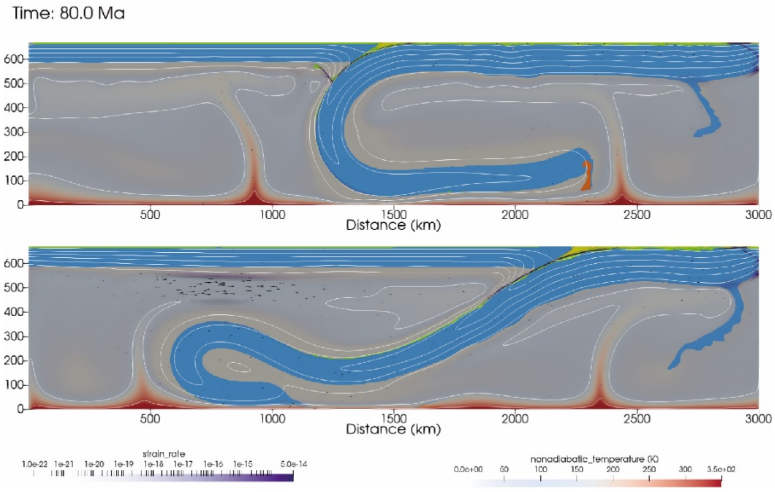

Figure 1: Plumes triggered by slab with different geometries.

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Quantification of thermally-controlled metamorphic decarbonation and carbonate dissolution in subduction zones

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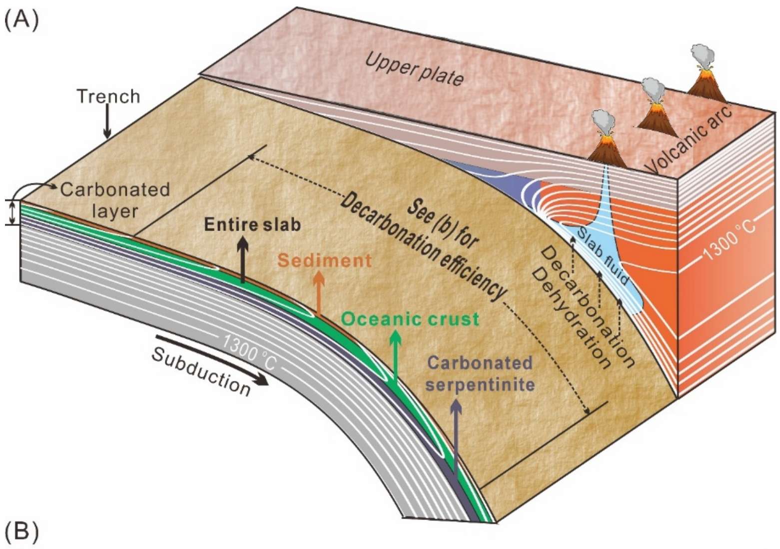
Keywords —Subduction zone, metamorphic decarbonation, carbonate dissolution, thermal structure, decarbonation efficiency

Oceanic subduction zone is the dominant (if not the only) pathway for transporting carbon into the interior of the Earth, and thus plays a critical role in deep carbon cycling. Several mechanisms have been proposed for slab decarbonation process, with two primary ones being metamorphic decarbonation and carbonate dissolution. The metamorphic decarbonation has been widely analyzed by numerical models in the closed system (i.e., with constant water content). However, the water and carbon evolutions in subduction zone are strongly coupled together, leading to an open system in which the water cycling not only affects the metamorphic decarbonation, but also controls the dissolution of carbonates. However, the decarbonation efficiency and the contributions of different decarbonation mechanisms to slab carbon removal remain controversial. Here, we develop a coupled thermo-metamorphic-dissolution model to investigate physicochemical decarbonation processes. Systematic numerical models with variable thermal parameters (Φ = slab age × subduction velocity / 100) have been conducted in both closed and open systems. The results indicate that the metamorphic carbon outflux in open system is lower than that in closed system, whereas the dissolved carbon outflux in open system is approximately three times higher due to fluid infiltration. Moreover, the metamorphic carbon outflux decreases exponentially with Φ in both closed and open systems. In contrast, the dissolved carbon outflux exhibits a nearly linear increase with Φ < 13 km, followed by an exponential decrease with $\Phi \geq$ 13 km. The new models provide systematic and quantitative constraints for the deep carbon cycling in subduction zones.



(B)

Thermal parameter (km) \ Decarbonation efficiency (%)		Entire slab	Sediment	Oceanic crust	Carbonated serpentinite
All Φ	Closed system	5.6–64.9	28.4–100	0–69.2	0–15.9
	Open system	0.3–26.4	1.5–77.5	0–21.6	0–22.2
Φ = 30 km	Closed system	6.6–10.4	31.6–51.5	0.3–0.5	~0.2
	Open system	4.3–8.0	10.8–18.8	2.0–6.2	3.0–5.1

Figure 1: Decarbonation efficiency in oceanic subduction zones. (A) Schematic illustration shows the decarbonation process and decarbonation efficiency of different lithological layers, with the predicted values shown in (B). The white lines indicate the thermal structure of subduction zones. (B) The ranges of decarbonation efficiency are summarized for all the models with variable Φ and also for the specific case with Φ = 30 km (i.e., the most favorable case in the present Earth).

Compaction-driven convection in the growing inner core

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Keywords — Inner core, Two-phase dynamics, Compaction, Permeability, Porosity, Convection

The Earth's inner core (IC) is known to exhibit heterogeneous structures with their origins still unknown. From the onset of nucleation, the IC can grow via sedimentation and compaction of iron crystals freezing out from the fluid outer core. Previous studies of IC growth have shown entrapment of fluid within the solid matrix, and unstable density profiles in 1D can appear depending on the efficiency of fluid percolation [1, 2]. In this study, we perform simulations of IC growth via compaction and melt percolation in spherical geometries for the first time (assuming axisymmetry). We find that it is possible for the IC to develop large scale convective flows under certain conditions and, in some instances, produce small-scale heterogeneites close to the IC boundary. Assuming representative values for the physical properties of the Earth's IC, we show that it is possible for the IC to exhibit large-scale convective motions today. The resulting fluid distribution and flows can have potential implications on the IC seismic structure and outer core dynamics.

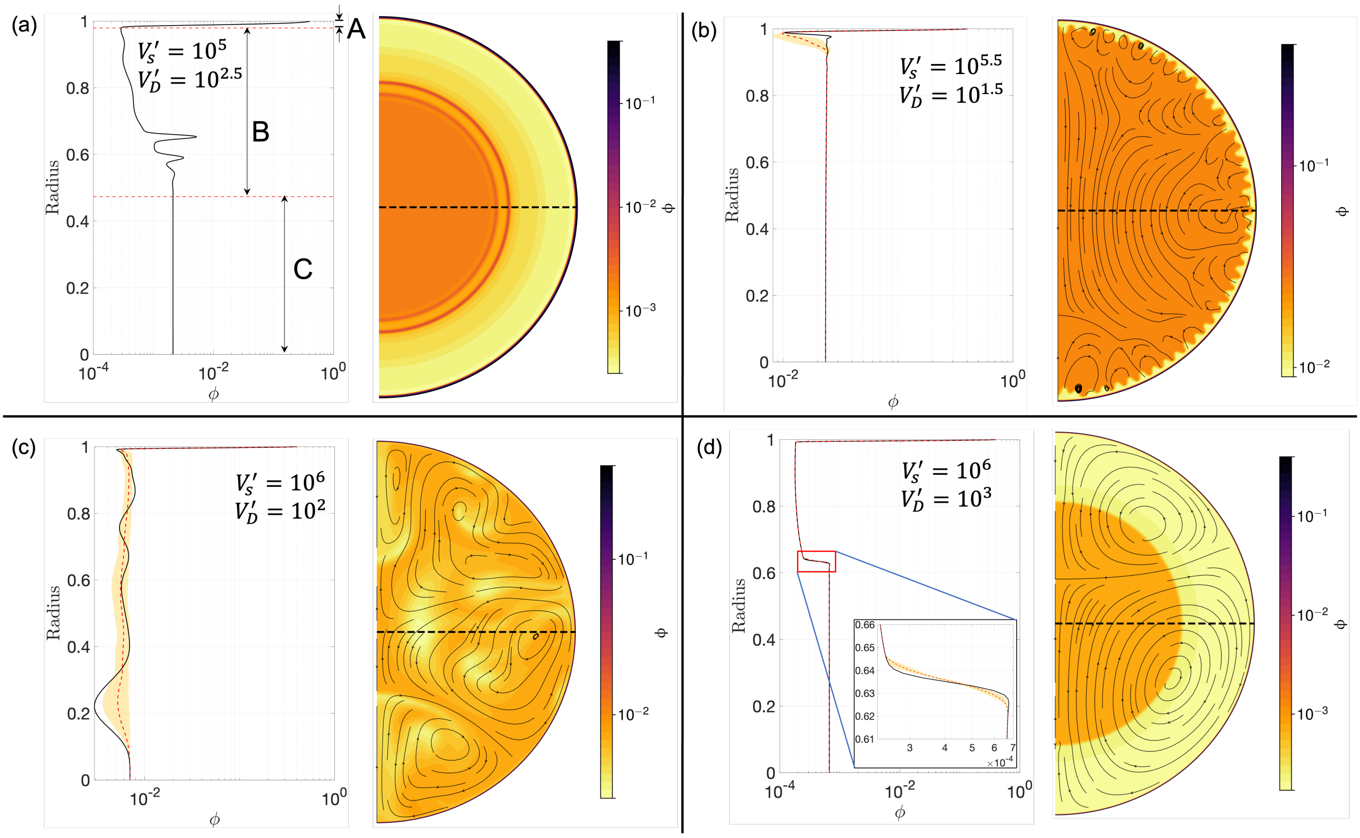

Figure 1: *Porosity profiles from different regimes of our simulations. The two nondimensional parameters that govern the dynamics are V_s' and V_D'. Black arrows indicate the streamlines.*

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Gravitational collapse of a metal-silicate mushy layer at the core-mantle boundary: a mechanism for core-mantle interactions and its implications

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Keywords — Core-mantle boundary, Core-mantle interaction, Dynamic topography, Mantle plumes, Lubrication theory, Core composition

The core-mantle boundary (CMB) is one of the most stable interfaces inside the Earth due to the large density and viscosity contrasts. Despite significant differences in physical, chemical, and transport properties, the possible mechanisms where the core and mantle can interact has become an active area of research. Detection of chemical signatures from the CMB can provide an unprecedented glimpse into the Earth's deep interior and ancient past, with some studies suggesting certain isotopic and elemental anomalies in ocean island basalts to be core tracers. However, there is still uncertainty regarding processes that can convey chemical signatures from the core to the mantle. In this study, we propose a new hybrid mechanism that results from collaborative feedback between dynamic topography, percolation of liquid metal into submerged rock, the gravitational collapse of a metal-silicate mush, and induced small-scale circulation above this mushy layer. The grain-scale intrusion of liquid iron into mantle rocks offers an opportunity for chemical and isotopic exchange to take place, while the gravitational collapse of the mushy layer can "soften" the CMB and enhance mantle downwellings, thereby encouraging further chemical exchange. Using a mantle convection model coupled to the gravitational spreading of a thin layer at the CMB, we will show how the enhancement of downwellings change with the rheology of the mantle and viscosity of the mushy layer. In addition, when reacted mantle material emerges from the mushy layer, we can monitor the evolution of concentration flux in upwelling plumes and track the rate of material being transferred from the CMB to the shallow Earth. This mechanism also has implications on phenomena in the lower mantle such as the emergence of thermochemical heterogeneities, small-scale convection near downwelling regions, and on core dynamics through the heat flux across the CMB.

Exploring the Impact of Subducting Sediment Properties, Shear Heating, and Fluid Pressure on Seismic Activity in Subduction Zones Using MEFISTO

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Abstract

Seismic activity in subduction zones is closely related to human society, as many major cities around the world are situated in these regions. Understanding the initiation mechanisms of megathrust earthquakes in subduction zones is thus crucial. This study compiles the subduction rates, sediment thicknesses at the trench, and temperature structures along the slab top of subducting plate across various subduction zones. Using MEFISTO—a 2D spring-slider forward earthquake simulator that incorporates fault healing and couples to a fluid flow model—we explore how different factors control the space-time distribution of earthquakes. Additionally, we introduce a new flow law that combines pressure solution creep and dislocation creep, allowing better predictions of diffusion creep strain rates in the megathrust fault from a microscopic perspective. This new flow law enables us to examine the influence of grain size, solubility and shear zone thickness of subducting oceanic sediments on megathrust's locking depth and seismicity. Furthermore, we consider the impact of shear heating effect dynamically, as we believe it is significant within the megathrust shear zone. Our predictions for locking depth improve upon incorporating shear heating effect. These updates enhance our constraints on the extent of the seismogenic zone, allowing us to explore the interplay among subducting sediment properties, shear heating, and thermogenic fluids in subduction zones.

Modelling dike intrusions in extensional settings: preliminary results for mid-ocean ridges and continental rifts

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Keywords — Dike magma intrusions, mid-ocean ridges, continental rifts

Tectonic extension results in lithospheric thinning, allowing for magma generation at depth. The generated melts ascend and may intrude into the brittle crust as narrow dikes. Intrusion modifies the local stress field, thus influencing faulting patterns in, for example, continental rifts and mid-ocean ridges. Previous numerical studies of mid-ocean ridges introduced the factor M, the kinematic ratio of axial magma accretion to far-field plate separation rate, to study the relationship between magmatic and tectonic extension and ridge faulting modes [1]. These studies demonstrated that M has a prominent effect on fault spacing, offset, and orientation. Normal faults at magma-rich ridges (M close to 1) migrate rapidly off-axis into cooler, more vital lithospheric regions, eventually becoming inactive. A new fault forms near the spreading axis and migrates off-axis again, replacing the inactive fault. At M = 0.5, the faults cease to migrate and form a long-lived detachment on one side of the axis. In magma-poor ridges where M < 0.5, the detachment fault migrates towards the hanging wall due to the accretion deficit in the conjugate plate before becoming truncated by a high-angle antithetic fault. The newly formed detachment faults near the axis continue this process, resulting in a flip-flop detachment faulting style.

Previous geodynamic simulations assumed a fixed dike injection zone at the spreading center. However, in tectonic extension scenarios like continental rifting [2], magma may intrude through multiple dikes at different times and locations. To address this complexity, we developed tectono-magmatic spreading models using ASPECT, implementing a routine for random dike generation that varies the location and size of dikes as a function of the melt region within the asthenosphere. This approach is applied to both mid-ocean ridge spreading and continental rifting settings. This study presents preliminary results of these models, providing insights into the dynamics of dike magma intrusion and its influence on faulting patterns during tectonic extension.

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The effects of continental lithospheric segments on long term evolution of Hellenic slab

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Subduction of the African plate beneath the Aegean has been active since the Jurassic. Currently, the subduction velocity is ~2 cm/yr, and the trench is rolling back with a velocity of ~1 cm/yr. While seismic tomography reveals that the slab-related structure penetrates to the lower mantle, reaching depths of about 1200 km, seismicity ceases sharply at depths of 200 km. Reconstruction of the subducting plate structure shows the presence of several fragments of continental lithosphere and lower crust that have been subducted since Early Cretaceous. Considering the presence of the continental segments on the subducting plate, the slab geometry and morphology consistent with seismic tomographic images is obtained by exploring a wide range of model parameters.

Here we test the hypothesis that seismicity pattern might be linked to the presence of subducted continental segments. Intermediate-depth seismicity has been mostly linked to the dehydration embrittlement mechanism, which is inactive in the dry continental lithosphere. Tracking the potentially hydrated oceanic plate material within the subducting slab provides insights into the areas where dehydration embrittlement could be active. Comparing the (P, T) conditions of the subducted hydrated material with stability phase diagrams quantifies the dehydration depths and thus provides an explanation for the observed seismicity. Our model shows that there is no wet subcrustal lithospheric material within the slab below 200 km depth and that the potentially hydrated crustal material should already be dehydrated before reaching the depth of 150 km, leaving no reason for active dehydration embrittlement at lower depths.

Influence of Possible Bulk Compositions on the Long-Term Evolution and Outgassing of Venus

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Keywords — Mantle convection, tectonic regimes, Venus

Venus' mass and radius are similar to those of Earth. However, Venus' interior structure and chemical composition are poorly constrained. Seemingly small deviations from the Earth might have important impacts in the long-term evolution and dynamics of Venus when compared to our planet and could help to explain the different present-day surface and atmospheric conditions and geophysical activity between these two planets. *Shah et al*. (2022) [1] presented a range of possible bulk compositions and internal structures for Venus. Their models, designed to fit Venus' moment of inertia and total mass, predict core radii ranging from 2930-4350 km and include substantial variations in mantle and core composition. In this study, we pick ten different Venus models from *Shah et al.* (2022) [1] that range from a small to a big, and from a S-free to a S-rich core. We run mantle convection evolution models for the different scenarios using the code StagYY [2, 3] and explore how different interior structures and chemical compositions affect the long-term evolution and dynamics of Venus. In our models, the bulk composition of the mantle affects the basalt fraction and the solidus and liquidus temperature profiles. We investigate how the composition and size of the core affects magmatism hence outgassing of water and other volatiles to the atmosphere, the basalt distribution, heat flow, temperature of the mantle and lithosphere, and observables such as the moment of inertia and Love numbers. Since the tectonic regime active on Venus is still unknown, we test different evolution scenarios for a planet covered by a stagnant lid, an episodic lid, and a plutonic-squishy lid. The models produce a range of predictions that can be compared to observations by planned missions to Venus, including EnVision measurements by the VenSpec spectrometers, comprising outgassing of water and other volatiles and surface composition. These can be used to constrain Venus' interior composition and structure, and reveal key information on the differences between Earth and Venus.

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On the shapes of thermochemical mantle plumes

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Keywords — thermochemical plume, viscosity variation, ASPECT

Recent observations from global and regional seismic tomographic models reveal broad mantle plumes (∼400 km in radius) stemming from the CMB, and many of these plumes appear to stagnate at ∼1000, 660, and 410 km depth, some of which are unexpected behaviors of purely thermal plumes [1]. Thermochemical plumes that entrain basaltic material in addition to the pyrolitic ambient mantle may be broader than a purely pyrolitic thermal plume and may stagnate at 410 km depth, where the relative buoyancy of a basaltic component hinders ascent. A pyrolite-dominant plume may stagnate at 660 km depth due to the endothermic bridgmanite to ringwoodite transition. The viscosity variations across the mantle due to variations in deformation mechanism, temperature, grain size, and water content can affect the radius of a plume. They may also help to explain the observed plume stagnation at ∼660 and 1000 km depth. Previous numerical studies explore how the basaltic material fraction, excess temperature, and size of a thermochemical anomaly affect the shape of thermochemical plumes in great detail. Still, the effect of radial and lateral viscosity variations on thermochemical plumes remains obscure.

Here, we use the community geodynamic modeling code ASPECT to explore how the lateral and radial viscosity variations affect the shape of thermochemical plumes. We prescribe a initial circular thermochemical anomaly at the CMB with a basaltic and pyrolitic composition (Fig. 1a). The density of the basaltic and pyrolitic materials in our model are determined directly from pressure-temperature look-up tables, which are computed using Perple_ X and are based on the thermodynamic database of [2]. The total density is then averaged based on the fraction of basaltic and pyrolitic materials, which can capture the density changes due to P-T dependent phase transitions of these two components more accurately. We use reference depth-dependent viscosity profiles that contain a viscosity hump at different depths to explore if the viscosity hump could lead to plume stagnation. For each reference viscosity profile, we only consider the thermal effects on the lateral viscosity variation and assume the compositional difference, strain rate, and grain size do not affect the viscosity. We vary the activation enthalpy of the upper mantle from 400 kJ/mol to 700 kJ/mol (corresponding to $\sim 4-10$ times viscosity variation per 100 K) and the activation enthalpy of the lower mantle from 200 kJ/mol to 500 kJ/mol ($\sim 2-5$ times viscosity variation per 100 K). Our preliminary results (Fig. 1b-d) show that the radius of a low-buoyancy plume decreases as the activation enthalpy becomes larger. The predicted plume radius is much smaller than the plumes imaged in the seismic tomographic models in the lower mantle. Stagnation at ∼410 km of a plume composed of some basaltic material is also not prominent when the activation enthalpy is large. Developing a comprehensive understanding of the compositional and rheological controls on plume dynamics will require that we match not only the constraints on plume shape offered by seismic imaging but also the geologic constraints on pre-magmatic uplift and melt volume and petrologic constraints on plume composition and excess temperature.

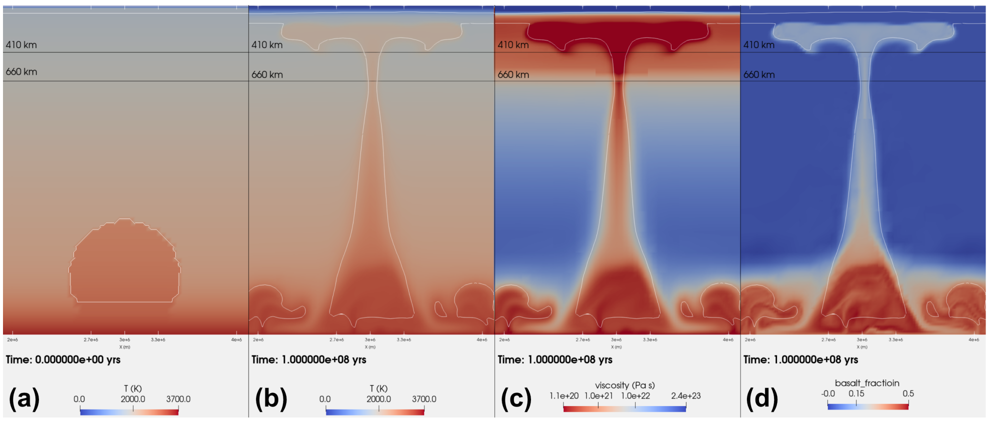

Figure 1: *The initial temperature field (a) and the temperature (b), viscosity (c), and basaltic material fraction (d) field at 100 Myr. The contours represent 200 K temperature anomaly. The initial anomaly has a radius of 500 km, an excess temperature of 450 K, and 15% basaltic material. The activation enthalpy is 500-750 kJ/mol in the upper mantle and 350-500 kJ/mol in the lower mantle.*

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New Insights into Plume Buoyancy Fluxes and Dynamic Topography from Numerical Modelling

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Keywords — plume-lithosphere interaction, plume buoyancy flux, dynamic topography

Mantle convection and plate tectonics control Earth's dynamic evolution. While the cold rigid slab subducts into the mantle, hot upwelling plumes can lubricate, push, and break up plates (Cande & Stegman, 2011; Stern & Gerya, 2018). Plume buoyancy flux is crucial in measuring how much mass and heat mantle upwellings bring to the surface. The traditional approach to calculating the plume buoyancy flux (i.e., multiplying the cross-sectional area of the hotspot swell by plate velocity) is based on two assumptions: that the swell is supported purely isostatically by the hot ponding plume material at the base of the lithosphere and that the asthenosphere moves at the same velocity as the overriding plate. However, hotspot swells are largely dynamically instead of fully isostatically supported (Cadio, et al., 2012; Ribe and Christensen, 1999). Moreover, at least some plumes (e.g., Iceland) can move faster than the corresponding plate motion (Poore et al., 2011). With increasingly available observational constraints for dynamic seafloor topography (Hoggard et al., 2020), it is time to update plume buoyancy fluxes globally.

