CIG Tectonics Modeling Tutorial

Overview and Schedule

Session 1. Introduction to ASPECT Basics

Session 2. Modifying and Coding in ASPECT

Session 3. Lithospheric Deformation*

- Overview of Viscoelasticity, Nonlinear Viscous Flow and Plasticity
- Example: (Bending Beam)
- Example: Continental Extension
- **Example: Brittle Thrust Wedge**
- Example: Subduction

Session 4. Two-Phase Flow

Session 5. Complex Model Design with the World Builder

Slides:
https://bit.ly/aspect-tutorial-slides
Questions:
post in Zoom chat ☺

Example: Brittle thrust wedge

Instructions:

1. Open a terminal and cd to the tutorial directory:

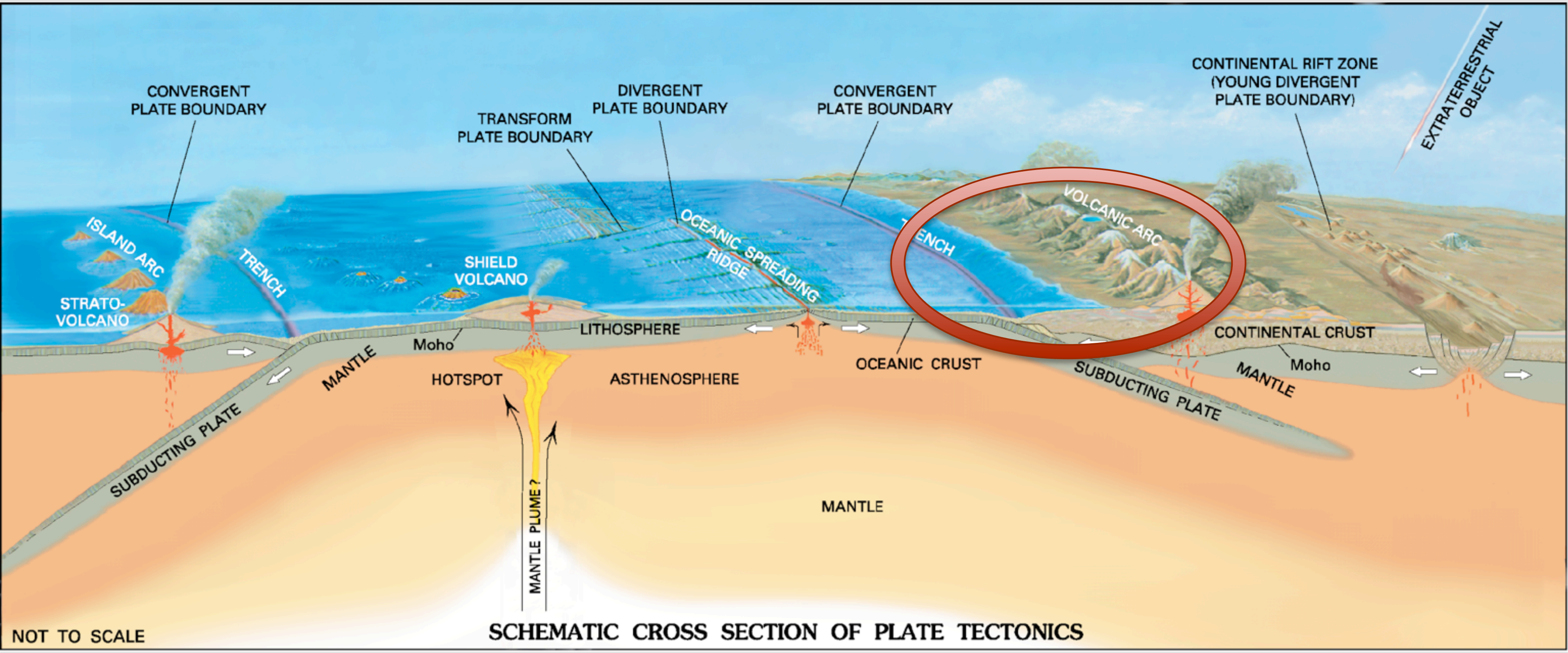
```
$ cd ~/aspect-tutorials/2020-tectonics-modeling-
  tutorial/session-3/
```

2. Run the model:

```
$ mpirun -np 2 ~/aspect/aspect-release
  brittle_thrust_wedge.prm
```

3. Running will take about 15 min

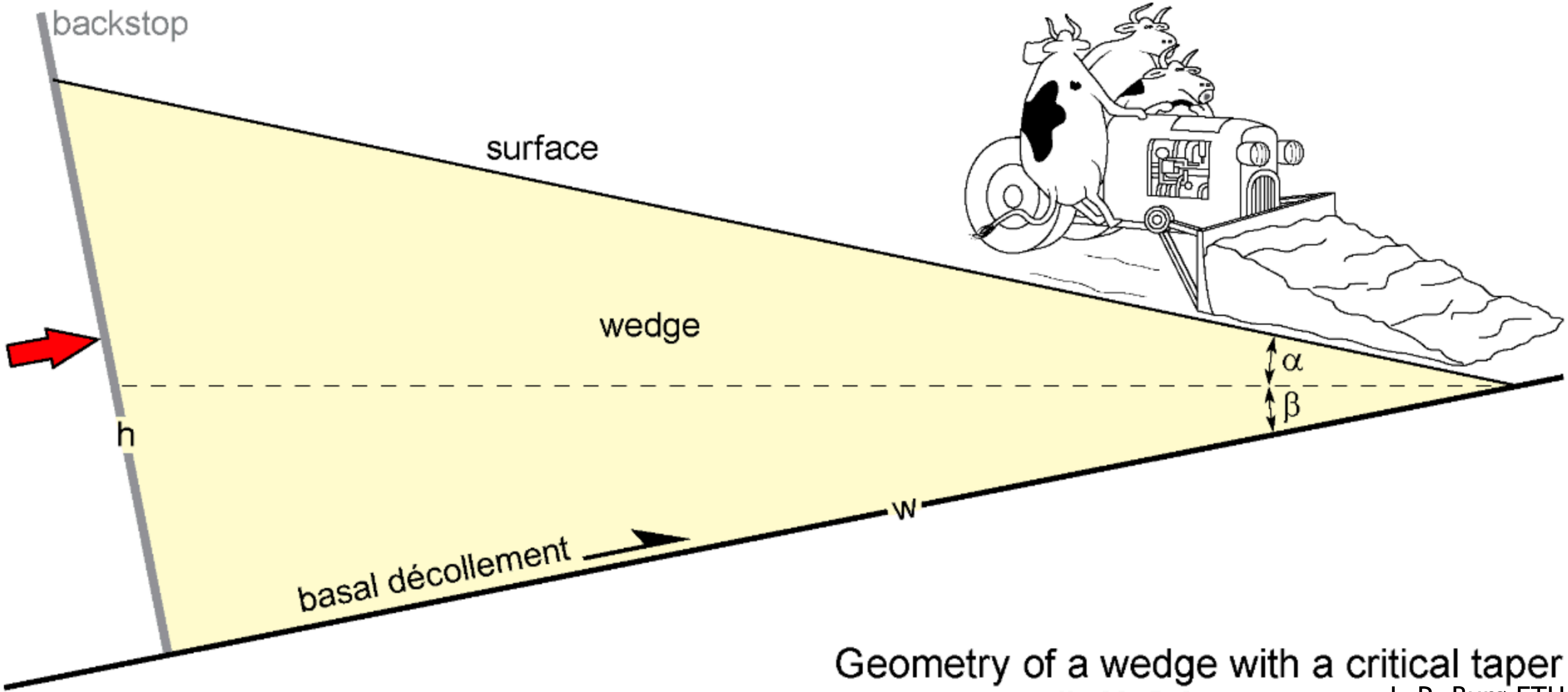
Compressional settings



Fold-and-thrust belts and accretionary wedges form by offscraping of sediments and crustal materials from a lower plate and stacking these in the foreland of an orogen or at a subduction zone trench (Buiter et al. 2016)

Critical taper theory

A wedge of sediments or crustal material in front of “bulldozer” will deform until a certain critical angle is reached, the critical taper θ = α + β.



