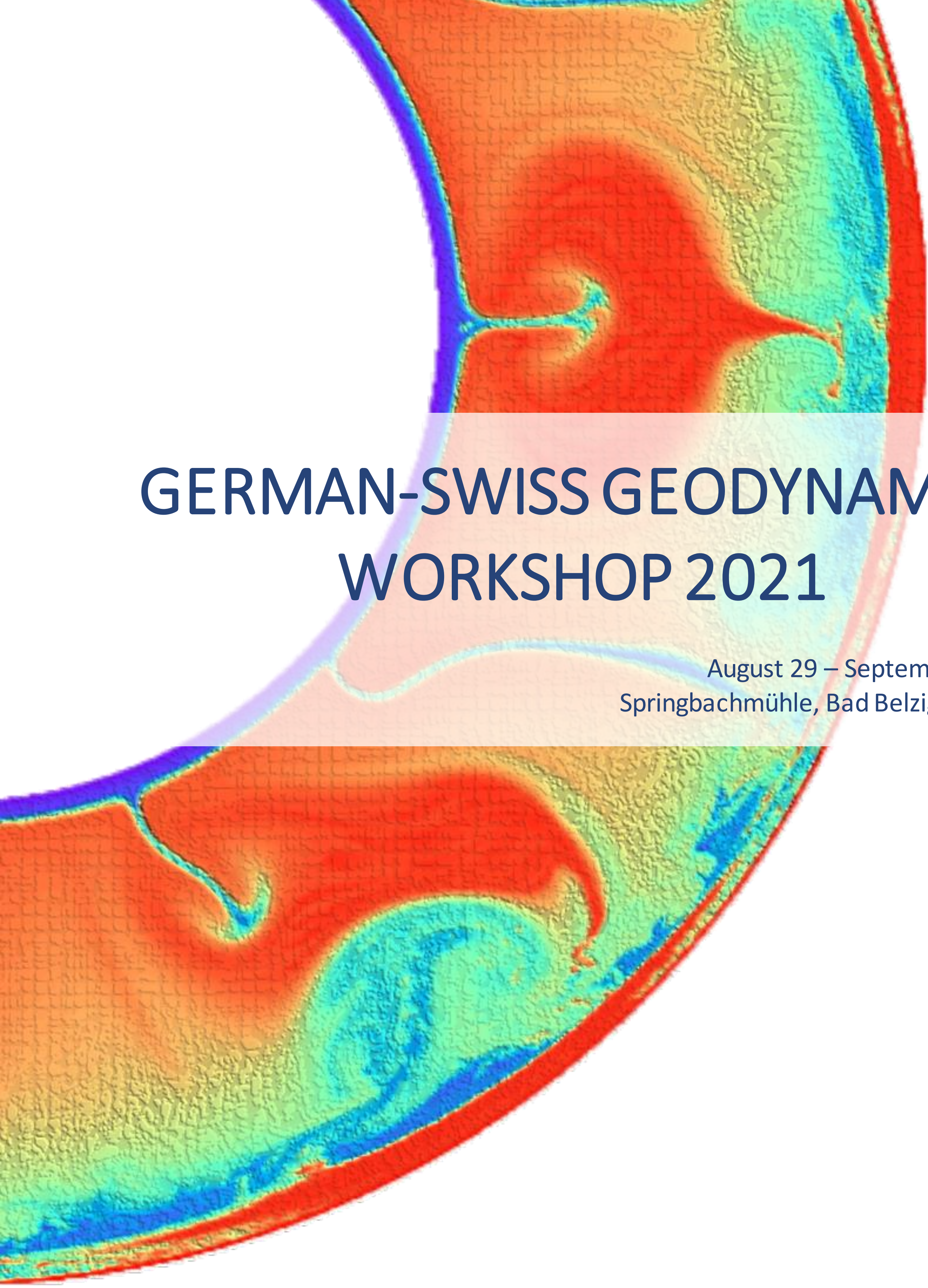

GERMAN-SWISS GEODYNAMICS WORKSHOP 2021

August 29 – September 1 2021
Springbachmühle, Bad Belzig, Germany

Deutsche Geophysikalische Gesellschaft e.V.

Freie Universität Berlin

TRR 170 LATE ACCRETION ONTO TERRESTRIAL PLANETS

DFG Deutsche Forschungsgemeinschaft

Scientific & Local Organizing Committee (SOC/LOC):

- Lena Noack (FU)
- Gregor Golabek (Uni Bayreuth)
- Alexander Balduin (FU)
- Caroline Brachmann (DLR)
- Oliver Henke-Seemann (TU / FU)
- Enrique Sanchis (FU)
- Julia Schmidt (FU)
- Sara Vulpius (FU)

Venue:

Springbachmühle Belzig
www.springbachmuehle.de
Mühlenweg 2
14806 Bad Belzig

Emergency contact:

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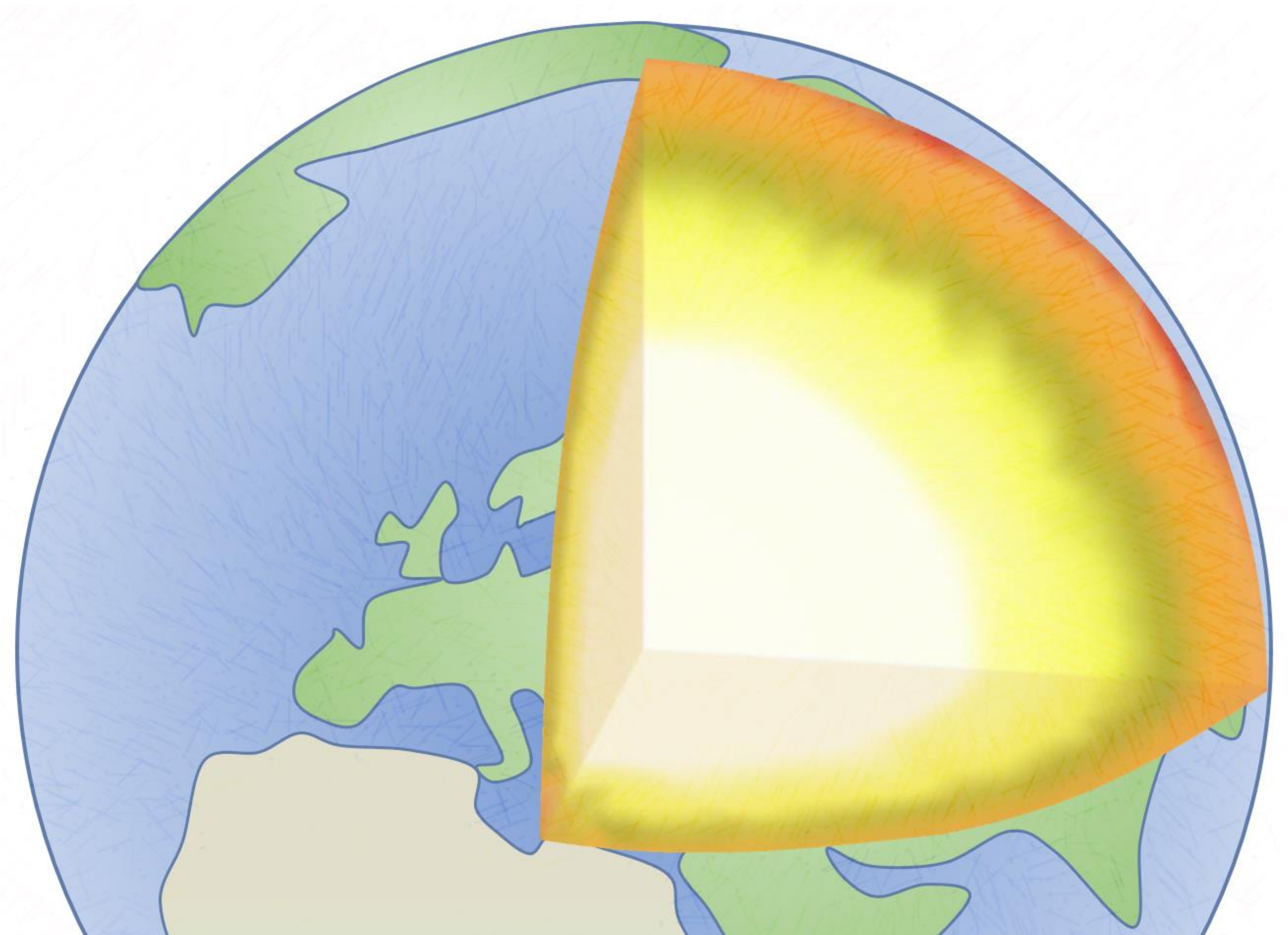
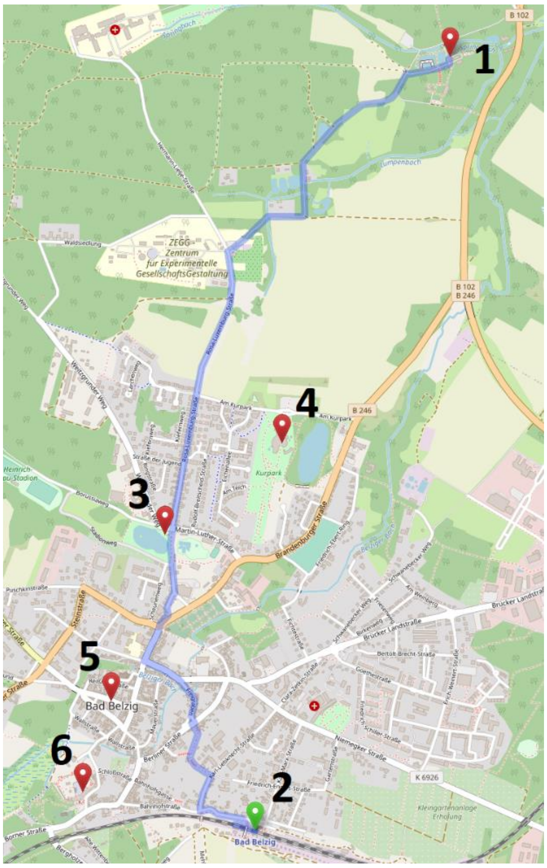


Bad Belzig map:

Directions from Bahnhof, Bad Belzig to Springbachmühle Belzig (~52 min on foot).



Landmarks:

1 Springbachmühle Belzig (workshop's venue)
2 Bahnhof, Bad Belzig
3 Haus am See (workshop's dinner)
4 SteinTherme Bad Belzig
5 Altstadt Bad Belzig
6 Castle Burg Eisenhardt

Workshop's Dinner:

The workshop's dinner will take place on Tuesday 31 August 2021 from 19:00h at:

Haus am See
Martin-Luther-Straße 14,
14806 Bad Belzig

*Directions from Springbachmühle Belzig to Haus am See on the left map (~32 min on foot).

Participants list:

Nr.	Last Name	First Name
1	Agarwal	Siddhant
2	Balázs	Attila
3	Balduin	Alexander
4	Ballantyne	Harry A.
5	Ballmer	Maxim D.
6	Baumeister	Philipp
7	Berlie	Nicolas
8	Brachmann	Caroline
9	Breuer	Doris
10	Brune	Sascha
11	Cacace	Mauro
12	Cheng	Karwai
13	Desiderio	Matteo
14	Fuchs	Lukas
15	Gerya	Taras
16	Glerum	Anne
17	Golabek	Gregor J.
18	Gray	Timothy
19	Gülcher	Anna
20	Henke-Seemann	Oliver
21	Jain	Charitra
22	Kaus	Boris
23	Király	Ágnes
24	Kiss	Dániel
25	Le Breton	Eline
26	Liu	Mingqi
27	Manjón-Cabeza Córdoba	Antonio
28	Marquart	Gabriele
29	Meier	Tobias G.
30	Moser	Lucas
31	Neuharth	Derek
32	Noack	Lena
33	Patočka	Vojtěch
34	Piccolo	Andrea
35	Pons	Michaël
36	Rogger	Julian
37	Rolf	Tobias
38	Roy	Poulami
39	Rummel	Lisa
40	Rüpke	Lars
41	Sanchis	Enrique
42	Scheck-Wenderoth	Magdalena
43	Schmalholz	Stefan Markus
44	Schmeling	Harro
45	Schmidt	Julia M.
46	Schuler	Christian
47	Spang	Arne
48	Steinberger	Bernhard
49	Stemmler	Dominic
50	Tackley	Paul J.
51	Thielmann	Marcel
52	van Agtmaal	Luuk
53	Vulpius	Sara
54	Wallner	Herbert
	Online participants:	
55	Becker	Thorsten W.
56	Davies	Hannah S.
57	Fleury	Aymeric
58	Fosso Teguia Moussé	Estelle Eric
59	Maurice	Maxime

