LaMEM short course

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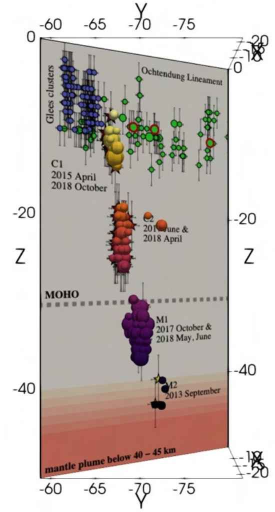
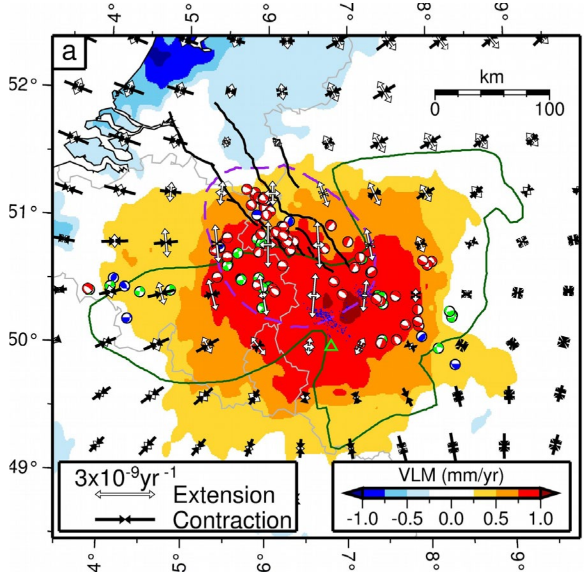


The “Eifel” anomaly

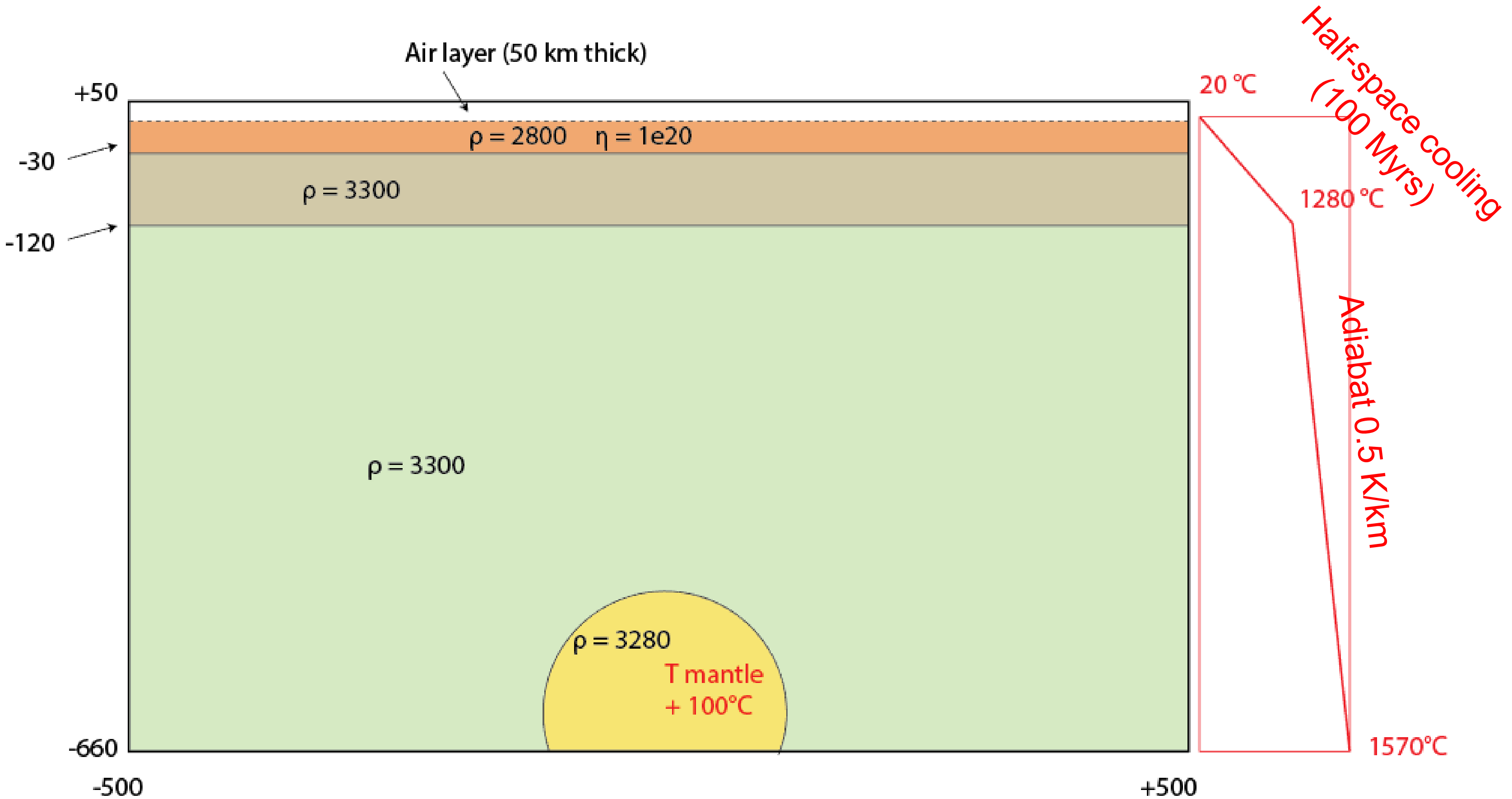


Kreemer et al. (2020)

Plume emplacement in a single LID

- Study the topography effect of plume emplacement at the base of the lithosphere

Simplified plume setup



- Create a simplified plume setup using the sketch (start with constant density and viscosity).
- How much uplift can we expect from the plume emplacement?

