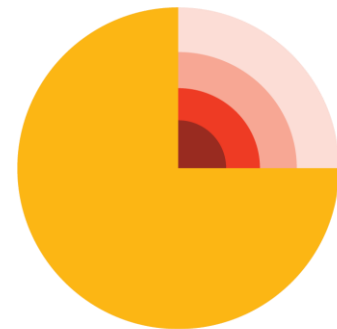


A decorative header bar featuring various geometric shapes in white outlines on an orange background, including circles, semi-circles, and concentric arcs.

Geodynamic Modelling (LaMEM)

Boris Kaus, Anton Popov
Johannes-Gutenberg University, Mainz
Germany



ChEESE

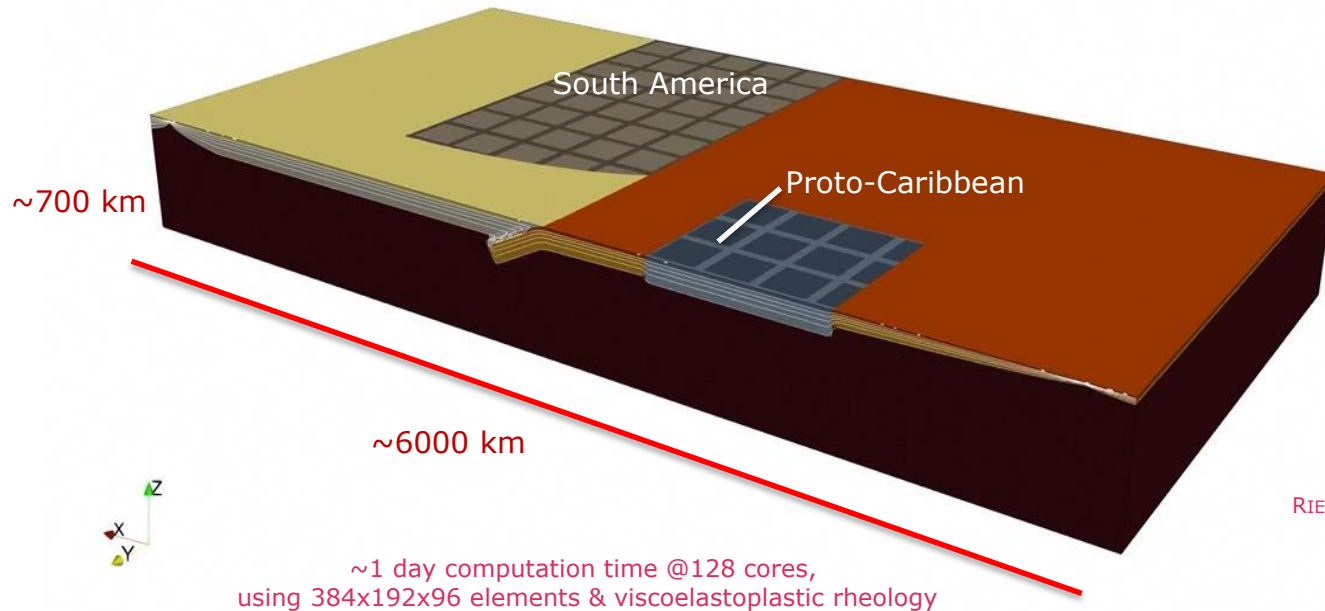


The Earth is dynamic

0.00 Myrs

Questions:

- How do tectonic plates collide?
- How does this compare to observations?