Here, we conduct thermomechanical models to study plume-lithosphere interaction and hotspot swell support. We use the finite elements code ASPECT in a high-resolution, regional, 3D, cartesian framework. We consider composite diffusion-dislocation creep rheology, and a free-surface boundary at the top. We systematically investigate the effects of plume excess temperature, radius, plate velocity, and mantle rheological parameters. From these results for plume spreading beneath moving plates, the buoyancy fluxes of individual plumes, as well as the relevant plume temperatures and radii are quantitatively constrained. Our model results show that plume radius and plume excess temperature control swell height and width in different ways, such that their effects can be distinguished. In the future, we will build a scaling law for buoyancy flux as a function of swell geometry in order to estimate global heat and material fluxes carried by plumes.

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Porous melt flow through continental crust modeled using pressure-, temperature- and water-dependent melting parametrization

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Keywords — continental crust, melting, porous flow, composition, deformation

Melting of the continental crust and transport of the melt through it are key processes that drive its compositional differentiation. In the cool upper crust, the melt is mostly transported through macro-scale cracks forming dikes. In a deeper supra-solidus crust, the mechanism of transport gradually changes towards a more diffuse, grain-scale porous flow (e.g. [1]), although certain segregation of melt and formation of melt-rich domains (leucosomes) is common. Here we focus on the grain-scale melt flow in hot continental crust and evaluate its effects on crustal differentiation, thermal state and deformation using two-dimensional numerical models.

To capture the interplay between melt transport and crustal composition, we describe melting as a composition-dependent process. To keep the model simple and computationally efficient, we approximate the rock and melt compositions each by a scalar variable that is related to the water content. The equilibrium melt fraction is then calculated from the solidus and liquidus temperatures that depend on this composition and on the pressure. Other material properties in the model (e.g. the permeability, densities, shear and bulk solid viscosities and melt viscosity) are defined based on observations, experiments, or theoretical models.

We demonstrate the characteristic features of our modeling approach on a crustal-scale (50x50 km box) model setup where melting is induced by a high-temperature anomaly at the bottom boundary, and motions of the solid and melt are driven by gravity. In this setup, we observe upwelling of the partially-molten rock above the hot anomaly and slow but long-lasting melt percolation that causes compositional differentiation into an enriched middle crust and depleted lower crust. We compare our results with those from a similar model setup but with a simpler (linear) parametrization of solidus and liquidus temperatures [2]. We further study the interplay between melt percolation and deformation in a km-scale (5x10 km) model of a crustal column in simple shear (Fig. 1). We examine the role of the shearing rate, melt productivity of the rock, pressure-temperature conditions and initial heterogeneities.

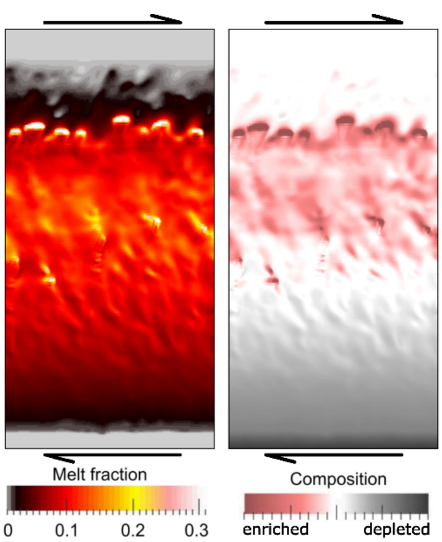

Figure 1: Example of simple-shear deformation of partially-molten crust. Melt fraction (left) and composition (right) at 6 Myr of model evolution. The top and bottom model boundaries are at 20-km depth, 630 °C and 30-km depth, 830 °C, respectively. Initial composition (~water content) in the rock is 1 wt% H_2O with random variations of max. 0.1 wt% H_2O.

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Why is the basal silicate layer of Mars absent in the Earth?

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Keywords — Magma Ocean, Mantle Differentiation, Melting and Crystallization

One of the most recent discoveries about Mars is also a puzzling one: the existence of a distinct silicate layer between the Mantle and the core[1,2]. Interpreting this layer as a remnant magma ocean is attractive because the magma ocean scenario readily explains all the layer's features on Mars. Moreover, finding this layer is an usual result of previously published models[e.g. 3]. According to these models, (semi-)fractional crystallization progressively enriches the magma ocean in incompatible elements including iron. The enrichment will increase the density of the magma ocean, which eventually will lead to an overturn, creating this silicate layer at the bottom of the mantle. However, the reason for the existence of this remnant in Mars but not in Earth, where it has not been detected by seismic techniques[4], remains elusive.

One of the processes of capital importance that is missing (or crudely represented) from current geodynamic models is 'remelting', whereby melting of crystal cumulates occurs as soon as solid-state convection starts, substantially before the end of magma ocean crystallization. Using boundary layer theory and numerical thermomechanical models, we calculate the evolution and differentiation of a solid mantle undergoing growth (crystallization) and remelting. Under these conditions, two possibilities appear, depending on the ratio between magma ocean cooling and mantle convection speeds: either (a) the magma ocean cools fast, and differentiates steadily, forming a silicate layer; or (b) the composition of the magma ocean is buffered by the re-melting incipient mantle, halting the differentiation, diluting iron, and precluding the formation of the dense silicate layer. On Earth, the greater planet size fosters fast mantle convection and stronger re-processing of the mantle, favoring case b. On Mars, a smaller planet size slows down convection, favoring case a (Figure 1).

We propose that the magma ocean scenario readily explains the discrepancies between Earth and Mars, without the need of an additional post-crystallization explanation. The basal silicate layer on Earth may have never been formed, while on Mars it had no problem forming. These results predict a dichotomy of mantles of rocky planets.

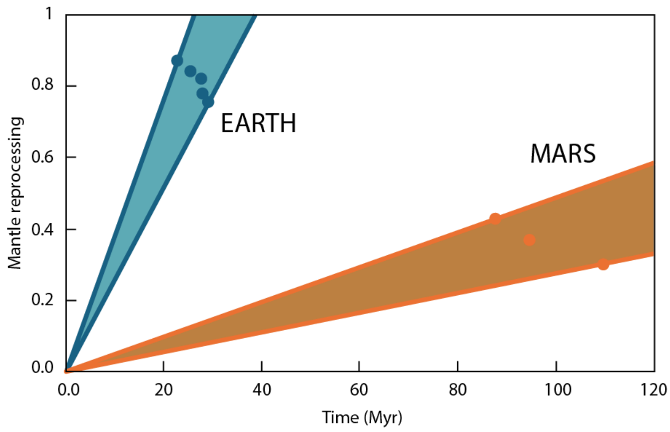

Figure 1: Mantle reprocessing efficiency of Earth vs. that of Mars. Reprocessing reflects the amount of mantle that has undergone melting. For Earth, due to stronger remelting, reprocessing happens at much shorter timescales

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The Role of Antigorite's Anisotropic Thermal Conductivity in Slab Thermal Evolution

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Keywords — deep Earth water cycle, double seismic zones, dehydration embrittlement, thermal runaway

Antigorite is a stratified mineral (phyllosilicate), in which the layers are stacked along the [001] crystallographic direction. This structure is relatively stiff along the foliation plane (001), but very compressible along the [001] direction. Moreover, under shear deformation, antigorite develops a crystallographic preferred orientation (CPO) with the [001] direction oriented perpendicularly to the shear plane. In subducting slabs, antigorite-bearing rocks are predicted to eventually align their [001] direction perpendicular to the slab dip.

The lattice thermal conductivity of a mineral Λ is closely related to its elastic stiffness. For this reason, we measured antigorite's in-plane $\Lambda^{[010]}$, and cross-plane $\Lambda^{[001]}$ thermal conductivities using the Time-Domain Thermo-Reflectance (TDTR) technique[1]. We found that $\Lambda^{[001]}$ is ~2-3 times lower than $\Lambda^{[010]}$, even at the high-P,T conditions of subducting slabs.

To investigate the large-scale effects of antigorite's anisotropic Λ we designed a finite difference heat diffusion model of a 2D vertically subducting slab, in which we prescribed the presence of a 3-km-thick layer of serpentinite. This insulating layer hinders the propagation of thermal energy toward the cold core of the slab. This effect would reduce the stability field of hydrous phases in the external part of the slab, thus promoting dehydration embrittlement. Furthermore, the presence of antigorite in pre-existing faults can trap the frictional heating inside shear zone, thus favouring the onset of thermal runaway. Potentially antigorite is a key mineral for the development of double seismic zones (DSZs).

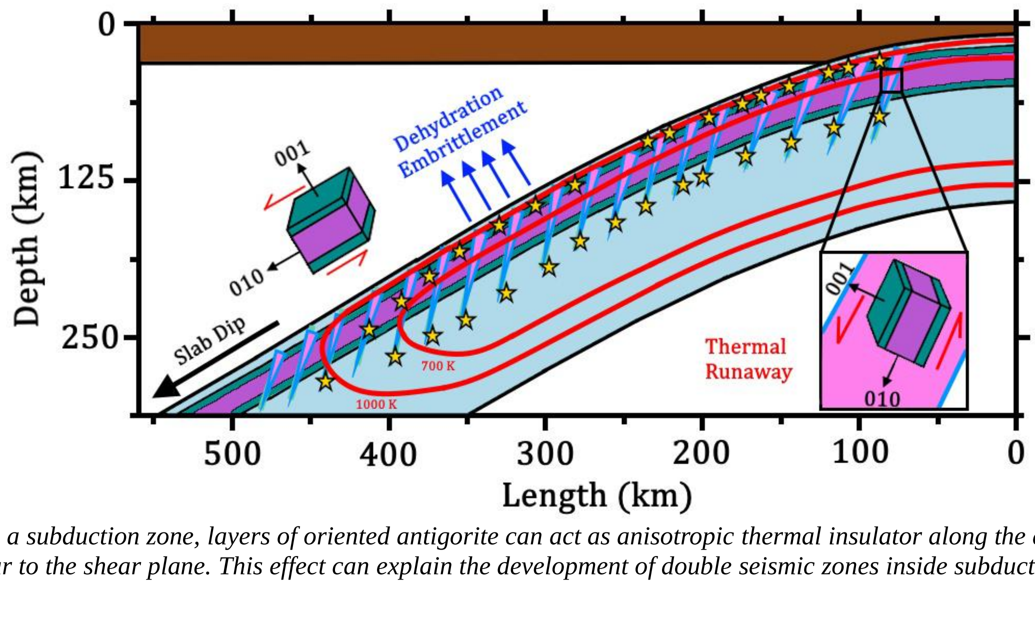

Figure 1: In a subduction zone, layers of oriented antigorite can act as anisotropic thermal insulator along the direction perpendicular to the shear plane. This effect can explain the development of double seismic zones inside subducting slabs.

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Eclogitization of the lower crust: A reactive thermodynamic–geodynamic approach

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Keywords — eclogitization, thermodynamics, lower crust

Many continental deformation zones involve crustal eclogitization, a large-scale transformation from granulite facies (dominated by orthopyroxene and plagioclase) to eclogite facies rocks (dominated by garnet and clinopyroxene). Eclogitization, in turn, drives densification of the lower crust and can lead to large-scale foundering and deformation. The rate of eclogitization reactions has been shown to be sensitive to aqueous fluid content through a dissolution–precipitation mechanism, which acts as a reaction catalyst. Geodynamic models that assume thermodynamic equilibrium may neglect important feedbacks among deformation, fluid infiltration, and densification.

Here we couple reactive thermodynamic models of eclogitization to geodynamic simulations. We accomplish this by conserving the mass, momentum, and energy of two mechanical phases: a single-component liquid phase representing pure water, and an 18-component solid phase representing the anhydrous mineralogy of the crust. Solid components are thermodynamically consistent [1] and flux into/out of the system according to a set of 26 reactions. Catalysis by aqueous fluids is incorporated into the reaction kinetics with a dimensionless Damköhler number.

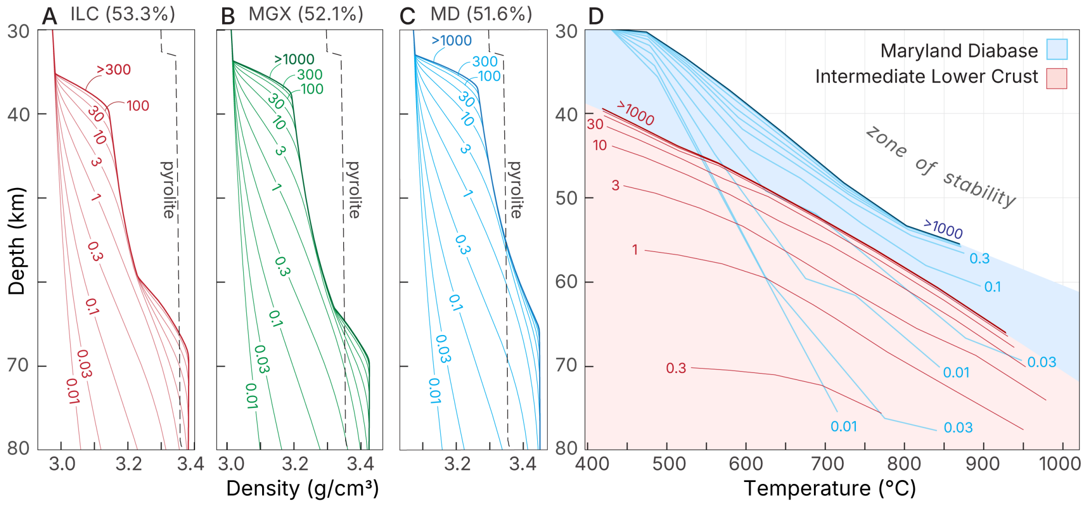

Figure 1: *Reactive density of 3 crustal compositions during thickening (A–C) and the depth at which they become unstable w.r.t. pyrolite as a function of temperature (D). Contours are dimensionless reaction rates (relative to thickening rate).*

We present a series of geodynamic-thermodyanmic models using the FEniCS [2] and ThermoCodegen [3] software packages. In a model of crustal thickening, we explore the effects of composition, reaction rate, and temperature on the eclogitization of orogenic crust. We show that gravitational instability and crustal foundering require relatively thick (>60 km), mafic crust (<54 % SiO_2) situated in a warm, fluid-fluxed environment, perhaps consistent with back-arc orogenic crust (Fig. 1). Foundering of such crust would result in gravitational instabilities >50 km in wavelength. In another model, we explore migration of liquid through an initially dry, metastable column of granulite. This system demonstrates the feedbacks among bulk density, compaction pressure, porosity, and eclogitization, which we apply to interpret partially eclogitized terranes (e.g., western Norway).

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Thermodynamically-based H_2O solubility maps and applications to Earth

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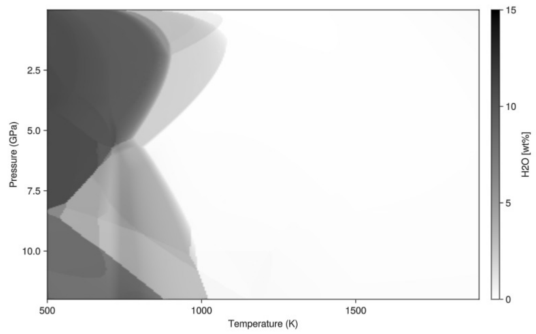
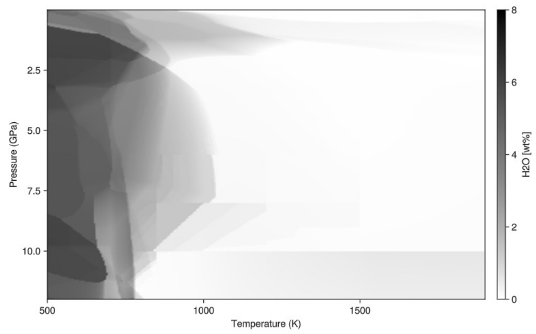
***Keywords* —** Mantle, Convection, Water, Melting, Hydration

The presence and distribution of water within the Earth's mantle has been a topic of considerable debate for nearly two decades. Limited observational accessibility and significant uncertainties regarding the water capacity of dominant mantle minerals have proven to be tedious obstacles during this time. More recently, the extensive mineral laboratory experiments and theoretical exploration of H_2O solubilities appear to facilitate the integration of these findings with advancing numerical models, with the potential to yield important insights into the water cycle throughout the Earth's mantle.

To this end, thermodynamically-derived (Perple_X) mineral proportions across different pressure-temperature conditions have been coupled with existing literature on solubility measurements in order to produce mantle H_2O storage capacity maps, which are a function of the system's overall composition and the oxide fractions of the individual phases present. These data sets are easily accessible through a customizable and parallelized Julia package. The implementation of the computed maps into a mantle convection multigrid Stokes solver (StagYY) yields results consistent with previous literature models. Our results suggest a moderately yet heterogeneously hydrated transition zone containing approximately 0.2% - 0.6% weight of water during the Earth's early history, along with a more homogeneous upper mantle. Surprisingly, hydration of the lower mantle seems to be very limited as subducting slabs are rarely able to sustain water-rich dense hydrous magnesium silicates (DHMS) during their descent, otherwise rapidly dehydrating before reaching the high solubility region associated with $CaCl_2$-type stishovite between 50 to 60 GPa. Effective melting temperatures are significantly reduced due to the hydration state of the upper mantle and transition zone, leading to extensive regional melting in areas where temperatures are particularly high.



(a) Mineral water capacity for upper mantle Harzburgite



(b) Mineral water capacity for upper mantle Basalt

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Predicting Seismic Discontinuity Topography from Thermochemical Mantle Circulation Models

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Keywords — Seismology, Mantle Convection

Phase transitions in the mid-mantle result in abrupt changes in bulk properties, including density and seismic velocities. The most significant seismic discontinuities in the mantle define the Mantle Transition Zone (MTZ) at around 410 km and 660 km depth, respectively usually associated with the transitions $Ol \rightarrow Wd$ and $Rw \rightarrow Brm + Pc$. However, these are not the only mid-mantle reactions that produce significant changes in bulk properties, e.g. the Rw-out reaction proceeds via akimotoite in cooler regions, and garnet decomposes as well at the base of the MTZ. Whilst the depths of phase transitions are dominantly controlled by temperature, composition also plays an important role, particularly in the heterogenous regions around downwelling slabs, where basalt and depleted harzburgite descend into the lower mantle adjacent to one-another.

The primary control of temperature on the topography of the 410 and 660 “discontinuities” has meant that there is a long tradition of interpreting the topographies on these discontinuities in terms of temperature [e.g. 1]. Recent studies have inverted for compositional as well as thermal variations using the amplitude of seismic reflections [2]. This highlights the potential utility of using discontinuity topography to constrain thermo-chemical geodynamic models. Papanagnou *et al* [3] predicts discontinuity topography for a thermal mantle circulation model and shows that different assumptions about global mantle composition can have a dramatic effect on predicted topography but they did not consider the role of lateral variations in composition in their predicted topography.

Here we illustrate a method to predict discontinuity topography that uses the distribution of chemical heterogeneity tracked in thermochemical mantle circulation models. On each grid-node we use local proportions of different bulk compositions to estimate the effect of compositional heterogeneity on seismic velocities using a mechanical mixing calculation on each grid-node. We apply our method to a range of geodynamic models, and test sensitivity to the assumptions in our end-member compositions. Finally, we compare our predictions to published seismic observations of 410 and 660 topography.

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The role of along-strike variations in interface rheology on subduction dynamics: constraints from 3D dynamic models

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Keywords — subduction, interface, rheology

Subduction zones can exhibit significant along-strike variability in various properties that can, in turn, induce along-strike variation in subduction dynamics. One such property is the strength of the plate interface; this can exhibit along-strike variation if, for example, different crustal lithologies are subducted. Often, subduction zones are studied using 2D models, which inherently assume uniformity along-strike, or 3D models that do not account for these along-strike rheological changes. While these models can test large system-wide variations in the interface rheology, how along-strike variations interact in a fully dynamic three-dimensional setting is poorly understood.

Here, we use ASPECT to investigate how along-strike variations affect an evolving subduction zone in 3D. The buoyancy driven models use thermally-defined subducting and overriding plates with a constant-viscosity subduction interface. Models are set up with two distinct interface viscosities, leading to a portion of the subduction zone with a strong interface and weak interface. We vary the interface viscosity from 10^{19} Pas, representing a sediment-rich interface, up to 10^{21} Pas, representing a strong mafic interface. We explore how these parameters affect the convergence rate, slab and overriding plate morphologies, and the stress distribution within the overriding plate.