Monday, 30 August 2021		
	Morning Session Day 1 (chair: Gregor J. Golabek)	
10:00-10:50	***Keynote***: Gülcher et al.	Coupled evolution of primordial and recycled reservoirs in Earth's mantle, and their present-day seismic signatures
10:50-11:10	Ballmer et al.	Crystallization of the Basal Magma Ocean: Consequences for Planetary Evolution
11:10-11:30	Desiderio et al.	The interplay between recycled and primordial heterogeneities: predicting Earth mantle dynamics via numerical modeling
11:30-11:50	Paul J. Tackley	On the use of Laboratory Rheological Data in Geodynamical Simulations
11:50-12:10	Fuchs & Becker	Rheological Memory in Plate-like Mantle Convection
12:10-12:30	Thielmann & Schmalholz	Contributions of grain size reduction and shear heating to slab detachment
12:30-13:30	Lunch Break	
	Afternoon Session Day 1 (chair: Paul J. Tackley)	
13:30-13:50	Fleury et al.	Thermal evolution of terrestrial planets with 2D and 3D geometries
13:50-14:10	Breuer et al.	Interior Structure and Thermal State of Venus
14:10-14:30	Ballantyne et al.	Identifying the Sweet Spot for an Impact-Induced Martian Dichotomy
14:30-14:50	Sanchis & Noack	Effects of tidal heating in Proxima Centauri b's thermal evolution
14:50-15:10	Meier et al.	Interior dynamics of tidally-locked super-Earths: Comparing LHS 3844b and 55 Cnc e
15:10-16:00	***Keynote***: Maurice et al.	The (Very) Early Lunar Mantle Dynamics
16:00-18:00	***Poster Session***	
1.	Becker & Fuchs	Dynamic weakening mechanism in Earth's mantle - A comparison between damage-dependent weakening and grain-size sensitive rheologies
2.	Berlie et al.	Towards a new method for solving tensile plasticity in magmatic systems
3.	Cheng et al.	Martian dichotomy: Impact-induced crustal production in mantle convection models
4.	Davies et al.	The Super-tidal cycle: how the supercontinent cycle controls the tides on our planet
5.	Glerum & Brune	Data-driven models of the East African Rift System: dynamic topography, strain localization and stress distribution
6.	Golabek & Jutzi	Modification of icy planetesimals by early thermal evolution and collisions: Constraints for formation time and initial size of comets and small KBOs
7.	Gray et al.	The emergence of modern plate tectonics and complex life: A global scale numerical modelling approach
8.	Gülcher et al.	Strain-weakening rheology in Earth's lower mantle and its effect on the planform of mantle flow
9.	Jain & Sobolev	Rheological controls on early-Earth dynamics
10.	Liu & Gerya	Self-organisation of magma supply controls crustal thickness distribution and tectonic pattern at mid-ocean ridges
11.	Long et al.	Interaction of thermo-chemical upwellings with the Mantle Transition Zone
12.	Manjón-Cabeza et al.	Systematics of the mobile-lid regime with grain-size evolution
13.	Neuharth et al.	Numerically modelling the formation of continental microplates through rift linkage
14.	Piccolo et al.	Interaction of proto plate-tectonic cells during the Archean: insight from 3D large scale modeling
15.	Pons & Sobolev	Interplay between the shortening magnitude and subduction dynamics in the Central Andes
16.	Rogger et al.	Data-based modelling of the atmospheric carbon mass balance from the Devonian to the present
17.	Rolf & Arnould	Tectonic regime control by strain-induced plastic weakening in global-scale mantle convection simulations
18.	Rummel et al.	Past and future volcanism in Germany, models and consequences
19.	Stemmler et al.	Impact of tectonic and surface processes on biodiversity
20.	Van Agtmaal et al.	India-Eurasia corner collision and extrusion: inferences from coupled thermo-mechanical and surface processes 3D models
21.	Wallner & Schmeling	Dykes in a crustal two-phase flow medium

Tuesday, 31 August 2021		
	Morning Session Day 2 (chair: Lisa Rummel)	
10:00-10:50	***Keynote***: Ágnes Király	Dynamic interactions between subduction zones
10:50-11:10	Rüpke et al.	Faulting and magmatism at ridge-transform intersections
11:10-11:30	Balázs et al.	Subsidence history, heat flow evolution and stratigraphy of transform and passive margins simulated by coupled 3D thermo-mechanical and surface processes models
11:30-11:50	Brune et al.	Life and death of normal faults: Quantitative analysis of fault network evolution in 3D rift models
11:50-12:10	Bagge et al.	Glacial-isostatic adjustment models using geodynamically constrained 3D Earth structures
12:10-12:30	Scheck-Wenderoth & Cacace	Linking Geologic and Geodynamics Modelling - a Quantitative Exploration Tool
12:30-13:30	Lunch Break	
	Afternoon Session Day 2 (chair: Gabriele Marquart)	
13:30-14:20	***Keynote***: Harro Schmeling	Melt transport mechanisms: from melt segregation, extraction to the formation of crustal magmatic systems
14:20-14:40	Kiss et al.	2D thermo-mechanical-chemical coupled numerical models of interactions between a cooling magma chamber and a visco-elasto-plastic host rock
14:40-15:00	Vulpius & Noack	The fate of volatiles during magma body crystallization
15:00-15:10	Break	
15:10-15:30	Brachmann et al.	Modelling the composition of volcanic gases on young terrestrial planets in the C-H-O-N-S system
15:30-15:50	Noack & Brachmann	Influence of plate tectonics on outgassing efficiency and gas composition
15:50-16:10	Baumeister et al.	Abundance of water oceans on high-density exoplanets from coupled interior-atmosphere modeling
16:10-16:30	Gerya et al.	Computational biogeodynamics: coupling of Earth’s interior, atmosphere, ocean, climate, landscape and life evolution models
19:00	Workshop’s Dinner	

Wednesday, 1 September 2021		
	Morning Session Day 3 (chair: Doris Breuer)	
10:30-10:50	Schmidt & Noack	Modelling the redistribution of trace elements for higher upper mantle pressures
10:50-11:10	Vojtěch Patočka	LIOUSHELL: Computing True Polar Wander on Dynamic Planets
11:10-11:30	Agarwal et al.	Deep learning for surrogate modelling of 2D mantle convection
11:30-11:50	Moser & Baumann	geomIO4py – An updated Python version of geomIO to create the 3D initial configuration of thermomechanical simulations
11:50-12:10	Schuler et al.	Reduced basis method for Stokes flow in geodynamic modelling
12:10-12:30	Kaus et al.	Developing the next generation geodynamics codes using Julia
12:30-13:30	Lunch Break	
	Afternoon Session Day 3 (chair: Boris Kaus)	
13:30-13:50	Spang et al.	Geodynamic inversion with uncertain initial geometries
13:50-14:40	***Keynote***: Stefan M. Schmalholz	Thermo-Hydro-Mechanical-Chemical modelling: applications to dehydration vein formation and reactive melt migration
	Departure	

Abstracts (in alphabetical order):

Deep learning for surrogate modelling of 2D mantle convection

SIDDHANT AGARWAL[1,2*], NICOLA TOSI[1], PAN KESSEL[2], DORIS BREUER[1], GRÉGOIRE MONTAVON[2]

[1] Planetary Physics, Institute of Planetary Research, DLR, Berlin, Germany (*correspondence: agsiddhant@gmail.com)

[2] Machine Learning Group, Berlin Institute of Technology, Berlin, Germany

The key parameters to mantle convection simulations are poorly constrained. Whereas the outputs can sometimes be observed directly or indirectly using geophysical and geochemical data obtained via planetary space missions. Hence, the "observables" can be used to constrain parameters governing mantle convection.

Given the computational cost of running each forward model in 2D or 3D (on the scale of hours to days), it is often impractical to run several thousands of simulations to determine which parameters can satisfy a set of given observational constraints. Traditionally, scaling laws have been used as a low-fidelity alternative to overcome this computational bottleneck. However, they are limited in the amount of physics they can capture and only predict mean quantities such as surface heat flux and mantle temperature instead of spatio-temporally resolved flows. Using a dataset of 10,000 2D mantle convection simulations for a Mars-like planet, we show that deep learning can be used to reliably predict the entire 2D temperature field at any point in the evolution.

We first use convolutional autoencoders to compress each temperature field by a factor of 140 to a latent space representation, which is easier to predict. As in [1], we test feedforward neural networks (FNN) to predict the compressed temperature fields from five input parameters plus time. While the mean accuracy of the predicted temperature fields was high (99.30%), FNN was unable to capture the sharper downwelling structures and their advection. To address this, we use long short-term memory networks (LSTM), which have recently been shown to work in a variety of fluid dynamics problems (e.g. [2]). In comparison to the FNN, LSTM achieved a slightly lower mean relative accuracy, but captured the spatio-temporal dynamics more accurately.

[1] S. Agarwal, N. Tosi, D. Breuer, S. Padovan, P. Kessel, G. Montavon, *A machine-learning-based surrogate model of Mars' thermal evolution*, Geophysical Journal International, Volume 222, Issue 3, September 2020, Pages 1656–1670, https://doi.org/10.1093/gji/ggaa234.

[2] Arvind T. Mohan, Dima Tretiak, Misha Chertkov & Daniel Livescu (2020). *Spatio-temporal deep learning models of 3D turbulence with physics informed diagnostics*, Journal of Turbulence, 21:9-10, 484-524. 10.1080/14685248.2020.1832230

Glacial-isostatic adjustment models using geodynamically constrained 3D Earth structures

MEIKE BAGGE[1]. VOLKER KLEMANN[1], BERNHARD STEINBERGER[1,2*], MILENA LATINOVIC[1], MAIK THOMAS[1,3]

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(*correspondence: bstein@gfz-potsdam.de)

[2]Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway

[3]Freie Universität Berlin, Berlin, Germany

Glacial-isostatic adjustment (GIA) is the key process controlling relative sea-level (RSL) and paleo-topography. The viscoelastic response of the solid Earth is controlled by its viscosity structure. Therefore, the appropriate choice of Earth structure for GIA models is still an important area of research in geodynamics. Here we construct 18 3D Earth structures that are derived from seismic tomography models and are geodynamically constrained. We consider uncertainties in 3D viscosity structures that arise from variations in the conversion from seismic model to a 3D GIA model, VILMA, to investigate the influence of such structure on RSL predictions. Depending on time, location and glaciation history (ICE-5G, ICE-6G, NAICE), the uncertainties in 3D viscosities can cause relative sea-level variability of >100 m (ice center) tens of meters (peripheral) and <10 m (far-field). We also present a focus on the Central Oregon Coast and the San Jorge Gulf to create models using regionally adapted 1D structures and compare the results to RSL predictions from 3D models. The results from 1D and 3D models reveal substantial influence of lateral viscosity variations on RSL. The 3D Earth structures of this study will be available e.g., for further applications to GIA studies.

Subsidence history, heat flow evolution and stratigraphy of transform and passive margins simulated by coupled 3D thermo-mechanical and surface processes models

ATTILA BALÁZS[1*], TARAS GERYA[1], DIDIER GRANJEON[2], DAVE MAY[3], GÁBOR TARI[4]

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(*correspondence: attila.balazs@erdw.ethz.ch)

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[3]Scripps Institution of Oceanography, UC San Diego, California, USA

[4]OMV Upstream, Vienna, Austria

Transform and passive margins emerging during the continental rifting and opening of oceanic basins are fundamental elements of plate tectonics. It has been suggested that inherited structures, plate divergence velocities and surface processes exert a first order control on the topographic and bathymetric evolution and thermal history of these margins and related sedimentary basins. Their complex spatial-temporal dynamics have remained controversial. Here, we conducted 3D magmatic-thermo-mechanical numerical experiments with the code I3ELVIS coupled to surface processes modelling (FDSPM) to simulate the dynamics of continental rifting, continental transform fault zone formation and persistent oceanic transform faulting and zero-offset oceanic fracture zones development. Numerical modelling results allow to explain the first order observations from passive and transform margins, such as diachronous rifting, heat flow rise and cooling in individual depocenters and contrasting basin tectonics of extensional or transtensional origin. In addition, the models reproduce the rise of transform marginal ridges and submarine plateaus and their interaction with erosion and sedimentation. Finally, a high-resolution 3D stratigraphic code (DionisosFlow) is used building on the thermo-mechanical model results to simulate and assess the distinct tectonic, climatic, and sedimentary processes and their role in the stratigraphy of transform margins. Comparison of model results with observations from natural examples yield new insights into the tectono-sedimentary and thermal evolution of several key passive and transform continental margins worldwide.

Beicip-Franlab is acknowledged for providing an academic license for DionisosFlow.

Identifying the Sweet Spot for an Impact-Induced Martian Dichotomy

HARRY A. BALLANTYNE[1]*, MARTIN JUTZI[1] AND GREGOR J. GOLABEK[2]

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[2]Bayerisches Geoinstitut, Universität Bayreuth, Bayreuth, Germany

The martian crustal dichotomy predominantly refers to the 4-8 km difference in elevation between the southern hemisphere and an apparent basin covering roughly 42% of the north, with this topographical picture being strongly reflected in distribution of crust below.

Most studies attempting to explain this feature have supported one of two theories; either the dichotomy formed solely through geodynamic processes [1], or a giant impact occurred that imprinted the crustal cavity in the northern hemisphere that is observed today [2]. Recent work has proved the importance of coupling these hypotheses, introducing a hybrid exogenic-endogenic scenario whereby a giant impact triggered a localized magma ocean and subsequent superplume in the southern hemisphere [3]. This has, however, only been investigated using a very limited range of initial parameters.

We aim to accurately refine this parameter-space using an extensive suite of smoothed-particle hydrodynamics (SPH) simulations, via the SPHLATCH code [4]. Each model includes the effects of shear strength and plasticity (via a Drucker-Prager-like yield criterion) as such effects have been shown to be significant on the scales concerned in this study [3,4]. Moreover, the sophisticated equation of state ANEOS is being used along with a Mars-specific solidus [5] to accurately calculate the physical environment in which such solid characteristics must be considered. For the analysis of the simulation outcomes we apply a newly developed scheme to estimate the thickness and distribution of (newly formed or re-distributed) post-impact crust.

Initial results have revealed promising hemispherical features in certain cases, with further analysis being made to compare the results to those of the observational data in a quantitative manner (e.g. through bimodal fitting of crustal thickness histograms and spherical harmonic analysis). In addition, the effects of a uniform, primordial crust being present on Mars before the dichotomy-forming event are being studied, as well as an investigation into the final distribution of the impactor material as this could be chemically distinct from the primordial martian composition. Finally, the effects of material strength have been found to be non-negligible, further highlighting the importance of such aspects on the length-scales involved in planetary collisions.

[1] Keller, T. and Tackley, P. J. (2009) Icarus, 202(2):429–443. [2] Marinova, M. M., Aharonson, O., and Asphaug, E. (2008) Nature, 453(7199):1216–1219. [3] Golabek, G. J., Emsenhuber, A., Jutzi, M., Asphaug, E. I., and Gerya, T. V. (2018) Icarus, 301:235–246. [4] Emsenhuber, A., Jutzi, M., and Benz, W. (2018) Icarus, 301:247–257. [5] Duncan, M. S., Schmerr, N. C., Bertka, C. M., and Fei, Y. (2018) Geophysical Research Letters, 45:10, 211–10,220.