Geometry of a wedge with a critical taper
J.-P. Burg ETH

Modified brittle thrust wedge benchmark

Based on the benchmark effort of [Buiter et al. (2016)]:

- 11 numerical codes
- 15 analog labs
- 3 experimental setups:
    1. Translation of a 20° stable wedge
    2. Formation of unstable subcritial wedge that goes to critical taper
    3. Formation of unstable wedge through initial deformation away from the mobile wall

Modified brittle thrust wedge benchmark

Based on the benchmark effort of Buiter et al. (2016):

- 11 numerical codes
- 15 analog labs
- 3 experimental setups:
    1. Translation of a 20° stable wedge
    2. Formation of unstable subcritical wedge that goes to critical taper
    3. Formation of unstable wedge through initial deformation away from the mobile wall

Modified brittle thrust wedge benchmark

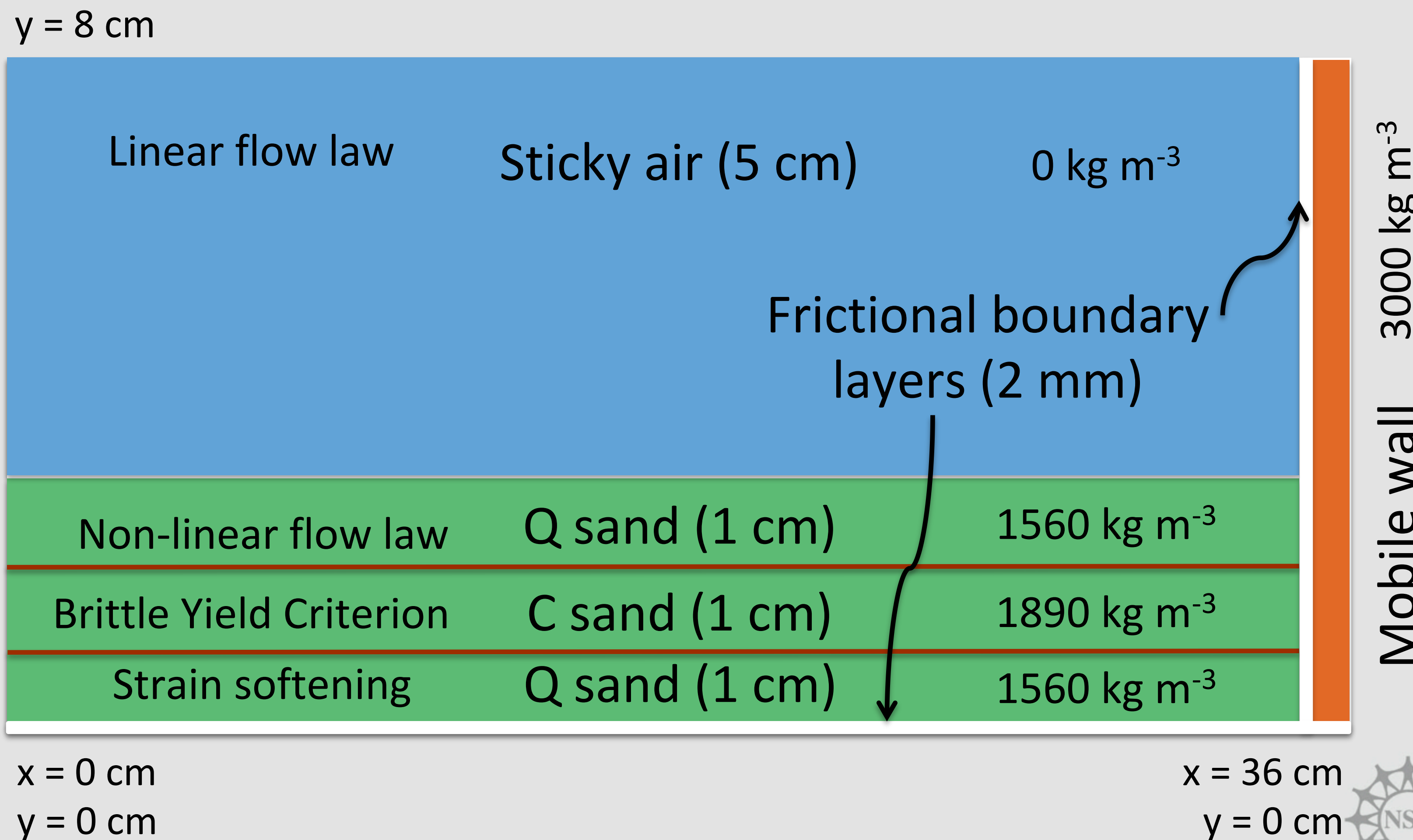
Based on the benchmark effort of Buiter et al. (2016):

- 11 numerical codes
- 15 analog labs
- 3 experimental setups:
    1. Translation of a 20° stable wedge
    2. Formation of unstable subcritical wedge that goes to critical taper
    3. Formation of unstable wedge through initial deformation away from the mobile wall