Simplified plume setup

TIPS:

- Start from the falling sphere setup with temperature and adapt it
- You can create a plate using the AddBox! function (similar to AddEllipsoid!)

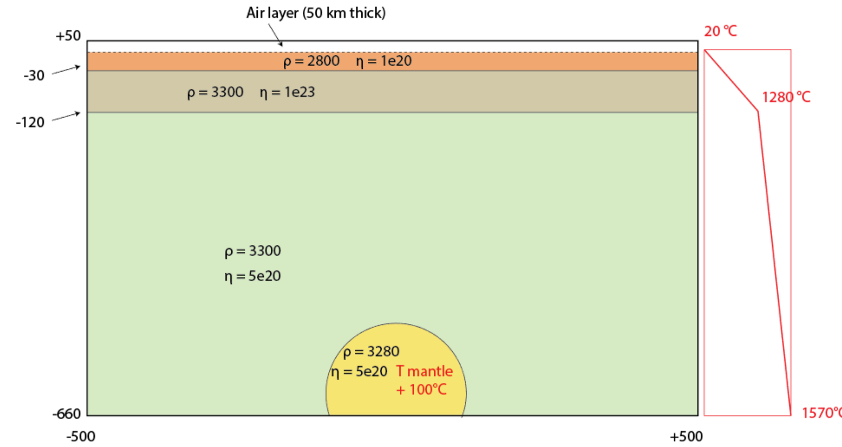
```
# add single plate using Addbox!
AddBox!(model;  xlim     = (minx, maxX),
                ylim     = (minY, maxY),
                zlim     = (minZ, maxZ),

                Origin   = nothing, StrikeAngle=0, DipAngle=0,

                phase    = LithosphericPhases(       Layers=[30 90],
                                                     Phases=[1 2 3] ),
                T        = HalfspaceCoolingTemp(     Tsurface     = Tair,
                                                     Tmantle      = Tmantle,
                                                     Age          = 100       ))
```

- LithosphericPhases() creates 3 layers and attribute phase 1, 2 and 3 to them
- HalfspaceCoolingTemp() applies a cooling age of 100 Myrs to phase 1 and 2

Simplified plume setup



TIPS:

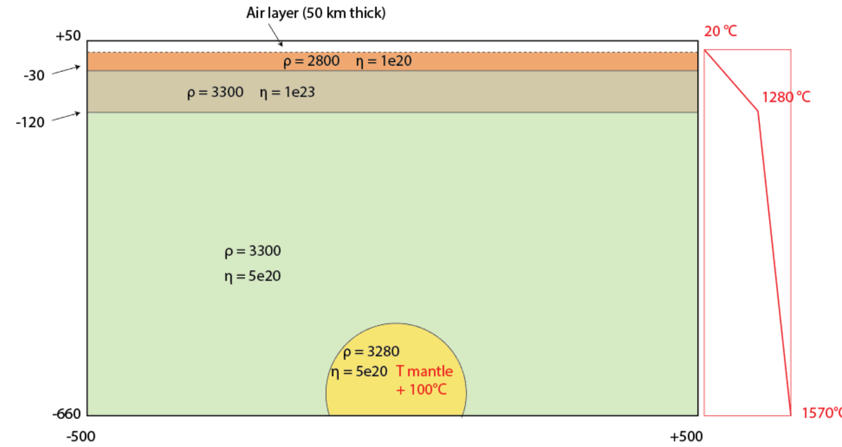
- The plume phase can be added either using AddEllipsoid!(), setting ConstanTemp(1650)

Or

- Using the equation of a circle with center = [x = 0, z = -600] and radius 100 km, filtering the particle coordinates inside the circle and applying a ΔT +100 and a phase

```
in_sphere                         = findall( ‘points in the circle’ )
model.Grid.Temp[in_sphere]       .+= 100.0
model.Grid.Phases[in_sphere]      .= 4
```

Simplified plume setup



TIPS:

- Linear gradient can be applied after defining lithosphere temperature profile such as:

```
Z                        = model.Grid.Grid.Z;
model.Grid.Temp          = model.Grid.Temp -Z.*Adiabat;
```

Where Adiabat = 0.5 K/km for the mantle (see Turcotte and Schubert for more information)

- Don't forget to overwrite the air temperature after applying the adiabat

```
model.Grid.Temp[Z.>0.0]                          .= 20.0;
```

Simplified plume setup

- Let’s add creep laws. Use quartzite for the crust, dry peridotite for the mantle

```
# eta              = 1e20,
disl_prof        = "Quarzite-Ranalli_1995",
```

```
# eta              = 1e23,
disl_prof        = "Dry_Olivine_disl_creep-Hirth_Kohlstedt_2003",
diff_prof        = "Dry_Olivine_diff_creep-Hirth_Kohlstedt_2003"
```

- Perform the simulation for < 50 timesteps, what is happening?