Crystallization of the Basal Magma Ocean: Consequences for Planetary Evolution

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Terrestrial planets evolve through multiple magma-ocean stages during accretion and differentiation. Magma oceans become progressively enriched in FeO upon fractional crystallization (FC), which should be dominant at least in the upper mantle. The resulting upwards enrichment of the cumulate package drives gravitational overturn(s), and ultimately stabilizes a FeO- and SiO_2-enriched basal magma ocean (BMO) (Ballmer et al., G³ 2017). Alternatively, a pyrolitic BMO may be formed due to a liquid-solid density crossover at high pressures. In any case, the slowly cooling BMO is expected to freeze by FC. However, we find that the consequences of FC of the BMO are inconsistent with geophysical constraints: the first FC cumulates (mostly $MgSiO_3$) are entrained by mantle convection, but final FeO-enriched cumulates stabilize a layer at the base of the mantle with extreme density anomalies of several 100s and up to 1000s kg/m^3. This layer is several 10s of km thick (or about 9% of the initial BMO volume) and should be extremely long-lived, but is not detected by seismic imaging.

Alternatively, the BMO may have evolved by reactive crystallization (RC). As long as the BMO-mantle boundary remains exposed due to the efficient entrainment of newly-formed cumulates, the BMO reacts with mantle pyrolite due to chemical disequilibrium. We find that the final RC cumulate sequence consists of two discrete layers: the first is Mg-rich bridgmanite (~$MgSiO_3$); the second is a moderately FeO-enriched pyrolite. The first layer is entrained by mantle convection due to its intrinsic buoyancy, but may resist efficient mixing due to its intrinsic strength, potentially providing an explanation for seismic scatterers/reflectors and ancient geochemical reservoirs in the present-day mantle. The second layer is swept up into thermochemical piles due to moderate density anomalies, providing a candidate origin for thermochemical piles as imaged as large low shear-velocity provinces (LLSVP).

In a second scenario for RC of the BMO, the BMO reacts with (partially) molten subducted Hadean/Archean crust instead of with solid-state pyrolite. This scenario is attractive, because large volumes of crust may be readily delivered to the lowermost mantle, and will produce dense magmas there, which sink into the BMO to promote efficient reaction. We find that the cumulate sequence for this scenario also consists of two discrete layers, and that the first layer is also dominated by $MgSiO_3$. The second layer (which may evolve into thermochemical piles), however, is bridgmanitic instead of pyrolitic, and enhanced in Fe_2O_3 and Al_2O_3 (i.e., with high oxygen fugacity). Such thermochemical-pile compositions are indeed in excellent agreement with the seismic signatures of the large low shear-velocity provinces (Vilella et al., EPSL 2021).

Our results imply that large rocky planets such as Earth, Venus or even Super-Earths may host only a rather short-lived BMO due to efficient RC (instead of inefficient FC due to slow cooling). In turn, small stagnant-lid planets with limited crustal recycling, such as e.g. Mars, may host longer-lived BMOs (Samuel et al., JGR-planets 2021). These predictions have important implications for the long-term thermal/chemical evolution of terrestrial planets.

Abundance of water oceans on high-density exoplanets from coupled interior-atmosphere modeling

PHILIPP BAUMEISTER[1,2]*, NICOLA TOSI[1], JASMINE MACKENZIE[2], JOHN LEE GRENFELL[1]

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(*correspondence: philipp.baumeister@dlr.de)

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Liquid water is generally assumed to be the an essential factor for the emergence of life, and so a major goal in exoplanet science is the search for planets with water oceans. On terrestrial planets, the silicate mantle is a large source of water, which can be outgassed into the atmosphere via volcanism. Outgassing is subject to a series of feedback processes between atmosphere and interior, which continually shape both atmospheric composition, pressure, and temperature, as well as interior dynamics [1,2].

We present the results of an extensive parameter study, where we use a newly developed 1D numerical model to simulate the coupled evolution of the atmosphere and interior of terrestrial exoplanets up to 5 Earth masses around Sun-like stars, with internal structures ranging from Moon- to Mercury-like. The model accounts for the main mechanisms controlling the global-scale, long-term evolution of stagnant-lid rocky planets (i.e. bodies without plate tectonics), and it includes a large number of atmosphere-interior feedback processes, such as a CO2 weathering cycle, volcanic outgassing, a water cycle between ocean and atmosphere, greenhouse heating, as well as the influence of a potential primordial H2 atmosphere, which can be lost through escape processes.

We find that a significant majority of high-density exoplanets (i.e. Mercury-like planets with large metallic cores) are able to outgas and sustain water on their surface. In contrast, most planets with intermediate, Earth-like densities either transition into a runaway greenhouse regime due to strong CO2 outgassing, or retain part of their primordial atmosphere, which prevents water from being outgassed. This suggests that high-density planets could be the most promising targets when searching for suitable candidates for hosting liquid water.

[1] Tosi, N. *et al.* The habitability of a stagnant-lid earth. *A&A* **605**, A71 (2017).

[2] Noack, L., Rivoldini, A. & Van Hoolst, T. Volcanism and outgassing of stagnant-lid planets: Implications for the habitable zone. *Physics of the Earth and Planetary Interiors* **269**, 40–57 (2017).

Dynamic weakening mechanism in Earth's mantle - A comparison between damage-dependent weakening and grain-size sensitive rheologies

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[3]Oden Institute for Computational Engineering and Sciences, The University of Texas at Austin, Austin, Texas, USA

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Strain-localization and plate boundary evolution is 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. Lithospheric deformation models often approximate weakening by visco-plastic rheologies and a decrease of the yield strength or effective viscosity with increasing deformation. Here, we analyze how a parameterized, apparent-strain, or "damage", dependent weakening (SDW) rheology, as can be easily implemented in convection computations, governs strain localization and weakening as well as healing in the lithosphere. The weakening and localization due to the SDW rheology can be compared to a grain-size sensitive (GSS) composite rheology (diffusion and dislocation creep). While we focus on GSS rheology to constrain the parameters of SDW, the analysis is not limited to grain-size evolution as the only possible microphysical mechanism.

We explore different types of strain weakening (plastic- (PSS) and viscous-strain (VSS) softening) and compare them to the predictions from different laboratory-based models of grain-size evolution for a range of temperatures and a step-like variation of total strain rate with time. PSS leads to a weakening and strengthening of the effective viscosity of about the same order of magnitude as due to a GSS rheology, while the rate depends on the strain-weakening parameter combination. In addition, the SDW weakening rheology allows for memory of deformation, which weakens the fault zone for a longer period. Once activated, the memory effect and weakening of the fault zone allows for a more frequent reactivation of the fault for smaller strain rates, depending on the strain-weakening parameter combination. Our results facilitate comparison between the weakening effects of simplified rheologies and provide an avenue to more easily explore deformation memory in mantle convection models.

Towards a new method for solving tensile plasticity in magmatic systems

NICOLAS BERLIE[1]*, BORIS KAUS[1], ANTON POPOV[1], DANIEL KISS[1]

[1]Institute of Geosciences, Johannes Gutenberg University Mainz, J.-J.-Becher-Weg 21, Mainz D-55128, Germany

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The understanding of magmatic systems is an important issue in geosciences as they impact natural cycles of the earth and human activities. However, the modelling of those systems presents several challenges to the geodynamic community. Given the wide range of temperatures and compositions within the system, the rheological behavior of the rocks is complex and varies on a small spatial and temporal scale. Numerically approaching these systems requires a code dealing with two-phases flow, visco-elasto-plastic rheologies, advective schemes suitable to deal with wide variation of velocities and two modes of plasticity: shear and tensile.

The ERC-funded MAGMA project aims to provide tools to numerically explore such systems, including a new thermo-mechanical code. This code solves the Stokes equations using finite-difference on a staggered-grid with linear and non-linear solvers from the PETSc infrastructures. We also compare the use of an analytical manually derived Jacobian matrix to one produced with Automatic Differentiation tools in Julia. In this contribution, we present preliminary results of a new regularized tensile plastic Griffith criterion to generate vertical dikes in our code using 0D and 2D examples.

Modelling the composition of volcanic gases on young terrestrial planets in the C-H-O-N-S system

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Subsequently to the magma ocean state, secondary atmospheres build up via early volcanic degassing of planetary interiors. The terrestrial planets Venus, Earth and Mars are believed to have originated from similar source material but reveal different present-day atmospheric compositions, pressures and temperatures. To investigate how such diverse atmospheres emerge, we have developed a model that allows us to compute the molar fractions of gases involved in volcanic degassing.

We simulate the gas chemical speciation in the C-H-O-N-S system since C-H-O-S volatiles can be stored in significant amounts in basaltic magmas and therefore make up about 95 % of the magmatic gases released by volcanoes on earth. Because of its important role in the terrestrial atmosphere Nitrogen was added to our calculations as well.

We consider the influence of temperature, pressure, oxygen fugacity and melt composition on the solubility of each phase as well as the speciation of all phases and fitted these parameters to conditions present on early Earth and Mars.

We show that oxygen fugacity has a major influence on the gas composition during degassing due to its important influence not just on the speciation of all volatiles but also on the solubility of Nitrogen and Sulfur in the magma. According to the volatile content of the melt, under reducing conditions H2, CO, H2S, S2 and NH3 are the main outgassed species, while H2O, CO2 and SO2 and N2 dominate in the oxidizing case.

We furthermore show that the temperature and pressure conditions of the source region in which the magma is formed and the chemical composition of the magma itself also play a key role in the chemical composition of volcanic gasses and that hence, varying parameters like planet mass, atmospheric pressure, tectonic regime, volatile budget or the abundance of heat sources can lead to significantly different atmospheric compositions and degassing rates.

Interior Structure and Thermal State of Venus

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Venus is similar to Earth in terms of size and bulk composition but its interior structure and present thermal state are not well constrained. Fundamental parameters such as the size of its core and whether the core is solid or liquid are unknown or uncertain [e.g., 1]. More constraints will be gained from precise measurement of the moment of inertia factor, MOIF, tidal Love number, k2 and the tidal phase lag, ◎. These parameters are related to the deformational response to tidal forcing of the Sun (period of 58.4 days) and will be measured with the NASA's Discovery mission Veritas and ESA's M5 mission EnVision, which were recently selected and are to be launched in 2028 and 2032, respectively. Here, we will present models of the interior structure and thermal state of Venus and discuss what we can learn from measurements of the MOIF, tidal Love number, k2 and the tidal phase lag, ◎◎

We first compute structural and thermal models [2], which are then used to compute the tidal response of the planet [3]. The interior models consist of three chemically separated layers: an iron-rich core surrounded by a silicate mantle and a crust. The mantle mineralogy is obtained using PERPLE_X [4] and the thermal state using a mixing length formulation [5]. The viscoelasticity of the mantle is parameterized using an Andrade rheology to calculate the phase lag. In general, the MOIF constraints the concentration of mass in the interior, and thus the core size, while the potential Love number helps to determine the state of the core and in case of a fluid core also its size. The tidal phase lag, which is related to the dissipation factor, Q, contributes to obtaining information on the thermal state of the interior because it is mostly sensitive to the mantle viscosity profile. Uncertainty of ±0.01 in k2 will allow us to distinguish between solid and liquid core and to constrain the core size for a fluid (outer) core. Uncertainty of ± 0.25o in phase lag will further allow us to constrain whether the rocky mantle is cold and stiff or warm and weak. In addition, an uncertainty of ±1 % in MOIF can further help to constrain compositional models for the interior of Venus.

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Life and death of normal faults: Quantitative analysis of fault network evolution in 3D rift models

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Quantifying the spatial and temporal evolution of fault systems is crucial in understanding plate boundary deformation and the associated seismic hazard, as well as to help georesources exploration in sedimentary basins. During the last decade, 3D lithospheric-scale geodynamic models have become capable of reproducing the entire life span of normal faults, from rift inception to continental break-up. But since these models represent faults as finite-width shear zones within a deforming continuum, an additional method is needed to isolate and characterise individual faults as a basis for quantitative fault network analysis.

Here we present such a method that describes fault systems as 2D networks (vertical or horizontal) consisting of nodes and edges. Building on standard image analysis tools such as skeletonization and edge detection, we establish a hierarchical network structure that groups nodes and edges into components that make up individual evolving faults. This allows us to track fault geometries and kinematics through time so we can understand the growth, linkage and disintegration of faults.

We find that the initial fault network is formed by rapid fault growth and linkage, followed by competition between neighbouring faults and coalescence into a mature fault network. At this stage, faults accumulate displacement without a further increase in length. Upon necking and basin-ward localisation, the first generation of faults shrink and disintegrate successively while being replaced by newly emerging faults in the rift centre that undergo a localisation process similar to the initial rift stage. We identify several of these basin-ward localisation phases, which all feature a similar pattern. In oblique rift models, where the extension direction is not parallel to the rift trend, we observe strain partitioning between the rift borders and the centre, where strike-slip faults emerge even at moderate divergence obliquity. Analysing the temporal evolution of modelled faults allows us to map observed stages of rift systems into a unifying framework that describes fault network evolution through time.

Martian dichotomy: Impact-induced crustal production in mantle convection models

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The Martian crustal dichotomy features a ~5.5 km contrast in topography and ~25 km difference in crustal thickness between the northern and southern hemispheres, and is thought to have formed within the first 400-500 Myr of the planet's history. Among the different theories which invoke an endogenic and/or impact origin for the dichotomy, Golabek (2012) [1] and Reese (2012) [2] suggested that a giant impact induces melt and hence crustal production, which creates the highlands in the southern hemisphere. On the other hand, it is shown that the Martian dynamo was active at 4.5 and 3.7 Ga [3]. While it has been suggested that early tectonics could facilitate the presence of a dynamo [4], it is not clear whether the dichotomy-associated crustal processes have such effect on the core.