Time

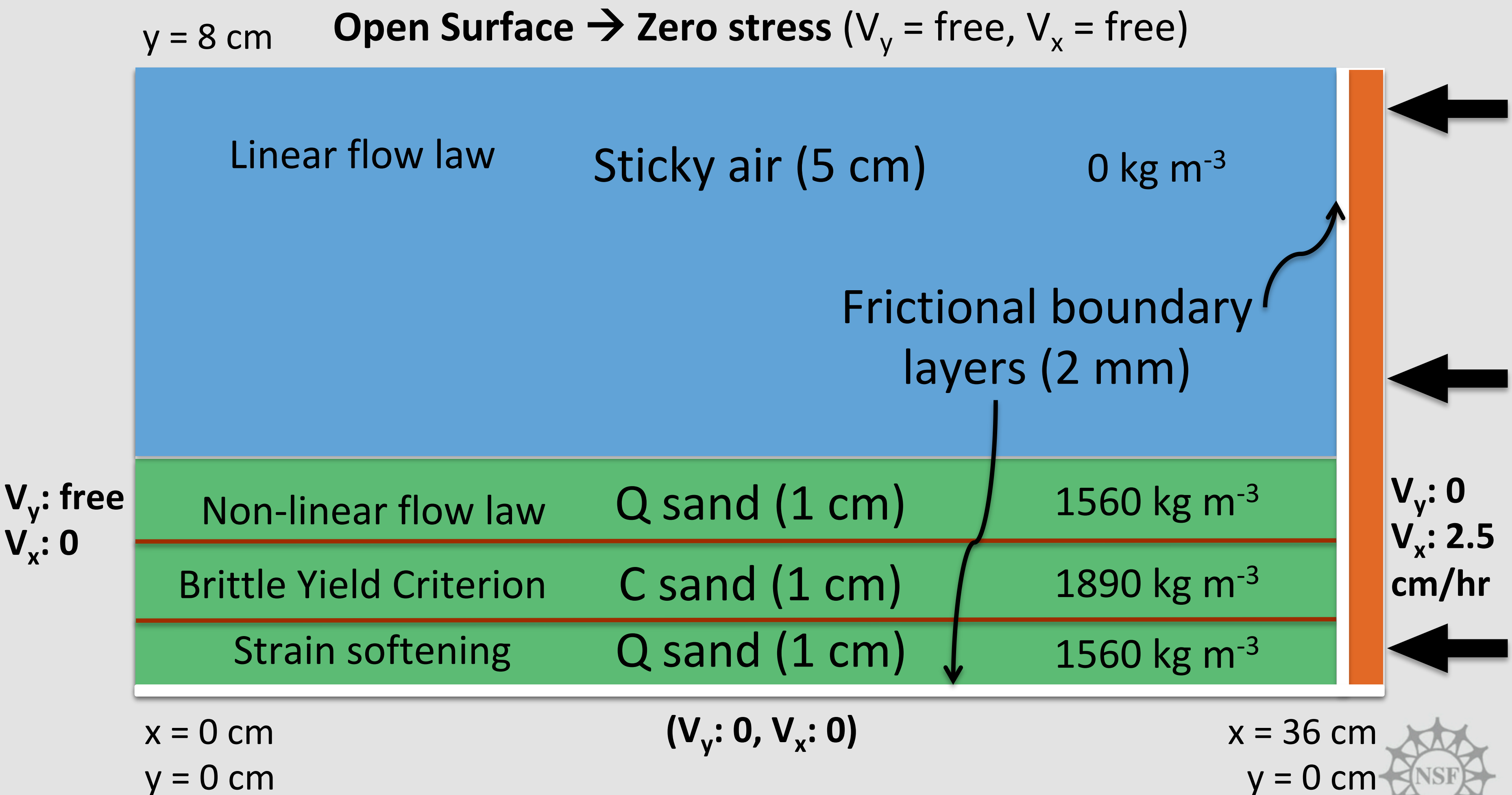
Numerical Model Design

Initial composition & material properties



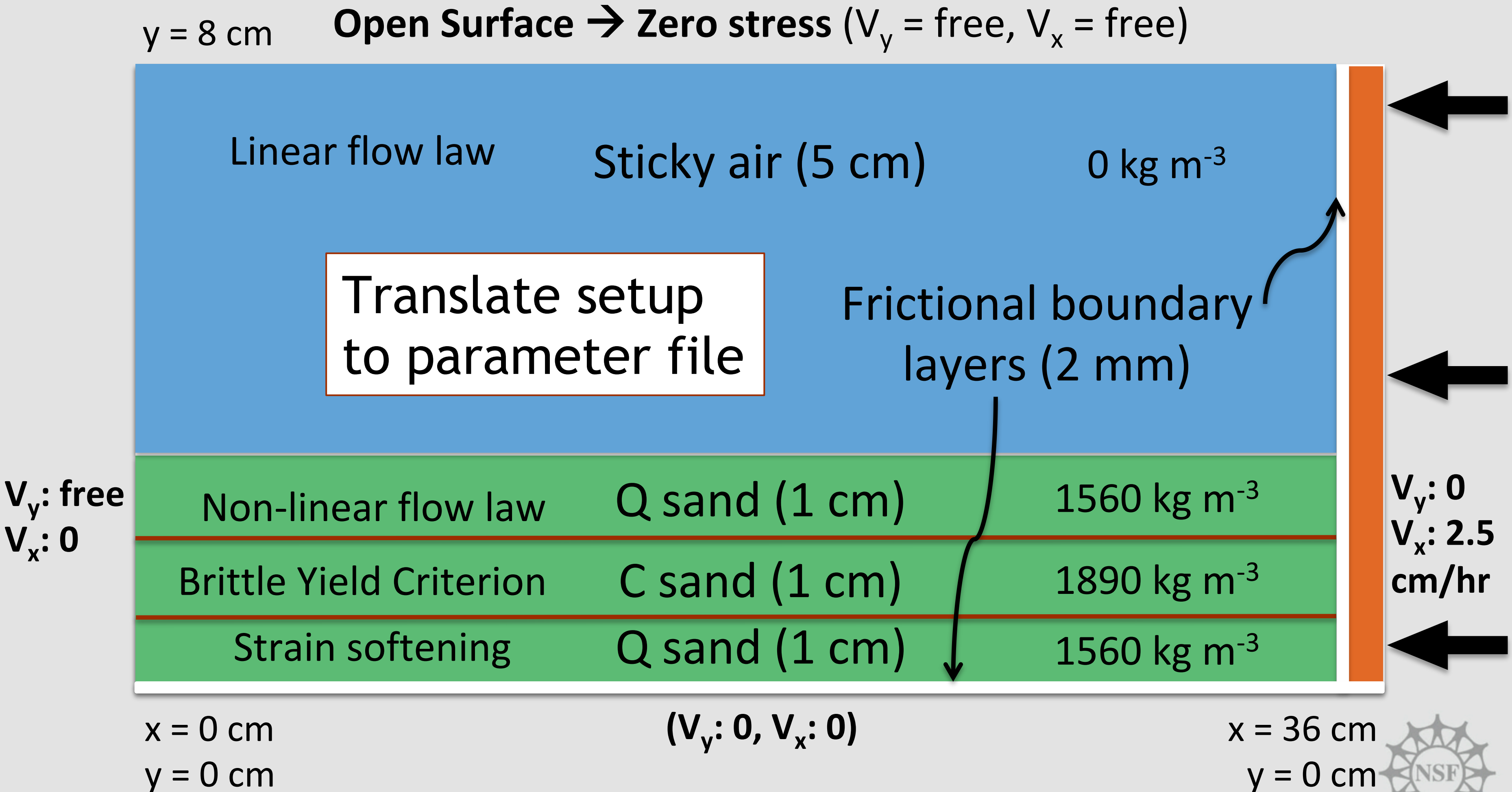
Numerical Model Design

Velocity Boundary Conditions



Numerical Model Design

Velocity Boundary Conditions



Parameter file: Global parameters

Open brittle_thrust_wedge.prm in ~/aspect-tutorials/2020-tectonics-modeling-tutorial/session-3/ with vi or leafpad

```
$vi brittle_thrust_wedge.prm
```

which is an adapted version of

```
$ASPECT_DIR/benchmarks/buiter_et_al_2016_jsg/
exp_2_low_resolution.prm
```

```
set Dimension                                  = 2
set Start time                                 = 0
set End time                                   = 14400 #10 cm
set Use years in output instead of seconds     = false
set CFL number                                 = 0.8
set Pressure normalization                     = surface
```

[seconds]

Pressure at top boundary is zero on average

Parameter file: Solver settings

```
set Nonlinear solver scheme    = single Advection,
                                 iterated Stokes
set Nonlinear solver tolerance = 1e-7
set Max nonlinear iterations   = 100
```

Viscosity depends on solution variables pressure and velocity (i.e. strain rate) → iterative solver

```
subsection Solver parameters

  subsection Stokes solver parameters
    set Linear solver tolerance             = 1e-8
    set Number of cheap Stokes solver steps = 200
```

Try poor, but cheaper preconditioner for GMRES solver

```
    set GMRES solver restart length         = 200
  end
end
```

Increase length of solver history taken into account; helps with localized viscosity jumps.

Viscoplasticity: Nonlinear solver

Time steps:

Nonlinear iterations:

In *Material model*:

1. Calculate an effective viscous viscosity η_{eff}^{v}
2. Calculate the viscous stress $\sigma^{v} = 2\eta_{eff}^{v}\dot{\varepsilon}_{eff}$
3. Calculate the plastic yield strength

$$\sigma_y^p = C\cos\phi + P\sin\phi$$

4. If $\sigma^{v} > \sigma_y^p$ → return $\eta_{eff}^{vp} = \dfrac{\sigma_y^p}{2\dot{\varepsilon}_{eff}}$
5. If $\sigma_y^p > \sigma^{v}$ → return η_{eff}^{v}

Solve Stokes equations with updated η_{eff} to get updated *P* and ***v***

Inner iterations

Exit iterations when tolerance or max met.