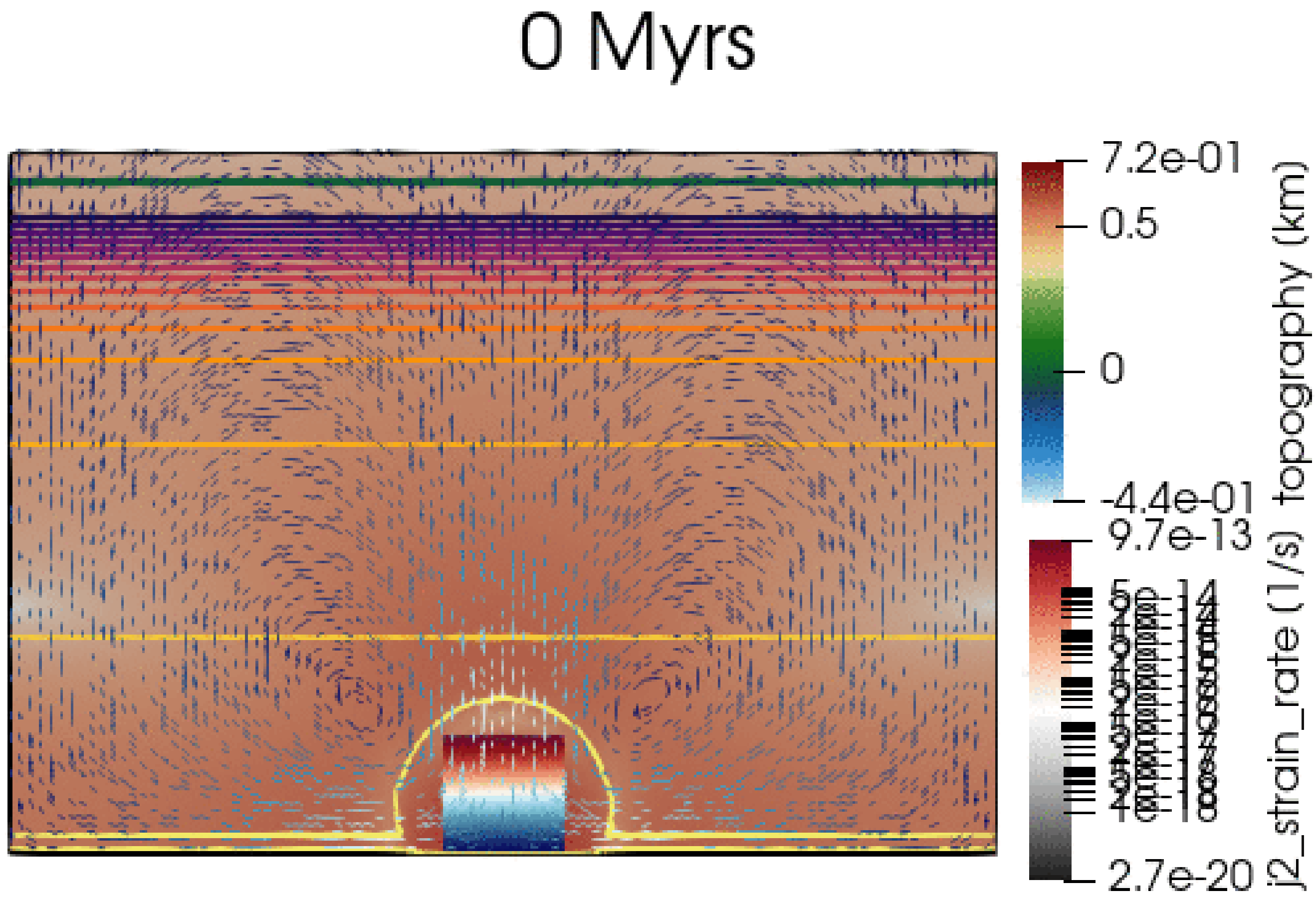
- Correct plume density, use a lower value such as 3280 and increase the number of timesteps to 600

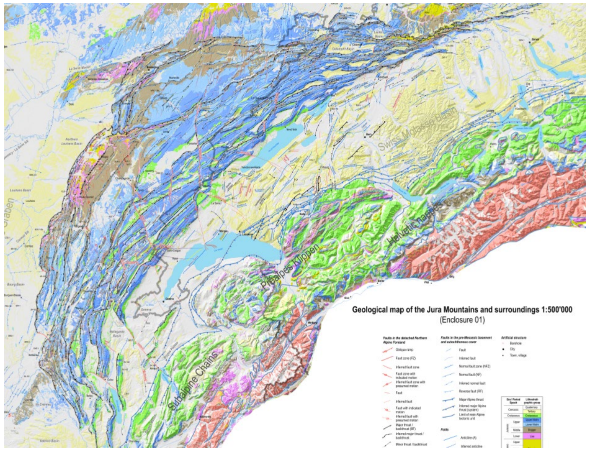
- Compare the strain-rate field with simulation using isoviscous rheology

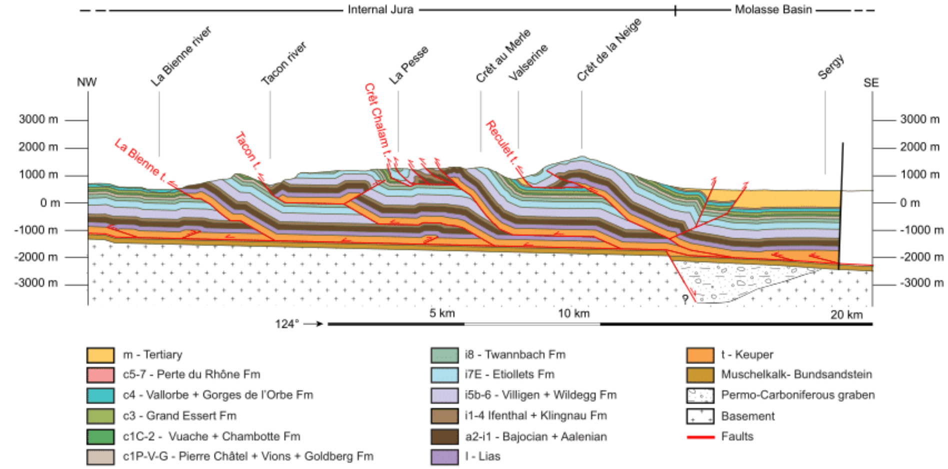
- What difference does it make to use non-linear creep laws?

```
Solver(          SolverType          = "direct",
                 DirectSolver        = "mumps",
                 PETSc_options       = [ "-snes_rtol 1e-2", "-snes_max_it 100"] )
```