Our results suggest that along-strike variations to interface viscosity can cause the convergence rate to depart from values observed in models with uniform viscosity interfaces (i.e., just one material). When coupled with a weak interface, a strong interface will have elevated convergence velocities, which increases the average interface stress and compressional forces in the overriding plate. Similarly, velocities at the weak interface will be reduced. This along-strike change in convergence velocity can also produce overriding plate rotation. The combination of this rotation and increased compression at the strong interface causes a difference in trench position along-strike, wherein the slab at a weak interface will rollback faster leading to the trench being in a retreated position relative to the trench along the strong interface (see Fig. 1).

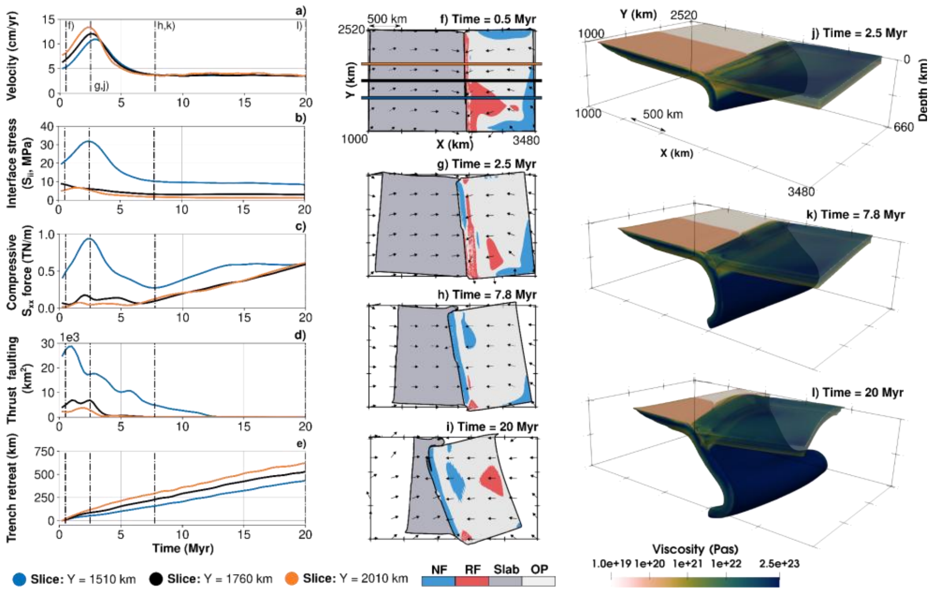

Figure 1: Comparison of model-outputs along-strike for a model with variations in interface viscosity.

Mid-ocean ridge unfaulting revealed by magmatic intrusions

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Mid-ocean ridges are quintessential sites of tectonic extension, where divergence between lithospheric plates shapes abyssal hills that cover ~2/3 of Earth's surface. Here we show that tectonic extension at the ridge axis can be partially undone by tectonic shortening across the ridge flanks. This process is evidenced by recent sequences of reverse faulting earthquakes ~15 km off axis at the Mid-Atlantic and Carlsberg Ridge. Using mechanical models, we show that shallow compression of the ridge flanks up to the brittle yield point is a natural consequence of lithosphere unbending away from the axial relief. Intrusion of magma-filled fractures, which manifests as migrating swarms of extensional seismicity along the ridge axis, can provide the small increment of compressive stress that triggers reverse slip earthquakes. Through bathymetric analyses, we further find that the reverse reactivation of mid-ocean ridge normal faults is a ubiquitous process that can reduce the amplitude of abyssal hills by as much as ~50%, shortly after they form at the ridge axis. This "unfaulting" mechanism exerts a first-order influence on the fabric of the global ocean floor, and provides a physical explanation for rare reverse-faulting earthquakes in an extensional environment.

Ocean basin scale geochemical heterogeneity in geodynamic models

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Keywords — recycling, whole-mantle, mid-ocean ridge, uranium

Isotopic analysis of mid-ocean ridge basalts (MORBs) reveals broad scale geochemical heterogeneity between, and sometimes within, ocean basins [1, 2], which may have been present for 100's of millions of years [3]. This indicates the presence of a preservation or replenishment mechanism which maintains the regional isotopic signatures, however the nature of the exact process is unclear. It has previously been shown that inter-basin mantle mixing has been limited over at least the last 250 Myr [4] due to a curtaining effect by subducting slabs, which likely contributes to the persistence of these long wavelength chemical anomalies. The chemical anomalies themselves are thought to represent enrichment from one or more of a variety of sources, including pollution of the upper mantle by subducted oceanic crust [5] and periodic addition of deeply subducted crustal material into the upper mantle via entrainment by deep-rooted plumes [6].

In this work we investigate the combined effects of deep recycling of oceanic crust and pollution of the upper mantle by U due to slab dehydration processes on the U-Th-Pb isotope system. The U system is particularly useful to study as changes to the U elemental and isotopic cycling over time are linked to changes in surface oxygen levels [5]. Three dimensional, spherical mantle circulation simulations driven by reconstructions of Earth's past plate motions allow us to assess the geographic distribution of geochemical heterogeneity in relation to Earth's surface features. We analyse the modelled isotopic composition of ridges in the Atlantic, Indian and Pacific Ocean basins and draw comparisons against data.

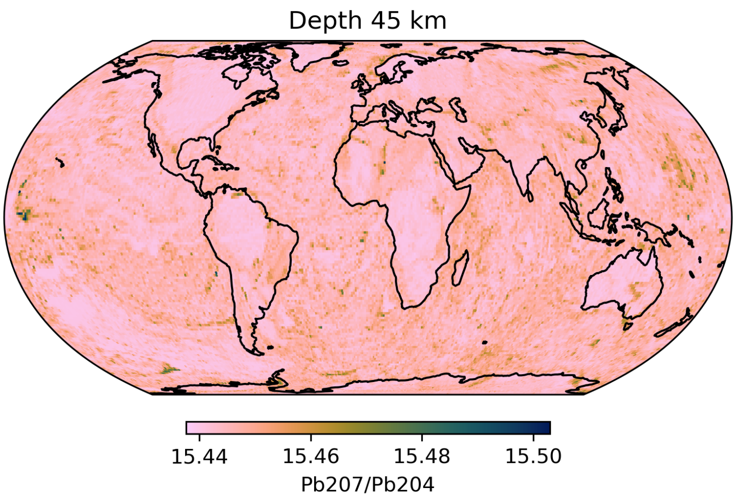

Figure 1: *Depth section coloured by* $^{207}Pb/^{204}Pb$

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Dynamic Component of the Asthenosphere: Lateral Viscosity Variations Due to Dislocation Creep at the Base of Oceanic Plates

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Keywords — asthenosphere, mantle convection, dislocation creep, LVV

The asthenosphere is commonly defined as an upper mantle zone with low velocities and high attenuation of seismic waves, and high electrical conductivity. These observations are usually explained by the presence of partial melt, or by a sharp contrast in the water content of the upper mantle. Low viscosity asthenosphere is an essential ingredient of functioning plate tectonics. We argue that a substantial component of asthenospheric weakening is dynamic, caused by dislocation creep at the base of tectonic plates. Numerical simulations of subduction show that dynamic weakening scales with the surface velocity both below the subducting and the overriding plate, and that the viscosity decrease reaches up to two orders of magnitude. The resulting scaling law is used in an a priori estimate of lateral viscosity variations (LVV) below Earth's oceans. The obtained LVV help explain some of the long-standing as well as recent problems in mantle viscosity inversions [1].

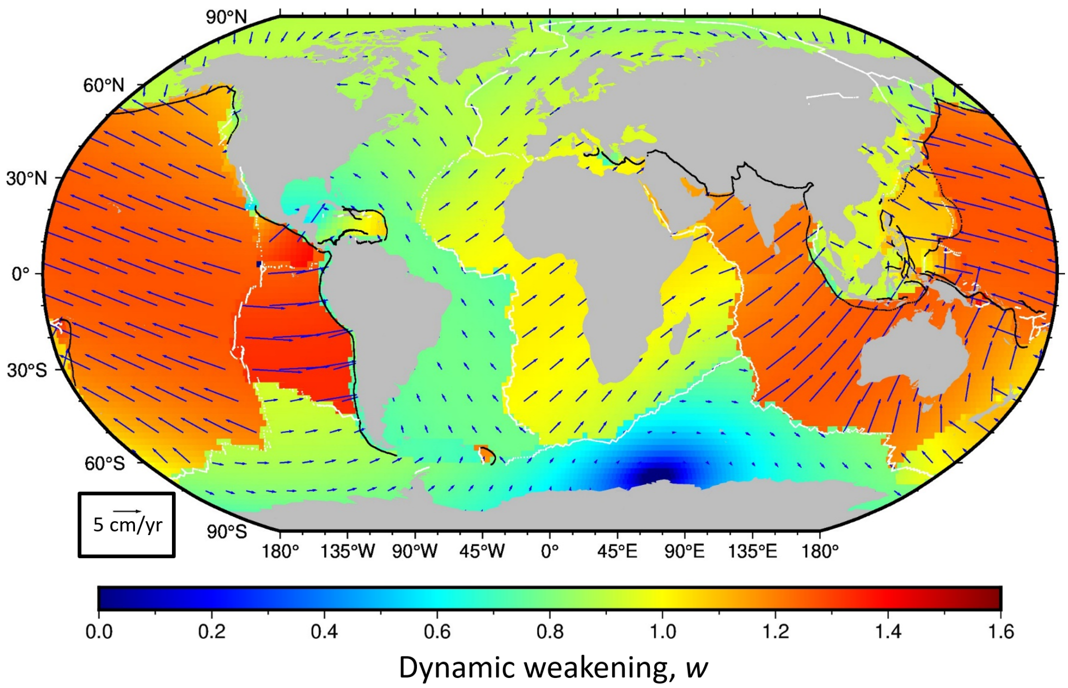

Figure 1: *Dynamic weakening below Earth's oceanic plates. Logarithm of the diffusion to dislocation creep viscosity ratio, w, showed in color, represents a first-order estimate of LVV in the asthenosphere.*

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Mantle structures beneath an evolving supercontinent: the interaction of slabs and plumes in response to variable lithosphere structure.

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***Keywords* —** Geodynamics, Lithosphere structure, Slab-plume interactions

The relationship between the lithosphere and the mantle during the supercontinent cycle is complex and poorly constrained. The processes which drive dispersal are often simplified to two end members: slab pull and plume push. We aim to explore the interaction between slab and plume processes throughout the supercontinent cycle and consider how subduction processes during supercontinent assembly may affect the way in which a supercontinent breaks apart. We consider lithosphere structure as one of many potential processes which may affect the evolution of upwellings and downwellings and therefore systematically vary the properties of oceanic, continental, and cratonic lithosphere, respectively within our 3D spherical simulations.

The viscosity and thickness of the lithosphere alters the trajectory of downwelling material beneath the supercontinent as it assembles. Where slabs and plumes interact, the cold slabs can reduce the magnitude of an evolving plume, which may limit the contribution of plume push forces on supercontinent breakup.

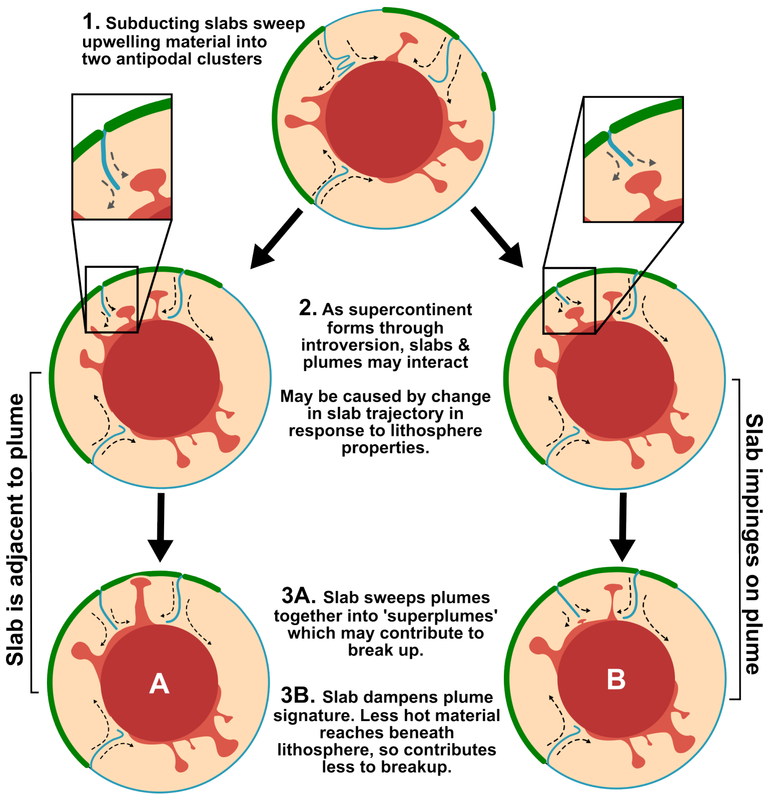

Figure 1: *Interactions of slabs and plumes during supercontinent cycle. Green lines represent continental lithosphere, blue lines represent oceanic lithosphere (and therefore also slabs in the mantle), black arrows indicate the direction of flow around a slab*

Intensified plate tectonics by self-reorganisation of global subduction network post-Snowball Earth

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Keywords — Global plate tectonics, subductions, plumes

The Earth has undergone periods of intensified plate tectonic activity closely linked to major climatic events such as the Snowball Earth episodes. It is proposed that climatic changes, together with enhanced surface processes, may have played a role in lubricating plate tectonic boundaries [1]. Modern plate tectonics is well depicted by the Wilson cycle, which describes the dynamics of the supercontinental cycle through the prolonged interaction of oceanic and continental plates over hundreds of millions of years. This cycle includes phases of supercontinent formation marked by major orogenic collisions, followed by phases of supercontinent breakup and dispersal, as evidenced by the geological record. While the dynamics of the Wilson cycle are closely linked to mantle and subduction processes, its link to climate remains to be fully established. Our hypothesis is that extreme climatic events triggered lubrication processes that may have accelerated the self-reorganization of global subduction zones, intensifying the primary driving forces from subduction dynamics and eventually leading to supercontinent breakup and plate tectonic reorganization. To investigate this, we have developed a series of 3D geodynamic models of the Earth using the ASPECT code. These models simulate different pre- and post-Snowball Earth scenarios by specifying the distribution of the supercontinent Rodinia at 1 Ga (Fig. 1) and Pangea at 250 million years ago and running the models self-consistently. Variations in the models include changes in the strength of the supercontinents and the surrounding oceanic domain as a proxy to simulate lubricated or non-lubricated systems. We conclude that extreme climatic events were essential to maintain and intensify plate tectonics over the past billion years.

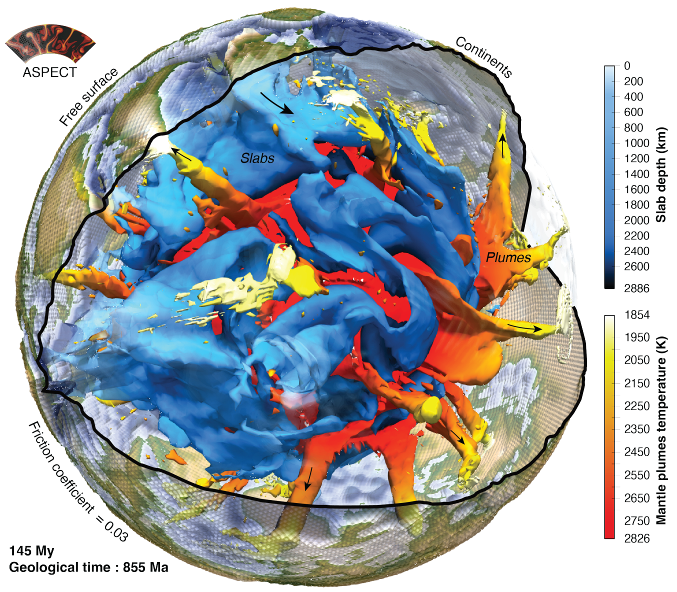

Figure 1: ***Reference 3D model computed with ASPECT.*** *The model shows topography generated from self-consistent geodynamical processes with 50 km surface resolution. Cold subductions(blue) are sinking into the mantle whereas warm mantle plumes (red) are rising towards the surface.*

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~~Smooth tensile plasticity implementation and~~ application examples

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***Keywords* —** Tensile Plasticity, Finite Element Method, Strain Localization

Modeling tensile failure in the elsto-visco-plastic rocks is a challenging task form the viewpoint of algorithmic formulation, discretization, and numerical stability. Many technical issues must be addressed before a robust and reproducible result can be achieved. These include designing a yield surface and flow potential that is free of apex points and discontinuities, regularization of the mesh-dependent behavior, deriving Jacobian matrices, and merging all of these components together in a context of a stable spatial discretization. Additional challenges arise in case that coupling with the fluid flow and/or heat diffusion is required.

Here we present a relatively simple visco-plastic model of Perzina type that incorporates a linear Drucker-Prager shear failure envelop, and a circular tensile cap. Compared to the previous similar implementations (e.g. [1]), our version of the cap surface enforces dimensional consistency and continuity of both segments throughout the entire stress space (see Fig. 1), and not only at the yield surface. This property results in a straightforward and convergent return mapping scheme. The expression for the two-segment yield surface can be written as follows:

$$F = \begin{cases} \tau_{II} - k\,p - c \\ a\left(\hat{R}_y - R_y\right) \end{cases}, \quad \hat{R}_y = \sqrt{\tau_{II}^2 + \left(p - p_y\right)^2}, \quad a = \sqrt{1+k^2}, \tag{1}$$

where τ_{II} is the effective deviatoric stress, p is the solid pressure, k, c, R_y, and p_y are the model parameters.

In this work we also cover coupling of the mechanical problem with the fluid flow in porous matrix, and discuss the implementation details that include stress update, linearization, selection of the primary variables for the local stress iterations, and a robust initial guess. Finally, we present and discuss a set of examples for a strain localization originating from an underground reservoir subjected to an excessive fluid pressure. The 2D domain is discretized using a stable sub-parametric Crouzeix–Raviart finite element shown in Fig. 1.

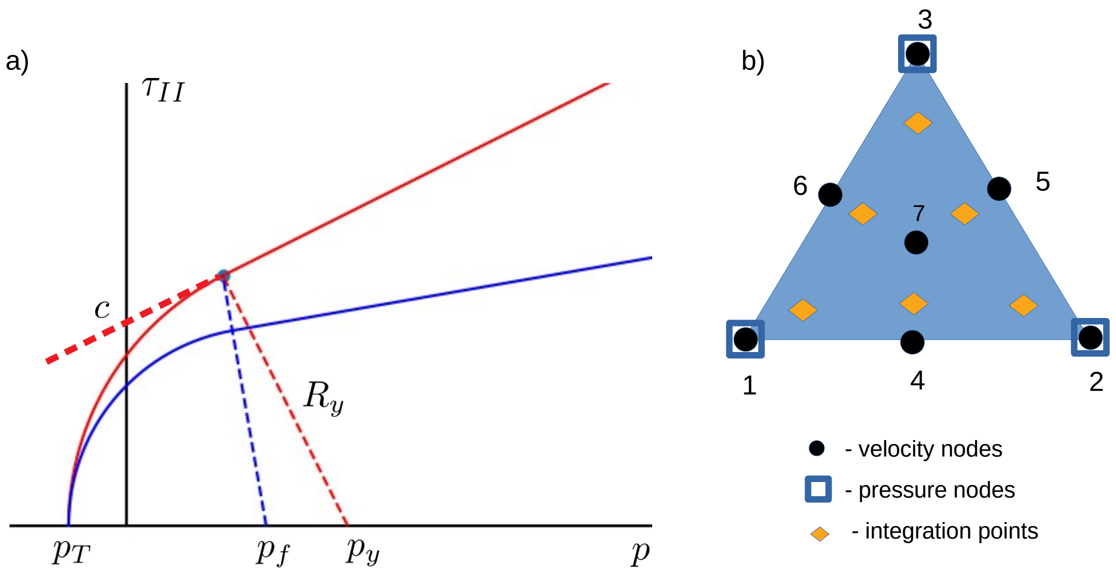

Figure 1: *Details of the plasticity model and spatial discretization; a) Smooth and continuous yield surface and flow potential in stress space; b) LBB-stable 7-node Crouzeix–Raviart finite element.*

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High-Order Interpolation with Limiting for Hybrid Finite Element Particle-in-Cell Methods for Computational Geodynamics

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Keywords — Numerical Methods, Rifting, Rheological & Mechanical Properties

Combining finite element methods with particle-in-cell methods is an important technique in computational geodynamics. It has been widely used to model mantle convection, lithosphere dynamics and other geodynamic processes. In these applications particles are used to advect properties of the medium such as the location of a given material, density, components of stress, chemical composition, etc. Particle methods reduce the (finite element) field-based advection equation for each material property to a system of ordinary differential equations for the trajectory of each of the particles carrying that property in the underlying flow field. This results in a problem that is simpler to solve than computing the numerical solution of the field-based advection equation for each property, since in the latter case it is necessary to employ specialized stabilization techniques in order to avoid oscillations.

On the other hand, replacing the field-based advection equations by quantities that are only defined at the locations of the particles introduces numerical errors associated with the interpolation of the material properties from the particles onto the underlying finite element grid. In some of our previous work with linear least squares particle interpolation algorithms [1] we demonstrated that in order to retain the optimal accuracy of the finite element formulation, in addition to needing a sufficiently accurate particle interpolation algorithm it is was also necessary to increase the number of particles per cell as the mesh resolution increases (i.e., as the grid cell size h decreases) in order to avoid a reduction in the convergence rate.

However this observation was for a specific type of linear least squares interpolation algorithm (e.g., see [1, 2]). This left open the question "Is there a high-order accurate least squares algorithm that attains the optimal order of accuracy for a *fixed* number of particles per cell as $h \to 0$?" In this work we present a quadratic least squares interpolation algorithm with this property.