RIEL ET AL. (ACCEPTED, 2023)
NATURE COMMUNICATIONS

Physics-based modelling

$$\frac{\partial u_i}{\partial x_i} = -\frac{1}{K} \cdot \frac{dP}{dt}$$

c onservation of mass

$$-r g_i = -\frac{\partial P}{\partial x_i} + \frac{\partial t_{ij}}{\partial x_j}$$

c onservation of momentum

$$\dot{e}_{ij} = \frac{1}{2h_{eff}} t_{ij} + \frac{1}{2G} \frac{Dt_{ij}}{Dt} + j \frac{\partial Q}{\partial s_{ij}} \quad \text{visco-elasto-plastic rheology}$$

$$rc \frac{DT}{Dt} = \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) + H_{sources}$$

conservation of energy

(nearly incompressible) Stokes flow

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \longrightarrow \quad \begin{pmatrix} \mathbf{K} & \mathbf{G} \\ \mathbf{G}^T & \mathbf{0} \end{pmatrix} \begin{pmatrix} \mathbf{u} \\ \mathbf{p} \end{pmatrix} = \begin{pmatrix} \mathbf{f} \\ \mathbf{g} \end{pmatrix}$$

$$-\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left(h_{eff} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) = -r g_i$$

Complexities mainly from the nonlinear rheology of rocks

Visco-elasto-plastic rheology

Viscous creep



stress $\sim$ strain rate
viscosity

$$\dot{\epsilon}_{ij}^{vis} = \frac{1}{2\eta(\tau, T, C, ..)} \tau_{ij}$$

Elastic strain



stress $\sim$ strain
elastic modulus

$$\dot{\epsilon}_{ij}^{el} = \frac{1}{2G} \frac{D\tau_{ij}}{Dt}$$

Plastic failure



stress $\leq$ yield criterion
cohesion/friction angle

$$\dot{\epsilon}_{ij}^{pl} = \dot{\lambda} \frac{\partial Q}{\partial \sigma_{ij}}$$

Rocks are nonlinear (Maxwell) visco-elasto-plastic materials:

$$\dot{\epsilon}_{ij} = \dot{\epsilon}_{ij}^{vis} + \dot{\epsilon}_{ij}^{el} + \dot{\epsilon}_{ij}^{pl}$$

LaMEM

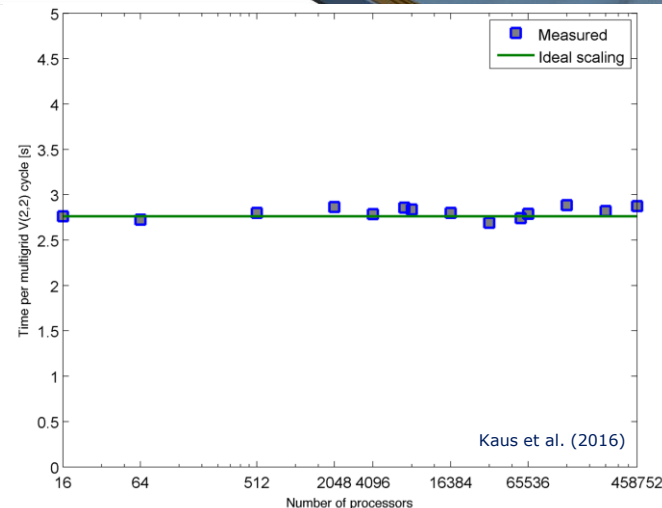
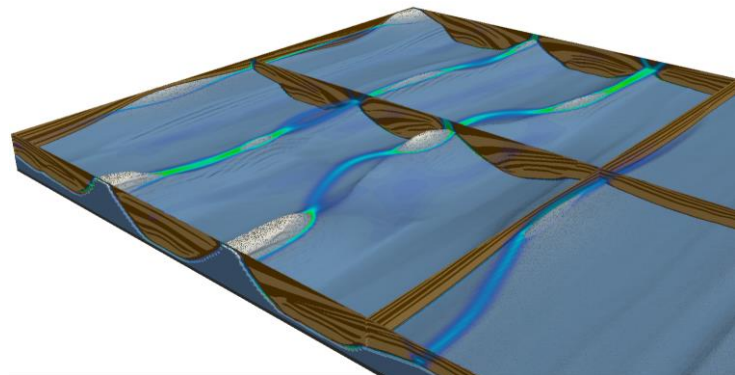
Lithosphere and Mantle Evolution Model