In this study, we explore the potential linkage between the crustal dichotomy formation and dynamo activity. We use the mantle convection code StagYY to simulate the long-term thermochemical evolution subsequent to a giant impact on Mars in 2D spherical annulus geometry. The impact is parametrized as a thermal anomaly at the start of simulation, and the resultant magma pond is treated with an enhanced thermal conductivity to account for the heat loss through turbulent flow. We systematically vary parameters that affect the interaction between the magma pond and surrounding solid mantle, including the impactor size, reference viscosity and magma thermal conductivity. Specifically, we look at the CMB heat flux as a criterion for a dynamo. Our results demonstrate that a giant impact induces crust production on the impacted hemisphere, and delamination of this crust increases the heat flux at core mantle boundary on the same hemisphere, favoring a hemispherical dynamo.

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The Super-tidal cycle: how the supercontinent cycle controls the tides on our planet

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Earth's continents in the present day are the dispersed fragments of the former supercontinent Pangea which existed from 330 - 180 Ma. In around 200 - 250 Myr, following the progression of the current supercontinent cycle, the Earth's continents will reform into another supercontinent. The supercontinent cycle is closely linked to the Wilson cycle which describes the life cycle of oceans as they form, grow, shrink, and eventually close. As oceans grow and shrink with the Wilson cycle the tides within them are affected. The present day North Atlantic Ocean, which formed due to the breakup of Pangea, is resonant with the M2 tide, causing macrotidal (>4m) tidal amplitudes and strengthening the global M2 tidal dissipation rate to 2.5 TW. Is this a unique occurrence in the present supercontinent cycle or is the tide periodically buoyed by resonance in ocean basins because of geometry changes brought about by the progression of the Wilson cycle? Here we will reconstruct predictions of the progression of the current supercontinent cycle into the future (+250 Ma) with GPlates which we will then use as a boundary condition for tidal modelling at 20 Myr intervals with OTIS (Oregon state Tidal Inversion Software). We present four unique scenarios of the Earth's future, each arguing a different style of supercontinent formation. In all scenarios of the future, we find that the Atlantic continues to widen over the next 25 Myrs, causing the tide within it to weaken as resonance is lost. However, we find several other occurrences of tidal resonance during the future scenarios, which causes tidal dissipation rates to increase to 70 – 250% of the present-day value. We then compare these results with tidal modelling studies of deep time (i.e., past supercontinent cycles) to analyse the effect the supercontinent cycle has on tides throughout Earth history. This periodic increase in tidal amplitudes and dissipation over geological time affects the evolution of the Earth-Moon system, and has implications for ocean circulation, climate, and the ocean's ability to host and support life in the past and future.

The interplay between recycled and primordial heterogeneities: predicting Earth mantle dynamics via numerical modeling

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The compositional structure of the present-day Earth's lower mantle is not well constrained, hampering our understanding of the long-term evolution of our planet. The geochemical and geophysical record point to the presence of both recycled and primordial mantle heterogeneities, but their geometry, distribution, and interaction are under debate and a unified model capable of explaining these observations is still missing. Two end-member models have been described: a "marble cake" scenario, in which convection stirs recycled oceanic lithosphere into thin streaks of basalt and harzburgite throughout the mantle; and a "plum pudding" scenario, where coherent blobs of MgSiO3-rich, primordial material resist convective entrainment due to their intrinsic strength. Previous geodynamic studies have successfully reproduced these regimes of mantle convection in numerical models, but few have investigated the interaction between the two. Here, we focus on the viscosity and density contrasts of recycled and primordial materials and their effect on mantle mixing.

We employ the finite-volume code StagYY to model mantle convection in a 2D, spherical-annulus geometry. We describe the style of mantle convection and heterogeneity preservation as we vary the intrinsic strength (viscosity) of the primordial material, and the intrinsic strength and density of basalt.

Preliminary results show a range of different mixing styles. A weaker primordial material is efficiently mixed, leading to a "marble cake" regime with thermochemical piles at the core-mantle boundary, streaks of recycled oceanic lithosphere and primordial "specks" diffused throughout the mantle. Conversely, higher viscosity allows for the primordial to be preserved in the form of "plum pudding" blobs alongside the "marble cake"-like features mentioned above. In addition, the rheology and density anomaly of basalt affect the appearance of both types of heterogeneity. For example, a regime with small and scarce primordial blobs is predicted for low values of basalt density anomaly. Conversely, a sudden and dramatic increase in the number and size of primordial domains is obtained when the density and/or basalt viscosity contrast are increased. Our results show how the long-term evolution of the planet is driven by the interaction between different mantle materials. Accurately modeling such an interplay is key to fully unravel the uncertainty surrounding the compositional structure of the lower mantle.

Thermal evolution of terrestrial planets with 2D and 3D geometries

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In mantle convection studies, 2-D geometries are predominantly used, due to their reduced computational costs when compared to full 3-D spherical shell models [e.g., 2, 3, 4]. However, these 2-D geometries still present drawbacks for modeling thermal convection. Although scaling and approximations can be applied to better match the average quantities obtained with 3D models [4], in particular, the convection pattern that in turn is critical to estimate melt production and distribution during the thermal evolution is difficult to reproduce with a 2D cylindrical geometry. To overcome this limitation, another 2D geometry called "spherical annulus" has been proposed [5]. Although steady-state comparison between 2D cylindrical, spherical annulus and 3D geometries exist [5], so far no systematic study of the effects of these geometries in a thermal evolution scenario is available.

In this study we implemented a 2-D spherical annulus geometry in the mantle convection code GAIA [6] and used it along 2-D cylindrical and 3-D spherical shell geometries to test their effects on mantle convection models.

First, we have performed steady state calculations in various geometries and compared the results obtained with GAIA with results from other mantle convection codes [5,7,8]. Secondly, we systematically studied the effects of the three geometries for various radius ratios, Rayleigh numbers, and heating modes. In a third step we run thermal evolution simulations for Mars, Mercury, and the Moon using the 2D and 3D geometries. We will present a detailed comparison between all geometries and planets, in particular focussing on the temperature evolution, convection pattern and stagnant lid thickness.

In all tests, the 2D spherical annulus showed closer results to the 3D geometry in terms of temperature, sheath velocity, and surface heat flux compared to the cylindrical geometry. In particular, the 3D results for models with a small core were better reproduced by the spherical annulus geometry.

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Rheological Memory in Plate-like Mantle Convection

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The creation and maintenance of narrow plate boundaries and their role in the thermo-chemical evolution of Earth remain major problems in geodynamics. The causes and consequences of strain localization remain debated, even though tectonic inheritance, i.e., the ability to preserve and reactivate weak zones over geological time, and strain localization appear to be critical features in plate tectonics. Here, we use a parameterized, apparent-strain, or "damage", dependent weakening (SDW) rheology, as can be easily implemented in convection computations, which shows a similar transient behavior as a grain-size sensitive composite rheology, one of the major candidates for weakening in the ductile lithosphere. We analyze how such a SDW 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.

SDW enables a memory of deformation, which weakens the lithosphere and allows for a self-consistent formation and reactivation of inherited weak zones. Reactivation within the models occurs in two different ways: a), as a guide for laterally propagating convergent and divergent plate boundaries, and b), formation of a new subduction zone by reactivation of weak zones. We focus on the hardening timescale of such weak zones which is mainly controlled by temperature and the SDW parameters. With a decreasing integrated hardening rate (i.e., a longer strain memory), the lithosphere becomes overall weaker and a decrease of the area of inherited strain due to a more frequent reactivation of existing weak zones is observed. A longer rheological memory results in a decrease in the dominant period of the reorganization of plates due to less frequently formed new plate boundaries. In addition, the low frequency content of velocity and heat transport spectra decreases with a decreasing dominant period. This indicates a more sluggish reorganization of plates due to the weaker and thus more persistent active plate boundaries. These results show the importance of a rheological memory for the reorganization of plates, potentially even for the Wilson cycle.

Computational biogeodynamics: coupling of Earth's interior, atmosphere, ocean, climate, landscape and life evolution models

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Earth's geodynamic evolution is intimately coupled to the evolution of its atmosphere, oceans, landscape and life and we aim to understand this coupling better through the emerging transdisciplinary field of biogeodynamics. Firstly, life is sustained by a critical set of elements contained within rock, ocean and atmosphere reservoirs and cycled between Earth's surface and interior via various tectonic, magmatic and surface processes. Second, plate tectonic processes such as redistributing continents, growing mountain ranges, forming land bridges, and opening and closing of oceans and marine gateways provide environmental pressures that isolate and stimulate populations to adapt and evolve; recombining these features further stimulates evolution. Modern plate tectonics - established sometime before the Cambrian explosion - is often viewed as a strong promoter of biological evolution. Compared to single lid tectonic styles, plate tectonics better creates and destroys continental and continental shelf habitats, supplies nutrients, modulates climate, and exerts continuous moderate environmental pressures that drive evolution.

Importantly, long timescales of biological evolution estimated from analysis of DNA changes and fossils are comparable to those of major geodynamic cycles such as the Supercontinent Cycle and the Wilson Cycle. Therefore, computational biogeodynamics (i.e., coupled modeling of Earth's interior, atmosphere, ocean, sea-level, climate, landscape and life evolution) stands as one of the frontier research tasks in geodynamics, ecology and evolution as well as related disciplines. Here, we propose the development and employment of both regional- and global-scale 3D high-resolution bio-geodynamical modeling toolkits, coupling (i) available global and regional magmatic-thermomechanical models of geodynamic processes, (ii) landscape evolution models, (iii) simulations of long-term atmospheric, ocean and climate change and (iv) spatially-explicit models of species speciation, evolution and extinction. We show preliminary results suggesting critical roles of plate tectonic motions and mantle plume-lithosphere interactions on life evolution and spatial-temporal biodiversity distribution. The implications for exploring exoplanets are obvious.

Data-driven models of the East African Rift System: dynamic topography, strain localization and stress distribution

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The East African Rift System (EARS) is the largest active continental rift on Earth. Inherited lithospheric strength variations, deriving from e.g. Proterozoic mobile belts and Archean cratons, have played a large role in forming the current geometry of the partly overlapping eastern and western EARS branches. These branches encompass the Victoria continental microplate that rotates counter-clockwise with respect to Nubia, in striking contrast to its neighboring plates. Previous numerical modeling (Glerum et al., 2020) has shown that this rotation is induced through the 'edge-driven' mechanism (Schouten et al., 1993), where stronger lithospheric zones transmit the drag of the major plates along the edges of the microplate, while weaker regions facilitate the rotation.

The current work investigates secondary forces driving deformation in the EARS and Victoria's rotation. To this end, regional spherical models are constructed based on observational data. Lateral crustal and lithospheric thickness variations are taken from recent geophysical datasets of the present-day African continent (Tugume et al., 2013; Globig et al., 2016). Mantle structure in terms of temperature and, thus, density is either scaled from seismic tomography models or generated through the addition of thermal upwellings mimicking the East African Superplume (Ebinger and Sleep, 1998). Plate motions are prescribed based on plate tectonic reconstructions. Preliminary results show that the counterclockwise rotation of Victoria, its rotation pole and its angular velocity as observed through GPS are consistently reproduced through the data-driven lithospheric strength distribution. With subsequent models we demonstrate the effect of mantle structure on dynamic topography, strain localization and stress distribution in the EARS.

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Modification of icy planetesimals by early thermal evolution and collisions: Constraints for formation time and initial size of comets and small KBOs

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Comets and small Kuiper belt objects are considered to be among the most primitive objects in the solar system as comets like C/1995 O1 Hale-Bopp are rich in highly volatile ices like CO. It has been suggested that early in the solar system evolution the precursors of both groups, the so-called icy planetesimals, were modified by both short-lived radiogenic heating and collisional heating. Here we employ 2D finite-difference numerical models to study the internal thermal evolution of these objects, where we vary formation time, radius and rock-to-ice mass fraction. Additionally, we perform 3D SPH collision models with different impact parameters, thus considering both cratering and catastrophic disruption events. Combining the results of both numerical models we estimate under which conditions highly volatile ices like CO, CO2 and NH3 can be retained inside present-day comets and Kuiper belt objects. Our results indicate that for present-day objects derived from the largest post-collision remnant the internal thermal evolution controls the amount of remaining highly volatile ices, while for the objects formed from unbound post-collision material the impact heating is dominant. We apply our results to present-day comets and Kuiper belt objects like 67P/Churyumov-Gerasimenko, C/1995 O1 Hale-Bopp and (486958) Arrokoth.

The emergence of modern plate tectonics and complex life: A global scale numerical modelling approach

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The modern episode of plate tectonics is increasingly considered to have begun in the Neoproterozoic following a period of reduced activity known as the 'boring billion' [1, 2] when Earth may have been in a less dynamic single lid mode [2]. The Neoproterozoic was also a period of radical change in other Earth systems – higher oxygen levels, the Cryogenian glaciations, and finally the emergence and rapid diversification of multicellular life in the Cambrian explosion. The study of the Neoproterozoic transition to modern plate tectonics is therefore central to the emerging multidisciplinary field of Biogeodynamics, the study of coupling between geodynamic processes, atmosphere, ocean, landscape, climate and the evolution of life [3].

The origins of modern plate tectonics on Earth have typically been ascribed to the secular cooling of the mantle enabling local episodes of unstable subduction to become more widespread and stable [4]. Sobolev and Brown [1] argue that major erosion and sedimentation events, such as the Cryogenian glaciations, were important controls on Earth's tectonic style. The presence of hydrated sediments in active subduction zones enhances their stability through lubrication, thus the Cryogenian glaciations may have reactivated the dormant plate tectonics of the 'boring billion' [2].

The transition to modern plate tectonics is necessarily a global problem operating on a timescale of hundreds of millions of years needed to develop/activate the global plate mosaic [4]. To model the transition numerically, we propose to combine global 3D models of mantle convection with free surface using StagYY [5] with a simplified model of erosion and sedimentation, and a parameterised description of margin strength which may be modified by subduction zone lubrication and sediment loading. The aim is to determine through modelling the conditions and timescales required to activate a plate tectonic regime from a single lid [2]. The results of these global models, particularly models of global topographic evolution, may also be used in conjunction with climate models and models of biological evolution to investigate the ability of different global tectonic regimes to sustain and diversify complex life.