We have also developed an algorithm for limiting the values of the interpolated properties in conjunction with these linear and quadratic least squares interpolation algorithms in order to eliminate overshoot and undershoot. The design of this algorithm is based on an idea that underlies certain flux limiters developed for finite difference methods for hyperbolic conservation laws. (Our limiters *are not* flux limiters; rather they explicitly limit the values of the material property that is being interpolated from the particles onto the grid.) The idea is to make the interpolation function

$$\phi(\boldsymbol{x}) = \alpha\,\phi^{l}(\boldsymbol{x}) + (1-\alpha)\,\phi^{h}(\boldsymbol{x}) \quad \text{where} \quad 0 \le \alpha \le 1$$

a convex combination of a low-order interpolant ϕ^l *that is intrinsically limited* (i.e., ϕ^l *cannot* overshoot / undershoot but is only low-order accurate) and a high-order accurate interpolant ϕ^h that can overshoot / undershoot and choose α so that $\phi(\boldsymbol{x})$ respects the *local* minimum and maximum of the particle property that is being interpolated.

This methodology has been implemented in the open source code ASPECT for geodynamic modeling [3, 4] where it is currently being tested and benchmarked in computational models of continental rifting.

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Volatile-assisted small-scale convection at the lithosphere–asthenosphere boundary

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Keywords — magma dynamics, mantle melting, convective flow

Multiple geophysical observations suggest a weaker and shallower lithosphere–asthenosphere boundary (LAB), and with short-wavelength variations that are inconsistent with thermal models (e.g., [1]). Sublithospheric small-scale convection is generally the preferred explanation of the LAB undulations [2][3]. However, seismic and resistivity anomalies cannot be explained using solely solid-state thermal variations. Small melt fractions (<5%) enriched in volatiles (H_2O, CO_2) may be a more plausible explanation [1][4]. Other studies interpret a low-seismic-velocity zone extending to 150–200 km depth as containing partial melt [5][6]. Despite growing evidence that melt may be more widely distributed in the asthenosphere, the persistence and dynamical consequences of small melt fractions remain unclear. Here, we use two-phase models of partially molten rock to investigate how volatile-assisted melt generation and migration may modify the dynamics of sub-lithospheric small-scale convection [7][8]. Volatiles may impact the energetics and dynamics in multiple ways, by lowering the melting temperature, promoting deep melting and inhibiting shallow crystallisation. Our results show that volatile-driven melting and fractionation promote development of small-scale convection. In models with CO_2, small-degree melting and small-scale convection persist throughout the asthenosphere for a long time. A quasi-steady state of convection can be reached in which a melt-free mid-asthenosphere region is sandwiched in between low-melt fraction regions.

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A continuum model of melt extraction across the ductile–brittle lithosphere

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Keywords — magma dynamics, lithosphere, complex rheology

Magma transport changes from porous flow in the hot, ductile mantle to fluid-filled fractures , known as dikes and sills, in the cold, brittle crust. Accurate representation of these processes in geodynamics models is crucial for understanding lithospheric deformation, as magma transports heat and impacts lithospheric stresses. We recently extended the two-phase flow theory to incorporate a viscoelastic–viscoplastic rheology of rocks with free surface [1]. In this contribution, we present further validation of the diking model in Li et al. [1] through comparison with the theory of Linear Elastic Fracture Mechanics [2]. We also show an application of melt transport across the brittle–ductile transition to explain the reduced magmatism in the Turkana Depression.

The Turkana Depression, located in between the Ethiopian and East African plateaus, is characterized by anomalous rift architecture. It is missing the narrow, magma-rich rift morphology observed in the Main Ethiopian Rift (MER) traversing the Ethiopian Plateau; instead, diffuse faulting and magmatism are widespread over several hundred kilometers. Geophysical studies indicate that strain accommodation is dominated by magmatic intrusion along MER, while in Turkana mostly by tectonic extension [3]. Considering that Turkana has thin crust compared to the neighbouring plateaus [4], and the mantle below has been inferred to be hot and partially molten [5], it remains unclear how magmatic extension developed in this region. Here, we hypothesise that variations in lithospheric strength across the Turkana Depression and the Ethiopian Plateau have influenced magma transport across the lithosphere and, hence, rift development [6]. We use models of melt transport to show that both the rheology of lithosphere and extension rate control the efficiency of magma extraction. Our results suggest that lithosphere weakening, either through multiple rifting episodes and/or magmatic intrusion, slows magma transport in the lithosphere.

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What controls segmentation of Oceanic Spreading Ridges?

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Keywords —Ridge Segmentation, Numerical Modeling, GPlates

Oceanic spreading ridges are segmented by transform faults of variable length. The average spacing of major transform faults is typically several hundred kilometers, but there are some small, closer-spaced ridge offsets of less than 30 km. Previous studies indicate that the ridge segmentation is driven by uneven magma supply [1] or oblique mantle flow [2]. In this study, we use 3D numerical model I3ELVIS [3] and plate reconstruction software GPlates (www.gplates.org) to investigate the key factor of what controls the spacing of transform faults. We reproduce the evolution of transform faults by oblique spreading, from small ridge offset to mature transform fault. We assess the effect of spreading obliquity, spreading rate, and potential temperature and calculate their correlation with transform fault length. We find that the length of transform faults can change with asymmetric spreading. The spreading obliquity exerts main control, while spreading rate and potential temperature have less effect on the transform fault spacing. By using GPlates, we find positive correlation between spreading obliquity and transform fault length, and this correlation is strongest in the Atlantic, where inherited obliquities derive from the Mesozoic rifting phase.

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Thermal effects of microcontinents subduction: insight from 2D numerical models

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Keywords — Microcontinent, Subduction, Numerical models

The oceanic lithosphere is characterised by the presence of many lithological heterogeneities, with dimensions vary from tens to hundreds of kilometres and width of 20-40 km [1], and can be subdivided into continental ribbons and microcontinents [2, 3]. In particular, microcontinents are completely detached from continental margins and isolated by oceanic lithosphere [3]. While previous works highlighted the mechanical effect of different rheologies of subducted microcontinents [4, 5], a systematic analysis of the thermal effects inside subduction systems in the case of microcontinent collision/subduction is still lacking. This analysis will be particularly useful for future comparison with the Pressure-Temperature (P-T) evolution of the remnants of subducted and exhumed crustal rocks.

Here, we investigated the effect of the introduction of microcontinents characterised by different sizes and initial distances from the trench on the topography and the thermal evolution of the subduction systems. We observed that when microcontinents are introduced into the system, four different styles of subduction can develop. The style of subduction has primary effects on both timing and location of peaks in the maximum topography and on the wedge dynamics, particularly on the amount of subducted material that recycles in the mantle wedge. This is significant because the upwelling to shallow depths increases the temperature in the inner and central portions of the mantle wedge (Fig. 1), directly affecting the metamorphic conditions recorded by subducted and exhumed rocks during their evolution.

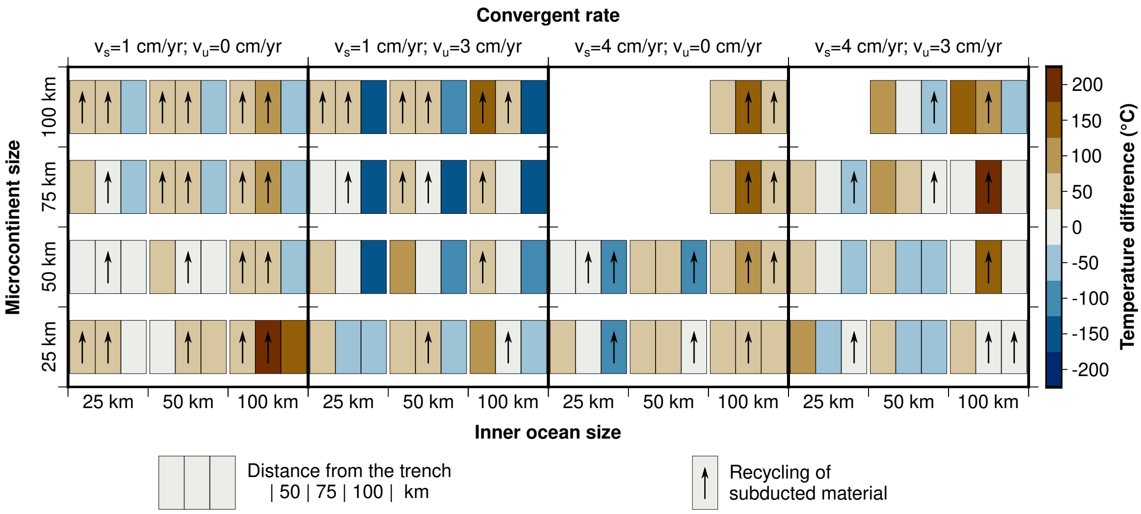

Figure 1: *Temperature differences between each model and its equivalent without microcontinent, calculated along geotherms located 50, 75 and 100 km far from the trench. Black arrows indicate portions of the wedge characterised by exhumation of subducted material.*

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The sphericity paradox and the role of hoop stresses in free subduction on a sphere

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Keywords — Subduction, thin-shell theory, Mariana subduction zone

Subducting plates are doubly-curved spherical shells in their undeformed state, which influences how they respond to loads. Here we study a viscous fluid model for gravity-driven subduction of a shell comprising a spherical plate and an attached slab. The shell is 100-1000 times more viscous than the upper mantle. We use the boundary-element method to solve for the flow. Solutions of a reference axisymmetric model show that while geometrical sphericity is (obviously) greater for larger plates, the effect of sphericity on plate flexure is greater for smaller ones (the ‘sphericity paradox’). Both axisymmetric and three-dimensional models show that the deviatoric membrane stress in the slab is dominated by the longitudinal normal stress (‘hoop stress’), which is about twice as large as the downdip stress and of opposite sign. The models show that extensional hoop stress does not occur in slabs that are convex landward, while the other three possible hoop stress/slab geometry combinations (extensional/concave, compressional/convex, compressional/concave) do occur. We test these two model predictions against slab shape and earthquake focal mechanism data from the Mariana subduction zone. The magnitude of the hoop stress exceeds that of the downdip stress for about half the earthquakes surveyed, providing only partial support for our first conclusion. However, hardly any of these earthquakes are associated with extensional hoop stress in convex portions of the slab, validating our second conclusion.

Compressible convection in large rocky planets

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Keywords — compressibility, convection, Super-Earths

The radial density of planets increases with depth due to compressibility, leading to impacts on their convective dynamics. To account for these effects, including the presence of a quasi-adiabatic temperature profile and entropy sources due to dissipation, the compressibility is expressed through a dissipation number, $\mathcal{D}$, proportional to the planet's radius and gravity. In Earth's mantle, compressibility effects are moderate, but in large rocky or liquid exoplanets (Super-Earths), the dissipation number can become very large as their radius and gravity are large. This paper explores the properties of compressible convection when the dissipation number is significant[1, 2]. We start by selecting a simple Murnaghan equation of state that embodies the fundamental properties of condensed matter at planetary conditions. Next, we analyze the characteristics of adiabatic profiles and demonstrate that the ratio between the bottom and top adiabatic temperatures is relatively small and probably less than 2. We examine the marginal stability of compressible mantles and reveal that they can undergo convection with either positive or negative superadiabatic Rayleigh numbers. Lastly, we show that, in the infinite Prandtl number case, solving the fully compressible (FC) equations of convection with a realistic equation of state (EoS) is however not much more difficult or numerically challenging than solving the approximate cases. We delve into simulations of convection in 2D Cartesian geometry performed using the exact equations of mechanics, neglecting inertia (infinite Prandtl number case), and examine their consequences for Super-Earths dynamics. We will discuss the cases where the heating is partially from below and from within. A large heat flow can be carried out along a steep adiabatic gradient in the shallow layers. This tends to increase the thickness of the lithosphere. In the extreme cases where the temperature difference between the bottom and top of the mantle is comparable or even smaller than the adiabatic temperature jump, the convection can be confined in the deepest layers, with a thick stagnant conductive lithosphere.

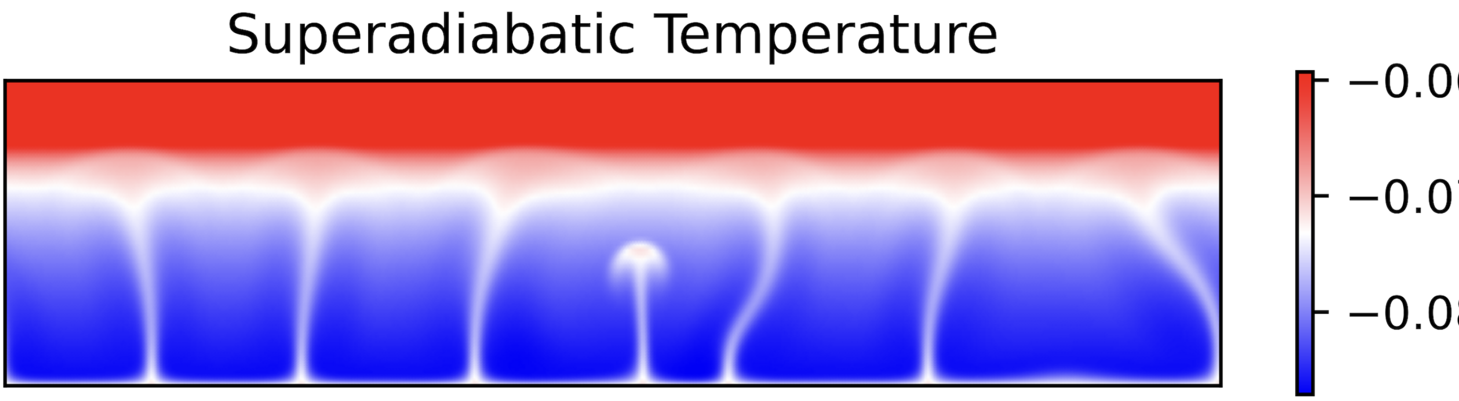

Figure 1:
When $\mathcal{D}$ is large, the conduction along the adiabat can become comparable to the heat transported by convection. This favors the presence of a thick conductive lithosphere and allows convection in the deep layers only, where the adiabatic gradient is small.

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The impact of strain rate weakening on the localization and stabilization of transform fault zones

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Keywords — rifting, transform fault zones, strain rate weakening

Tectonic plate boundaries represent a zone of localized reduced lithospheric strength. Brittle and ductile weakening mechanisms play an important role in strain localization and are therefore important for the formation of various plate boundary structures, including transform fault zones. Although oceanic transform fault zones are abundant and can extend for tens to hundreds of kilometers, their localization, subsequent continental rifting history and preservation are still unclear. Furthermore, the role of different weakening mechanisms leading to long-lived, large-offset oceanic transform fault zones needs to be further investigated.

Here we aim to better understand the role of strain rate weakening mechanism in particular to the development of continental rifts and oceanic transform fault zones. To this aim, we conducted a series of high-resolution 3D petrological-thermomechanical models with the code i3ELVIS (see Fig. 1). These models include elasto-visco-plastic rheology with strain rate induced weakening, partial mantle melting, oceanic crustal growth, thermal contraction and mantle grain size evolution. A particular focus is on the evolution of locally high plastic strain rate values during the evolution and stabilization of transform fault zones, during rifting and subsequent oceanic spreading. Our study preliminary suggest that strong slip rate-dependent weakening of oceanic fractures help stabilizing of oceanic transform faults within their characteristic ridge-transform spreading pattern.

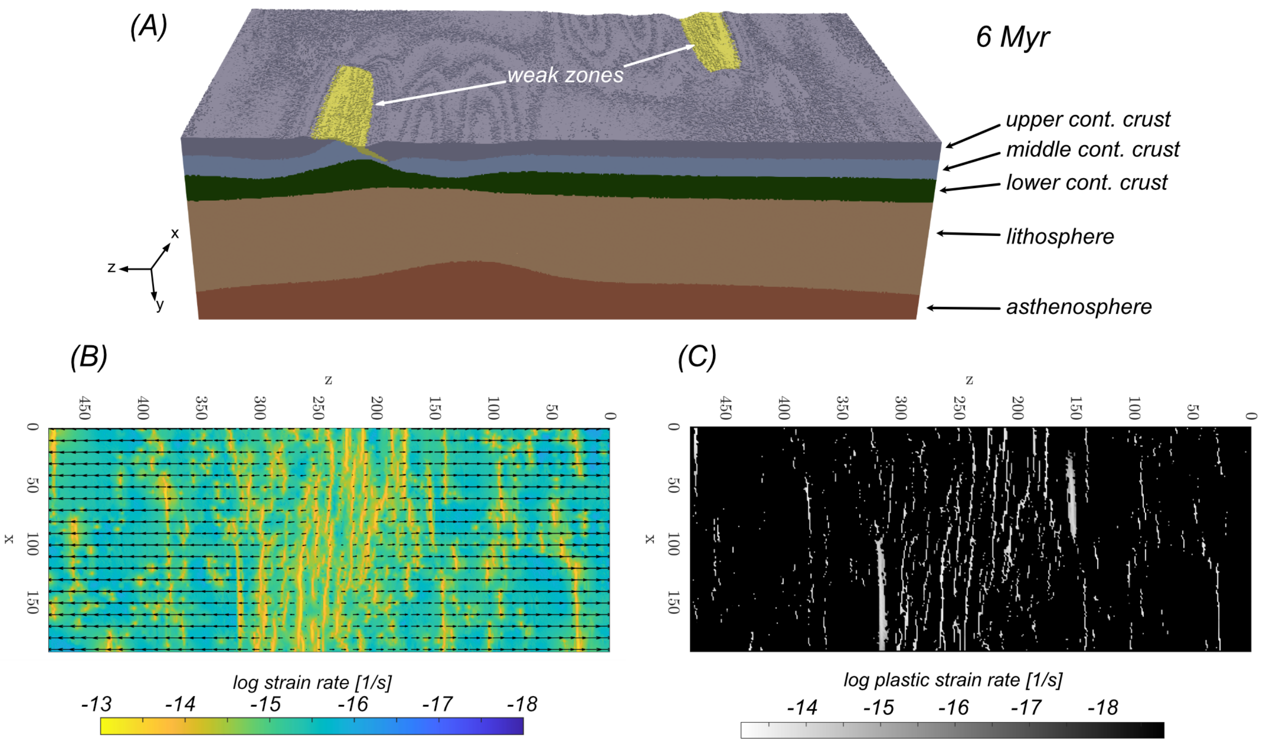

Figure 1: *Preliminary results at 6 Myr from a model with strain rate weakening of 10^{-15} 1/s. A) Snapshot of the composition where the crust starts to thin due to the imposed divergence rate. B) and C) Snapshots of the total strain rate and only the plastic part of the strain rate (horizontal section at 18 km depth, i.e. middle crust).*

~~Shear Wave Radial Anisotropy from Slab-Induced~~ Thermochemical Plumes in the lower mantle

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Keywords — Mantle plumes, Seismic anisotropy

Seismic anisotropy, where wave propagation varies with direction, is likely to occur in the lowermost few hundred kilometers of the mantle, particularly near the boundaries of Large Low-Shear-Velocity Provinces (LLSVPs). This anisotropy may indicate significant deformation, potentially resulting from mantle flow interacting with the edges of these provinces or the formation of mantle plumes. This study explores plume generation induced by subducted slabs from thermochemical piles and the flow behavior of the lower mantle using compressible 3-D global mantle convection models in the geodynamic modeling software ASPECT, coupled with mantle fabric simulations code ECOMAN. In our simulations, we assume the LLSVPs are chemically distinct. We therefore initialize our models with a 100-km-thick chemically distinct layer at the base of the mantle, which is then shaped into themo-chemical piles during the model evolution. Our models include a plate reconstruction spanning the past 250 million years. We incorporate the Clapeyron slope of the phase transition from Bridgmanite to post-Perovskite, based on the mineralogical study by [1], in our mantle fabric calculations. We tested several geodynamic models with varying density and viscosity ranges for the LLSVP. Our modeling of the lattice preferred orientation of Bridgmanite and post-Perovskite in the lower mantle reveals that the lower mantle is generally isotropic, except in regions of plume generation and LLSVP pile boundaries where vertically polarized shear waves (Vsv) are faster. Subducted slabs generate flow in the lowermost mantle, characterized by fast horizontally polarized shear waves (Vsh) that transition to fast Vsv at the margins of the LLSVPs due to the rheological contrast between the highly viscous LLSVP and the less viscous surrounding mantle. Our results show that the slip system [001](100) of Bridgmanite and [100](001) of post-Perovskite can produce fast Vsv in plume generation zones where post-Perovskite transforms to Bridgmanite, and fast Vsh at the base of the subducted slab where post-Perovskite is preserved in the D" layer. Our findings align with previous shear wave radial anisotropy tomography models at 2700 km depth, where faster vertically polarized shear waves are observed within the LLSVPs [2]. However, the simulated anisotropy mostly concentrates at the edges of the LLSVPs which also corroborates previous shear wave splitting study that shows strong anisotropy has been developed at the margins of African LLSVP [3]. The radial anisotropy is consistent with a viscosity of LLSVP that is 100 times higher than that of the surrounding mantle. Higher viscosities related to compositional heterogeneities within the LLSVP would result in more robust margins, causing the mantle flow to deflect vertically at its edges.

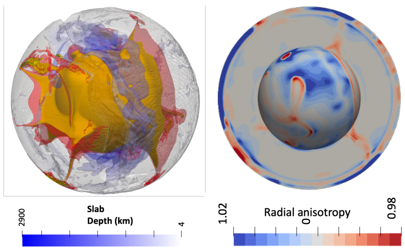

Figure 1: *The left figure illustrates slab-induced plume generation on both sides of the chemical pile, with slabs depicted by depth, mantle plumes in red, and chemical piles (LLSVPs) in yellow. The right figure presents the simulated radial anisotropy at a depth of 2700 km, calculated using the flow field from the geodynamic model.*

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Melt generation from thermochemical plumes

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***Keywords* —** eclogite, melt production, mantle plume, Julia

Large Igneous Province (LIP) volcanism has been linked to climatic perturbations and mass extinctions, with effects that last long after the most productive phase of extrusive volcanism has ended. Although the paradigm of LIP formation associated with voluminous decompression melting within an ascending mantle plume head followed by long-lived hotspot volcanism associated with the plume tail is well established, the limited evidence for pre-magmatic uplift and modest plume excess temperatures inferred from petrology preclude a purely thermal origin for plumes. Instead, plumes likely sample a mantle reservoir enriched in a compositionally dense component – eclogite.