Physics

- Conservation of momentum, mass and energy
- Compressible/incompressible poro-visco-elasto-plastic rheology

Numerical implementation

- 3D staggered finite-difference, marker & cell method
- MPI-parallelization, using PETSc
- Galerkin multigrid preconditioners & Newton solvers for nonlinearities
- Adjoint-based sensitivity/inversion framework
- Written in C; runs on >458'000 processors
- Typical 3D runs on 64-128 cores in a few hours, for ~60 Mio cells



LaMEM

Lithosphere and Mantle Evolution Model

bitbucket.org/bkaus/lamem/wiki/Home

LaMEM

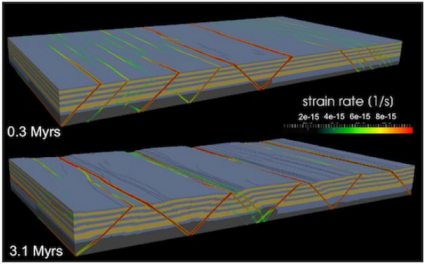
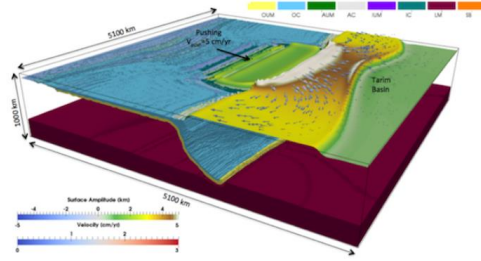
Wiki

LaMEM / Home

Clone wiki

View History

LaMEM Userguide



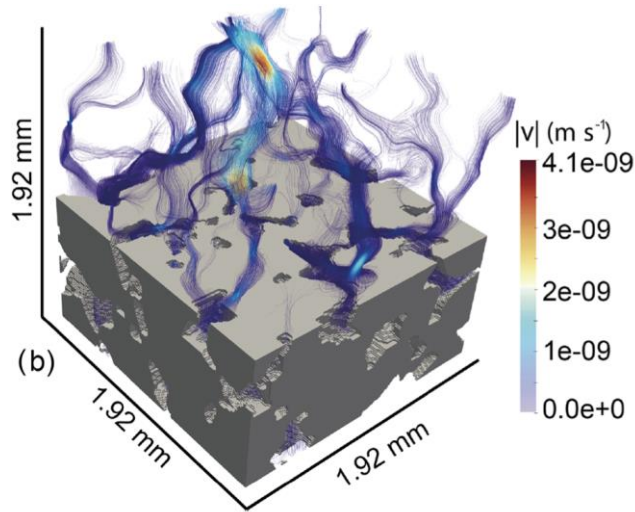
LaMEM (Lithosphere and Mantle Evolution Model) is a software package to simulate 2D/3D geological and geomechanical processes, which runs on anything from your laptop to a massively parallel machine. It takes (poro)-visco-elasto-plastic rheologies into account, and can be used to simulate anything from the collision of tectonic plates to the flow of fluids through porous rocks.

The purpose of this wiki is to get you started with installing and running LaMEM and give a few worked-out examples that explain how to run