Viscoplasticity: Nonlinear solver

Time steps:

Nonlinear iterations:

In *Material model*:

1. Calculate an effective viscous viscosity η^{v}_{eff}
2. Calculate the viscous stress $\sigma^{v} = 2\eta^{v}_{eff}\dot{\varepsilon}_{eff}$
3. Calculate the plastic yield strength

$$\sigma^{p}_{y} = C\cos\phi + P\sin\phi$$

4. If $\sigma^{v} > \sigma^{p}_{y}$ → return $\eta^{vp}_{eff} = \dfrac{\sigma^{p}_{y}}{2\dot{\varepsilon}_{eff}}$
5. If $\sigma^{p}_{y} > \sigma^{v}$ → return η^{v}_{eff}

Solve Stokes equations with updated η^{v}_{eff}

to get updated

Inner it

Nonlinear solver tolerance
Max nonlinear solver iterations

Linear solver tolerance
Number of cheap Stokes solver steps
GMRES solver restart length

Parameter file: Discretization

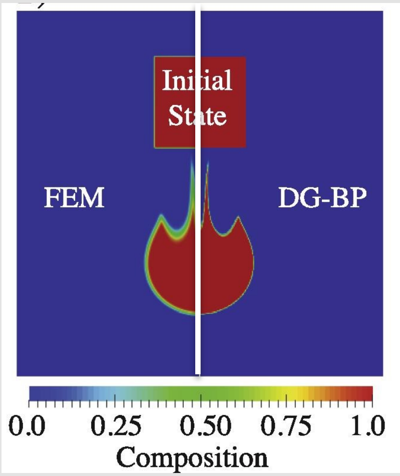
```
subsection Discretization
  set Temperature polynomial degree                = 1
  set Use discontinuous composition discretization = true
```

Discontinuous Galerkin (DG) for compositional fields instead of continuous discretization
→ preserves compositional boundaries better

```
  subsection Stabilization parameters
    set Use limiter for discontinuous composition solution
                                      = true
    set Global composition maximum    = 1, 1, 1, 1, 100
    set Global composition minimum    = 0, 0, 0, 0, 0
  end

end
```

I.c.w. DG: set global min and max limit for each compositional field



He et al. 2017, PEPI

Parameter file: Geometry

```
subsection Geometry model
   set Model name                 = box

   subsection Box
     set X extent                 = 0.36
     set Y extent                 = 0.08
     set X repetitions            = 45
     set Y repetitions            = 10
  end
end
```

Dimensions: 36x8 cm

Divide the coarse grid to get 1:1 aspect ratio of mesh cells.

Parameter file: Composition

```
subsection Compositional fields
  set Number of fields = 5
  set Names of fields  = qsand,csand, bound, block, total_strain
end

subsection Initial composition model
  set Model name                 = function
  subsection Function
    set Variable names         = x,y
    set Function constants     = w1=0.35, w2=0.355, h1=0.002, \
                                 h2=0.012, h3=0.022, h4=0.032
    set Function expression = if((x<w1 & y<=h2 & y>h1) \
                                  || (x< w1 & y>h3 & y<=h4), 1,0);\
                                 if((x<w1 & y>h2 & y<=h3), 1,0); \
                                 if((x>=w1 & x<=w2 & y>h1) \
                                  ||(y<=h1), 1, 0); \
                                 if(x>w2 & y>h1,1,0); \
                                 0

  end
end
```

Use backslash \ to continue expression on a newline

total_strain is zero everywhere

Parameter file: Composition

```
subsection Boundary composition model
  set Fixed composition boundary indicators = right
  set List of model names                 = initial composition
end
```

Fix composition at inflow boundary,
but not elsewhere because material will move and strain will increase over time

Parameter file: Temperature

```
subsection Initial temperature model
  set Model name                         = function

  subsection Function
    set Function expression              = 293
  end

end

subsection Boundary temperature model
  set Fixed temperature boundary indicators = bottom,top,\
                                              right
  set List of model names                = initial temperature
end
```

Temperature plays no role,
but we should set boundary conditions for inflow boundaries.

Parameter file: Velocity & stress BC

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

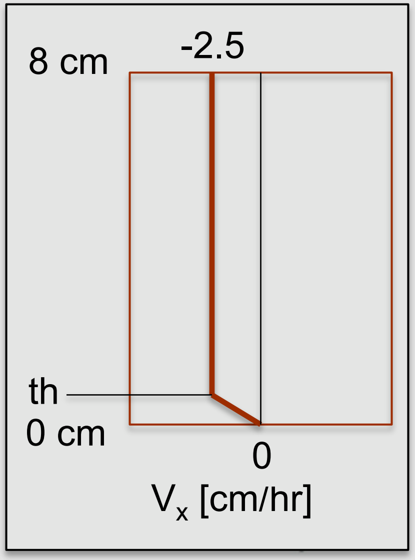
```
subsection Boundary velocity model
  set Zero velocity boundary indicators       = bottom
  set Tangential velocity boundary indicators = left
  set Prescribed velocity boundary indicators = right: function

    subsection Function
      set Variable names           = x,y
      set Function constants       = cm=0.01, h=3600, th=0.002
      set Function expression      = \
                        if(y>th, -2.5*cm/h, -(y/th)*2.5*cm/h); 0
    end
end
```

Prescribe the motion of mobile wall on the right boundary, with a gradual transition to zero towards the bottom of the domain. NB: velocity is interpreted in m/s.

```
subsection Boundary traction model
  set Prescribed traction boundary indicators =
          top: zero traction
end
```

Top boundary is open to flow leaving the domain to compensate for prescribed inflow.

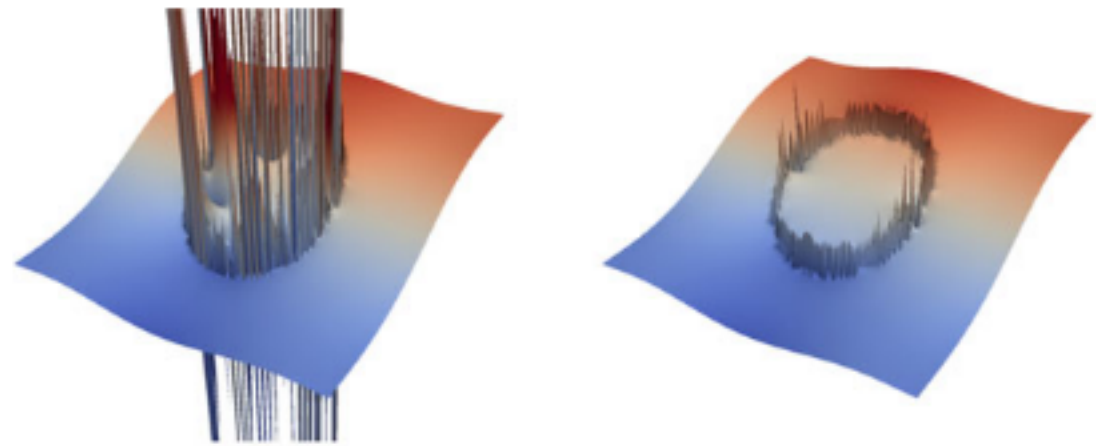


Parameter file: Material parameters

```
subsection Material model
  set Material averaging                    = harmonic average
  set Model name                            = visco plastic
```

Average material properties over mesh cell when assembling.

P field of sinker benchmark with strong density and viscosity contrast.



$[-45.2, 45.2]$ $[-2.67, 2.67]$

[Heister et al. 2017, GJI]

Parameter file: Material parameters

```
subsection Material model
  set Material averaging                   = harmonic average
  set Model name                           = visco plastic

  subsection Visco Plastic
    set Reference temperature              = 293
    set Reference viscosity                = 1e8
    set Minimum strain rate                = 1e-20
    set Reference strain rate              = 2e-5
    set Minimum viscosity                  = 1e5
    set Maximum viscosity                  = 1e12

    set Thermal diffusivities              = 1e-6
    set Heat capacities                    = 750
    set Densities                          = 0,1560,1890,1560,3000,1e5
    set Thermal expansivities              = 0
    set Viscosity averaging scheme = harmonic
```

Average material properties over mesh cell when assembling.

Same value used for all compositions.

Supply values for n_compositions+1 fields

Average contributions of all compositions to viscosity in evaluated points harmonically.