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Coupled evolution of primordial and recycled reservoirs in Earth's mantle, and their present-day seismic signatures

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The lower mantle is the most voluminous reservoir in the Earth's interior and controls the style of mantle convection, and through it, the long-term thermochemical evolution of our planet. Knowing its composition and structure, however, remains a scientific challenge. Topics that receive particular attention are the nature of chemical heterogeneity in the lower mantle, and how such heterogeneity has evolved over time. Several mantle heterogeneity styles have been proposed, involving the preservation of intrinsically-dense and/or intrinsically-strong (e.g., enhanced in the strong mineral MgSiO3-bridgmanite) materials in the mantle. Origins of these chemical reservoirs include crustal materials that are recycled by subduction, or primordial materials formed during early Earth's evolution and preserved in the mantle to the present-day. So far, only few, if any, studies have quantified mantle dynamics in the presence of different types of heterogeneity with distinct physical properties.

In this talk, I will present our study on the coupled evolution and mixing of (intrinsically-dense) recycled and (intrinsically-strong) primordial material in the mantle using numerical models of global-scale mantle convection [1]. Primordial heterogeneity (MgSiO3-enhanced) is initialized as chemical layering in the mantle, while additional heterogeneity is introduced over time by subduction of crustal materials. We characterize the scale and distribution of chemical heterogeneity in the mantle, and their effect on the planform of mantle flow. Our results robustly predict that primordial and recycled heterogeneity can coexist with each other, and ultimately, we suggest that the modern mantle may be in a hybrid state between previously-proposed mantle structures.

Finally, I will put our model predictions in context with geochemical studies on early Earth geodynamics as well as seismic discoveries of present-day lower-mantle heterogeneity. For the latter, synthetic seismic velocities are computed from our output model fields. Preliminary results suggest that, if present, MgSiO3-enriched domains in the mid-mantle may be "hidden" from seismic tomographic studies, and other approaches are needed to establish the presence/absence of these domains in the present-day deep Earth.

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Strain-weakening rheology in Earth's lower mantle and its effect on the planform of mantle flow

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Rocks in the Earth's interior consist of different mineralogical phases with different rheological properties. In Earth's lower mantle, the main rock-forming minerals are bridgmanite (Br) and smaller amounts of ferropericlase (Fp). Bridgmanite is substantially stronger than ferropericlase, and lower mantle rheology may be highly dependent on the relative mineral abundances and spatial distribution of these two phases. It has been suggested that for bridgmanite- depleted compositions, the viscosity decreases with accumulating strain due to the interconnection of the weaker Fp minerals. This implies that deformation may localize in the lower mantle, which would in turn affect the planform of mantle flow and potentially aid the preservation of compositionally distinct and "hidden" reservoirs away from the regions of localized deformation.

To better understand the feedback between the viscosity structure obtained by deforming Br-Fp aggregates and the dynamics of mantle convection, we present 2D spherical annulus numerical models of thermochemical convection that includes a new implementation of strain-weakening (SW) rheology. This macro-scale SW rheology is based on micro-scale solutions found in prior studies, and includes a parametrization for rheological healing of mantle materials.

We find that, in particular, the dynamics of mantle plumes are affected by SW rheology. Weakened plume conduits act as lubrication channels in which mantle materials flow at high velocities, and their thermal anomaly is significantly lower than those of mantle plumes in non-SW models. Moreover, in SW models, convection cells are smaller and the convective vigour is higher. Finally, thermochemical piles at the base of the mantle are stabilized by SW rheology. These preliminary results imply that lower mantle rheology is key for the style of convection in the mantle, including the survival of chemically heterogeneous reservoirs in the deep Earth.

Rheological controls on early-Earth dynamics

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The present-day Earth exhibits subduction-driven plate tectonics, which is a surface expression of processes happening in the deep interior. For the early Earth, following the magma ocean solidification stage, a variety of tectonic regimes have been proposed albeit without any consensus: heat-pipe tectonics, plutonic-squishy lid, stagnant lid. Furthermore, the rheological changes required to make the (supposedly gradual) transition to modern style plate tectonics on Earth remain hotly debated. And the inception time of plate tectonics has been suggested to range anywhere from Neoproterozoic Era (1.0-0.54Ga) to as far back as the Hadean Eon (4.5-4.0 Ga).

Recently, it has been proposed that sediments accumulated at continental margins as a result of surface erosion processes could have acted as a lubricant to stabilize subduction and aid with the initiation of plate tectonics after the emergence of continents around 3 Ga [1]. Before that time, the flux of sediments to the ocean was very limited. However, it was suggested [1] that subduction zones were already present at that time but were likely initiated only above hot mantle plumes. This tectonic regime of regional plume-induced retreating subduction zones was very different from the modern type of plate tectonics, but nevertheless might have been efficient in production of early continental crust and transporting surface water and recycling of the crust into the deep Earth. We propose to test this hypothesis of surface-erosion controlled plate tectonics preceded by plume-induced retreating subduction tectonic regime in global convection models by introducing magmatic weakening of lithosphere above hot mantle plumes and by adapting the effective friction coefficient to mimic the lubricating effect of sediments. With parameters suited for early Earth conditions (including different estimates of mantle potential temperature [2,3]), and considering both intrusive (plutonic) and eruptive (volcanic) magmatism, these models are capable of self-consistently generating oceanic and continental crust. This allows the modelling results to be compared and validated against geochemical data.

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Developing the next generation geodynamics codes using Julia

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Julia recently emerged as a very powerful high-level computer language for (parallel) scientific computing, which allows you to "write codes like in MATLAB", while "achieving the speed of Fortran/C". Here we will discuss our efforts in making Julia a development platform for geodynamic applications that significantly simplifies the process of going from a working solver to a production code. We are working on several packages that simplify certain steps that many geodynamics codes have in common:

GeoParams.jl is a package in which you can specify constitutive relationships (e.g., creeplaws). It automatically handles the (non-)dimensionalization of all input parameters, includes pre-defined creep laws (e.g., dislocation and diffusion creep laws), plotting routine and includes computational routines that can be integrated in your code.

PETSc.jl is the main interface from Julia to PETSc, including MPI support and automatic installations of PETSc (one of the main hurdles that existing users faced). We have also recently extended the package to include an interface to DMSTAG, such that you create a staggered finite difference grid and assemble the stiffness matrix in a straightforward manner. You can use automatic differentiation tools in Julia to create the Jacobians for nonlinear equations, which again minimizes the required lines of code (compared to their C counterparts). At the same time, the full range of (nonlinear multigrid) PETSc solvers is available. This is thus very well suited to write implicit solvers.

ParallelStencil.jl and ImplicitGlobalGrid.jl are packages that are devoted to solving stencils in a very efficient manner on (parallel) GPU or CPU machines, which scales to very large GPU-based computers. It is particularly efficient in combination with pseudo-transient iterative solvers and allow running codes on modern architectures.

GeophysicalModelGenerator.jl is a package that gives you a simple way to collect geophysical/geological data of a certain region and combine that to construct a 3D geodynamic input model setup.

Ongoing efforts include the development of a grid generation and a marker and cell advection package that work, seamlessly with both ParallelStencil and PETSc. This will allow developers to apply both direct-iterative and pseudo-transient implicit solvers to the same problem, while only having to make minimal changes to the model setup. Combined, these packages will make the step from developing a new (nonlinear) solver to having an efficient (3D) production code much easier.

Dynamic interactions between subduction zones

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Fundamental properties of subducting slabs, such as their buoyancy, the dip direction and the rheology of the slab and the surrounding mantle, determine the first order motions and geometries of subduction zones. Due to the horizontal migration of slabs n the mantle, subduction zones often "approach" each other, altering the dynamics of single subductions. In this presentation, I will summarize the dynamics of subduction zone interactions in four simple geometries, that are most commonly used to describe the geodynamic history of tectonically complex areas. Using data from geological and geophysical observations and the results of many geodynamics models, we can conclude some common features of subduction zones interactions, such as: changing slab dips, reduced trench migration rates, complex flow patterns in the mantle, and strong rotations of lithospheric blocks. These features are resulted from the stress transfer between neighboring slabs which ultimately changes the force balance of individual subduction zones. Understanding the dynamics of such complex systems can help to interpret geological and geophysical data, and to reconstruct the tectonic history of areas, where multiple subduction zones are/were active simultaneously. A great example for such a tectonically complex area is the Central Mediterranean, which I will discuss in the light of the conclusions we make about the dynamics of subduction zones interactions.

2D thermo-mechanical-chemical coupled numerical models of interactions between a cooling magma chamber and a visco-elasto-plastic host rock

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A recent focus of studies in geodynamic modeling and magmatic petrology is to understand the coupled behavior between deformation and magmatic processes. Here, we present a 2D numerical model of an upper crustal magma (or mush) chamber in a visco-elasto-plastic host rock, with coupled thermal, mechanical and chemical processes, accounting for thermodynamically consistent material parameters. The magma chamber is isolated from deeper sources of magma (at least periodically) and it is cooling, and thus shrinking. We quantify the changes of pressure and stress around a cooling magma chamber and a warming host rock, using a compressible visco-elasto-plastic formulation, considering both simplified idealized and more complex and realistic geometries of the magma chamber.

We present solutions based on a self-consistent system of the conservation equations for coupled thermo-mechanical-chemical processes, under the assumptions of slow (negligible inertial forces), visco-elasto-plastic deformation and constant chemical bulk composition. The thermodynamic melting/crystallization model is based on a pelitic melting model calculated with Perple_X, assuming a granitic composition and is incorporated as a look-up table. We will discuss the numerical implementation of plasticity (mode-1 and dilatational shear failure) and of the thermodynamic data, show the results of systematic numerical simulations, and illustrate the effect of volume changes due to temperature changes (including the possibility melting and crystallization) on stress and pressure evolution in magmatic systems.

Self-organisation of magma supply controls crustal thickness distribution and tectonic pattern at mid-ocean ridges

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Variations in mantle sources and magmatic processes lead to significant changes of crustal thickness distribution and spreading pattern at mid-ocean ridges. Crustal thickness varies from relatively uniform distribution at fast ridges to great fluctuations with mantle rocks exhumation at slow and ultraslow ridges. Similarly, spreading pattern changes from symmetric configuration to highly asymmetric plates accretion with detachment faults and oceanic core complexes. Recent modelling studies suggested that magmatism may play a key role in the variation. Yet, the physical mechanisms controlling spatial-temporal distribution and intensity of magmatic activity at mid-ocean ridges remain elusive. Here, through 3D self-consistent magmatic-thermomechanical numerical models, we systematically investigate effects of mantle potential temperature and spreading rate on the crustal thickness distribution and tectonic pattern at spreading ridges. Numerical results show that along mid-ocean ridges, there are two fundamentally different types of ridge sections that form spontaneously and alternate due to the dynamical tectono-magmatic plate boundary instability from asymmetric plate growth and self-organization of mantle flow and melting partitioning beneath the ridge: (1) normal ridge sections, NR, with elevated topography, normal thickness of oceanic crust and hot thermal structure, and (2) fracture zone sections, FZ, with lowered topography, thin/absent crust, exhumed mantle rocks, and cold thermal structure. The tectono-magmatic instability is critically controlled by both spreading rate and regional spatial-temporal mantle potential temperature variations. The thickness of brittle/plastic layer is sensitive to spreading rates, especially at slow and ultraslow spreading ridges, resulting in symmetric spreading pattern with thin brittle/plastic layer at fast and intermediate spreading ridges and deeply penetrating asymmetric detachment faults with thick brittle/plastic layer at slow and ultraslow spreading ridges. Mantle potential temperature is crucial in magma supply and has a great effect on the spatial-temporal variations of crustal thickness. Our results also clarify the systematic along-axis variation in tectonic and magmatic processes. The predicted relationship finds a good agreement with natural observations and suggest that spontaneous self-organization of magma supply controlled by spreading rate and mantle potential temperature plays critical roles in shaping tectonic and crustal patterns of mid-ocean ridges.

Interaction of thermo-chemical upwellings with the Mantle Transition Zone

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The study of intraplate volcanism informs about mantle thermochemical structure and dynamics. For example, bilaterally asymmetric zonation of isotopic signatures as evident along several hotspot chains (e.g., Hawaii, Samoa, Society, Easter, Galapagos, Tristan-Gough, Shona) has been related to material entrainment by plumes in the lowermost mantle and large-scale heterogeneity (such as seismically-visible LLSVPs). However, recent full-waveform tomography models suggest that plumes are commonly deflected in the mid mantle and transition zone, instead of ascending straightly as predicted by classical plume theory. Therefore, any direct links between the geographical distribution of hotspot volcanism, including geochemical asymmetry, and lower-mantle structure remain putative. In order to address these issues, we here investigate the upwelling dynamics of thermochemical plumes through the transition zone, plume-lithosphere interaction and mantle melting at the base of the lithosphere using high-resolution, 3D-regional geodynamic models (3168x2640x1320 km). In our suite of numerical model cases, we explore the effects of plume excess temperature and thermal buoyancy flux, average plume eclogite content, mantle viscosity profile, and Clapeyron slope at the 660. In order to track an asymmetric chemical zonation of the plume, the back side of the plume carries 2% more eclogite than the front side in most of our models.