<https://bitbucket.org/bkaus/lamem>

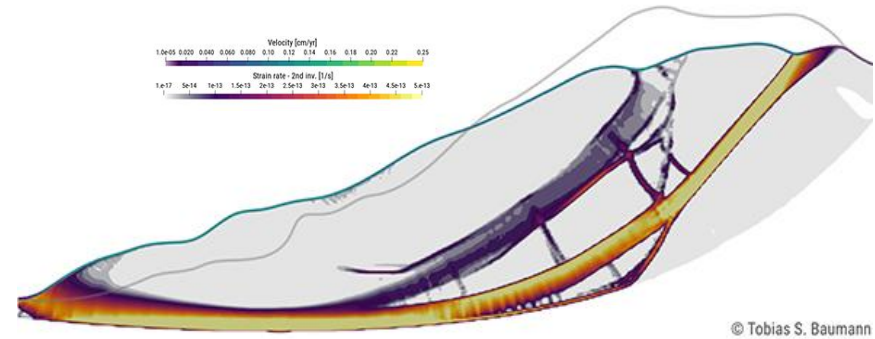
Processes on different scales

Fluid flow through rocks



Eichheimer et al. (2019), *Solid Earth*

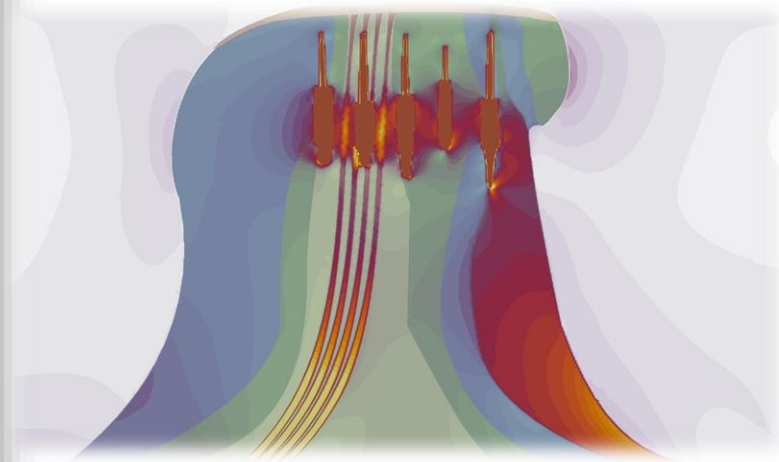
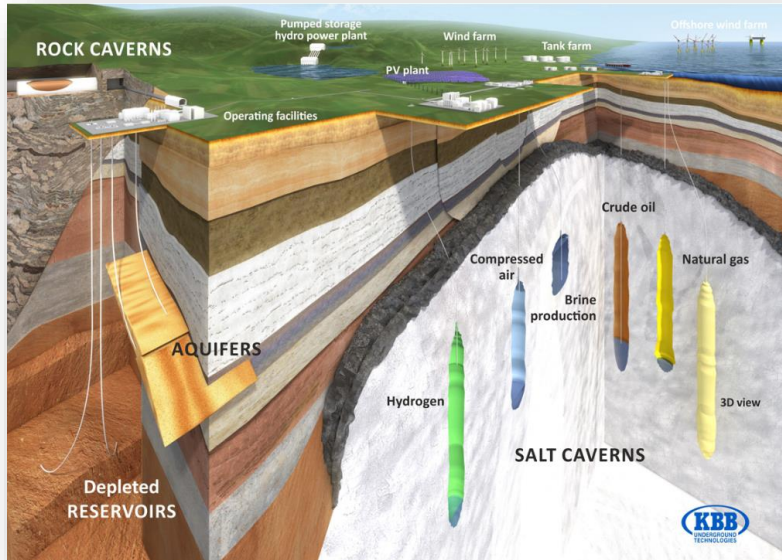
Hang instabilities @ volcanoes