Simplified plume setup





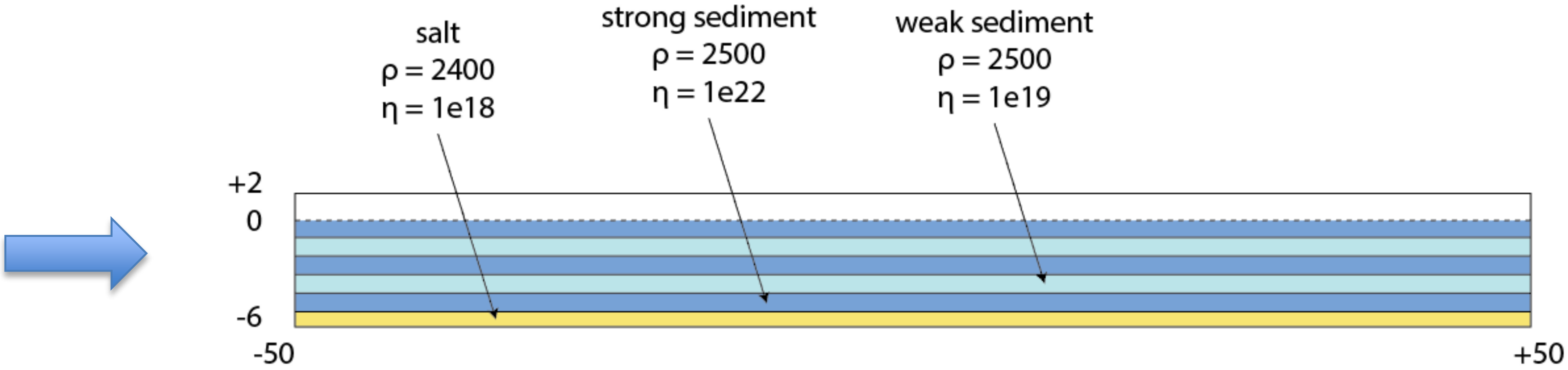


Jura Mountains

Fold and thrust belt

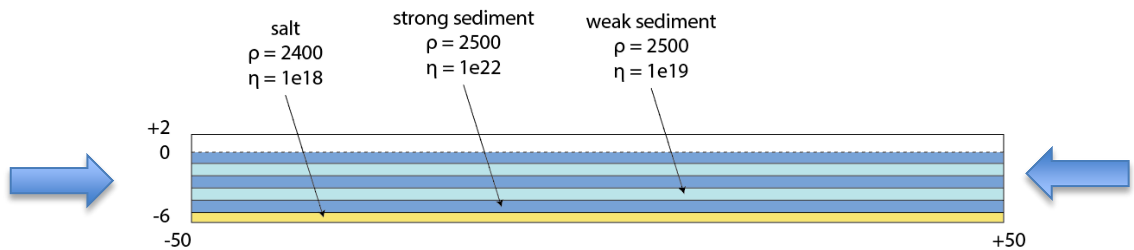
- How are folds generated?
- What is the relation between folds and thrusts?

Fold (and thrust) setup



$\dot{\varepsilon}_{xx}$ = 1e-14 (compression)

Fold (and thrust) setup



TIPS

- Copy and past the falling sphere setup with free surface

- Change the resolution to the following

```
Grid(                x               = [-50.0,50.0],
                     y               = [-0.25,0.25],
                     z               = [-6.0,2.0],
                     nel             = (256,1,48) )
```

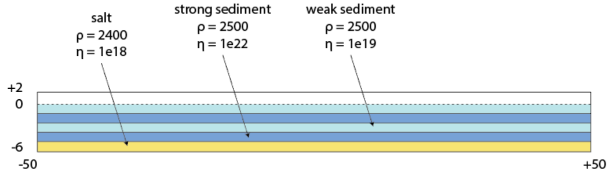
Notice that the size in the Y direction is chosen to be 0.5, so that the cell size is as close as possible to a cube.

- Update boundary condition to use prescribed xx strain-rate

```
exx_num_periods = 1,
exx_strain_rates= [-1e-14],
noslip          = [0, 0, 0, 0, 0, 0]),
```

- Choose nstep_max = 150

Fold (and thrust) setup



TIPS

- To create a layer, you can use the AddBox!() function

```
AddBox!(model;  xlim=(model.Grid.coord_x[1], model.Grid.coord_x[2]),
                ylim=(model.Grid.coord_y[1], model.Grid.coord_y[2]),
                zlim=(-5.0, 0.0),

                Origin              = nothing,
                StrikeAngle         = 0,
                DipAngle            = 0,
                phase               = ConstantPhase(2),
                T                   = nothing )
```

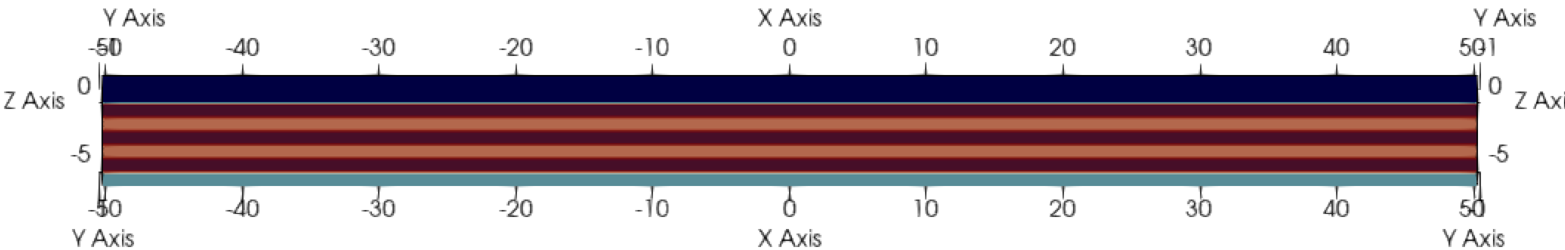
Notice minX = model.Grid.coord_x[1] and maxX = model.Grid.coord_x[2]