As a function of model parameters, we distinguish four different regimes of plume behavior. (1) For high plume temperatures or buoyancy fluxes, and for low eclogite contents, the plume behaves similar to a classical plume, rising straightly through the mantle and narrowing at the 660 viscosity jump. (2) For rather low Clapeyron slopes (of about -2 MPa/K), the plume undergoes strong time-dependency (pulsations), starting from 660 km depth upward. (3) For low plume temperatures or high eclogite contents (i.e., low buoyancy ratios), the plume fails and ponds at 300~410 km depth, and ultimately sinks back to the base of the upper mantle. (4) Only for unrealistically low Clapeyron slopes < -2.5 MPa/K, or in cases with a viscosity jump at 1000 km depth (instead of at 660 km depth), the plume fails and ponds at the base of the mantle transition zone (MTZ). These results highlight the moderate effect of the 660 phase change for realistic Clapeyron slopes (-2 or -1.5 MPa/K or higher) on plume dynamics. The effects of plume narrowing and related buoyancy excess beneath the 660 help to push the plume through the otherwise flow-impeding exothermic phase dissociation. In turn, the potential "zone of death" for thermochemical plumes is the 300~410 km depth range, where the density difference between eclogite and pyrolite is greatest. We also find that the compositional zonation is maintained during plume ascent in all cases, including pulsating plumes. However, the distinct effects of the physical changes across the MTZ on the dynamics of either side of the asymmetric plume can promote stronger eclogite-derived melting on the eclogite-poor side of the plume, with implications for the interpretation of geochemical data.

Systematics of the mobile-lid regime with grain-size evolution

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Grain-size evolution is widely considered as a possible key mechanism in the generation of planetary tectonic regimes, and could (for instance) explain why Venus does not present continuous subduction zones in contrast to Earth [1]. Despite its admitted importance, little is known about how grain-size evolution affects tectonics on a planetary scale. Most previous self-consistent studies did not probe the plate tectonic regime or did so without exploring key parameters, such as different rates of growth or dissipation fractionation ratio. In this work, we present first results of a systematic study of planetary mantle convection with composite rheology and self-consistent grain-size evolution in the mobile-lid regime.

We use StagYY [2] with implemented grain-size evolutions equations [3] to carry out high resolution models of mantle convection in spherical annulus geometry. We explore parameters controlling grain growth and reduction, together with other rheological mechanisms such as the dislocation/diffusion creep ratio and the lithospheric yield strength. First results indicate that grain growth impacts on the occurrence of plate tectonics in a complex fashion. Subduction zones do not only occur where grain-size is smaller, but also where there is a sharp grain-size contrast in the lithosphere. Furthermore, small variations of the creep equation parameters concerning grain size seem to be more important than the grain size itself. Lower mantle dynamics also change considerably, as grain growth dominance pushes the lower mantle to a more isoviscous structure. This leads to 'fatter' plumes in agreement with recent tomographic studies [4] and to a stark viscosity contrast between upper and lower mantle (not imposed a priori in our models).

In conclusion, our work is consistent with previous results, but also suggests that the system is more complex and unpredictable than previously thought: potential uncertainties in laboratory measurements have a great impact on the tectonic regime. Future work will focus on the applicability to other bodies (planets) and the differences between 2D and 3D.

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The (Very) Early Lunar Mantle Dynamics

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From all known terrestrial bodies, the Moon shows the most compelling evidences of having once been largely molten [1]. The crystallization of such a primordial magma ocean set the initial conditions for solid mantle dynamics. It also corresponds to the oldest event that isotopes chronometers can record in lunar samples [2], indirectly providing clues about the time of the Moon-forming giant impact. Furthermore, various processes such as the orbital evolution of the Earth-Moon system [3] have been shown to be influenced by the presence of a magma ocean on the Moon. Therefore, understanding the solidification of the lunar mantle and the associated chronology is crucial to improve our picture of the early solar system.

It has been shown [4] that large scale magma oceans crystallizing over a protracted period of time can involve onset of convection in the solidified part of the mantle before the end of the planet's solidification. This scenario is particularly relevant for the Moon, which magma ocean crystallized beneath an insulating floating plagioclase lid. In this work [5], we show that the onset of thermal convection in the solid cumulates is likely to occur while the lunar magma ocean is still extent. Moreover, we find that the secondary melting in hot plumes induces transfer of heat from the solid cumulates to the magma ocean, exerting a strong influence on the timing of crystallization, and prolonging the solidification of the Moon up to 200 Myr. This result helps draw a more accurate picture of the early Moon chronology, the age of the Moon-forming impact, and thus the last episode of core formation on the Earth.

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Interior dynamics of tidally-locked super-Earths: Comparing LHS 3844b and 55 Cnc e

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The vigour and style of mantle convection in tidally-locked super-Earths may be substantially different from Earth's regime where the surface temperature is spatially uniform and sufficiently cold to drive downwellings into the mantle. The thermal phase curve for super-Earth LHS 3844b suggests a solid surface and lack of a substantial atmosphere. The dayside temperature is around 1040 K and the nightside temperature is around 0 K, which is unlike any temperature contrast observed at present day for planets in the Solar System [1]. On the other hand, the thermal phase curve of super-Earth 55 Cnc e suggests much hotter temperatures with a nightside temperature around 1380 K and a substellar point temperature around 2700 K [2]. The substellar point is also substantially shifted eastwards, which requires efficient energy circulation in the atmosphere. Here, we use constraints from thermal phase curve observations to model the interior mantle flow. To constrain the surface temperature of 55 Cnc e, we use the results from general circulation models varying the atmospheric composition and optical depth.

For LHS 3844b we find that the surface temperature dichotomy can lead to a hemispheric tectonic regime depending on the strength of the lithosphere and the heating mode in the mantle. In a hemispheric tectonic regime, downwellings occur preferentially on one side and upwellings rise on the other side. Such a regime could influence a planet's atmosphere through interior-exterior coupling mechanisms (e.g. volcanic outgassing). For 55 Cnc e, large parts of the surface could be molten. At first order we therefore expect that a magma ocean could homogenise the temperatures at the interface between the magma ocean and the underlying solid mantle and therefore reduce the likelihood of hemispheric tectonics operating on 55 Cnc e.

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geomIO4py – An updated Python version of geomIO to create the 3D initial configuration of thermomechanical simulations

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Creating input geometries for three dimensional numerical simulations can be a challenging task. The MATLAB toolbox geomIO[1] provides a good interface to create three-dimensional geometries from multiple two-dimensional cross sections. This is achieved by drawing geological units (layers, intrusion bodies, slabs, faults, etc.) on cross sections as Bezièr curves. To increase quality, further cross sections are interpolated between the drawn ones. The drawn and interpolated curves are converted into 3D triangulated volumes that can be used to assign markers or meshes with mechanical properties. With the development of geomIO4py, we are standardizing the file format of these volumes as STL (https://en.wikipedia.org/wiki/STL_(file_format)), which is a widely used format that is also used for 3D printing. In addition, porting the MATLAB version to Python has a number of advantages. Python is an open source programming language that comes with numerous high quality libraries. Thus we can reduce the geomIO code and instead rely on robust and fast libraries from third-party providers. This will keep the code more readable and we hope to attract more community users to help us improve this tool. We will demonstrate the new python workflow with an example of a subduction setup.

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Numerically modelling the formation of continental microplates through rift linkage

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Continental microplates are enigmatic plate boundary features that can form in extensional and compressional regimes. Here we focus on extensional microplate formation and temporal evolution in continental rift settings. When rift segments form at offsets where they can evolve into an overlapping configuration, they sometimes interact and rotate the region located between them. This region, known as a microplate, rotates until an eventual rift jump attaches it to the margin opposite the dominant ridge. The Victoria microplate in the East African rift system is one example of an early stage, actively rotating continental microplate [1]. Moreover, along rifted margins, areas of relatively thick crust are sometimes interpreted as continental microplates (e.g., the Sao Paulo Plateau and Flemish Cap). Although there exists evidence of actively rotating and remnant continental microplates, there are not enough examples to capture the microplate formation and evolution from initial fault propagation, to overlap and rotation, and eventually, to continental-breakup.

In this study we use the geodynamic finite-element software ASPECT to run 3D numerical models from rift inception to continental breakup [2]. We vary the along-strike and strike-perpendicular offsets, as well as the crustal strength, and find that offset rifts in continental crust connect through one of four regimes: (1) an oblique rift, (2) a transform fault, (3) a rotating continental microplate or (4) a rift jump with no microplate formation. The connection type is dependent on the strike-perpendicular offset and crustal strength, and we find that rotating microplates form at offsets >200 km in weak to moderately strong crustal setups. In models where microplates form, the rift jump direction and microplate size are comparable to the Flemish Cap and Sao Paulo Plateau.

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Influence of plate tectonics on outgassing efficiency and gas composition

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Accurate measurements of a planet's mass, radius and age together with compositional constraints from the stellar spectrum can help us to deduce potential evolutionary pathways that rocky (exo-)planets can evolve along, and allow us to predict the range of likely atmospheric properties that can then be compared to observations.

However, for the evolution of composition and mass of an atmosphere, a large degeneracy exists due to several planetary and exterior factors and processes, making it very difficult to link the interior (and hence outgassing processes) of a planet to its atmosphere. The community therefore thrives now to identify the key factors that impact an atmosphere, and that may lead to distinguishable traces in planetary, secondary outgassed atmospheres. Such key factors are for example the planetary mass (impacting atmospheric erosion processes) or surface temperature (impacting atmospheric chemistry, weathering and interior-atmosphere interactions).

Here we investigate the signature that a planet evolving into plate tectonics leaves in its atmosphere due to its impact on volcanic outgassing fluxes and volatile releases to the atmosphere - leading possibly to distinguishable sets of atmospheric compositions for stagnant-lid planets and plate tectonics planets. These preliminary findings will need to be further investigated with coupled atmosphere-interior models including various feedback mechanisms such as condensation and weathering as well as atmospheric escape to space.

LIOUSHELL: Computing True Polar Wander on Dynamic Planets

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Almost three decades ago, the problem of long-term polar wander on a dynamic planet was formulated and simplified within the framework of normal mode theory. The underlying simplifications have been debated ever since, recently in a series of papers by Hu et al. (2017a, 2017b, 2019), who clarify the role of neglecting short-term relaxation modes of the body. However, the authors still do not solve the governing equations in full, because they make approximations to the Liouville equation (LE). In this work I use a time domain approach and for previously studied test loads I solve both the relaxation of the body and the LE in full. I also compute the energy balance of true polar wander (TPW) in order to analyze the existing LE approximations. For fast rotating bodies such as the Earth, I show that the rotation axis is always aligned with the maximum principal axis of inertia (ω||MMOI) once free oscillations are damped. The ω||MMOI assumption is also re-derived theoretically. Contrary to previous beliefs, I demonstrate that it is not necessarily linked to the quasi-fluid simplification of the body's viscoelastic response to loading and rotation, but that it is an expression of neglecting the Coriolis and Euler forces in the equation of motion. For slowly rotating bodies such as Venus, the full LE together with energy analysis indicate that previous estimates of TPW in the normal direction need to be revisited. The numerical code LIOUSHELL is made freely available on GitHub.

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Interaction of proto plate-tectonic cells during the Archean: insight from 3D large scale modeling

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In the plate tectonic convection regime, the outer lid is subdivided into discrete plates that are displaced mainly by slab pull forces. It is not yet clear how, when and why plate tectonics became the dominant geodynamic process on our planet. Many lines of research suggest that it could have started during the Meso-Archean (3.0-2.9 Ga). However, it is not understood how plate tectonics initiated. In recent years, a credible solution to the problem of subduction and plate tectonic initiation has been proposed, involving a plume-induced subduction mechanism[1] presumably sufficient to kick-start plate-tectonic like behavior.

The Archean Eon was characterized by a high mantle potential temperature (Tp)[2], which is associated to weaker plates and a thick and buoyant lithosphere. In these conditions, slab pull forces are inefficient. Therefore, plume-related proto-plate tectonic cells may have been interacting differently with each other or not at all. Moreover, due to the secular change of Tp, the dynamics may have changed with time.

Here, we investigate the effects of the composition and Tp independently to understand the implications for plume-induced subduction initiation. We employ a finite-difference visco-elastoplastic thermal petrological code using a large-scale domain. The crucial question we are exploring is whether these configurations allow the generation of stable plate boundaries. The models will also research whether the presence of continental terrain helps to generate plate-like features and whether the processes are strong enough to create new continental terranes or assemble them.

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Interplay between the shortening magnitude and subduction dynamics in the Central Andes

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In Central Andes, the Overriding continental South American Plate (OP) is advancing westwards forcing the trench to retreat and the subducting oceanic Nazca plate to roll-back. However, paleo-reconstructions of the margin position demonstrate that the trench velocity slowed down over the last ~50 My and became lower than the OP velocity. This difference of velocity is expressed by the shortening of the Andes. One reason for this can be the anchoring of the slab in the lower mantle [1]. Although this hypothesis provides an explanation for the initiation of shortening, it cannot explain the observed pulses of shortening [2] as well as latitudinal variations of its magnitude (~300 km at ~18-21°S to ~100 km at 15°S latitude).

Moreover, weakening mechanisms of the OP such as lithospheric delamination have intensified the tectonic shortening and contributed to formation of the Altiplano-Puna plateau [3]. Also, the difference in deformation style of the foreland basin, thick-skinned (e.g the Puna) and thin-skinned (e.g the Altiplano), respectively, is correlated with variations in the magnitude of shortening. Our hypothesis is that OP strength variations result in variable rates of trench roll-back and subduction dynamics. To test this hypothesis and in try to reproduce observed spatial and temporal variations of tectonic shortening in central Andes, we have built an E-W-oriented 2D geodynamic model along the Altiplano-Puna plateau which incorporated the flat subduction episode at ~35 Ma and following evolution of the lithospheric deformation (Fig. 1). For that purpose, we used the ASPECT code. We will discuss our new findings that demonstrate that not all key factors driving orogeny in central Andes have been considered in modelling studies so far.