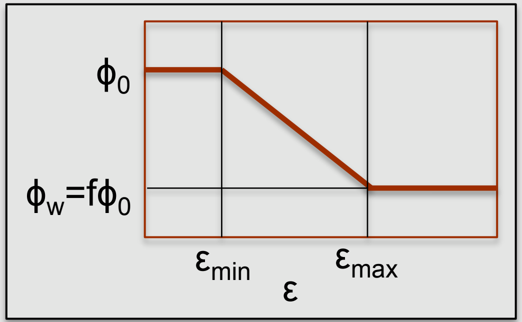
Parameter file: Material parameters

```
    set Viscous flow law = dislocation
    set Prefactors for dislocation creep              = 5e-5,
                       5e-15, 5e-15, 5e-15, 5e-18, 5e-18
    set Stress exponents for dislocation creep        = 1
    set Activation energies for dislocation creep     = 0
    set Activation volumes for dislocation creep      = 0

    set Angles of internal friction = 0, 36, 36, 16, 0, 1e18
    set Cohesions                   = 1e18, 30, 30, 30, 1e18, 1e18

    set Strain weakening mechanism                  = total strain
    set Start plasticity strain weakening intervals = 0.5
    set End plasticity strain weakening intervals   = 1
    set Cohesion strain weakening factors           = 1
    set Friction strain weakening factors           = 1, 0.861,
                                              0.861, 0.875, 1, 1
  end
end
```

Manipulate dislocation parameters to provide constant viscosities.



Use the total strain (strain rate integrated over time) to weaken the internal friction angle on the strain interval [0.5,1.0].

Parameter file: Mesh refinement

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

```
subsection Mesh refinement
  set Initial adaptive refinement                    = 2
  set Initial global refinement                      = 0
  set Minimum refinement level                       = 0
  set Normalize individual refinement criteria = true
  set Refinement criteria merge operation            = plus
  set Coarsening fraction                            = 0.10
  set Refinement fraction                            = 0.9
  set Run postprocessors on initial refinement = false
  set Skip solvers on initial refinement             = true

  set Skip setup initial conditions on initial refinement = \
       false

  set Strategy                                       = minimum \
       refinement function, density, maximum refinement function
  set Time steps between mesh refinement             = 2
```

2 levels of AMR

Coarsen as well as refine

Save time by not solving on the coarse grid,

but do setup initial conditions, because refinement is based on density(T,c_i).

Parameter file: Mesh refinement

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

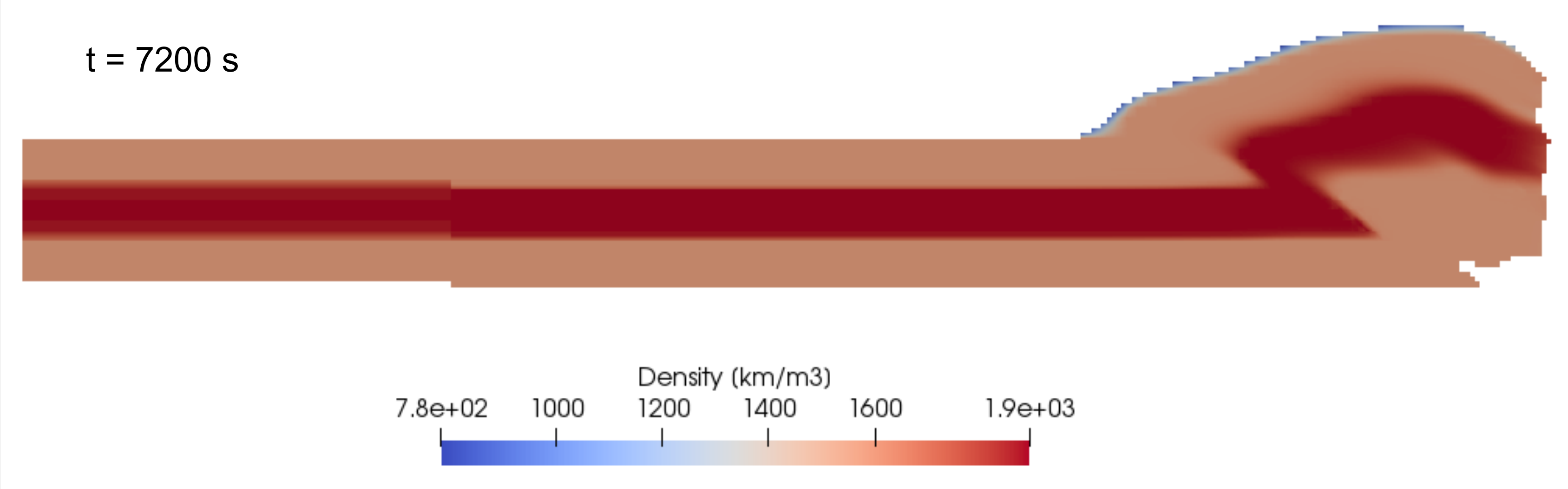
```
subsection Minimum refinement function
   set Coordinate system    = cartesian
   set Variable names       = x,z,t
   set Function constants   = bound=0.0025, crust=0.037, \
                              block=0.34, block_r=0.36, \
                              cm=0.01, hour=3600
   set Function expression = \
      if((z<=crust & x>0.08 & x<=block-3*cm/hour*t)| \
         (x>block-3.5*cm/hour*t & x<block_r-2*cm/hour*t)| \
          z<=bound,2, \
           if(z<=crust&x<=0.08,1,0))
 end
 subsection Maximum refinement function
   set Coordinate system    = cartesian
   set Variable names       = x,z,t
   set Function constants   = crust=0.037
   set Function expression = if(z>crust&x<=0.08,0, \
                                 if(z<=crust&x<=0.08,1,2))
 end
end
```

Time-dependent function that follows the boundary layer along the mobile wall.

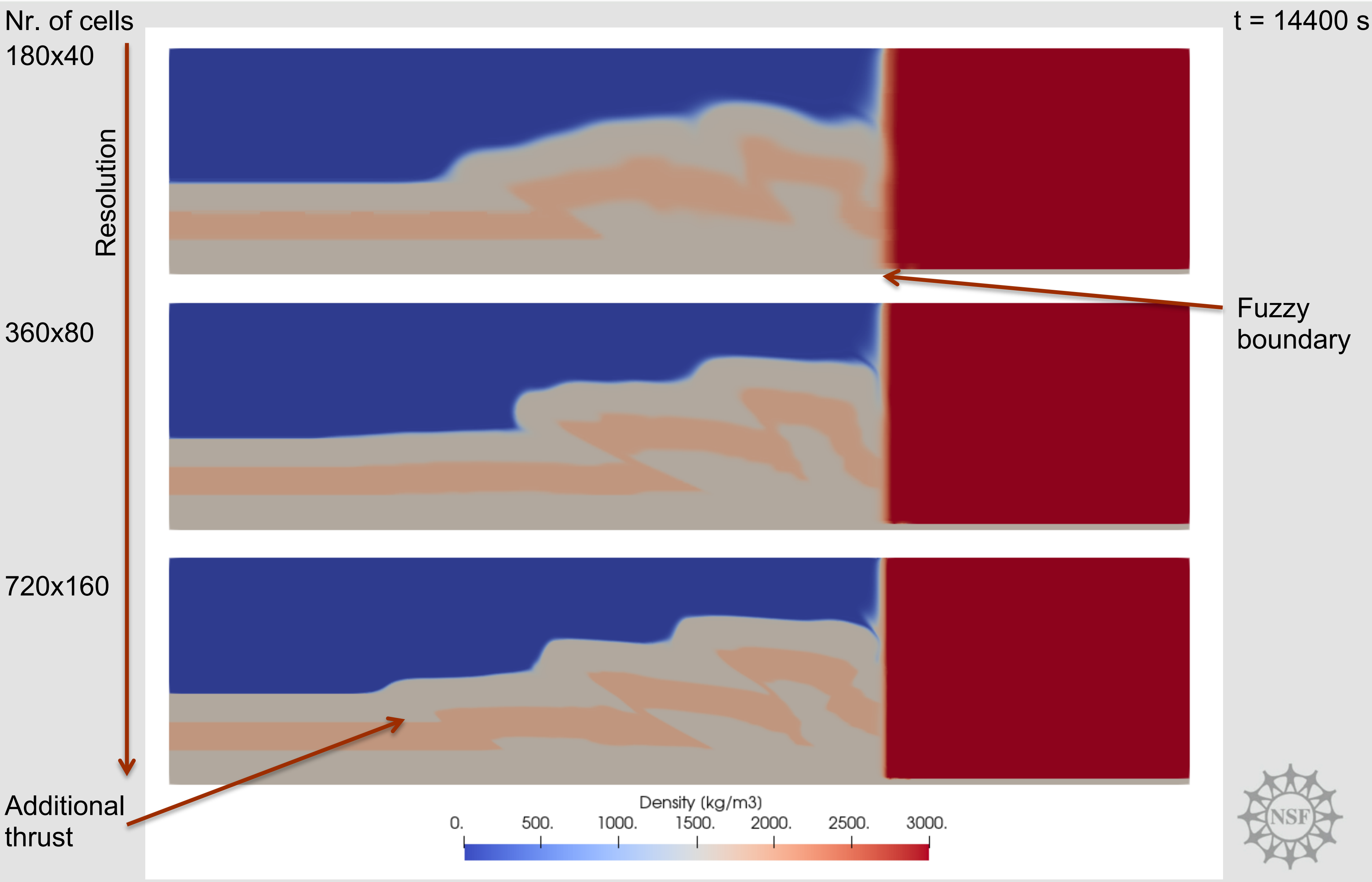
Save time by setting a lower max resolution in undeforming sand.