- Note that you need only 4 phases: Air, strong sediment, weak sediment and salt

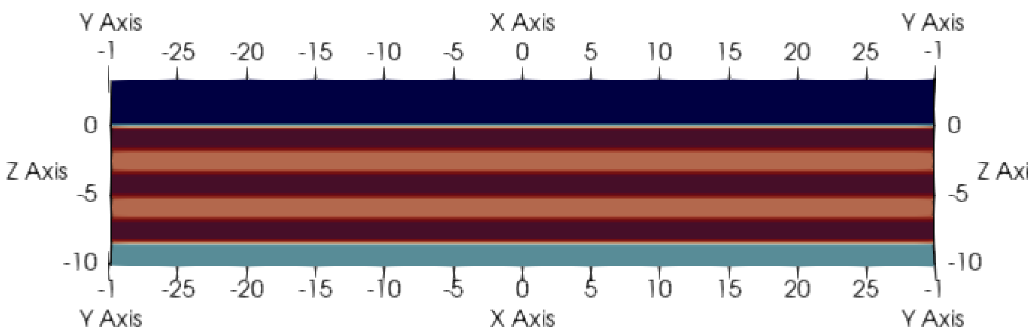
Fold (and thrust) setup

- Results

0.00 Myrs

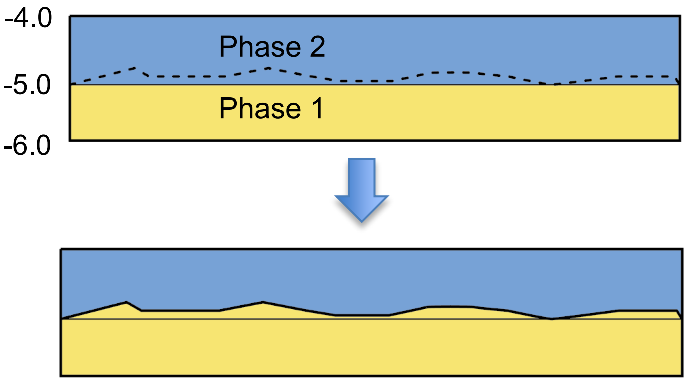


1.64 Myrs



- Why do you think there is no fold forming? How to fix that?

Fold (and thrust) setup



- Natural sedimentary layers are irregular
  → we need randomness!

- How to add randomness? Make use of the subarray filter with point wise operation and add randomness for each sedimentary layer interface.

```
Z = model.Grid.Grid.Z;
```

```
model.Grid.Phases[Z .> val1 .&& Z .<= val2 ]  .= val3;
```

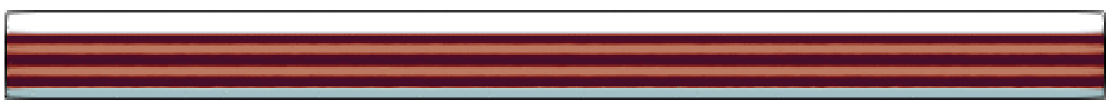
… and the random function: “rand()” that sends back a random value between 0.0 and 1.0

Note that “rand()” can also be used in a pointwise manner as “rand.()”

Fold (and thrust) setup

Iso-viscous folding

0.00 Myrs



- Results from one simulation are different, why?

Fold (and thrust) setup

- Now that we have folding, let's add plasticity (brittle deformation)

- Adding brittle deformation is quite straightforward, simply add "ch" and "fr" to the phase() definition

However, plasticity largely increases computational time!

```
sediments2 = Phase(      Name                = "sediments2",
                         ID                  = 3,
                         rho                 = 2500,
                         eta                 = 1e24,
                         G                   = 5e10,
                         ch                  = 20e6,
                         fr                  = 20      );
```

ch = cohesion, fr = frictional angle

- Change solver options to the following (speeds up calculation)