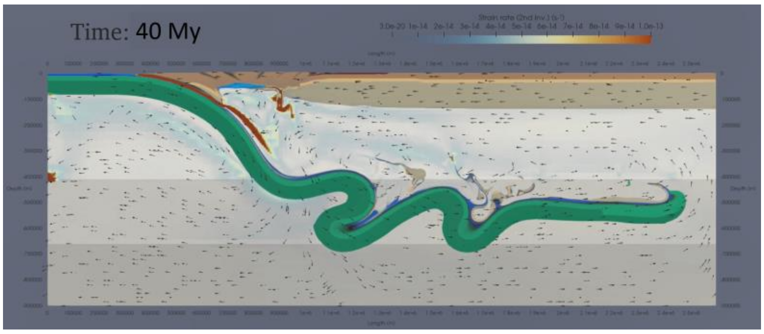

Figure 1: 2D subduction model replicating deformation patterns and lithospheric structure of Central Andes at 21°S at present time

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Data-based modelling of the atmospheric carbon mass balance from the Devonian to the present

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Stabilizing mechanisms of Earth's climate are key for the persistence and diversity of life over geological timescales. To prevent catastrophic excursions of temperature, the Earth thermostat theory suggests that carbon dioxide (CO2) fluxes into the atmosphere, mainly by solid Earth degassing, should be largely compensated by continental and seafloor weathering as well as the burial of organic carbon (C). CO2-driven temperature changes, increasing or decreasing CO2 consumption via silicate weathering, is thereby considered as the main negative feedback mechanism leading to a steady-state in atmospheric CO2. In this study, we use reconstructions of paleogeography and the distribution of the major climatic zones combined with proxy data of atmospheric CO2 and O2 to calculate the main components of the global C cycle from 400 Ma ago to the present. For the calculation of C fluxes, the parametrizations from state-of-the-art biogeochemical models are used [1]. While providing a data-driven and spatially explicit estimation of the major C fluxes, we assess whether the Earth thermostat theory of balancing C in- and outputs into the atmosphere has been fulfilled. We show that the modelled atmospheric C mass balance fluctuates around zero, in general support of the Earth thermostat theory. Nevertheless, imbalances of up to 1.6e+13 mol C a-1 are modelled with largest discrepancies during the Devonian, the Triassic-Jurassic boundary, the mid-Cretaceous and the early Cenozoic. We further assess the potential of uncertainties in reconstructions and proxy data as well as different parametrizations of the C fluxes to resolve these imbalances. The mass balance is observed to be less sensitive to variation in the used CO2 proxy data, climate sensitivity and global runoff compared to variation in the solid Earth degassing rate, the marine- and terrestrial organic C burial and the plant-mediated silicate weathering enhancement. With terrestrial- and marine plant productivity generally being represented very simplistically in current biogeochemical models of atmospheric CO2, we suggest that an improvement of the parametrization of organic C production, considering plant evolutionary aspects and feedbacks on the inorganic C cycle, should be given more emphasis.

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Tectonic regime control by strain-induced plastic weakening in global-scale mantle convection simulations

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Earth's tectonic evolution and its link to mantle dynamics are controlled by the preexisting structure of the lithosphere which guides strain localization and causes the necessary weakness to (re-)activate plate boundaries. Recent global-scale mantle convection models self-consistently reproduce Earth-like tectonic regimes, but in most cases ignore rheological inheritance (i.e., memory on previous deformation). Here, the code StagYY is used to investigate a generic simple form of rheological inheritance via strain-induced plastic weakening [1], before we move on to consider grain-size sensitive rheologies [2].

Based on many simulations in a wide 2D cartesian box, the control of strain-induced weakening on the resulting tectonic regime is demonstrated. Strain-induced weakening impacts the stability fields of the different tectonic regimes (as a function of the strength of intact lithosphere), but does not generate novel tectonic regimes. Decreasing the critical strain (at and above which maximum weakening is observed) facilitates development of an Earth-like regime with time-dependent plate tectonics. Increasing temperature-dependence of the strain healing rate complicates the formation, but does not rule out, this regime. While the critical yield stress that still allows for plate-like behavior is apparently larger with strain-induced weakening, the effective shift (accounting for the yield stress reduction due to strain weakening) is small and only ~10% under the tested conditions.

Finally, strain accumulation inside continental lithosphere is small because of the necessity of high rheological strength to maintain their stability: lower intrinsic strength allows for accumulation of more strain, but also makes continental lithosphere more prone to tectonic recycling. However, during continental collision events at least some strain is accumulated and preserved in the immediate proximity of the colliding continental margins.

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Past and future volcanism in Germany, models and consequences

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Cenozoic volcanism in Europe is widespread and several models exist to explain its occurrence. When looking for a repository for highly radioactive waste in Germany, it has to be ensured that the area will not be affected by future volcanism, at least for one million years. Therefore, we have to use all available data that can provide information about the current and possibly future geodynamic and magmatic state to evaluate potential future volcanic activity. Past processes and magmatism indicate how volcanic activity has been related to thermal, tectonic and overarching geodynamic processes. Some indicators show that phenomena possibly connected with cenozoic volcanism reach far beyond the extent of individual volcanic fields and thus large scale processes must be considered. Existing models include the influence of the alpine orogeny on the stress field and the evolution of the European Cenozoic Riftsystem (ECRIS), but also on the lithospheric deformation (buckling/folding) in the foreland of the Alps and the possible remobilisation of material in the asthenosphere. Other models include buoyancy driven upwelling of enriched or hot material from the mantle transition zone. Additionally, the general tectonic constellation in central Europe with young orogens in the south and thick old cratonic lithosphere in the east and north might be relevant for the lithospheric deformation and mantle processes. Consequently, the physical and chemical state of the lithosphere and sub-lithospheric mantle and their evolution are crucial parameters to evaluate potential future volcanic activity in Germany.

In the BGR project “Magmatism”, we aim to assess the regional potential of future volcanic activity in Germany using a multi-criterial approach including a variety of indicators from seismic observations, over mantle fluids and petrological aspects to plate reconstructions and geodynamic simulations to test individual models. These assessments are intended to contribute to the identification of a safe repository for high-level radioactive waste.

Faulting and magmatism at ridge-transform intersections

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Oceanic Transform Faults (OTF) are fundamental to plate tectonics. At transforms, tectonic plates move horizontally past one another along small circles of plate motion, displaying strike-slip motion with lithosphere or crust being neither created nor destroyed. Oceanic fracture zones are the passive extension of the active transform faults and are visible as thousands of kilometers long scars in the ocean floor. In terms of subsidence, they should follow a simple trend given by plate cooling.

We have recently analyzed multibeam bathymetric data from 41 oceanic transform faults and their associated fracture zones and found that this assumption is incorrect (Grevemeyer et al., 2021). Rather, we find that the seafloor along transform faults is systemically deeper than at the associated fracture zones, which are therefore not simple passive continuations of their active transforms. To investigate the underlying mechanisms, we first used 3-D geodynamic models (using ASPECT) to understand what makes the pronounced transform valley. In a second step, we further analyzed the bathymetric data to find out what drives the anomalous subsidence at the ridge transform intersection (RTI). Our models show that a surface strike-slip kinematic boundary condition, will, due to the age-offset that causes an asymmetry in plate strength, turn into a slightly oblique and thereby extensional shear zone at depth. We interpret this extensional component as the process that makes the valley. This implies a progressive shift from near seafloor strike-slip tectonics to oblique shearing at depth. Detailed analyses of the bathymetric data showed that when this thinned lithosphere passes the opposite ridge-transform intersection, it appears to experience magmatic addition explaining the shallower relief of the fracture zones. This makes accretion at transform-fault systems a two-stage process, fundamentally different from accretion elsewhere along mid-ocean ridges.

Effects of tidal heating in Proxima Centauri b's thermal evolution

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The recent discovery of a terrestrial planet orbiting Proxima Centauri, our closest neighbor (an M5.5V star of 0.1 MSun mass and only 1.3 pc distance to the Sun), offers an excellent planet laboratory to study the most important theories of planet evolution and composition. The planet (Proxima b) is orbiting the star in its habitable zone at a separation of only ~0.05 AU and an orbital period of ~11 days, and most recent studies suggest a non-zero eccentricity of about 0.17. With a mass of >=1.2 MEarth, Proxima b is expected to have a rocky composition, which might resemble the Earth. It is therefore an excellent target to characterize terrestrial planets similar to Earth, avoiding the inherent biases of only studying the terrestrial planets of the solar system.

Due to its close orbit and expected eccentricity, Proxima b most likely suffers from severe tidal heating, which can have an extreme incidence in the planet's habitability and the survival of an atmosphere. In this work, we perform a comprehensive analysis of the incidence that different distribution patterns of tidal heating can have on Proxima b's interior and thermal evolution. To accomplish this goal, we consider various cases for the tidal heat distribution, which depend on the assumed planet's interior structure. In the simplest case, the distribution is homogeneous throughout the interior of the planet. More complicated distribution patterns with radial and/or lateral dependence (for a homogeneous body, for a two-shell body with a differentiated core; Beuthe 2013) are also investigated. The different models alter how tidal heat is distributed throughout the planet's interior, which can highly affect its overall thermal evolution.

Furthermore, due to its proximity to the central star, Proxima b may as well be in synchronous rotation with Proxima Centauri. This can cause an extreme surface temperature variation between the hemisphere that permanently faces the star and the opposite hemisphere. In this work, the effect that synchronous rotation may have on Proxima b's interior is also explored.

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Linking Geologic and Geodynamics Modelling - a Quantitative Exploration Tool

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3D geologic modelling has matured into a useful tool to assist conventional exploration methods especially in complex tectonic areas thereby helping to address both fundamental and more practical questions as those related to the geodynamic evolution of the investigated site, its hazard and resource potential. Such modelling exercises relied on intensive data integration from different sources combined into a digital representation (digital twin) of the subsurface, both in terms of the system geometrical characteristics and of its physical properties. As a complete knowledge of the natural system and its internal state is not possible, geologic modelling must face an unavoidable source of uncertainty. The latter aspect is conventionally tackled by forward geophysical modelling, where the misfit between the computed and observed response can be used as an informative metric to guide the model building stage. However, the use of geophysical data alone provides ambiguous, that is non-unique solutions to the problem at hand, with for example different geometric (think about gravity) or compositional (think about mantle tomography) representations of the internal configuration being able to reproduce the same geophysical response. The purpose of this contribution is to discuss the concept of extending the conventional approach described above by integrating concepts derived from physics-based geodynamic modelling and AI methods to improve the predictive capabilities of computer assisted explorative investigations. Based on different study cases, we will show that these hybrid models can provide a higher predictive capability compared to conventional methods, being also able to account for sources of epistemic uncertainties arising either from an uneven distribution or lack of hard data or from a simplifying physical description of the causative dynamics of the system being investigated.

Thermo-Hydro-Mechanical-Chemical modelling: applications to dehydration vein formation and reactive melt migration

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Many geodynamic processes, such as subduction or magmatism, involve the coupling of thermal (e.g. heat conduction), hydrological (e.g. porous flow), mechanical (e.g. viscous shearing) and chemical (e.g. dehydration reaction) processes. However, our knowledge of these coupled processes is still limited, and the quantification of such coupled processes remains challenging. One possibility to study such coupled processes is the application of mathematical models and their corresponding numerical solutions. Such mathematical models for the coupled processes mentioned above are frequently termed Thermo-Hydro-Mechanical-Chemical (THMC) models. I present the fundamentals of a particular type of THMC models and show two applications of this model: (1) A two-dimensional (2D) HMC model for the formation of dehydration veins in viscously deforming serpentinite and (2) 1D and 2D THMC models for melt migration and chemical differentiation by reactive porosity waves. The HMC model is applied to olivine veins in meta-serpentinites, observed in the Erro-Tobbio unit (Ligurian Alps, Italy). I discuss the different characteristic time scales controlling dehydration vein formation and quantify the impact of deformation and kinetic rates on the growth velocity of the dehydration veins. The THMC model is applied to melt migration around the lithosphere-asthenosphere boundary to better understand the formation of so-called petit-spot volcanoes, which are observed on the subducting Pacific plate east of Japan. These models show that chemical differentiation, particularly the variation of silica content, affects melt migration since it changes the densities of solid and melt. Both HMC and THMC models are numerically solved with the pseudo-transient finite difference method, for which I explain the main features. I will also briefly discuss the numerical solutions for CPU and GPU computer architectures.

Melt transport mechanisms: from melt segregation, extraction to the formation of crustal magmatic systems

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At various regions within the dynamic earth melts are generated due to decompressional melting, reduction of the solidus temperature due to volatiles or due to elevated temperatures. They segregate from these partially molten regions, rise by various transport mechanisms and may form crustal magmatic systems where they are emplaced or erupt. The physics of various aspects of this magmatic cycle will be addressed.

The basic mechanism of melt transport out of source regions is two-phase flow, i.e. a liquid phase percolates through a solid, viscously deforming matrix. The corresponding equations and related issues such as effective matrix rheology are addressed. Beside simple Darcy flow, special solutions of the equations include solitary porosity waves. Depending on the bulk to shear viscosity ratio of the matrix and the non-dimensional size of these waves, they show a variety of features: they may transport melt over large distances, or they show transitions from rising porosity waves to diapiric rise. Other solutions of the equations lead to channeling, either mechanically or chemically driven. One open question is how do such channels transform into dykes which have the potential of rising through sub-solidus overburden. A recent hypothesis addresses the possibility that rapid melt percolation may reach the thermal non-equilibrium regime, i.e. the local temperature of matrix and melt may evolve differently.

Once basaltic melts rise from the mantle, they may underplate continental crust, generate silicic melts, and intrude the crust forming magmatic systems. Recently Schmeling et al. [1] self-consistently modelled the formation of crustal magmatic systems, mush zones and magma bodies by including two-phase flow, melting/solidification and effective power-law rheology. In these models melt is found to rise to mid-crustal depths by a combination of compaction/decompaction assisted two-phase flow, sometimes including solitary porosity waves, diapirism or fingering. These models are compared to setups in which melt is artificially extracted and emplaced at predefined shallow depth. This comparison allows a quantitative evaluation of the so called heat pipe mechanism.