Visualizing the results

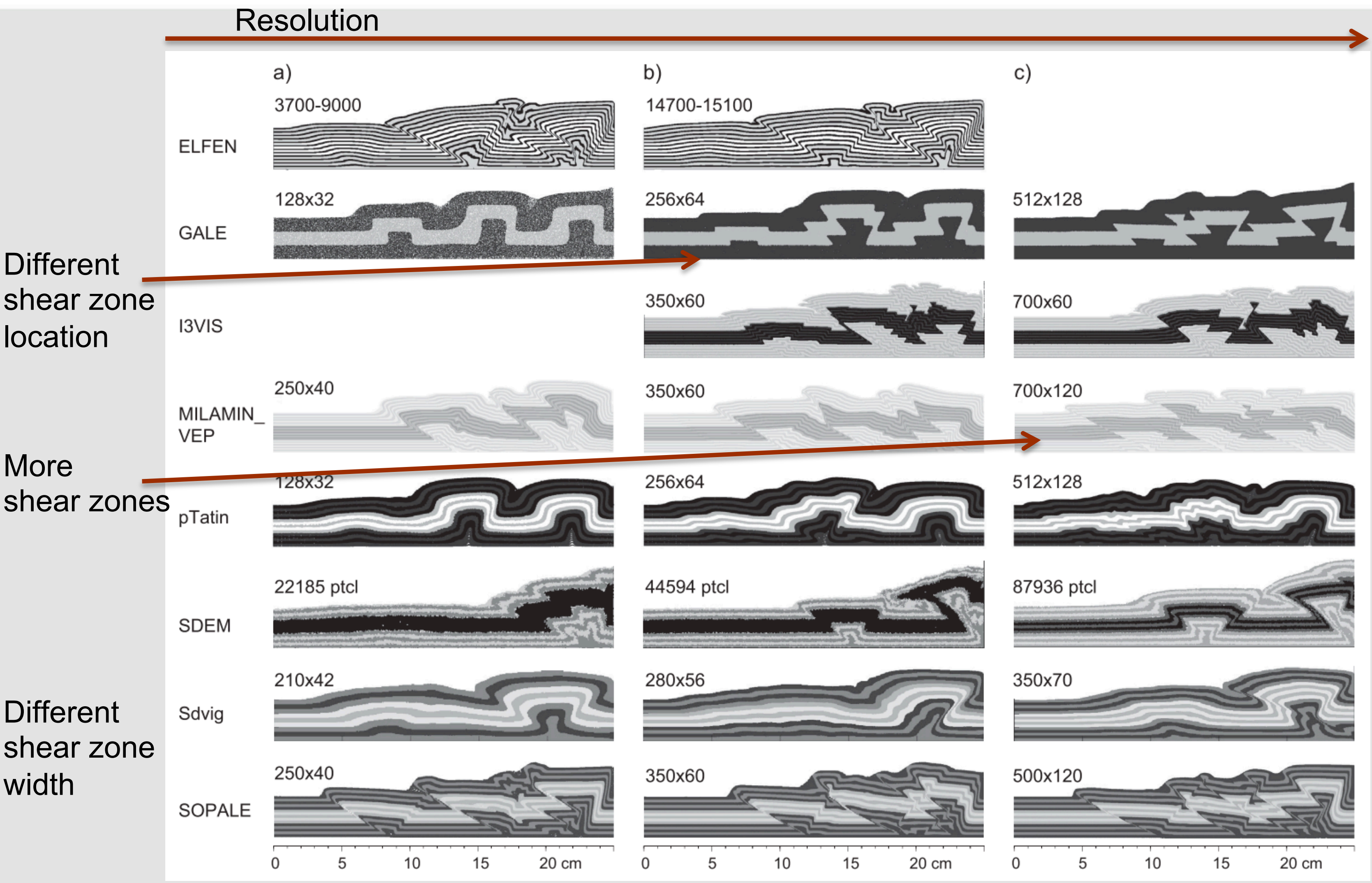
1. Start ParaView by typing `paraview &` in the terminal
2. Load solution.pvd
3. Let's cut off the sticky air and mobile wall block:
    1. Use the *Calculator* to sum ***qsand*** and ***csand***
    2. Use the *Threshold* filter with 0.5 minimum on the result
    3. Select the ***density*** field to display
4. Press play!
5. Make snapshots at 2 and 6 cm compression (t = 2880 and 8640 s)
6. Investigate strain and strain rate. Are all faults still active?