Here we present models for plume ascent and melting, with an emphasis on quantifying the melt production as a two-component eclogite/pyrolite plume impinges upon the lithosphere. Melt production is computed using the parameterization of Yasuda et al. [1, 2]. We quantify the melt production rate, the total melt production, and the carbon release during melting. Similar to Leitch and Davies [3, 4], we find that the eclogitic component greatly enhances the melt production relative to a pyrolitic reference case. Both the instantaneous and cumulative melt production are very sensitive to the plume excess temperature. However, the carbon release is less sensitive to excess temperature because of the (assumed) efficient removal of volatiles during low-degree partial melting.

The models are carried out using a two-dimensional geodynamic modeling code implemented in the Julia programming language. We adopt the conservative finite difference plus marker-in-cell approach of Gerya and Yuen [5]. The Julia language enables performance comparable to compiled languages like C++ but with the ease of development and hassle-free installation of scripting languages like Python or MATLAB and permits development within the Jupyter (**Ju**lia, **Pyt**hon, **R**) environment. Our modular implementation allows for the easy construction of geodynamic models in 2D Cartesian or axisymmetric coordinates and is particularly well suited to teaching courses on geodynamic modeling. Many of the essential operations on Lagrangian particles and Eulerian fields are parallelized using Julia's `Threads.jl` functionality.

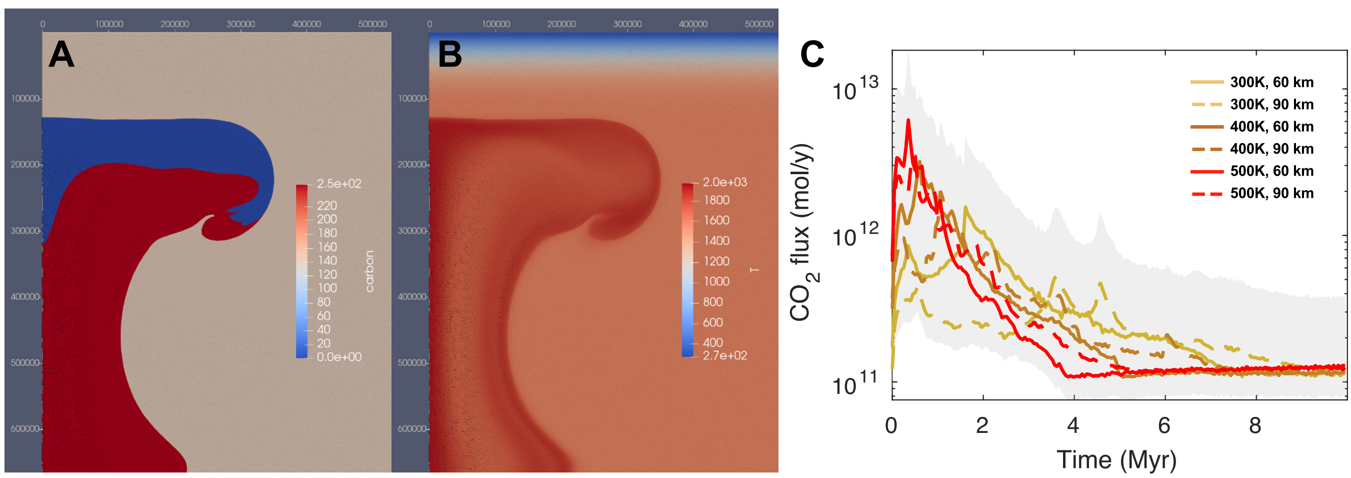

Figure 1: *(A) Carbon content in a numerical model of plume ascent. The blue region has been depleted of carbon while the red region has not yet undergone melting and retains carbon. (B) Temperature field from the same model as (A). (C) Carbon release as a function of time for models with different lithospheric thickness and initial temperature anomaly, as indicated in the legend.*

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Effect of grain-size and textural weakening in polyphase crustal and mantle lithospheric shear zones

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Keywords — Rheology, shear zones, numerical modelling

Strain localization to form narrow plate-boundary shear zones in Earth's lithosphere requires a significant amount of strain weakening. Here we investigate the relative contributions of grain-size-sensitive weakening versus textural weakening in polyphase shear zones in granitoid and peridotitic rocks through two-dimensional centimetre-scale bulk simple shear numerical models. The models deploy both constant grain size (only textural weakening) and dynamic grain-size evolution based on the paleowattmeter. Our results reveal that for granitoid rocks, textural weakening dominates, especially at temperatures around 550 °C, while grain-size-sensitive weakening plays a secondary yet significant role (see Fig. 1). For peridotitic rocks, intense weakening is evident below temperatures of ~1000 °C due to grain-size reduction, while textural weakening has a minor effect on weakening for experiments above 1000 °C. Two-dimensional experiments are compared to one-dimensional, single-phase models to reveal the effect of geometrical complexities in stress and grain-size evolution. These results are discussed in the context of natural lithospheric shear zones and are compared with established piezometers for individual mineral phases. Our findings underscore the vital role of grain-size-sensitive rheologies, particularly in the mantle lithosphere, for the initial weakening of ductile shear zones. These insights offer quantitative constraints that advance our understanding of the long-term strength of lithospheric plate boundaries.

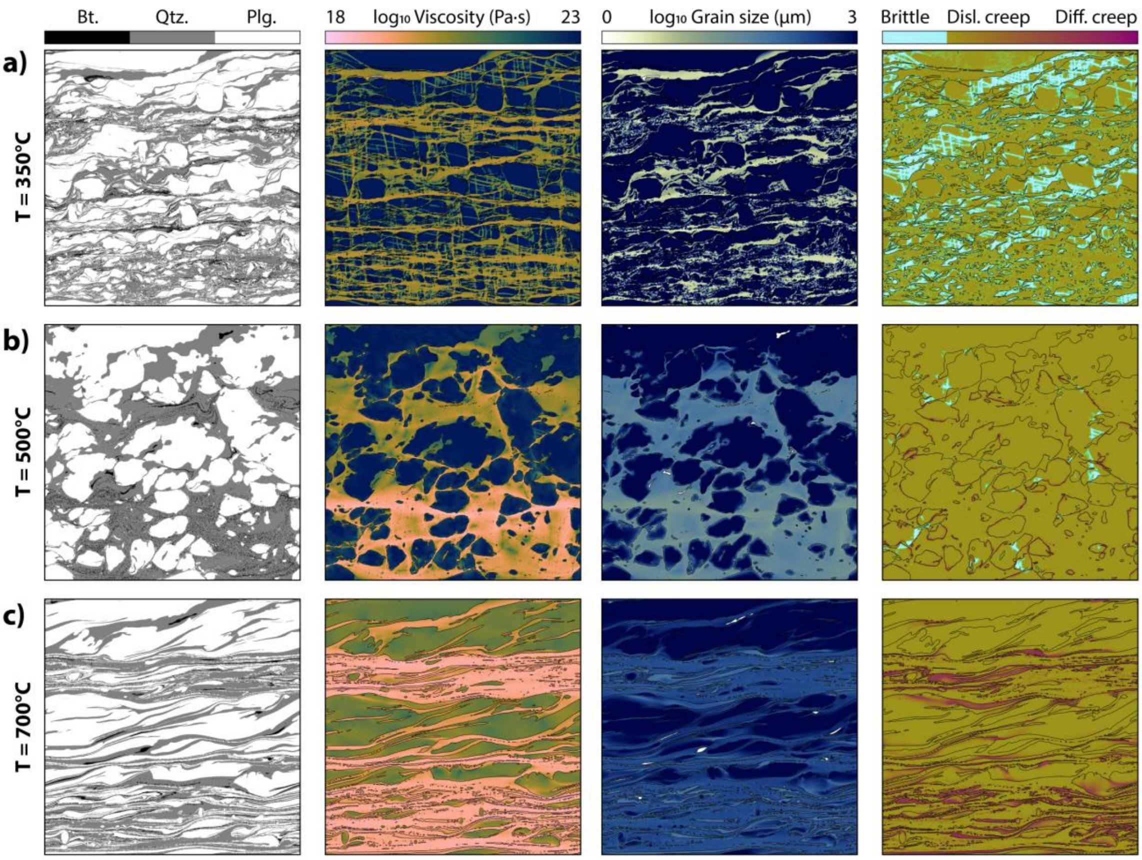

Figure 1: Marker composition, viscosity, grain size, and deformation mechanism of numerical experiments with a granitoid crustal mineral assemblage after a bulk shear strain of $\gamma = 20$. a) 350 °C, b) 500 °C, c) 700 °C.

Evolution of the constituent material of LLSVP-like V_S anomalies in mantle convection models

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Keywords — Geodynamics, LLSVPs, primitive mantle

The Large Low Shear Velocity Provinces (LLSVPs) are basal mantle structures, located beneath the Pacific and Africa, which are defined by their negative anomaly in δV_S. Since the first detection of LLSVPs, the reason for their seismic signature has been questioned, whether it is purely thermal, chemical or thermo-chemical in nature. The origin and age of LLSVPs have also been interrogated in the context of mantle dynamics as plumes seem to be associated with these structures and correlate with intraplate volcanism locations. The LLSVPs are often invoked as a potential reservoir to store primitive mantle in order to explain primitive He ratios observed in oceanic island basalts. Such a scenario would suggest that at least some part of the LLSVPs are long-lived, quasi-stable structures. Previous 3D geodynamic experiments suggest that LLSVP longevity is achieved through replenishment of the constituent material [1], potentially disqualifying them as a reservoir of primordial material. However, 2D experiments have shown that remnants of a primordial layer may become trapped within accumulations of recycled, dense oceanic crust for extended periods of time [2]. It remains to be seen if a similar process may occur in 3D simulations. Using the 3D spherical mantle convection code TERRA [3] and seismic conversion tables [1], we investigate the ability of geodynamic models to generate negative anomalies in δV_S in the lowermost mantle throughout the simulation. The aim of this work is to observe the potential evolution of the constituent material of detected V_S anomalies (replenishment). We compare the bulk composition, temperature, age and heterogeneities of this material to the ambient mantle. Preliminary results suggest that the detected structures are warmer than the ambient mantle and that primitive material is not necessarily associated with low V_S material.

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Can grain size variations cause spontaneous ductile strain localization?

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The deformation of the lithosphere, both in the crust and mantle, is mostly localized in shear zones, which can be observed at all scales, having widths from tens of km to the mm. Observations of these shear zones show that heterogeneity in compositions or microstructure is a key ingredient in the development of strain localization. Such observations often document a marked grain size reduction within the shear zones. Grain size variations may strongly affect the mechanical behavior of rocks. Diffusional creep and other grain boundary accommodated deformation mechanisms are heavily dependent on grain size variations, with a rate of deformation which is inversely proportional to the grain size to a power between 1 and 3. Therefore, quantifying if grain size variations may result in development of strain localization is key to comprehending how does deformation evolve and is distributed across the Earth lithosphere. Here we present a proof-of-concept study addressing ductile strain localization due to variations in grain size through space and time. We developed a stochastic module for description of the rheological parameters the explicit Finite Element code ADELI3D in which, by using simple Gaussian distributions, we can represent a broad range of grain sizes in both a damaged and an undamaged state, which are a function of the local power dissipation, and thereby evaluate if such variations may produce strain localization and, if yes, quantify the relations between grain size variations and intensity of strain localization. A traditional power law is used to represent the materials' rheology, and a parametric study on the influence of the strain rate dependency on stress is conducted. As a result, we present regime diagram for different study cases. Preliminary results show that strain localization requires to 2 to 3 orders of magnitude variations between the mean of the damaged and undamaged distributions of the microstructural parameters. By increasing the difference between the means of the damaged and undamaged distributions, the strain localization domain increases.

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From long-term lithosphere dynamics simulations to quasi-instantaneous models

Christian Schuler, Boris Kaus

Thermomechanical forward modelling over millions of years is often used to simulate lithospheric and mantle dynamic processes. Long-term geodynamic processes can be studied by systematically running forward simulations and varying input parameters. Yet, as those models are computationally expensive, many run quasi-instantaneous models instead for one or several timesteps. The advantage of these models is that they are computationally cheaper and that they can be initialized with geophysical data, such as seismic tomography. Here, we want to test how well quasi-instantaneous models can reproduce the plate velocities from long-term models and which model parameters are crucial in this.

In the case of instantaneous models, the temperature structure and rheology of the lithosphere and mantle can be inferred by analyzing geological data. However, the stress distribution and the historical stresses that play a role in stress build-up are largely unknown. Therefore, running instantaneous models without prior knowledge about the stress distribution can give quite different results than those obtained from long-term viscoelastoplastic forward simulations. To address this issue, the initial step is to test whether the horizontal plate motion of a viscoelastoplastic forward simulation can be reproduced by an instantaneous viscoplastic model, provided that the temperature structure and phase distribution, as well as the low viscosity zones, are known in advance. It is then further analysed how information from long-term forward simulations can generally be used to inform instantaneous models as a priori knowledge.

Exploring the Relationship between Time-Dependent Driving Forces and the Fate of Continental Rifts

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Keywords — Continental rift, failed rift, time-dependent boundary force

Once initiated, a continental rift either continues until rupturing the lithosphere into two plates or fails to reach the breakup stage. Constant-velocity boundary conditions have been popular choices in numerous studies on rifting processes, but traction boundary condition had to be employed to study whether a rift would fail or succeed [1]. In this study, we now consider temporal variations in boundary tractions, essential for studying passive rift systems associated with evolving plate configurations. We use ASPECT, a community code for geodynamic simulations, to study how a continental rift system responds to time-dependent driving forces. The time dependence is quantified by three parameters: The amount of magnitude reduction, the start timing of reduction, and the length of the reduction period. We explore how the rift evolves in a series of models with different combinations of these three parameters. We considered a fixed amount of reduction, 25 % from 160 MPa in our preliminary models (Fig. 1a). They showed that when an early-stage rift, corresponding to the one at 2 Ma in the reference model, lost its driving force's magnitude by 25% over a 1, 2, 4 and 6 Ma, it became a failed rift by the end of the 20 Ma model duration. However, when the force magnitude reduction occurred more slowly for 8 Ma, the early-stage rift could complete the continental breakup by the end of the simulation. A mature rift corresponding to the one at 6 Ma in the reference model, the 25% reduction of rift driving force was not sufficient for stopping the rift: The mature rift reached the continental breakup regardless of the reduction period lengths although the slower the reduction, the longer the continental breakup took. Greater amounts of force magnitude reduction would be needed for such a mature rift to fail eventually. An intermediate-stage rift corresponding to the reference model's state at 4 Ma failed only when the reduction occurred over the shortest period considered, 1 Ma (Fig. 1b). The slower reductions did not stop the intermediate-stage rift from completing the continental rupture (Fig. 1b).

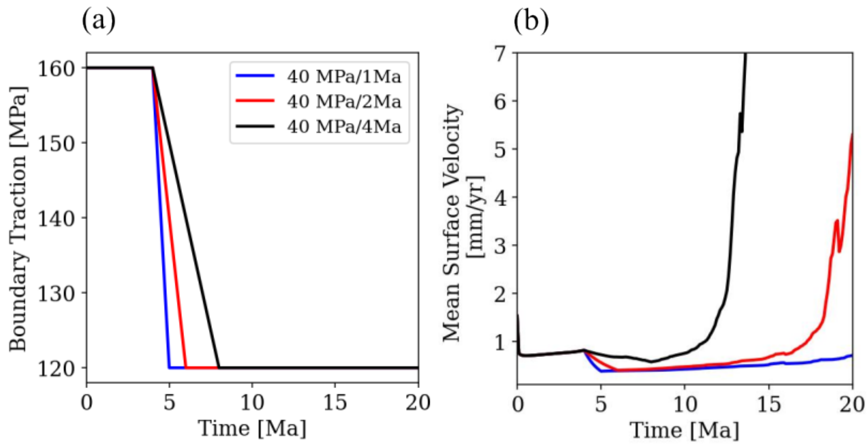

Figure 1: (a) Boundary traction magnitude as a function of time in three cases where the initial magnitude is 160 Ma and 25% reduction to 120 MPa occurs over 1 (blue), 2 (red) and 4 Ma (black). (b) The time evolution of mean surface speed in the intermediate-stage models.

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Volatile and Trace Element Storage in a Crystallizing Martian Magma Ocean

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Keywords — Magma Ocean, Volatiles, Mars

Immediately following core formation on Mars, the planet underwent a magma ocean (MO) phase. Volatiles released from the MO fostered a primitive atmosphere (PA) which modulated heat loss from the cooling planet through the greenhouse effect. The solidification and degassing of the MO are therefore coupled. In this work, we investigate two important aspects of this evolution: 1) the dynamics of melt trapping at the freezing front of the residual mantle (RM) and 2) the oxidation state during crystallization. For crystallization rates applicable to the martian MO, compaction is inefficient, leading to large fractions of melt trapped together with the crystals accumulating in the RM. The H_2O content of the martian RM is strongly influenced by dynamic melt trapping. Following MO crystallization, up to 55.4% of the initial H_2O in the MO is sequestered in the RM, with the rest outgassed to the surface. Dynamic melt trapping also limits variations in trace element concentrations and fractionations. Resulting variations in important isotopic parent/daughter ratios (Sm/Nd, Lu/Hf) cannot account for all of the isotopic diversity inferred for martian basalt source regions, hence requiring alternative mechanisms. The redox state of the MO exerts a strong control on the total CO_2 content of the RM and the time of crystallization. Under oxidizing conditions, the residual mantle stores 0.01% of the delivered CO_2 but under the most reducing conditions we examined, the residual mantle can sequester 80.4% in the form of trapped carbonated melt and graphite/diamond [1].

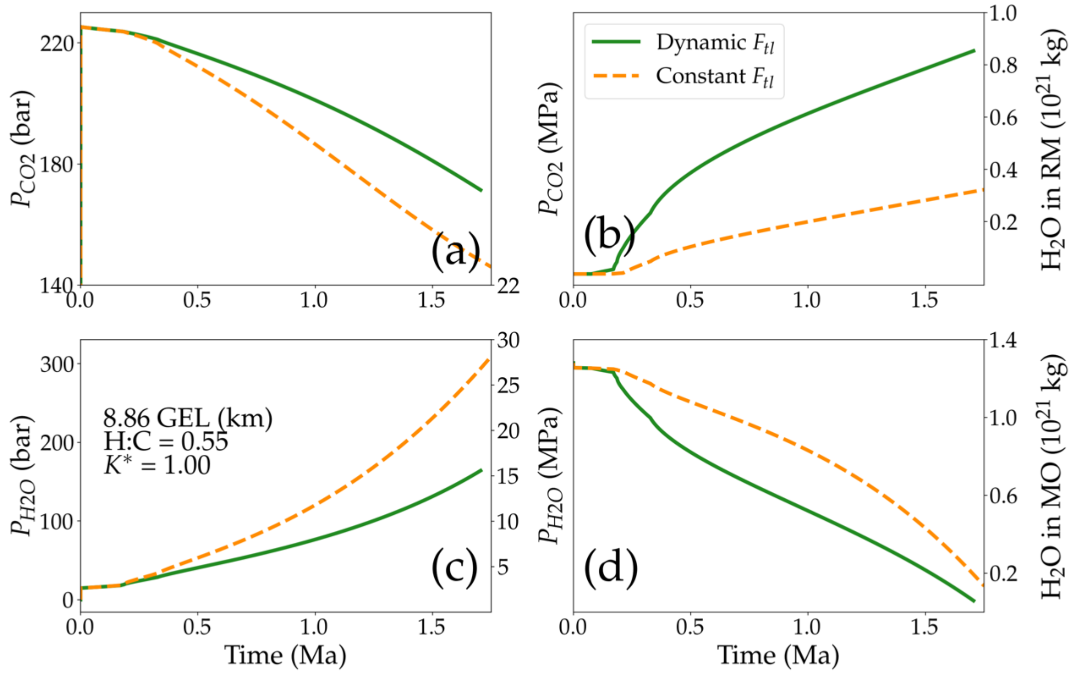

Figure 1: Comparison of evolving volatile masses and pressures between models of dynamic melt trapping (solid green lines) and a constant trapped melt fraction (broken orange lines) of 1 vol%. The initial bulk H_2O content in both cases is equal to 8.86 km GEL (1.28×10^{21} kg). Carbon content in the bulk was calculated using a chondritic H:C ratio of 0.55, and the redox condition of the simulation corresponds to $K^* = 1$.

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Thermal structure and seismicity distribution in the Lesser Antilles Arc

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The Lesser Antilles Arc (LAA) has a striking difference between seismicity in the north and south. Whilst the north resembles more of a typical subduction zone with trench-parallel thrust events, the south has very little seismicity at all. To better understand this difference and the seismic potential of the LAA in general, we are trying to unpick the effects of temperature, fluids, state of stress and pre-existing structures.

First, we created a new slab geometry that extends to 500km depth by combining an existing geometry from the VoiLA project with Slab2.0. Then, using this new slab geometry, we created a set of kinematically driven 2D thermal models to understand the thermal structure and rheological conditions. Using Perple_X, we could then use the thermal structure to predict the depth to which hydrous minerals, such as antigorite, remain stable. Our models show that the depth distribution of Wadati-Benioff zone seismicity can be explained by variations in temperature due to dip, which affect fluid release and/or rheology. After that, we calculated the curvature of the slab to show that the largest and deepest intraslab seismic moment release is linked to the largest changes in slab geometry. Currently, we are working on expanding our existing seismicity catalogue, using Pickblue, with the aim of gaining further insight into the distribution and style of seismicity. Particularly, we are looking to image any structures that may explain the difference between north and south, such as a slab tear.

What tectonic regime prevailed during the first billion years of Earth's evolution?

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Keywords — Hadean and Eo-Archean Earth, tectonic regime, subduction, continental crust production

The type of the tectonic regime on Earth during the first billion years of its evolution remains unclear, largely because of a lack of the relevant geochemical data. The prevailing point of view, mostly based on the results of geodynamic models, is that there was stagnant lid, heat-pipe or plutonic-squishy-lid tectonic regime with no or minor contribution of subduction [1]. Recently, geochemical study of melt inclusions trapped in olivine from ca. 3.27 Ga komatiitic lava flows in Barberton Greenstone Belt, South Africa, discovered Hadean source of magmas with strong evidence of chemical fractionation by extraction of continental crust (Nb/U=38.02±3.88, Ce/Pb=16.21±0.89) [2].