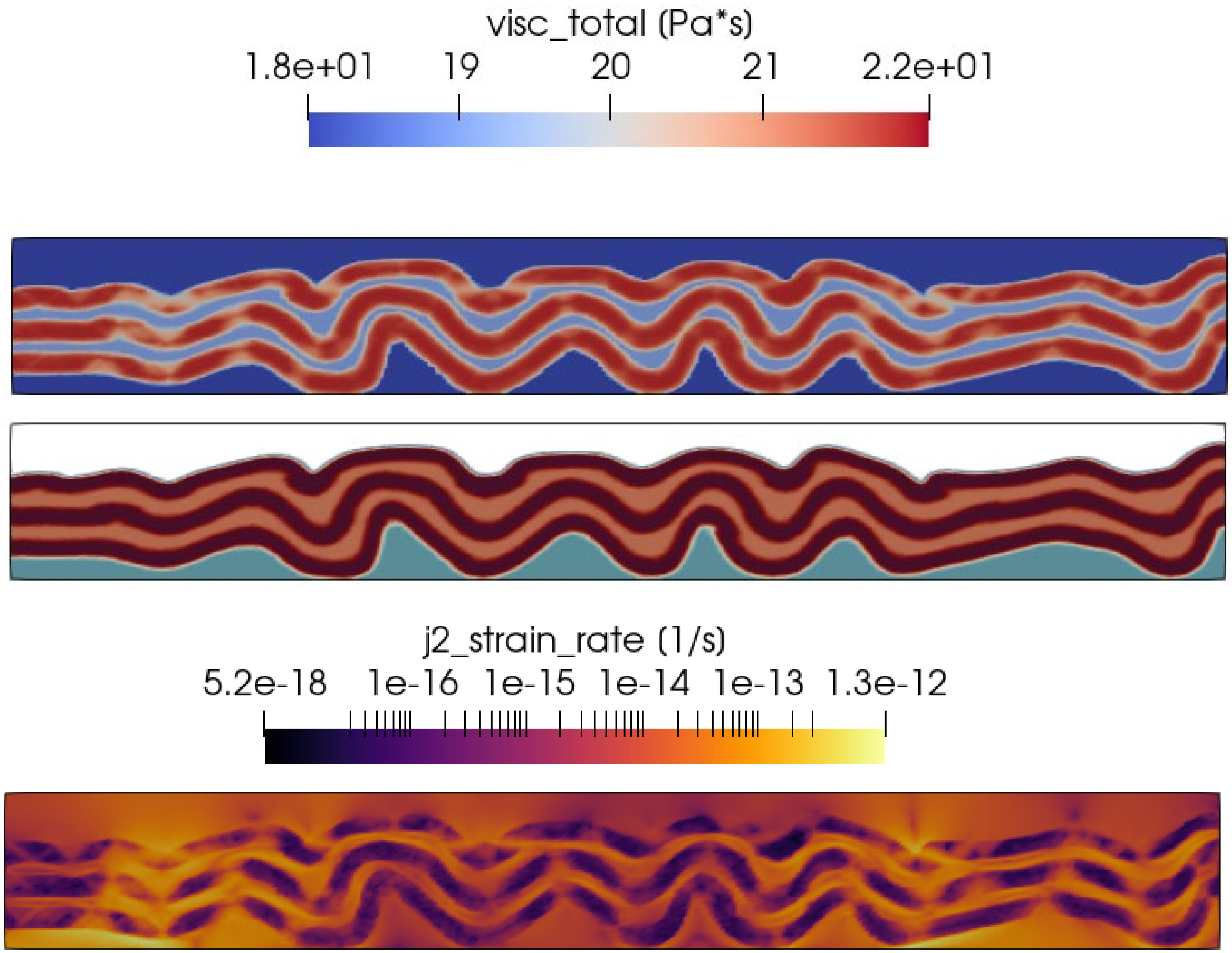
```
                Solver(            SolverType          = "direct",
                                   DirectSolver        = "mumps",
                                   PETSc_options       = [ "-snes_rtol 1e-2", "-snes_max_it 100"] )
```

- Perform the simulation

- How much does that change the results? Why?
  (Check viscosity, and strain-rate invariant fields)

Fold (and thrust) setup

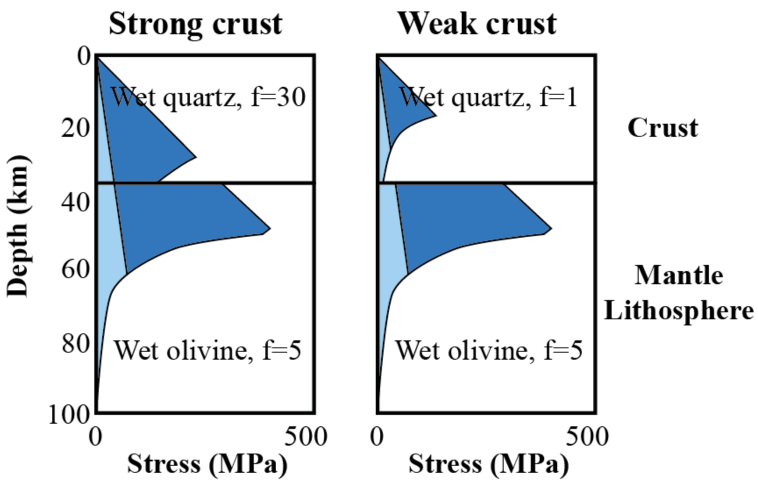
- Results with Drucker-Prager yielding

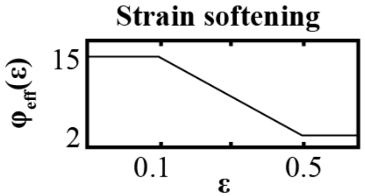


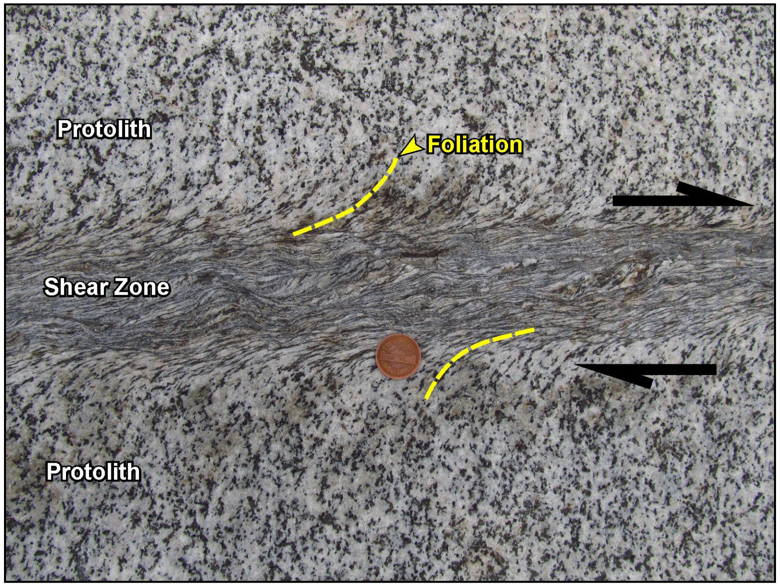
- No much localization: fault/shear zone are well defined!