Sensitivity analysis: Resolution



Comparing to other codes: Resolution



Buiter et al. 2016

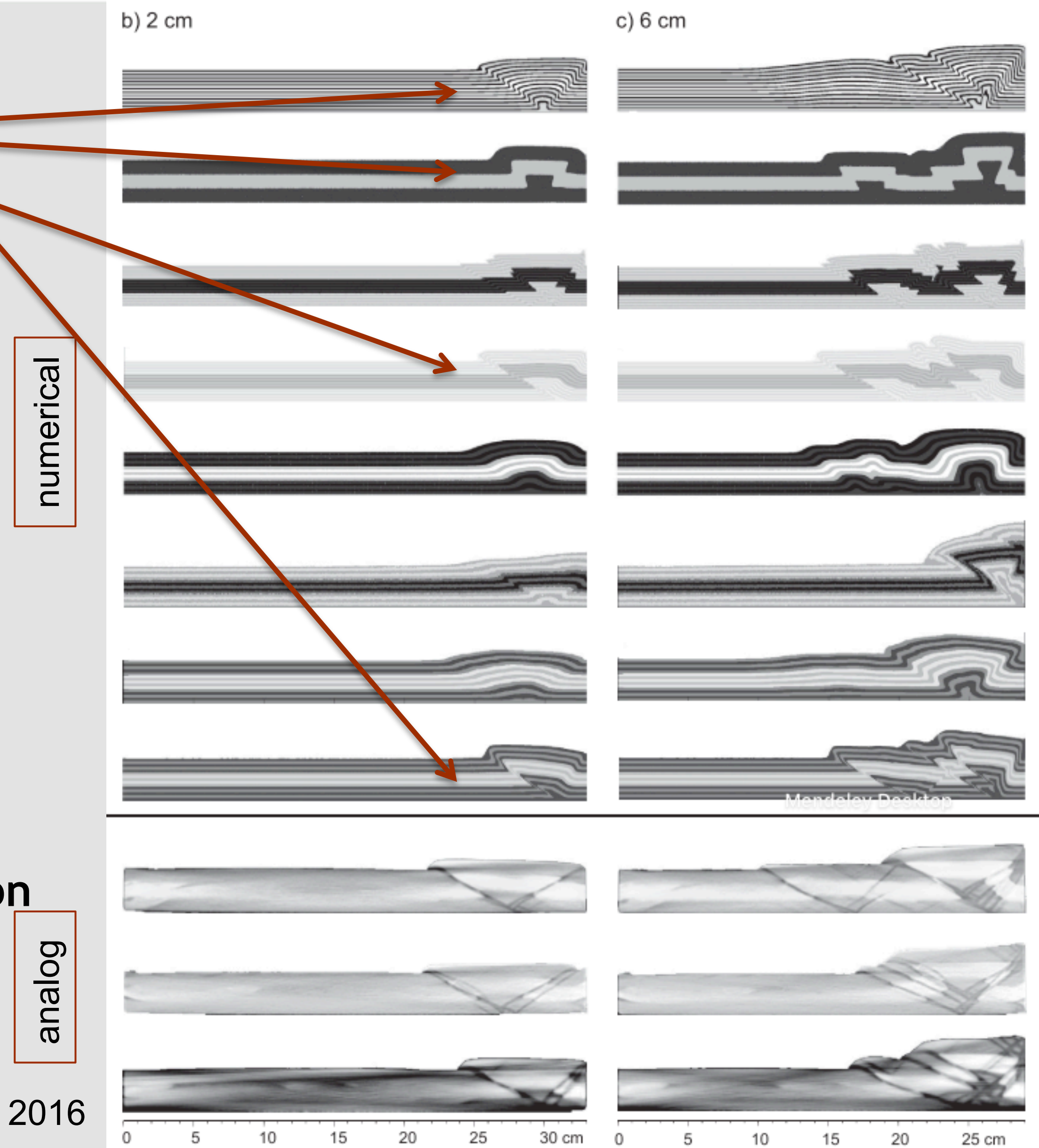
Comparing to other codes: Evolution

Two modes of deformation:
1. Series of thrust popups
2. Mainly forward dipping thrusts

Converge to critical taper

Other variations in:
1. rate of thrust formation
2. nr of thrusts
3. dip angle
4. thrust spacing

Differences due to:
1. numerical solution techniques
2. resolution
3. **boundary friction implementation**
4. remeshing methods



Buiter et al. 2016

Model Extension

Parameters

✓ Grid resolution: keep uniform, higher resolution throughout the sand layer

✓ Particles instead of fields: less diffusion of the boundary layer

✓ Time step size: the official benchmark uses dt = 3.6 s

✓ Strain-weakening: only the plastic strain

✓ Higher viscosity ratio

✓ 3D

Model Extension

Parameters

✓ Grid resolution: keep uniform, higher resolution throughout the sand layer

✓ Particles instead of fields: less diffusion of the boundary layer

✓ Time step size: the official benchmark uses dt = 3.6 s

✓ Strain-weakening: only the plastic strain

✓ Higher viscosity ratio

✓ 3D

Try to change the material model parameters to only use plastic strain instead of the total strain.

Have a look at the manual p. 467 for the parameter options.

Model Extension

Parameters

✓ Grid resolution: keep uniform, higher resolution throughout the sand layer

✓ Particles instead of fields: less diffusion of the boundary layer

✓ Time step size: the official benchmark uses dt = 3.6 s

✓ Strain-weake

✓ Higher viscos

✓ 3D

Only use plastic strain:

```
subsection Compositional fields
  set Number of fields            = 5
  set Names of fields             = qsand, csand, bound, block, \
                                    total_strain
end
subsection Material model
 subsection Visco Plastic
   set Strain weakening mechanism = total strain
```

Model Extension

```
subsection Compositional fields
  set Compositional field methods = particles
  set Compositional field methods = particles, particles, \
                                    particles, particles, \
                                    particles
  set Mapped particle properties  = qsand:initial qsand,csand:initial csand, \
                                    bound:initial bound, block:initial block, \
                                    total_strain:total_strain
end

subsection Postprocess
  subsection Particles
    set Number of particles = 1e6
    set Integration scheme = rk4
    set Particle generator name = random uniform
    set List of particle properties = composition, initial composition, \
                                      viscoplastic strain invariants
set Maximum particles per cell = 200
    set Minimum particles per cell = 195
    set Interpolation scheme = nearest neighbor
    set Allow cells without particles = true
    set Load balancing strategy = remove and add particles
    set Update ghost particles = true
    set Time between data output = 144
  end
end
```

Overview and Schedule

Session 1. Introduction to ASPECT Basics

Session 2. Modifying and Coding in ASPECT

Session 3. Lithospheric Deformation*

- Overview of Viscoelasticity, Nonlinear Viscous Flow and Plasticity
- Example: (Bending Beam)
- Example: Continental Extension
- Example: Brittle Thrust Wedge
- **Example: Subduction**

Session 4. Two-Phase Flow

Session 5. Complex Model Design with the World Builder

Slides:
https://bit.ly/aspect-tutorial-slides
Questions:
post in Zoom chat ☺

Example: Prescribed subduction

Instructions:

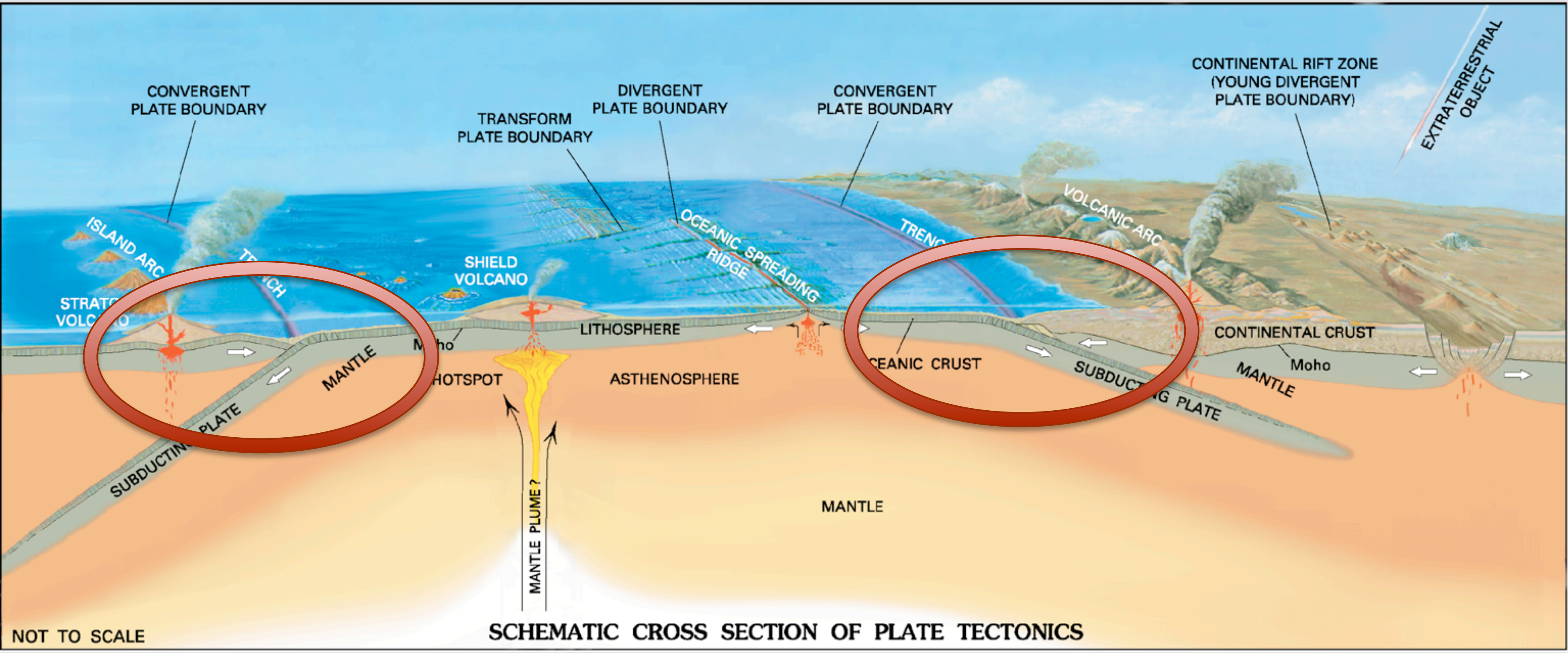
1. Open a terminal and cd to the tutorial directory:

```
$ cd ~/aspect-tutorials/2020-tectonics-modeling-tutorial/session-3/
```