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Modelling the redistribution of trace elements for higher upper mantle pressures

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During partial melting inside the mantle, incompatible trace elements prefer to partition into the melt. Because of a lower density compared to the surrounding solid rock, the trace element enriched melt will rise towards the surface and contribute to the global redistribution of trace elements significantly. Given time, this process will leave the crust enriched and the upper mantle depleted in incompatible trace elements. In this context, partition coefficients are an important tool to assess how strongly a certain element is either redistributed from a certain mineral towards the melt or how well it can be incorporated into its crystal lattice. Even though it is known that partition coefficients depend on pressure, temperature, and composition, studies investigating trace elements typically have to rely on constant partition coefficients throughout the mantle. However, between the pressures of 0-15 GPa, clinopyroxene/melt partition coefficients for sodium vary by two orders of magnitude along both, solidus and liquidus. Because of sodium's characteristic as a best fitting element in clinopyroxene and the logarithmic relationship partition coefficients of one charge exhibit, a similar variation is expected for all trace element partition coefficients that can be derived from the sodium partition coefficients.

Based on an earlier model [1], we developed a thermodynamic model for sodium in clinopyroxene/melt. From the model results, we deduced a P-T dependent equation for sodium partitioning that is applicable up to 12 GPa between the peridotite solidus and liquidus [2]. As mentioned before, sodium can be incorporated almost strain-free into clinopyroxene and can therefore be used as a reference to model other trace elements' partition coefficients, including the heat producing elements K, Th, and U. This opens the opportunity to insert P-T sensitive partition coefficient calculations into mantle melting models, which will make elemental redistribution calculations and thus, models for mantle and crust evolution, much more accurate.

[1] Blundy, J. et al. (1995): *Sodium partitioning between clinopyroxene and silicate melts*, J. Geophys. Res., 100, 15501-15515.

[2] Schmidt, J.M. and Noack, L (2021): *Parameterizing a model of clinopyroxene/melt partition coefficients for clinopyroxene to higher upper mantle pressures*, accepted in GeoProcessing 2021

Reduced basis method for Stokes flow in geodynamic modelling

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Geodynamic modelling is a powerful tool to get an insight into the dynamics of the earth. Solving the Stokes equations is usually the most time consuming factor while performing geodynamic simulations, especially if 3D problems are considered. Therefore applications in which many forward problems have to be solved, e.g inversion frameworks like Bayesian inference, become unfeasible rapidly.

In order to deal with this problem the Reduced Basis (RB) method is applied to the Stokes equations. This method tries to find solutions to a specific number of input parameters within a predefined range at a low computational cost. These parameters can be physical parameters like the viscosity of a phase in Stokes flow or geometrical parameters like the extension of a continental plate. The RB method attempts to find a small number of basis functions that represents the solutions to the forward problem for the predefined parameter space sufficiently well.

In this work, a subduction setup with linear rheology is considered. Different geometries of the subducting plates are treated as an input for the RB method. Then the RB method is applied to the Stokes equations solved by a finite difference method on a staggered grid implemented in the thermomechanical code LaMEM [1]. It is shown that it is possible to find a small number of basis vectors which represents the subduction setup both in the 2D and 3D case within a reasonable error.

By changing the geometry of the input setup, the nodal viscosity and density values change as well. As the RB method requires access to the discretized system of the forward problem in order to calculate a RB solution, the assembling process would have to be performed every time a new RB solution is evaluated. At this point we make use of the Discrete Empirical Interpolation Method (DEIM). This method finds a small number of interpolation points with whom all other viscosity and density nodes can be interpolated. Together with the affine decomposition of the discretized Stokes system, it is demonstrated that DEIM increases the efficiency of the RB method dramatically.

Geodynamic inversion with uncertain initial geometries

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Advanced numerical methods and increasing computational power have enabled us to incorporate numerical forward models into geodynamic inverse frameworks. We now have several strategies to constrain the rheological properties of the crust and lithosphere. Yet, the initial geometry of geological formations (e.g., salt bodies, magma bodies, subducting slabs) and associated uncertainties are, in most cases, excluded from the inverse problem and assumed to be part of the a priori knowledge. Usually, geometrical properties remain constant, or we employ simplified bodies like planes, spheres, or ellipsoids for their parameterization.

Here, we propose a simple and intuitive method to parameterize complex three-dimensional bodies and incorporate them into geodynamic inverse problems. Our approach enables us to automatically create an entire ensemble of initial geometries within the uncertainty limits of geophysical imaging data. This not only allows us to account for geometric uncertainties, but also enables us to investigate the sensitivity of geophysical data to the geometrical properties of the geological structures.

We present 3 areas of application for our method, covering salt diapirs, magmatic systems and subduction zones, using both synthetic and real data. The examples demonstrate that the evolution of the models strongly depends on their initial geometry. Given sufficient observables like surface velocities, gravity anomalies or fault zones, our parameterization allows us to invert for the unknown initial geometry.

Impact of tectonic and surface processes on biodiversity

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The evolution of life on Earth is fundamentally linked to the dynamics of the lithosphere and deep mantle, and coupled to the Earth's surface, oceans and climate, but those dimensions are rarely studied together. We used a fast general circulation model for ocean and atmosphere (FOAM [1]) with a paleo-digital elevation model [2] for the timespan from 540 Ma up to recent times to generate climate model scenarios. Using variables like air surface temperature and precipitation combined with the digital elevation model considering different tectonics scenarios we show how simulations with gen3sis [3], an eco-evolutionary biodiversity model, can inform about the conditions for the formation of biodiversity. By varying Earth dynamics e.g., the movement of tectonic plates, collisions, rifting we can investigate the causal connections between changes at Earth's surface like mountain building or creation of new oceans, the formation and destruction of habitats, we explore different scenarios generating specific biodiversity patterns. By combining these models and their respective results, we can develop a new methodology for understanding the feedback loops between geodynamics, climate and life evolution. In the current scenario, we investigate the differences in biodiversity between the natural movement of continental plates and a static Earth.

Ultimately, we aim to apply our models to important events in Earth's history like supercontinent formation, continental breakup, large igneous province eruptions, and the transition from single lid to plate tectonics.

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On the use of Laboratory Rheological Data in Geodynamical Simulations

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While it is typical in the lithospheric dynamics community to input laboratory-measured rheological parameters into geodynamical models, in the mantle convection community it is still typical to use idealized rheologies that do not correspond to any measured rock, or to assume olivine creep parameters for all materials. The use of laboratory data gives the hope of achieving greater realism but the (stress, strain-rate) conditions occurring in nature are many orders of magnitude lower than those in laboratory experiments, raising concern as to the robustness of greatly extrapolated rheological behaviour.

Here, a review is given of the available laboratory data that could be used for the common rock types (e.g. "basalt", "harzburgite", "normal mantle", "continental crust") and to what extent the results of different experimental studies are consistent with each other both over the range of measurement and when extrapolated to geological conditions. For crust/shallow mantle rocks there is abundant data, but predicted viscosities of seemingly similar materials can differ by orders of magnitude when extrapolated to geological conditions. Peierls creep could either be very important or not important at all, depending which experimental study is chosen. Data becomes scarcer at higher pressures, with scaling arguments and ab initio calculations being the main constraints on lower mantle rheology.

In conclusion, laboratory data alone is not sufficient to uniquely predict the viscosities of various rock types under geological conditions; matching models to natural observations (such as post-glacial rebound, flow velocities, geoid and topography, etc.) is essential for calibration.

Contributions of grain size reduction and shear heating to slab detachment

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The detachment of subducting slabs has been frequently invoked to explain different phenomena such as magmatism, rapid exhumation of metamorphic rocks, topographic uplift and the occurence of intermediate-depth earthquakes. Despite its potential importance for all these phenomena, the slab detachment process is still incompletely understood, in particular in relation to ductile weakening mechanisms.

Here, we therefore investigate the impact of three coupled weakening mechanisms on the viscous detachment of a stalled lithospheric slab: structural weakening due to necking, material weakening due to grain size reduction (using a two-phase grain damage model) and thermal weakening due to shear heating. We consider a combined flow law of dislocation and diffusion creep. To understand and quantify the coupling of these three nonlinear weakening processes, we derive a mathematical model, which consists of three coupled nonlinear ordinary differential equations describing the evolution of slab thickness, grain size and temperature. Using dimensional analysis, we determine the dimensionless parameters which control the relative importance of the three weakening processes and the two creep mechanisms. We derive several analytical solutions for end-member scenarios that predict the detachment time, that is the duration of slab detachment until slab thickness becomes zero.

Furthermore, we use numerical solutions of the system of equations to systematically explore the parameter space with a Monte Carlo approach. Comparison to the analytical prediction shows that they are capable of predicting slab detachment times, even for scenarios where all three weakening and both creep mechanisms are important. At worst, the deviation of the analytical predictions from the numerical results amounts to 50 %.

When both grain and thermal damage are important, the two damage processes generate a positive feedback loop resulting in the fastest detachment times. For Earth-like conditions, we find that the onset of slab detachment is controlled by grain damage and that during later stages of slab detachment thermal weakening becomes increasingly important and can become the dominating weakening process. We therefore argue that both grain and thermal damage are important for slab detachment and that both damage processes could also be important for lithosphere necking during continental rifting leading to break-up and ocean formation.

India-Eurasia corner collision and extrusion: inferences from coupled thermo-mechanical and surface processes 3D models

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Plate tectonics, surface processes and climatic variations shape and drive the formation of orogens. Oceanic and continental subduction, and subsequent collision result in transient topographic signatures. Surface processes, erosion and sediment re-distribution change the stress and temperature field within the lithosphere, which can significantly influence the style of deformation and the resulting topographic fingerprints. The India-Eurasia collision zone provides an ideal natural example where these interactions can be studied. To this aim, we use a 3D coupled numerical modelling approach. The dimensions of this large-scale regional model are x * y * z = 2120 * 204 * 1320 km3, on a coarse resolution of 10 * 3 * 10 km. This domain size has rarely been used in previous work. Each grid cell contains 5 x 3 x 5 markers such that small-scale structures can still form. We use non-Newtonian, visco-plastic rheologies and account for diffusion-advection-based erosion and sedimentation. The northward indentation (push) of India is combined with laterally varying velocity boundary conditions, applied to the south-eastern and eastern boundaries of the model domain, to see how this affects the topographic signature. These experiments were conducted using the thermo-mechanical code I3ELVIS (Gerya and Yuen, 2007) coupled to the FDSPM surface processes code, based on diffusion-advection (Munch et al., 2017). The results of the experiments will aid in identifying and understanding the processes involved in this complex natural example of continental corner collision.

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The fate of volatiles during magma body crystallization

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After the solidification of the magma ocean, outgassing from the interior is the prevailing volatile source of early Earth´s atmosphere. Besides the well-studied extrusive degassing, this process also includes the often-neglected intrusive volatile release, although at least today, intrusive magma production rates are assumed to be significantly higher compared to extrusive rates. This renders the investigation and quantification of possible volatile exsolution mechanisms from intrusive magma bodies crucial.

The process of fractional crystallization within a magma body has an influence on the solubility and thus on the associated volatile release. During cooling of an intrusion, nominally anhydrous minerals precipitate from the melt. These minerals mainly incorporate elements that are compatible with their crystal lattice. Since volatiles such as H2O and CO2 behave like incompatible elements, they accumulate in the remaining melt. At a certain point, the melt is saturated and the exsolution of a volatile phase initiates.

In this study, we model the effect of fractional crystallization on the solubility and the related volatile release. We focus on the exsolution of H2O and CO2 from basaltic magma bodies within the lithosphere. Another important factor influencing the volatile release is the formation of hydrous minerals (e.g., amphibole). We include this mechanism in our calculations, since hydrous phases can incorporate huge amounts of H2O. To determine the fate of the accumulating volatiles, we compare the density of the developing melt with the density of the host rock. If the host rock has a higher density, the liquid phases (melt and volatiles) will ascend either directly to the surface or to the upper crust. The associated change in the lithostatic pressure has an additional impact on the volatile release.

Our results demonstrate that fractional crystallization significantly reduces the solubility of H2O and CO2. This in turn leads to an enhanced release of volatiles from the intrusive magma body. While the exsolution of H2O is diminished by the precipitation of hydrous minerals, the decrease in density and thus in pressure facilitates H2O release.

Dykes in a crustal two-phase flow medium

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For understanding the crust's structural and compositional evolution we study magmatic systems by geodynamic numerical modelling. We describe the crust by a thermo-mechanical-compositional two-phase flow formulation. It is based on conservation equations of mass, momentum, energy, and composition for solid and melt. The rheology is non-linear visco-plastic following a power law and Byerlee's Law for plasticity. A simplified binary melting model is used for melting. Full compaction of the solid matrix, melting, melt segregation, and freezing is included [1].

Segregation and advection of melt is relatively slow, but sometimes fast transport is observed. A rough substitution is extraction and intrusion (or extrusion) of melt [2]. A melt fraction limit and an emplacement level must be given. Modelling exhibits effective influence, ascent is accelerated (x4 and more), shallower intrusion level can be reached. The simple mechanism has several shortcomings: the presetting of an emplacement zone, the vertical transfer of melt, parameters are hard to constrain.

Dyking should be a better approximation, because it can be formulated more physically, controlling parameters have physical meanings and are empirically constrained, at least in the upper brittle crust it is observed and it makes the magmatic system more self-consistent. Due to the different time scales of segregation and viscous deformation it is reasonable to treat dykes elastic, thus time-independent.

The Boundary Element displacement discontinuity Method is well suited for cracks and the calculation of dyke propagation. Francesco Maccaferri provided his BEM-code [3] for combination with our Finite Difference code FDCON. The integration or assembly is in progress. Preliminary tests without feedback triggered after some time many ascending dykes slowing down the job runtime. Dykewise parallelization reduced the runtime. From the coupling, more explicit extraction and intrusion of the dyke's melt, problems are expected. First trials of extraction showed an imploding source region which is ok due to the full drainage of a narrow melt supply column; installing a remaining porosity solved the problem, a planned wider supply region will help too. Dyke's melt emplacement will lead to decompaction; in the usually colder and stiffer area probably too high stresses will appear and provide numerical instabilities. Solution of the problems are expected from a distribution, weakening, damage rheology or new ideas. My state of art will be presented.

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