Fold (and thrust) setup

- Strain softening







- Strain softening: as the rock is plastically deformed it becomes increasingly weaker which allow to localize deformation

Fold (and thrust) setup

- Create a new model setup by copying the previous isoviscous folding one
- Add a Softening() law

```
#===================== define material properties of the phases ============================#
softening = Softening(  ID              = 0,                    # softening law ID
                        APS1            = 0.2,                  # begin of softening APS
                        APS2            = 0.6,                  # end of softening APS
                        A               = 0.99  )               # reduction ratio
```

- Several Softening laws can be added for different phases.

APS = accumulated plastic strain → 0.2 means 20% of deformation

APS1 is the value at which cohesion and frictional angle start to be reduced until APS2 is reached.

The reduction is defined by A → 0.99 means 99% of strength reduction with respect to the starting brittle strength of the phase.

Fold (and thrust) setup

```
#===================== define material properties of the phases ============================#
softening = Softening( ID              = 0,                       # softening law ID
                       APS1            = 0.2,                     # begin of softening APS
                       APS2            = 0.6,                     # end of softening APS
                       A               = 0.99   )                 # reduction ratio
```

- Then the strain softening law can be added to the "Phase()" such as

```
sediments2 = Phase(    Name            = "sediments2",
                       ID              = 3,
                       rho             = 2500,
                       eta             = 1e24,
                       G               = 5e10,
                       ch              = 20e6,
                       fr              = 20,
                       frSoftID        = 0    );
```

- Then don't forget to add the softening law to the model:

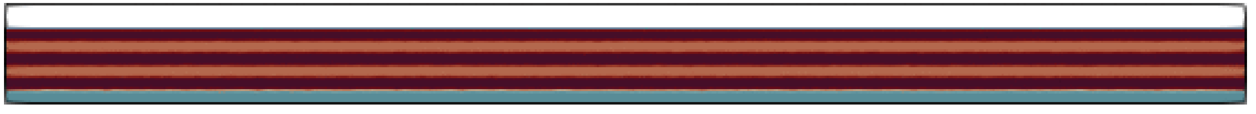
```
add_phase!( model, air, salt, sediments1,sediments2 )
add_softening!( model,  softening)
```