Heap, Baumann et al. (2021),
Journal of Geophysical Research



Salt caverns & energy transition

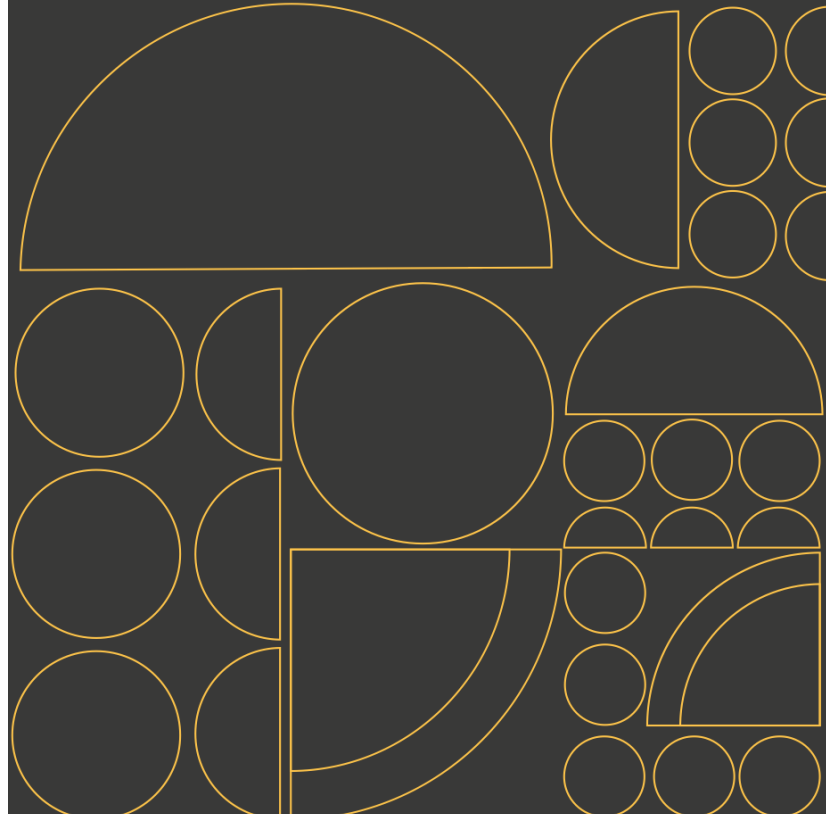


Uncertainty quantification: Is it safe given imprecisely known material parameters?

- Salt is potential host rock for a nuclear waste repository in DE (safe >1 Mio years)



Planned work



PD 8

Geodynamics to Geohazards



Geodynamics to geohazards

01

Improve workflow

Rapidly deploy geodynamic codes to any part of the world while taking observations into account

02

Couple codes

Project stresses & material properties from a geodynamic code (pTatin) to seismic hazard codes (SeisSol)

03

Prepare for GPU

Port geodynamic codes to GPU machines



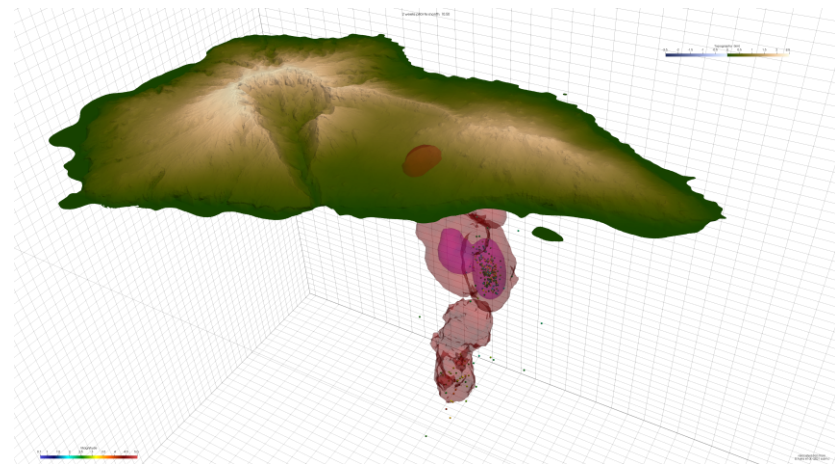
WP5 1.9

(workflow)

- Implement a Julia interface for LaMEM
- Rapidly generate setups for any place on Earth using GeophysicalModelGenerator.jl
- Leverage the large ecosystem of available Julia packages
- Simplify installing LaMEM on different machines, by adding it to the Julia package manager



GeophysicalModelGenerator.jl



2021 LaPalma volcanic eruption
(seismicity isosurfaces & topography)

WP 2. Improving LaMEM

- Make use of GPU functionality of PETSc
- Implement matrix-free GMG solvers
- Implement BFBt solvers
- Implement coarse grid solvers that run on only a subset of the cores