To understand the physical processes responsible for this geochemical signature, we conducted physics-based geodynamic modelling. We used the mantle convection code StagYY [3] in 2D spherical annulus domain including cooling of the core, generating both basaltic and felsic melts with consideration of water containing phases and including the effect of water on density. We also model the evolution of Rb-Sr isotopes as well as Nb, U, Ce and Pb trace elements. We computed a series of models by varying lithosphere's hydration and frictional strength. Our models infer that in order to fit the geochemical observations, the water supply into the lithosphere must have been high enough to allow production of ca. 40 to 70% of present-day continental crust mass during the Hadean. In addition, the tectonic regime during the Hadean and the Eo-Archean times must have been sufficiently mobile, i.e., with periods of extensive subduction lasting several 10s of million years (Figure 1A). Classical episodic low mobility regimes with rare partial resurfacing and sagduction as well as stagnant lid or heat-pipe regimes are not consistent with geochemical observations (Figure 1B).

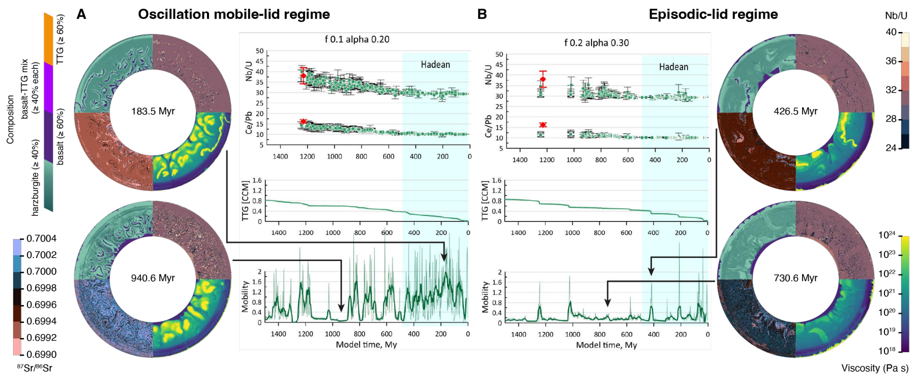

__Figure 1: Models versus geochemical observations.__ Green circles with error bars show evolution of trace elements in Hadean fraction ($^{87}Sr/^{86}Sr<0.6997$) of potential komatiite source in typical models. Models representing sufficiently mobile regime (block A) and generating more than 40% of present-day continental crust mass (CCM) during the Hadean agree with geochemical data (red symbols with error bars). Models representing low-mobility regimes (block B), even generating similar or larger amount of continental crust are not consistent with geochemical observations. Snapshots show the evolution of models with time where four quadrants represent different fields (clockwise from top left: composition, Nb/U, viscosity, $^{87}Sr/^{86}Sr$).

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Thermal runaway as driving mechanism of deep earthquakes – Constraints from numerical models

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Keywords — numerical modelling, deep earthquakes, ductile localization

Deep-focus earthquakes occur at depths > 70 km below the surface where brittle failure is unlikely due to the large lithostatic pressure. Instead, they require a ductile localization mechanism that can significantly reduce rock strength and create highly localized shear zones. The feedback loop of shear heating, temperature-dependent viscosity and localization is called thermal runaway and has been linked to deep-focus earthquakes.

We present one- and two-dimensional (1D and 2D) numerical, thermomechanical models that investigate the occurrence, nucleation and temporal evolution of thermal runaway in a simple shear setting. The models are characterized by a visco-elastic rheology where viscous creep is accommodated with a composite rheology of diffusion and dislocation creep as well as low-temperature plasticity. We utilize the pseudo-transient iterative method in combination with a viscosity regularization and adaptive time stepping to solve this nonlinear system of equations and avoid resolution dependencies. 2D models are implemented to run on multiple graphics processing units (GPU).

We observe two distinct types of behavior. After elastic loading, models either release stress over hundreds to thousands of years, accompanied by low slip velocities and moderate temperature increase, or they release stress within seconds to minutes while slip velocity and temperature increase drastically – Thermal runaway occurs. With nondimensional scaling analysis, we unite eight different input parameters into two nondimensional numbers that allow inferring the behavior. The ratio t_r/t_d describes the competition between heat generation by viscous dissipation and heat loss due to thermal diffusion whereas the ratio U_{el}/U_{th} compares the elastic and thermal energy before stress relaxation.

2D experiments show that thermal runaway allows highly localized ductile ruptures to nucleate at small heterogeneities and propagate like brittle fractures. Rupture trajectories are usually parallel to the direction of background deformation but bend in the vicinity of other ruptures to allow for a link up. The results demonstrate that thermal runaway can create highly localized, propagating shear zones that reach slip and rupture velocities in line with earthquakes at upper mantle and transition zone conditions.

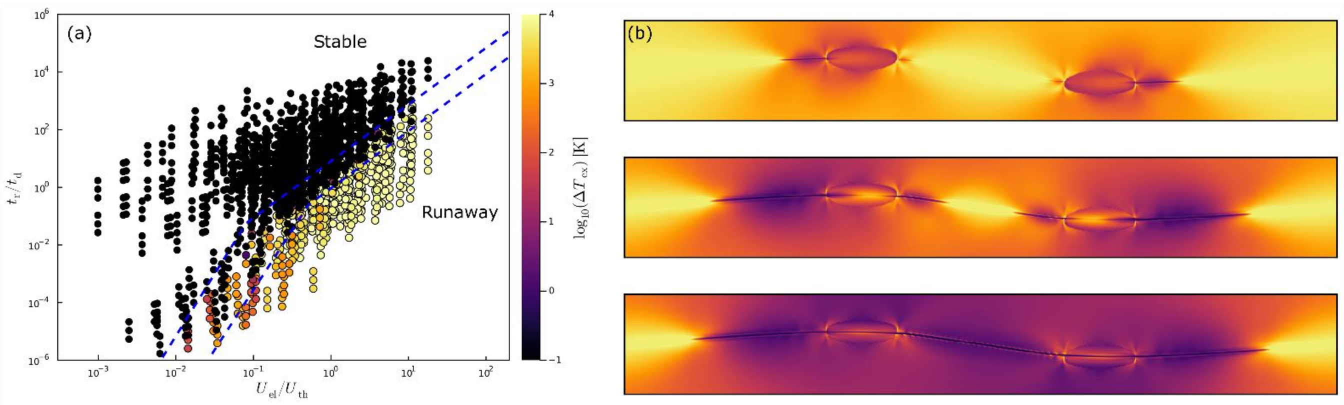

Figure 1: (a) Nondimensional scaling separates models into stable regime and runaway regime. (b) Ductile rupture propagation by thermal runaway in 2D.

Recipe for a global catastrophic overturn

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Keywords — keyword1, keyword2, keyword3

On timescales of planetary evolution, the strong temperature-dependence of viscosity in silicates leads to lithospheres that are inherently strong, and lead to creation of a thick, insulating conductive lid (known as a stagnant lid). This is generally the conceptual model for smaller planetary bodies like Mars, Mercury, and the Moon. In contrast, Earth has plate tectonics by virtue of the fact the lithosphere has finite material strength and is therefore broken into an ensemble of quasi-rigid plates that rotate with respect to each other. The absence of large expanses of real estate on Venus that are as heavily cratered as Mars or the Moon suggests its entire surface has been been paved over or recycled at some point during its history. Somehow the lithosphere of Venus has been recycled, but likely from a different process than what operates on Earth.

A popular method to explore various hypotheses of how planetary lithospheres can become unstable, and be subsequently recycled into the planet's interior, is the use of geodynamic models, specifically mantle convection models that account for a lithosphere that is capable of failure when the stresses exceed its maximum (known as a yield stress). Previous studies have identified a planetary tectonic regime with an interesting behavior in which after the lithosphere has aged enough to a certain thickness, its strength can no longer support the weight of it, resulting in a catastrophic global overturn [1]. Models indicate such events can be episodic [1].

We revisit this topic of global tectonic regimes using the StagYY code [2] to calculate numerical models of mantle convection with temperature-dependent viscosity. The models are Boussinesq and have a 2D semi-spherical annulus geometry. We actually compare identical models with three model resolutions ranging from 256×64 (low resolution) to 1024×256, to 2,048×512 (high resolution). The resolution is important because it allows for better resolution of the stress field, which directly effects when and where the yield stresses are reached. In general, higher resolution models allow for stresses to concentrate into smaller regions, and redistribution of stresses that exceeded the yield stress can then cause other places to yield. Because resolution effects stress distributions, we also investigate the role of the yield stress using 2 values (100MPa and 500MPa).

We also examine the influence of an aspect is not typically accounted for in previous models, which is the presence of a 20-30km thick basaltic crust. This is a very important feature of the lithosphere because the positive compositional buoyancy of the crust helps stabilize the lithosphere by counteracting the negative buoyancy due to thermal contraction. However, the crust itself has an even lower material strength than the underlying mantle material, and therefore can also yield.

We report here a large diversity of outcomes depending on the resolution, magnitude of yield stress, and total buoyancy of the crust. We have generated a suite of 27 models that have evolved for billions of years. In these models, global recycling of the lithosphere does occur for some combinations, but such events occur over long time periods rather than short period of time (ie catastrophic). We also see many models with regional recycling of the lithosphere, which can eventually recycle all of the planet's lithosphere, although not in a catastrophic manner. A few stagnant lids are also observed to persist. However, we find that for the cases with the most realistic values of crustal buoyancy and yield stress, and for those cases that have the highest model resolution, the tectonic regime that is most favored is that of Peel-back delamination (PBD) [3]. PBD was recently proposed as a mechanism of regional-scale lithospheric recycling initiated at Venusian rift zones and occurs when the lithospheric mantle is sufficiently thick and negatively buoyant to decouple and peel away from the overlying positively buoyant crust.

This work will place a large number of diverse tectonic regimes into context and illuminate the key aspects of why various outcomes result from a given set of model parameters.

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Why are plume excess temperatures much less than the temperature drop across the core-mantle boundary (CMB)?

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Keywords — mantle plume, temperature, viscosity

While temperature drop across the mantle's basal thermal boundary layer (TBL) is likely >1000 K, the temperature anomaly of plumes believed to rise from that TBL is only up to a few hundred Kelvins. Reasons for that discrepancy are still poorly understood and a number of causes have been proposed. Here we use the ASPECT software to model plumes from the lowermost mantle and study their excess temperatures. We use a mantle viscosity that depends on temperature and depth with a strong viscosity increase from below the lithosphere towards the lower mantle, reaching about 10^{23} Pas above the basal TBL, consistent with geoid modelling and slow motion of mantle plumes. Based on the mineral physics derived thermodynamic database with pyrolitic composition of the mantle, the difference between a plume adiabat and an ambient mantle adiabat just below the lithosphere is about two thirds of that at the base of the mantle, e.g. 1280 K vs. 835 K. 3-D models of isolated plumes become nearly steady-state > 10-20 Myr after the plume head has reached the surface, with excess temperature drop compared to an adiabat for material directly from the CMB usually less than 100 K. In the Earth, plumes are likely triggered by slabs and probably rise preferrably above the margins of chemically distinct piles. This could lead to reduced excess temperatures, if plumes are more sheet-like, similar to 2-D models, or temperature at their source depth is less than at the CMB. Excess temperatures are further reduced when averaged over the plume conduit or melting region.

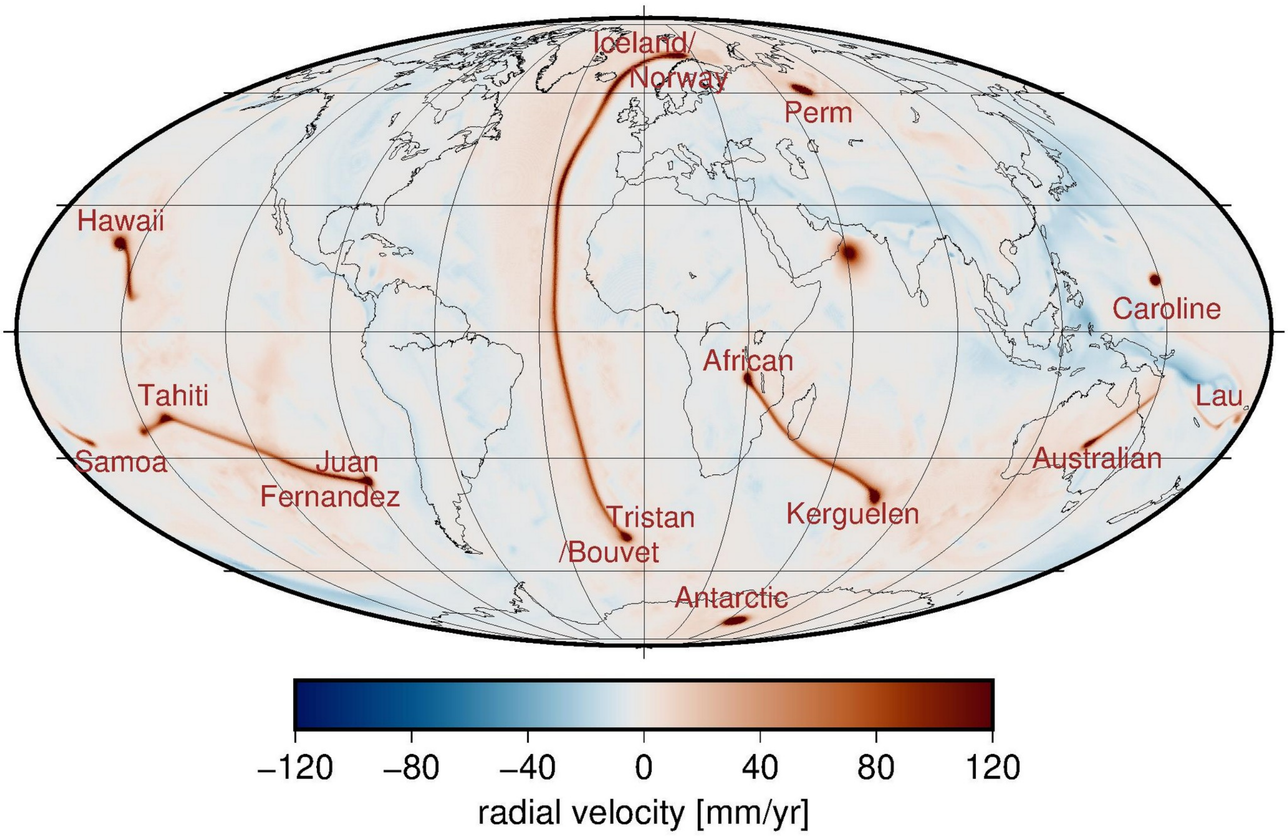

Figure 1: Radial velocity at depth 500 km at present-day for a 3-D spherical model with 250 Myr plate reconstructions as surface boundary conditions forcing subduction, and thermochemical piles on the CMB formed from an initally flat layer. Plumes are named after suggested actual plumes in that vicinity, but locations do not exactly match, except for Hawaii.

Subduction dynamics depend strongly on the rheology of the plate interface. However, geodynamic modeling studies that explore the strength and dynamic impacts of the subduction interface often neglect the rheological evolution of the subduction interface. The development of weak lithologies (e.g. serpentinite) along the plate interface is controlled by the thermal state and composition of the downgoing slab: fluids are liberated from the downgoing slab that progressively react with the largely anhydrous rocks in the mantle wedge, forming weak, hydrous lithologies that may, in turn, weaken the interface further as subduction matures. To track such feedbacks over time, and isolate the geodynamic impacts of such emergent weak lithologies, we build dynamic subduction models using the open-source finite element code ASPECT (Kronbichler et al., 2012; Heister et al., 2017). We have developed an ASPECT plugin to couple evolving metamorphic phases, as determined via lookup tables read into the code, with the rheology of the respective phase. By quantifying fluid release due to phase transitions from the downgoing slab, we determine the degree of progressive partial hydration of the mantle wedge, the rheological consequences for the plate interface, and how this impacts large-scale subduction dynamics. Specifically, convergence rates are 50-100 % higher relative to cases without weakening because of the development of a weak serpentinite shear zone. This growing layer of weak minerals above the downgoing slab is stabilized by the low density of serpentinite, which counteracts the downdragging from the overriding plate. Furthermore, we find that sediment, beyond lubricating the interface itself, also lubricates the interface via the release and subsequent binding of fluids in hydrous, ultramafic rocks, such as serpentinites. In line with previous work, our work suggests that much of the ingrowth of weak minerals at the interface takes place during subduction infancy (~10 Myr), due to the warm thermal state of the slab, suggesting the need for an upward revision of serpentinization estimates.

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Numerical Study of Fault Interactions through Seismic Cycles Using the Boundary Element Approach

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The mechanics of fault interactions during the seismic cycle are fundamental for earthquake physics but many aspects remain incompletely understood. We adopt a two-stage numerical approach to explore stress and slip transfer between faults by performing boundary element method (BEM) earthquake simulations using natural and idealized fault geometries. The first stage focuses on interactions among fault segments within a natural fault system using the *interact* software [1]. We focus on the Alpine Fault, a major transform fault in southwest New Zealand, and explore the geometrical connectivity of interacting faults considering possible rupture scenarios. We perform one-step calculations to solve for fault interactions for given stress boundary conditions in a homogeneous elastic half-space. We then compare the results between individually rupturing fault segments and simultaneously rupturing fault groups to understand the interaction patterns at a basic level. We intend to broaden our study area to both the Alpine Fault and the Hope-Kelly Fault within the Marlborough Fault system. The second stage involves quasi-dynamic earthquake cycle simulation in an elastic half-space using the software *HBI* [2] to explore differences between static and quasi-dynamic fault interactions and different frictional properties. Combining insights from these methods should allow us to get a better handle on stress and slip transfer within a complex fault system in light of single rupture versus long-term slip behavior.

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Outgassing on stagnant-lid planets: Influence of rheology

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Keywords — exoplanet, mantle convection, outgassing

Outgassing from the interior is a key process influencing the evolution of the atmospheres of rocky planets. For planets with a stagnant lid tectonic mode, previous models have indicated that increasing planet size very strongly reduces the amount of outgassing, even to zero above a certain planet mass [1]. This is because melt is buoyant only above a certain depth, which becomes shallower with increasing planet size (hence "g"); for large enough planets this depth may even lie within the lithosphere, preventing eruption and outgassing.

However, uncertainties in rheology strongly influence the temperature structure of planets, hence (i) the depth at which melt is generated and (ii) the thickness of the lithosphere. One major uncertainty is the rheology of post-perovskite, which constitutes a large fraction of the mantle in large super-Earths. [2] find that diffusion is anisotropic; it is not clear whether the "upper bound" or "lower bound" is relevant to large-scale deformation, but both result in high viscosity at very high pressures, strongly influencing the radial temperature profile [3]. In contrast, [4] argues that a different mechanism - interstitial diffusion - acts to make viscosity almost independent of pressure and relatively low in the post-perovskite regime.

Another uncertainty is the reference viscosity (the viscosity at a reference temperature, pressure and stress), as this depends on bulk composition, water content, grain size and other properties. Lower reference viscosity results in thinner lithosphere and crust (e.g., [5]).

Thus, numerical simulations are performed of the long-term (10 Gyr) thermo-chemical evolution of stagnant-lid planets (coupled mantle and core) with masses between 1 to 10 Earth masses, varying the reference viscosity and the rheology of post-perovskite. The simulations are based on the setup of [3] with the addition of partial melting and basaltic crustal production, and outgassing of a passive tracer that partitions into the melt and outgasses 100% upon eruption.

Results indicate that:

- the previously-found trend of lower percentage outgassing with larger planet size is reproduced, but
- outgassing does not fall to zero even in a 10 Earth mass planet. Outgassing of between 15% and 70% is found for 10 Earth mass planets (up to ~100% for Earth mass planets).
- Post-perovskite rheology (interstitial, lower-bound or upper-bound) makes only a minor difference to long-term outgassing, but does influence the timing of outgassing.
- Reference viscosity makes a large difference to outgassing, with lower viscosities leading to substantially larger outgassing percentages.
- Internal heating plays a major role: stagnant-lid planets initially heat up due to low heat transfer efficiency, thinning the lithosphere and producing widespread melting.

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In this contribution we investigate the effect of mechanical anisotropy on the deformation of the lithosphere.
We use two-dimensional anisotropic numerical models of lithosphere deformation and study both compression and extension of lithospheres. The effect of initial anisotropy directions, anisotropy strengths and evolving anisotropy (directions and strength) on modes of lithosphere deformation are emphasised.

The role of viscoelastic stress transfer and reaction-induced volume change in deep-focus earthquake generation

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Keywords — phase transformation, viscoelastic rheology, deep earthquakes

The nucleation and rupture processes of deep-focus earthquakes have remained enigmatic ever since their discovery. These earthquakes occur mostly within the mantle transition zone where brittle failure is extremely unlikely due to the elevated pressures at these depths. Hence, other mechanisms have to be invoked to explain the occurrence of these events. To date, two main hypotheses have been put forward to explain deep focus earthquakes: transformational faulting (due to the polymorphic phase change of metastable olivine to either wadsleyite or ringwoodite) and thermal runaway (due to the conversion of deformational work to heat). More recently, it has been proposed that the feedback between those two mechanisms may explain the observed two-stage ruptures of large deep-focus earthquakes. To better understand the potential feedback between transformational faulting and thermal runaway, it is necessary to quantify the stresses induced by the phase change due to i) the grain size reduction and corresponding viscosity reduction of the transformed material and ii) the volume reduction of the transformed phase. The former process triggers a stress transfer from the transformed material to the untransformed material, whereas the latter results in elevated stresses around the transformed phase.