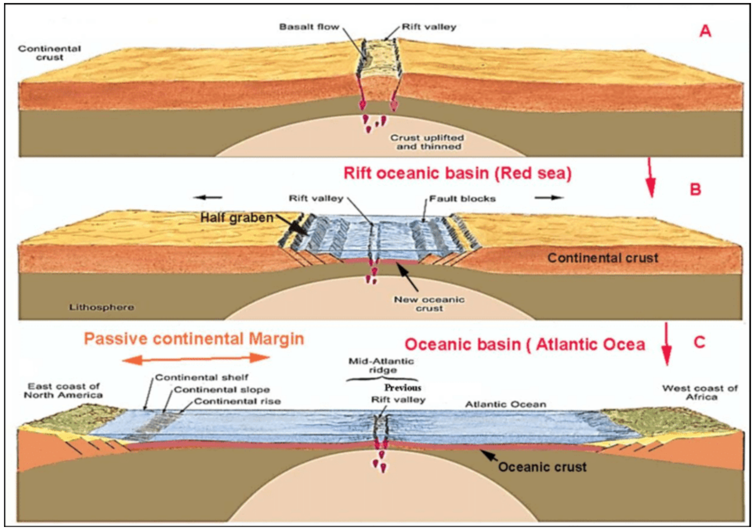
- Perform the simulation

Fold (and thrust) setup

- Example of modeling results with softening

0.00 Myrs

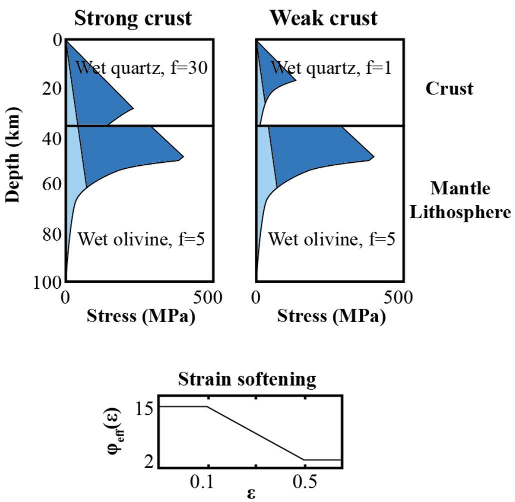


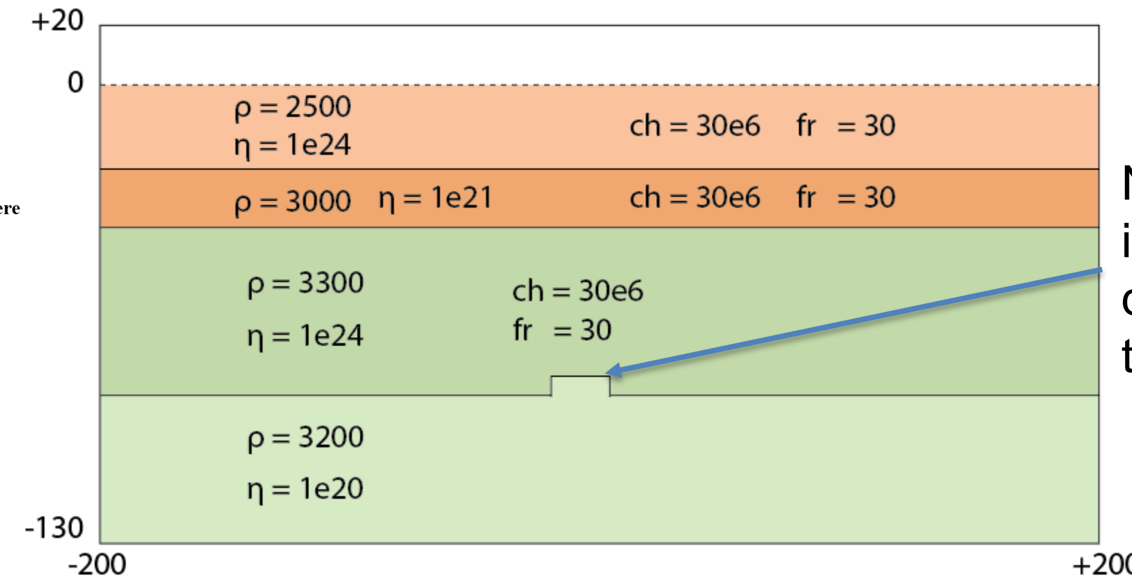


Rifting setup

- How do plates break apart?

Proposed rifting setup

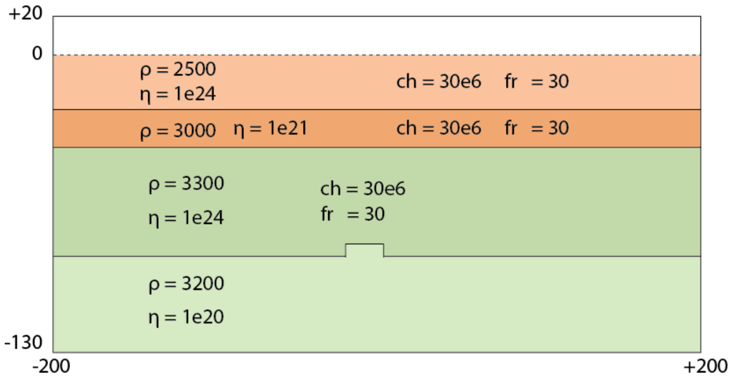




Notch to initiate rift in de center of the model

- Notice that to approximate warm asthenosphere we use low viscosity lower density.
- Create a simplified rifting setup using iso-viscous rheologies
- Start from the “fold and thrust” setup

Rifting setup



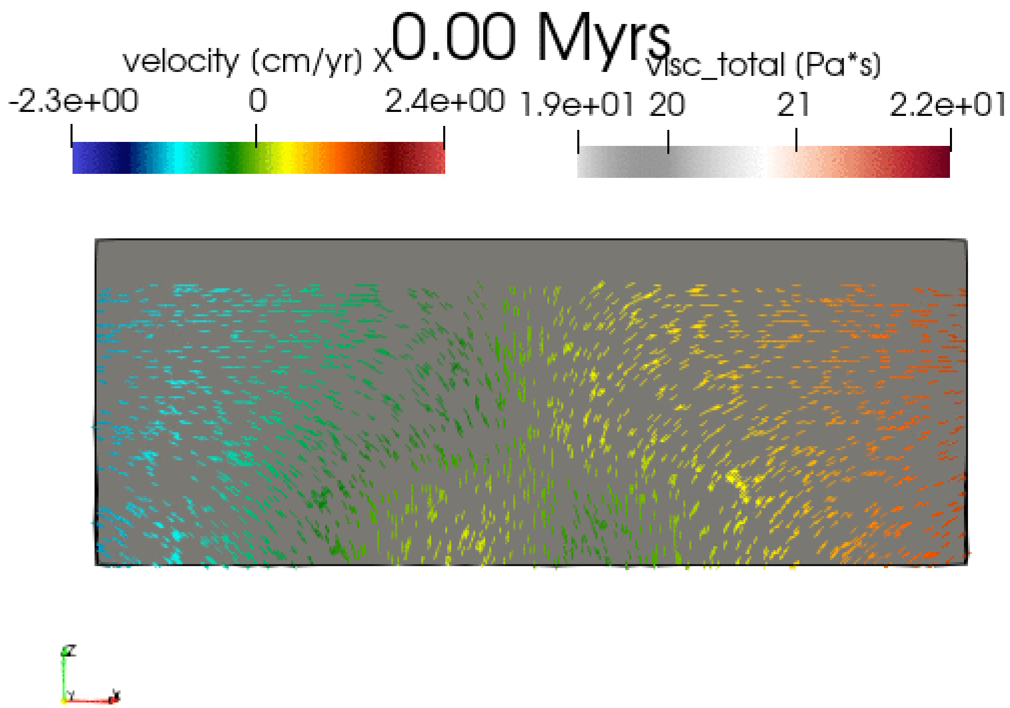
- In Model() add a new section, to add random noise to the particles

```
ModelSetup(         advect          = "rk2",
                    interp          = "stag",
                    mark_ctrl       = "subgrid",
                    rand_noise      = 1,
                    nmark_lim       = [27, 64],
                    nmark_sub       = 3 ),
```

- Perform the simulation for 300 timesteps

Rifting setup

- Example of simulation result



- Exercise: update to a thermo-mechanical rifting model
  - Add a temperature profile (using similar approach as what we did for the plume, with adiabatic gradient for the asthenosphere)
  - Use viscous creep rheology (Dry Olivine for the mantle phases, Dry plagioclase for LC and wet quartz for the upper crust)

Rifting setup

- Exercise 1: update to a thermo-mechanical rifting model
  - Add a temperature profile (using similar approach as what we did for the plume, with adiabatic gradient for the asthenosphere)
  - Use viscous creep rheology (Dry Olivine for the mantle phases, Dry plagioclase for LC and wet quartz for the upper crust)
- Exercise 2: Add density diagrams