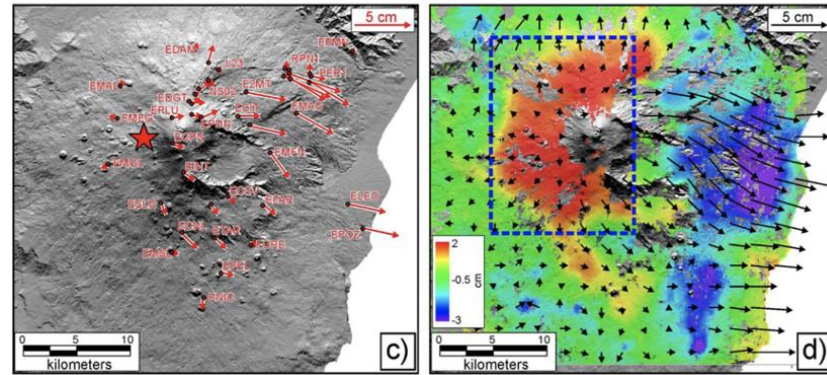


SC 8.1 Magmatic systems & landslides

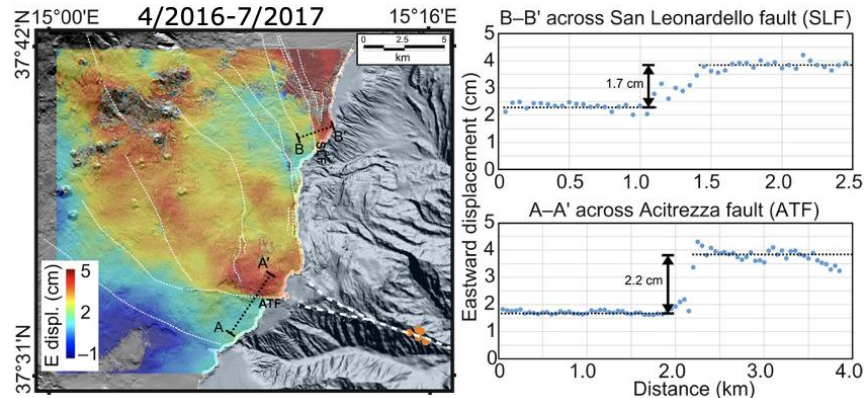
The Etna case

- The eastern flank of the Etna slides into the Mediterranean
- Deformation mostly along major faults
- Submarine data confirms this
- Gravity collapse of magma pushing?

2007-2008



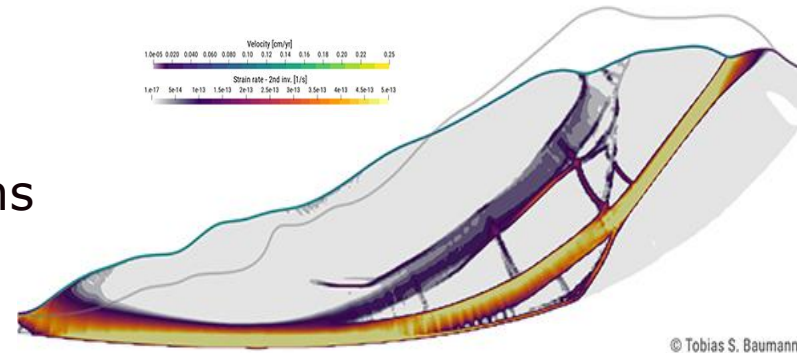
Bonforte et al. (2017) G^3



Urlaub et al. (2018) *Science Advances*

SC 8.1 Science Goal

- Generate high-resolution 3D visco-elasto-plastic models of Etna
- Simulate the hang instability
- Sensitivity results to variations in material parameters & thermal structure
- Requires high resolution (~ 50 m)



Thank you



@cheese-coe



<http://cheese2.eu>



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