Here, we investigate the role of both mechanisms using numerical models with a viscoelastic compressible rheology. We quantify the impact of the different processes by using a combination of analytical and numerical models. The competition between viscoelastic stress relaxation and reaction-induced volume changes can be quantified as the ratio of two nondimensional numbers. Based on this ratio, we can then quantify the role of each process to the stress amplification around inclusions with different geometries. Depending on the importance of the respective mechanism, stress histories differ significantly and reach different stress levels, which has a strong impact on the activation of ductile weakening mechanisms such as thermal runaway.

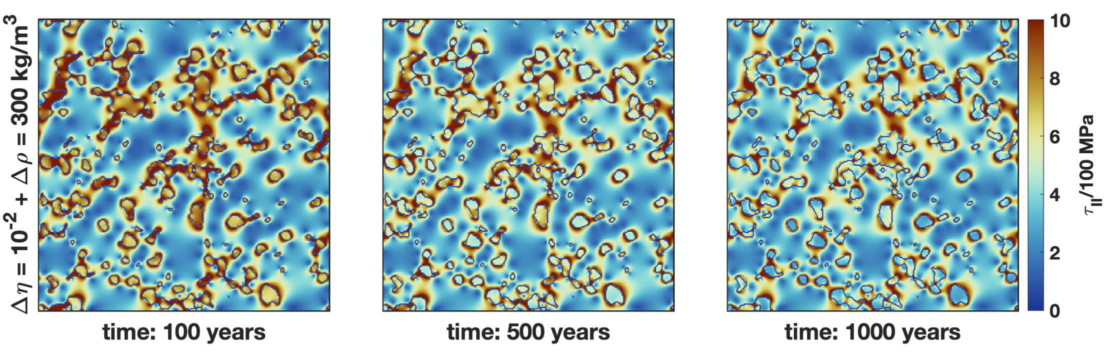

Figure 1: *Stress field in a random heterogeneous two-phase medium in response to a volume-reducing phase transformation.*

Exploring exotic Finite Element pairs for the Stokes equations in geodynamics

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Keywords — Finite Elements, Benchmark, Stokes flow

The Finite Element method is widely used in Computational Geodynamics to solve the Stokes equations. It is well known that there are 'rules' as to which velocity and pressure space can be used to represent these fields when the mass and momentum conservation equations are solved. In the past years I have investigated the role of the most common (stable or stabilized) finite element pairs for both quadrilaterals and triangles [1, 2].

While doing so I have unearthed a rich literature in which authors invariably propose various (stable) FE pairs that ultimately never catch on in geodynamics nor in CFD in general.

I have implemented a great deal of them out of curiosity and tested them on the typical array of manufactured solutions used in geodynamics. I will report on these and highlight their pro's and con's.

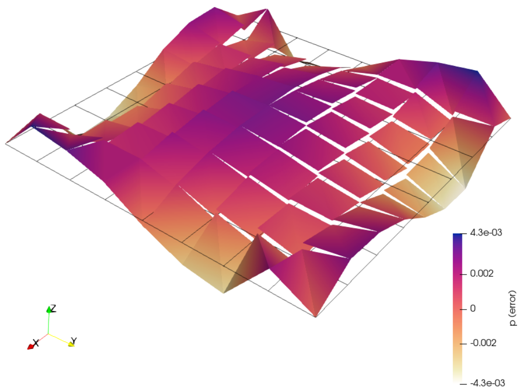

Figure 1: *Pressure error obtained with the so-called* $Q_{2,1:1,2} - Q_1'$ *element pair [3] on a* 16×16 *mesh for the Donea & Huerta manufactured solution [4].*

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Influence of varying thermal conductivity on the thermal evolution of Earth's mantle and core

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Keywords — mantle convection, thermal conductivity, core-mantle boundary heat flow

From an energy balance perspective, constraining the heat flow across the core-mantle boundary (CMB) is essential for understanding the thermal history of Earth's mantle and the core. The heat transfer at the CMB is primarily governed by heat conduction, which includes vibrational phonon transport (lattice contribution) and diffusive radiative transfer (radiative contribution) [1]. Therefore, constraining the thermal conductivity for lower mantle material is crucial for estimating CMB heat flow. However, current estimates of thermal conductivity for lower mantle minerals are highly uncertain. The lattice thermal conductivity is estimated around 10 W/(m K) under CMB condition, but it could be influenced by mineral composition and the post-perovskite phase transition [2, 3]. The radiative contribution is less understood, with recent studies producing divergent estimates of radiative thermal conductivity for lower mantle minerals, ranging from 0.35 W/(m K) to 4.2 W/(m K) at CMB condition [4, 5]. Adopting the highest estimate could result in around a 50% increase in the estimated total thermal conductivity compared to traditionally assumed values.

To investigate the impact of these uncertainties on mantle convection, we incorporated variable thermal conductivities (5 - 15 W/(m K) at the CMB) into a global thermochemical geodynamic model, StagYY. The simulations were conducted using a 2D spherical annulus geometry over a 4.5 Gyr timespan. The model incorporates depth-dependent thermal conductivity, parameterized core cooling, heat-producing elements partitioning, and crust formation, but excludes an initial primordial mantle reservoir at the CMB. Preliminary findings from our models reveal a complex relationship between thermal conductivity and CMB heat flux at present day. In stagnant-lid tectonic models, higher thermal conductivity leads to higher CMB heat flux in the initial 1 Gyr and lower CMB heat flux at 4.5 Gyr. However, in models with mobile-lid tectonics, changing thermal conductivity would not significantly affect CMB heat flux at present day. In terms of thermal evolution, models with thermal conductivities between 5 and 10 W/(m·K) show similar mantle temperature evolution and could both fit potential mantle temperatures inferred from petrological data from [6].

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Spontaneous ductile strain localization in the Earth mantle: key ingredients and regime diagram

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Strain localization is the rule rather than the exception in the lithosphere. Yet, modelling spontaneous strain localization in the ductile (viscous) regime, which prevails on ~90% of the lithosphere, remains a real challenge. Observations in shear zones, which are the expression of ductile strain localization, in nature and experiments show that heterogeneity in the mechanical behavior is key for strain localization. This heterogeneity exists at all scales, in particular at small ones, and evolves in response to the mechanical fields. In the ERC RhEoVOLUTION, we posit that poor representation of this heterogeneity and its evolution during deformation is the locking point for generating strain localization in geodynamical models and examine how strain localization may arise in rocks deforming by ductile processes by associating a stochastic description of the mechanical properties of the medium with simple laws describing how these properties evolve in response to the resulting spatial variations in stress and strain rate. These models show that initial heterogeneity in the rheological behavior and damage/healing due to evolution of the microstructure leading to spatial variations in the mechanical behavior controlled by the mechanical energy dissipation field are necessary, but not sufficient conditions to produce strain localization during viscous deformation. An additional condition is that the rate of energy consumption by the damage process is within a range from the average mechanical energy dissipation in the system. These results are used for constructing a regime diagram for viscous strain localization in the lithospheric mantle.

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Warm plate tectonics and metamorphosis in the Paleoproterozoic

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Keywords — the Paleoproterozoic era, continental collision, orogenesis

Modern-day plate tectonics on Earth is a unique phenomenon in the Solar System, as it exists only on our home planet today. However, it most likely did not operate in the early Earth [1]. Moreover, even long after the initiation of plate tectonics, its style was different than today due to higher mantle temperatures, or episodic alternations between the current and some other tectonic mode. During the Paleoproterozoic era, the plate tectonic mode was likely in transition (e.g. [2] and [3]). This project explores how those differences in the tectonic mode affect our interpretation of metamorphic pressure-temperature-time (P-T-t) data or the complex bedrock geology of the Svecofennian orogeny, which formed much of the bedrock in southern Finland 1.92-1.77 Ga ago [4].

The project uses numerical models of tectonic scenarios based on the Svecofennian orogeny, reflecting its volcanic arc accretion and microcontinental collision phases. These geodynamic models aim to unravel the formation of major Svecofennian structures, such as orogenic belts, fault networks and the extraordinary thick lithosphere in Central Finland Also, we aspire to constitute a broader picture of Paleoproterozoic orogenesis, as it is still rather scarcely modeled period in Earth's history.

The principal tool used in the project is geodynamic modeling software ASPECT ([5] and [6]), which is capable to model both the crust and the mantle. Hence it is a suitable way to explore temporal and spatial evolution of continental collision and orogenesis. In addition, petrological modeling will be combined with geodynamic models to simulate phase changes, due to changing P-T-t conditions. Furthermore, P-T-t paths will be extracted from the geodynamic models to compare to the rock record, using metamorphic petrology.

Very preliminary models will be presented, mainly relating to microcontinental collision. The following hypotheses and research question are forming the basis of the project:

- More frequent slab breakoffs and higher lithospheric temperatures resulted in episodic collision/subduction in the Paleoproterozoic, and further on wider and lower orogenic belts. Such episodicity also led to complex and overlapping fault patterns.
- P-T-t paths from geodynamic models can be used to distinguish the type of plate collision. Extracting these P-T-t conditions quantitatively as a function of time, their predictions could help to interpret bedrock geology in the highly complex Svecofennian region.
- Shallow subduction could provide a viable mechanism for Svecofennian lower crust eclogitization/high seismic velocity zone and extraordinary lithospheric thickening.

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Corner collision and orogenic syntaxis formation driven by Indian slab flattening and crustal flow effects

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Keywords — collision, crustal flow, surface processes

Despite decades of study, many features of the Tibetan-Himalayan orogenic system remain poorly understood. For example, the formation and role of the Eastern Himalaya Syntaxis (EHS) in the evolution of the orogenic system are unclear [1]. Separately, east- and southeastward extrusion of Tibetan crust around the eastern corner through a channel at mid-lower crustal depth has been discussed intensely, but remains enigmatic [2]. This flow might have played an important role in the formation of the Hengduan mountains in the Southeastern margin of the Tibetan plateau. It is important to understand this area, because these mountains are a regional, temperate biodiversity hotspot [3].

Here we use high-resolution, coupled 3D numerical models (I3VIS) with surface processes (FDSPM) [4], [5] of continental corner collision to investigate all these processes in one reference frame (Fig. 1). In these models, a syntaxis forms consistently in the eastern corner of the collision. The results demonstrate that a transient channel forms in the northern and eastern margins of the plateau. This channel is accelerated by mid-lower crustal indentation and significant Indian slab advance, while the upper crust halts and starts to retreat. Meanwhile, the Indian slab flattens significantly due to differential advance and significant crustal thickening in the plateau. These results challenge the assumption that the Indian slab has always been flat. Without a proto-plateau, none of these processes occur.

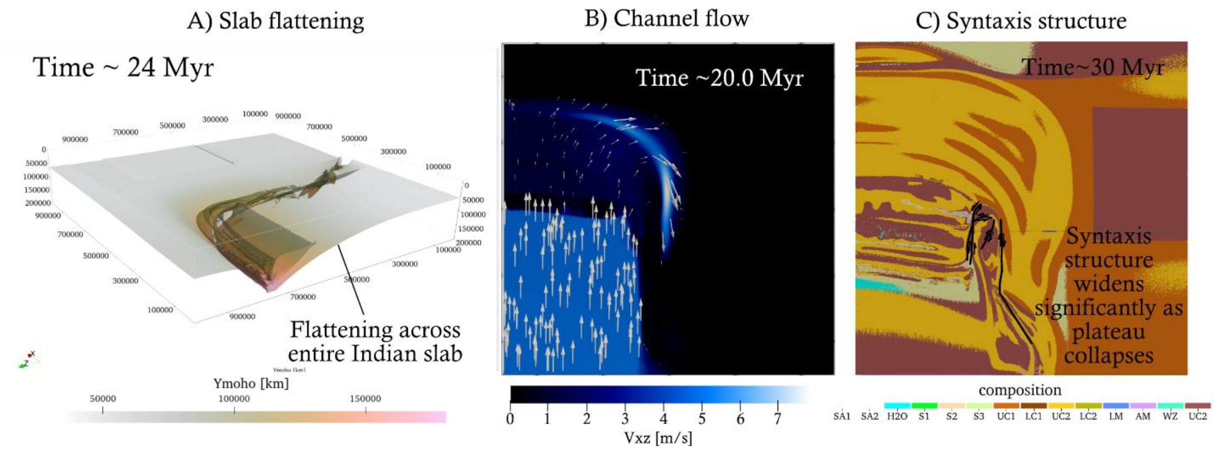

Figure 1: Slab flattening, crustal channel flow (horizontal slice at y=60km) , and syntaxis structure (horizontal slice at y=35 km) are strongly related in our simulated corner collision, suggesting that this may be the case for the India-Asia collision too.

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From intraplate deformation to plate boundary: thermal and mechanical feedbacks driving lithospheric weakening in simple 2-D extension models

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Keywords — Geodynamics, localization of deformation, rheology, numerical modeling

Abstract: The initiation of new plate boundary can be envisioned as a spatio-temporal evolution of a vast, diffuse, intraplate deformed zone towards a narrow, highly-deforming boundary. It can also occur by reactivation of an inherited weak zone. In all cases, breaking a plate requires a weakening of the lithospheric cold mantle.

In numerical models, plate-like behavior often features a « yield strength » formulation that is not clearly related to any actual deformation mechanisms. On the other hand, the effective viscosity for mantle rocks has multiple dependencies, that may co-evolve in geodynamic settings, such as temperature and strain rate increase during asthenosphere upwelling associated with plate extension.

Under a range of relevant thermomechanical conditions, what are the processes involved in the temporal evolution of strain localization, and how does this localization occur over time thanks to lithosphere weakening? How is the mantle rheology affecting deformation evolution?

We design 2-D extension models at the lithosphere and upper mantle scale under various relevant conditions to simulate deformation in the ductile lithosphere and investigate the interplay between temperature, strain rate and rheological behavior leading to plate breakup. Some models also feature a hot upwelling circular anomaly below the base of the plate. We use different rheological parameterizations that are sensitive to temperature and strain rate, including combinations of olivine flow laws, high- and/or low-temperature dislocation creep, diffusion creep and yield stress. These numerical experiments provides temporal evolution of thermomechanical fields. We focus on the conditions controlling strain localization.

We describe different criteria used to assess successful strain localization and quantify the temporal evolution of weakening, the mechanisms involved, and the positive or negative feedbacks between thermomechanical fields (temperature, strain rate) and lithosphere strength. Additionally, we relate these factors to the geodynamic evolution of the system, described by thinning rate and upwelling rate. These criteria are used to build regime diagram of localization timing and rheological control as a function of imposed extension rate and initial age of lithosphere for various rheologies.

We show that the interplay between strain rate (thinning) and temperature (upwelling) enhances the strain localization leading to the formation of a new plate boundary, especially for a low-temperature dislocation rheology proceeding at the bottom of the ductile lithosphere. In contrast, without dislocation creep (e.g. yield stress and diffusion creep), there is no significant interaction between thermal and mechanical controls at the base of the lithosphere; one dominates independently of the other, making strain localization slower and much less efficient.

Subductability of continental lithosphere

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Keywords — Continental lithosphere, subduction, slab pull, India-Asia collision

Continental plate is generally considered to resist subduction due to its buoyancy. However, various types of evidence, including mineralogical, geochemical, geophysical, and paleomagnetic observations, suggest the possibility of ultra-deep subduction of continental lithosphere, even extending to depths beyond 300–400 km (1-4); however, some continental lithospheres may exhibit shallow subduction (<100 km) or subduction cessation after the closure of oceanic basins (5). The contrasting results point to the puzzling issue of subductability of continental lithosphere, which is important for our understanding of the evolution and destiny of continental subduction-collision zones (6). Here, systematic thermo-petrological models are conducted to quantitatively evaluate the subductability of CL by analyzing its density structure and slab-pull evolution during subduction. The results indicate that the metamorphic densification of deeply subducted CL (upper, middle, lower crust and lithospheric mantle) provides considerable driving force for continental subduction, which is generally higher than the estimated resisting force for the Phanerozoic and Proterozoic lithosphere subduction, whereas the subducted Archean lithosphere generates less driving or even resisting force due to the depleted composition. The effects of multiple factors, including the scraping of continental crust, subduction velocity, subduction angle and variable bulk-rock compositions of continental crust, are further quantified. A representative case study of Himalayan orogen reveals the slab pull of present subducted Indian CL, ranging from 13 to 29 TN/m, is a major contribution for continuous India-Asia collision.

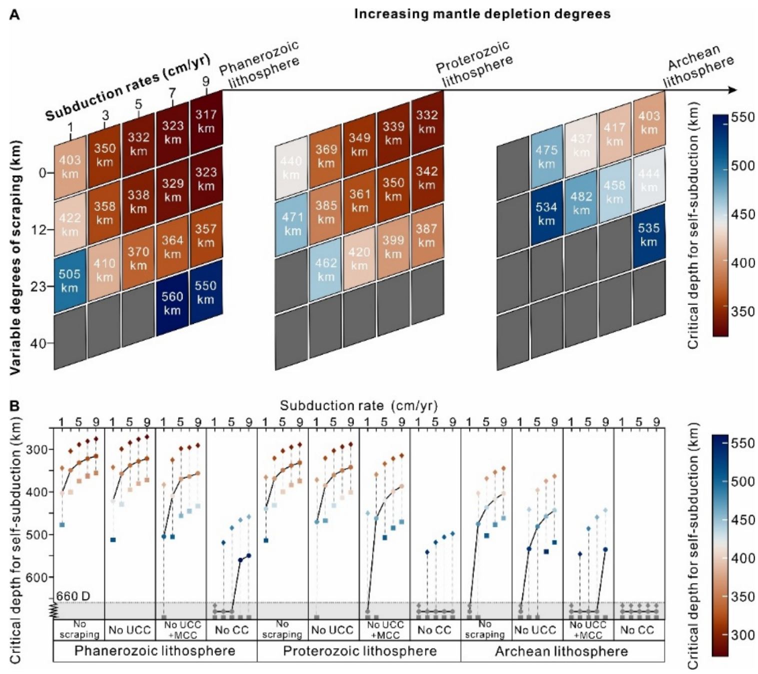

Figure 1: (A) The critical depths for self-sustained continental subduction, as a function of the SCLM compositions, subduction rates and thicknesses of scraping CC. An average value of 38 TN/m is assumed for the overall resistance. (B) The predicted critical depths under the assumption of the upper limit, average value, and lower limits of possible resistance forces, i.e., 27 TN/m (diamond), 38 TN/m (cycle) and 49 TN/m (square). The grey blocks in (a) and (b) indicate the self-sustained subduction cannot occur even with a continental slab extending to 660D. The colorbar is used to represent the critical depth.

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Implementation of anisotropic viscosity in ASPECT

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Keywords — numerical model, anisotropic viscosity

Since the recent discovery of the relationship between olivine crystal preferred orientations (CPO) and viscous anisotropy, many studies have been searching for a representation of anisotropic viscosity (AV) in numerical models. Lev and Hager (2011) simplified the problem by assuming transverse isotropy and used the ratio between shear viscosity and normal viscosity as the magnitude of anisotropy. However, this approach is only useful in two dimensions and cannot accommodate more complex anisotropic viscosities that have been associated with anisotropic fabrics in laboratory studies. To accommodate such 3-dimensional fabrics, Signorelli et al. (2021) represented anisotropic flow as follows:

$$\dot{\varepsilon}_i = \gamma \cdot J_{Hill}(\sigma)^{n-1} A_{ij} \sigma_j,$$

where A_{ij} represents the direction dependency as a rank 4 tensor, which is reduced into a 6-by-6 matrix due to its symmetric properties. This anisotropy tensor has only 6 independent components derived from Hill (1948)'s orthotropic yield criteria (Hill's coefficients: F, G, H, L, M, and N), which we compute from the olivine CPO:

$$A = \frac{2}{3}\begin{bmatrix} F+H & -F & -H & 0 & 0 & 0 \\ -F & G+F & -G & 0 & 0 & 0 \\ -H & -G & H+G & 0 & 0 & 0 \\ 0 & 0 & 0 & L & 0 & 0 \\ 0 & 0 & 0 & 0 & M & 0 \\ 0 & 0 & 0 & 0 & 0 & N \end{bmatrix}$$

The time-dependent evolution of CPO-induced AV and its impact on flow have not been considered in geodynamic models and have never been tested with 3D models. We implement anisotropic viscosity tensor using the approach of Signorelli et al. (2021) and using visco-plastic rheology within the finite element code ASPECT. The anisotropic viscosity tensor is stored in the compositional field and is updated each time step when the conditions for dislocation creep are fulfilled. The computation of anisotropic viscosity tensor requires the texture information to be stored as particle properties and therefore this material model requires the use of particles. We test our implementation with a shear box setting and compare the results and computation efficiency by comparing a regular visco-plastic material model and with an anisotropic viscosity material model. We anticipate that this implementation will enable the use of ASPECT to understand the impact of anisotropy viscosity on a wide range of geodynamics problems.

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Earthquake nests are defined as volumes of intense intermediate-depth seismicity which are isolated from any surrounding seismic activity. The high seismic activity within these earthquake nests occurs continuously and thus sets them apart from other seismic sequences such as earthquake swarms or aftershocks. Among the known earthquake nests, the Hindu Kush earthquake nest is the most active and has produced a large earthquake ($M_W \geq 7$) every 10-15 years. The intermediate-depth seismicity in this nest extends to larger depths than in other earthquake nests (up to 250 km) and is characterized by a bimodal distribution with an earthquake gap at approximately 150 km depth. Despite the depth of these earthquakes, they pose a significant seismic hazard. The continuous seismic activity is commonly related to subducting and detaching slabs. Beneath the Hindu Kush, the Indian continental margin with an eclogitized lower crust subducts and detaches.

To understand the physical mechanisms and the tectonic environment of this intermediate-depth earthquake nest, we therefore aim to conduct data-driven numerical simulations to determine the deformation state in the Hindu Kush and the controlling mechanisms of the detachment process. As a first step, we used the open source julia package GeopyhscialModelGenerator.jl to create a synopsis of existing datasets of earthquake locations, seismic tomographies, Moho maps etc.

Based on this data collection, we then create 2D numerical models to determine the role of different parameters on slab detachment and stresses within the Indian slab. In particular, we aim to quantify the impact of subducted continental crust on slab detachment depths.

Linking Earth's Climate and Mantle Dynamics through Paleogeographic Reconstructions

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Keywords — atmosphere-mantle interaction, paleogeography, numerical modelling

The long-term evolution of Earth's climate is intricately linked to geospheric changes, resulting in complex interactions of mantle dynamics, lithospheric processes and climate evolution. Traditionally, Earth System Models of varying complexity have been employed to simulate numerous oceanic, atmospheric, and terrestrial processes. However, these models do not include a crucial component of the Earth system: the interior. Mantle processes drive plate tectonics and significantly influence atmospheric CO_2 levels through degassing, impacting Earth's climate. The configuration of continents and the concentration of greenhouse gases, both governed by plate tectonics, are vital in shaping Earth's carbon cycle and thereby climate. A key mechanism that links both atmosphere and mantle is the erosion and susequent transport and sedimentation of weathered material into subduction zones. The influx of sediments into subduction zones has been shown to alter the rheology of the subducting slab, influencing subduction speed and slab chemistry, which in turn affects mantle convection processes (e.g., Bello et al., 2015).

Here, we present a framework for coupling the PANALESIS paleogeographic reconstruction (Vérard, 2019) to an Earth System Model of Intermediate Complexity (EMIC) and a mantle convection model. Climate outputs from the EMIC drive a landscape evolution model to calculate sediment influx into subduction zones. Degassing rates from mantle convection simulations are used to determine atmospheric CO_2 levels and generate climate lookup tables for various degassing scenarios. These datasets inform a temporally continuous carbon cycle model to update previous $p\mathrm{CO}_2$ curves for the Phanerozoic and beyond. This approach is a step towards an integrated setup of lithospheric and mantle dynamics and climate modeling.

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Can low-temperature thermochronometers record the timing of lithospheric delamination?

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Keywords — lithospheric delamination, thermochronology, crustal thermal processes

Lithospheric delamination is a process by which continental lithospheric mantle and possibly lower crust is separated from a continental plate and sinks into the convecting mantle [e.g., 1, 2]. This process typically occurs in regions undergoing or having undergone significant tectonic shortening and thickening, and delamination can result in thinner than expected mantle lithosphere, regional magmatism, and land surface uplift. Removal of the mantle lithosphere and/or regional magmatism both provide a heat source to the crust that would be expected to increase crustal temperatures over timescales of up to tens of millions of years. Furthermore, land surface uplift can produce an erosional response that results in enhanced rates of rock exhumation. Both of these effects should affect low-temperature thermochronometers, which are radiometric dating systems in minerals that record the time since a parcel of rock cooled below a given temperature, typically 50—350 °C (i.e., its effective closure temperature). This raises the question: can low-temperature thermochronometers record the timing of lithospheric delamination?

In short, probably not. We explored this question using numerical models in the 1D thermal and thermochronometer age prediction software T_c1D [3]. The simulation duration was 50 million years with initial thicknesses of 35 km and 90 km for the crust and mantle lithosphere, respectively. We considered generic delamination scenarios focussing on the thermal effects of delamination for both episodic removal of the whole mantle lithosphere [e.g., 1] and more gradual mantle lithosphere removal due to density inversion of the lowermost crust and mantle relative to the surrounding asthenosphere [e.g., 2]. The timing of mantle lithosphere in the episodic scenarios was varied from 50—10 Ma, while the gradual reduction occurred over times of 5—50 My. Although both scenarios produce younger predicted thermochronometer ages compared to scenarios without delamination, the predicted ages do not correspond to the timing of mantle lithosphere removal. Current work is exploring the role of enhanced rock exhumation rates due to surface uplift on the predicted thermochronometer ages. Although this could possibly produce even younger predicted thermochronometer ages, it is still unlikely that the timing recorded by the ages would correspond to the timing of delamination.

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Velocity structure, plate flexure and tectonic tilt along the Emperor Seamount Chain

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Keywords — seismic structure, effective elastic thickness, Emperor Seamount Chain

The Hawaii-Emperor seamount chain stretches westward from the “Big Island” of Hawaii for over 6000 km until the oldest part of the chain are subducted at the Kuril-Kamchatka and Aleutian trenches. Regarded as the iconic hotspot-generated seamount chain it has been sampled, mapped, and studied to give insights into numerous oceanic phenomena, including seamount and volcano formation and associated intraplate magma budgets, the past absolute motions of the Pacific plate, the drift of the Hawaiian plume, and the thermal and mechanical properties of oceanic lithosphere. Previous work[1] used a high-resolution free-air gravity anomaly and high-resolution bathymetry data set, together with fully 3-dimensional flexural models with variable volcano load and infill densities, to estimate the optimal effective elastic thickness, T_e, and load and infill densities along the Emperor Seamount Chain. Here, we use these parameters to calculate the tectonic tilt of a pre-existing volcano that occurs as each new volcano in a seamount chain is progressively added by flexure to the Pacific oceanic plate. We found tilts in the range 0.1-3 degrees which are modest compared to other cases of progressive flexure, for example, at seaward dipping reflector sequences in volcanic rifted margins (~5-15 degrees) but may be significant enough to modify the morphology of volcano summits and the stratigraphy of the sequences that accumulate in their flanking moats. They may also modify the physical properties of the edifice such as their magnetisation vectors.

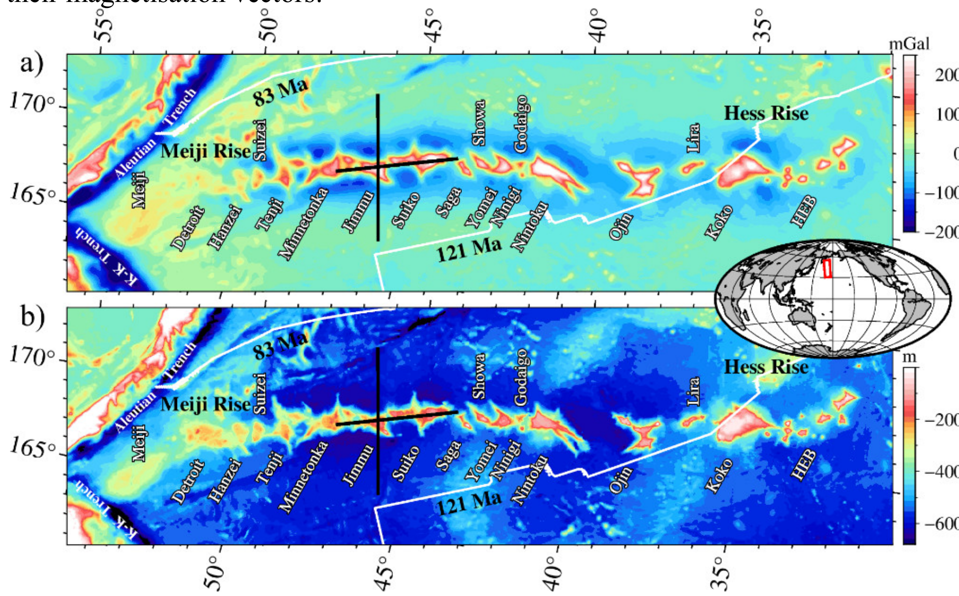

Figure 1: Oblique Mercator projection of the Emperor Seamounts region showing the free-air gravity anomaly (a) and bathymetry (b) of the Emperor Seamount chain. White lines show the 83 and 121 Ma isochrons. Thick black lines show seismic refraction and reflection Lines 1 and 2. K-K = Kuril-Kamchatka. Inset locates the Emperor Seamount chain in the northwest Pacific Ocean.

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Impact of metamorphic transformations on the rheology of rocks: insights from numerical models

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Keywords — volume change, weakening, strain localization, kinetics

Density and viscosity variations triggered by metamorphic transformations can lead to important changes in rock strength. Implementing these dynamic effects, especially important changes in viscosity, is not straigthforward as it can lead to mesh-dependent results. The first aim of our poster is therefore to present numerical methods allowing to account for the dynamic effects of a transformation (e.g. volume and viscosity changes) in models without mesh dependency. In a second time, we propose to illustrate the impact of (i) reaction-induced volume changes on brittle failure and (ii) phase nucleation on the weakening of rocks. We show that transformation-induced volume change occurring out of equilibrium can, by itself, generate sufficient shear stress to fail the rocks at high-pressure conditions (Fig.1a). Intermediate-depth earthquakes in continental subduction zones could therefore be explained by volume changes induced by eclogitization. The interplay between negative volume change and frictional plastic yielding can also enhance the propagation of the eclogitization process by a runaway mechanism as long as the reaction is not limited by the lack of reactants (Fig. 1b). Eventually, heterogeneous nucleation controlled by the strain energy has been implemented. Results from these models show that nucleation of weak and dense reaction products has an even greater impact than the intrinsic properties of these reaction products. Weakening in these simulations is triggered by the propagation of plastic shear bands between closely spaced nuclei that generate significant stress increases in their vicinity (Fig. 1c).

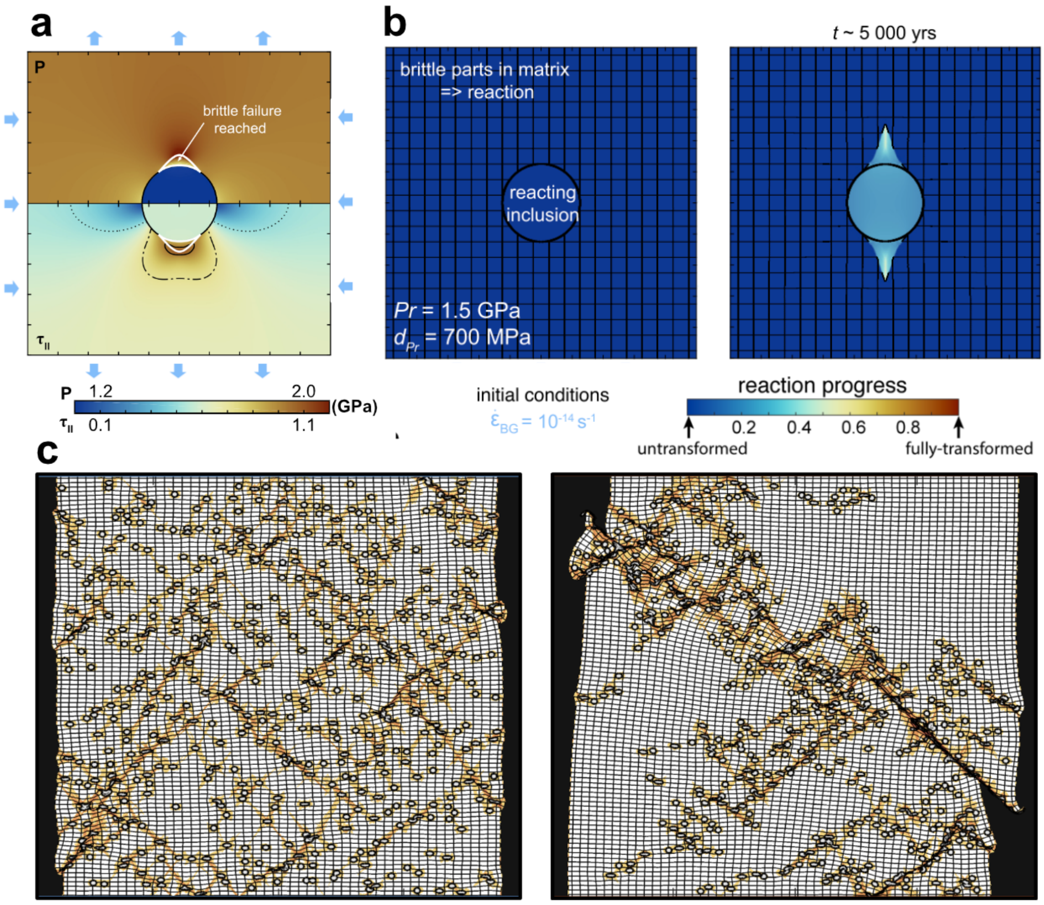

Figure 1: *(a) Embrittlement due to volume change shown in the pressure field (top) and shear stress field (bottom). (b) Transformation propagation in areas of the model where sufficient accumulated plastic strain has been reached. (c) Comparison of strain localisation between model with homogeneous nucleation (left) and strain energy controlled nucleation (right)*

Modeling the Evolution of Transform Faults: Influence of Mid-Ocean Ridge Spreading Dynamics

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Keywords — transform fault, mid-ocean ridge

The transform faults, prominent plate boundaries situated on the seafloor, have long been investigated for their role in modulating the spreading mechanisms associated with adjacent mid-ocean ridges. The presence of transform faults may either augment or weaken magmatism along the ridge, influencing fault patterns, crustal thickness, and lithospheric characteristics in the region. However, the reciprocal impact of spreading rate and magma supply on the development and demarcation of transform faults remains controversial.

Our study focuses on the Mid-Atlantic Ridge (MAR) between latitudes 30°N and 35°N, characterized by the presence of significant transform faults - Atlantis, Hayes, and Oceanographer - alongside others that have been abandoned. Recent analyses of multi-beam bathymetry and seafloor magnetic data demonstrate that the spreading rate of the ridge varies due to the distance to these transform faults and shows asymmetries on both side of the ridge. Additionally, observational data suggest that while long-offset transform faults generally maintain stability despite fluctuations in magma supply at adjacent ridge segments, shorter-offset faults tend to be abandoned in response to axial reorganizations by e.g. ridge propagation.

In this study, we aim to construct a three-dimensional model to elucidate the dynamics of transform faults in response to fluctuations in magma supply at adjacent ridge systems. The ridge-spreading model was developed using the open-source geodynamic tool, Advanced Solver for Problems in Earth's Convection (ASPECT). This model incorporates varied lengths of ridge offsets, transform fault rheology, ridge-spreading rates, and magma supply variations. By analyzing the evolution of ridge offsets, we assess whether shorter transform faults are more likely to be abandoned or replaced by non-transform offsets compared to longer transforms.

Investigating Interactions between Subduction Initiation and Plate Reorganizations from A Global Perspective

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Keywords — Subduction initiation, plate reorganization, numerical modeling

Subduction initiation (SI) creates new subduction zones and provides driving forces for plate tectonics, being a key process of the plate tectonic regime on Earth. Although SI has been extensively studied in 2D regional numerical models, a global perspective on SI remains elusive. Geological observations and plate reconstructions both indicate that SI is coeval with the global or local plate reorganizations. The tectonic plate reorganizations are marked by rapid changes of plate motions occurring over a few million years and are recurrent throughout Earth's history. One of the most well-known plate reorganization events occurred at approximately 53-47 Ma ago, characterized by the bending of Hawaii-Emperor Seamount Chain. Simultaneously, several SI events occurred in the Pacific Plate, such as Izu-Bonin-Mariana (~52 Ma) and Tonga-Kermadec (~50 Ma). The relationship between SI and plate reorganizations, as well as their collective impacts on continental evolution, is poorly understood. This study is committed to exploring the interaction between SI and plate reorganizations using 3D global mantle convection models. We reproduce SI coeval with plate reorganizations in these numerical models. We analyze the changes of stress distribution in the lithosphere during the plate reorganizations and their effects on SI. A variety of different interplays between SI and tectonic plates reorganizations have been identified based on their chronology and driving mechanisms. In our numerical results, we find that most of SI events prefer to occur in the young oceanic basins, inducing by convergence forces from the plate reorganizations. Two major plate reorganization events, occurring at 100 Ma and 50 Ma ago respectively, are used to compare with the numerical modeling results. The effects of key parameters, such as lithosphere thickness and strength, will be examined. Plate reconstruction models will also be included to study the interaction between SI and plate reorganizations in the future.

Interactions between Slab Remnants in the Transition Zone and Mantle Plumes

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Keywords — Mantle Plumes, Slab Remnants, Magmatism, Mantle Transition Zone

Understanding the interactions between mantle plumes and slab remnants in the mantle transition zone is important for revealing mantle convection patterns, material and fluid cycling, and magmatism. In regions affected by fossil and recent subduction events, ascending mantle plumes often interact with slabs in the transition zone. However, our understanding of these processes are still not well understood.

This study investigates the main factors influencing mantle plume evolution through high-resolution thermomechanical modeling using I2ELVIS[1]. Our models explore how the presence, physical properties, and shapes of slab remnants affect the ascent of mantle plumes. We analyzed factors such as slab gaps, slab thickness, and temperature anomaly of the mantle plume to understand their impact on splitting plumes and their ascend towards the surface. Special attention was given on how slab remnants in the transition zone alter the flow path of mantle plumes, causing bending, branching, or local ascent obstruction. We aim to quantify the impact of slab remnants on magma distribution and fluxes. Our results can be compared with Cenozoic magmatic regions widely distributed in Southeast Asia.

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Coble Creep May Control Lower Mantle Rheology

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Constraining the dynamics of Earth's silicate rich lower mantle informs our understanding of the entire planet. Of the lower mantle's set of phases, MgSiO3 bridgmanite is by far the most influential. Occupying up to 70% of the Earth's lower mantle volume, the ubiquity of this mineral suggests that it controls much of the lower mantle's thermal and chemical transport. Bridgmanite is stable at depths exceeding 660 km following the decomposition of ringwoodite to $(\mathrm{Mg}, \mathrm{Fe})\mathrm{SiO3}$ and $(\mathrm{Mg}, \mathrm{Fe})\mathrm{O}$. Currently, the dominant deformation mechanism of Earth's lower mantle has long been speculated. Until recently, the lack of seismic anisotropy throughout much of the lower mantle has led many to suggest that diffusion creep is preferable to dislocation creep, in which the latter typically leaves a seismically observable signature because of the crystal preferred orientation generated by specific crystallographic slip systems. Nevertheless, this stance has recently been questioned due to the possibility of dislocation climb, which, unlike dislocation glide, generates no seismic anisotropy. The distinct advantage of dislocation creep for geodynamic models is the lack of dependence on the grain size, a much-contested parameter. Furthermore, unlike diffusion creep, dislocation creep adheres to a linear dependence on the system's shear stress. This property facilitates the propensity for dislocation creep to generate low viscosities under conditions of high stress.

Nevertheless, both pure climb creep and Nabarro-Herring creep are intrinsically rate limited by the slowest diffusing species within the lattice. Thus, models suggest both Nabarro-Herring and pure-climb require relatively high vacancy concentrations, $\mathrm{X_V}$, to explain the Earth's observed viscosity profile, greater than $X_V = 10^5$. The incorporation of hydrogen may generate the most likely sources of such vacancies. Another possible explanation is that materials could be deforming via Coble creep. This diffusion mechanism facilitates the propagation of vacancies and atoms along grain boundaries rather than through the lattice interior. However, to date, relatively poor constraints have been placed on the essential parameters of grain boundary diffusivity and width, not to mention the mean grain size of the lower mantle. Mineral physics has strengthened our rheological understanding of the lower mantle through computational and experimental approaches alike. Deformation experiments performed in either diamond anvil cell or D-DIA apparatus allow for the in-situ measurement of stress-strain relations. Such experiments performed on mantle minerals and analogues can be used in conjunction with microstructure analysis of quenched samples.

On the other hand, computational methods have modelled the kinetics of processes such as diffusion and dislocations, and more recently, grain boundaries. Such approaches have led to an enhanced understanding of the different pathways through which atoms migrate, as well as the relative strength of slip systems within lower mantle minerals. Grain boundaries have shown to influence the rheology of polycrystalline aggregates through the nucleation of dislocations and the migration of interfaces. Nevertheless, it is through the process of Coble creep that the role of grain boundaries in Earth materials is most important. Coble like its lattice counterpart, Nabarro-Herring, deforms a material through the diffusional flux of atoms and vacancies between different surfaces. However, unlike Nabarro-Herring, Coble creep is an order of magnitude more sensitive to the grain size of the medium. Furthermore, grain boundaries typically facilitate faster diffusion along the interface when compared to the lattice interior, a process that further controls wider properties such as ionic conductivity.

This work utilises a developed Machine Learning Potential to establish low energy grain boundary structures for MgSiO3 bridgmanite at six different orientations. Following the analysis of grain boundary properties such as width, energy and structure, the diffusivity of the grain boundary region is obtained through large scale molecular dynamics calculations and the mean squared displacement analysis. The properties of grain boundary width and diffusivity are then used to place constraints on the grain-size dependent viscosity of the lower mantle via the Coble Creep formula.

Integrating Lithospheric and Mantle Dynamics to Quantify Plate Driving Forces

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The coupling between lithospheric plates and underlying mantle dynamics is essential for comprehending surface tectonics. However, integrating the complexities of the plate–mantle system into a unified model is challenging due to the interaction of various physical processes governing mantle flow across different time and length scales, as well as the need to account for physical properties that vary significantly from the Earth's surface to the core–mantle boundary.

To address this, we use global mantle convection models that combine data from several geoscientific disciplines. Specifically, our models include: (1) observed surface topography, (2) crustal thickness data from the CRUST1.0 model and lithospheric thickness data from Priestley et al. (2018), (3) a thermal model of the lithosphere (Osei Tutu et al., 2018), (4) weak plate boundaries from the Global Earthquake Model, (5) sub-lithospheric mantle structures from the LLNL-G3D-JPS global tomography model, and (6) subducted slab geometries based on the Slab2 model. These models use adaptive mesh refinement (minimum cell size ∼ 8 km) to accurately represent the present-day mantle deformation field and deform the computational grid to incorporate the observed topography.

These models are developed in a modular manner using the geodynamic modeling software ASPECT and the Geodynamic World Builder, allowing us to combine different features and datasets. By adjusting rheological parameters, we optimize the fit to observed plate deformation and assess the relative significance of mantle-driving forces. We find that a low-viscosity mid-mantle layer (660–1000 km depth) is required for slabs to effectively transfer slab pull forces to the surface plates. Our best-fit models have plate boundaries that are 3 to 4 orders of magnitude weaker than the surrounding lithosphere and low asthenospheric and mid-mantle viscosities (∼1e20 Pa s). They achieve a 94% directional fit and a speed residual of 0.7 cm/yr relative to the observed plate motion, and are comparable or better than the available models. Including topographic variations allows us to compute a Earth-like stress state in our best-fit models.

These findings enhance our understanding of the driving mechanisms behind mantle flow and plate motions, providing valuable global constraints for regional studies of plate boundary dynamics and surface processes.

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