2. Run the model:

```
$ mpirun -np 2 ~/aspect/aspect-release prescribed_subduction.prm
```

Convergent settings



At convergent boundaries, plates can subduct underneath the overlying plate. This can be accompanied by mountain building, volcanism, earthquakes, fluid release into the overlying mantle, mantle melting, metamorphism, exhumation, phase changes…

Subduction ingredients

Minimum requirements:

1. A weak zone that decouples the subducting plate from the overriding plate

2. A weak layer (e.g. crust) that decouples the subducting plate from the surface and allows it to go down

3. Something to initiate subduction, i.e. a negatively buoyant slab tip or prescribed plate motions or far-field forces

→ Construct simple model of oceanic-oceanic plate subduction

Be aware of…

- Diffusion of the weak zone
- Dependency of results on mesh element aspect ratio and resolution in the weak zone
- Dependency on averaging methods of the compositional contributions to viscosity
- Shape (e.g. round vs. angular) and thickness of the weak zone can affect model evolution

Modified subduction benchmark

Based on the benchmark effort of Quinquis (2014):

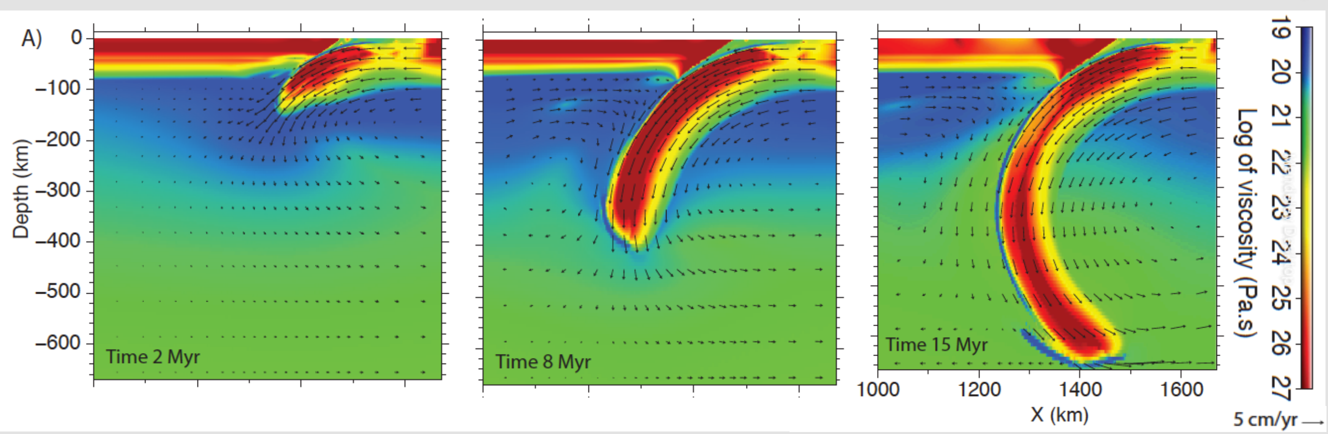
- 7 numerical codes
- 4 experimental setups:
    1. Linear viscous rheology
    2. Linear viscous rheology with temperature advection
    3. Thermo-mechanical (TM) model with simplified visco-plastic rheology
    4. TM model with visco-plastic rheology including strain weakening

Modified subduction benchmark

Based on the benchmark effort of Quinquis (2014):

- 7 numerical codes
- 4 experimental setups:
  1. Linear viscous rheology
  2. Linear viscous rheology with temperature advection
  3. Thermo-mechanical (TM) model with simplified visco-plastic rheology
  4. TM model with visco-plastic rheology including strain weakening

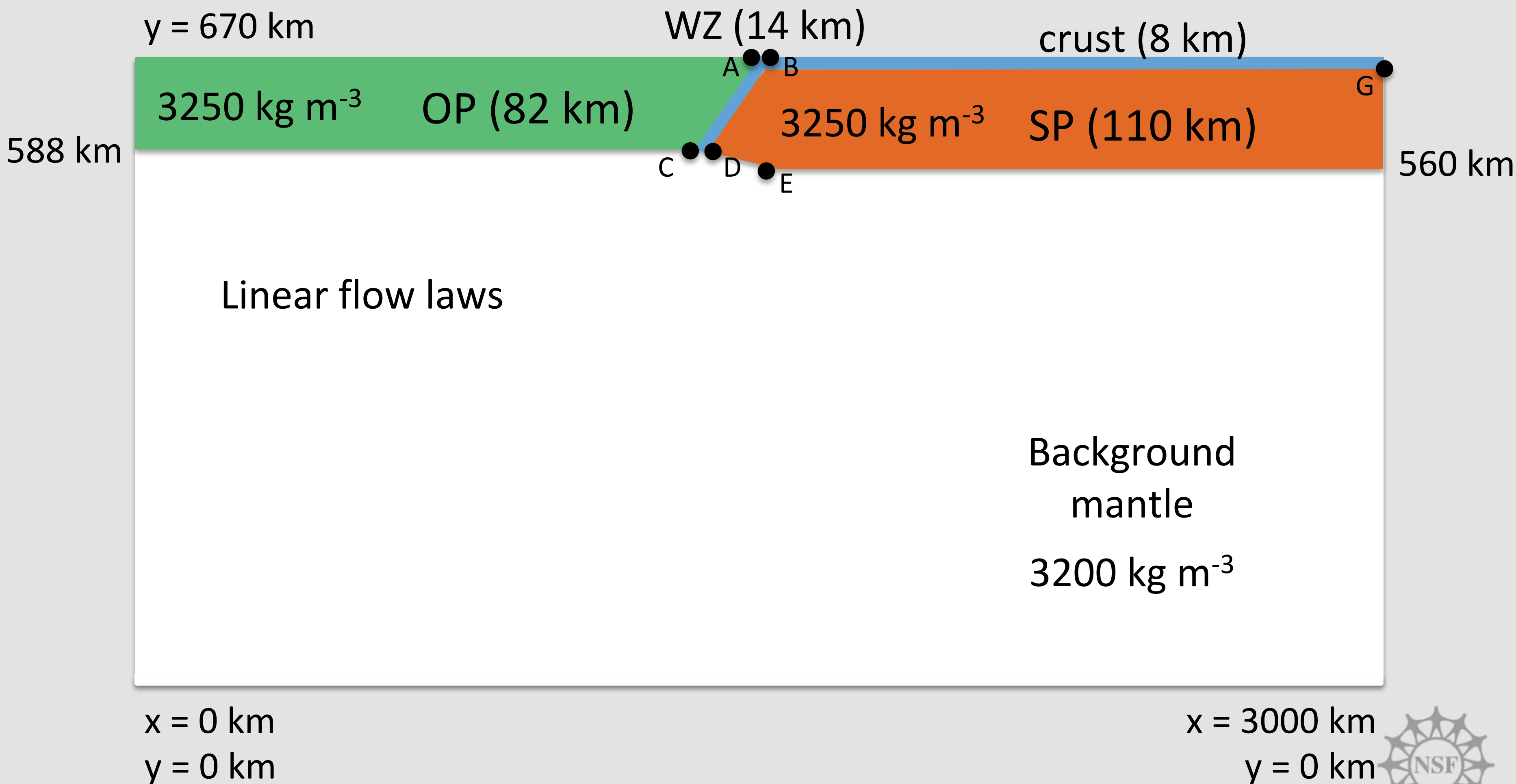
Time



Case 4

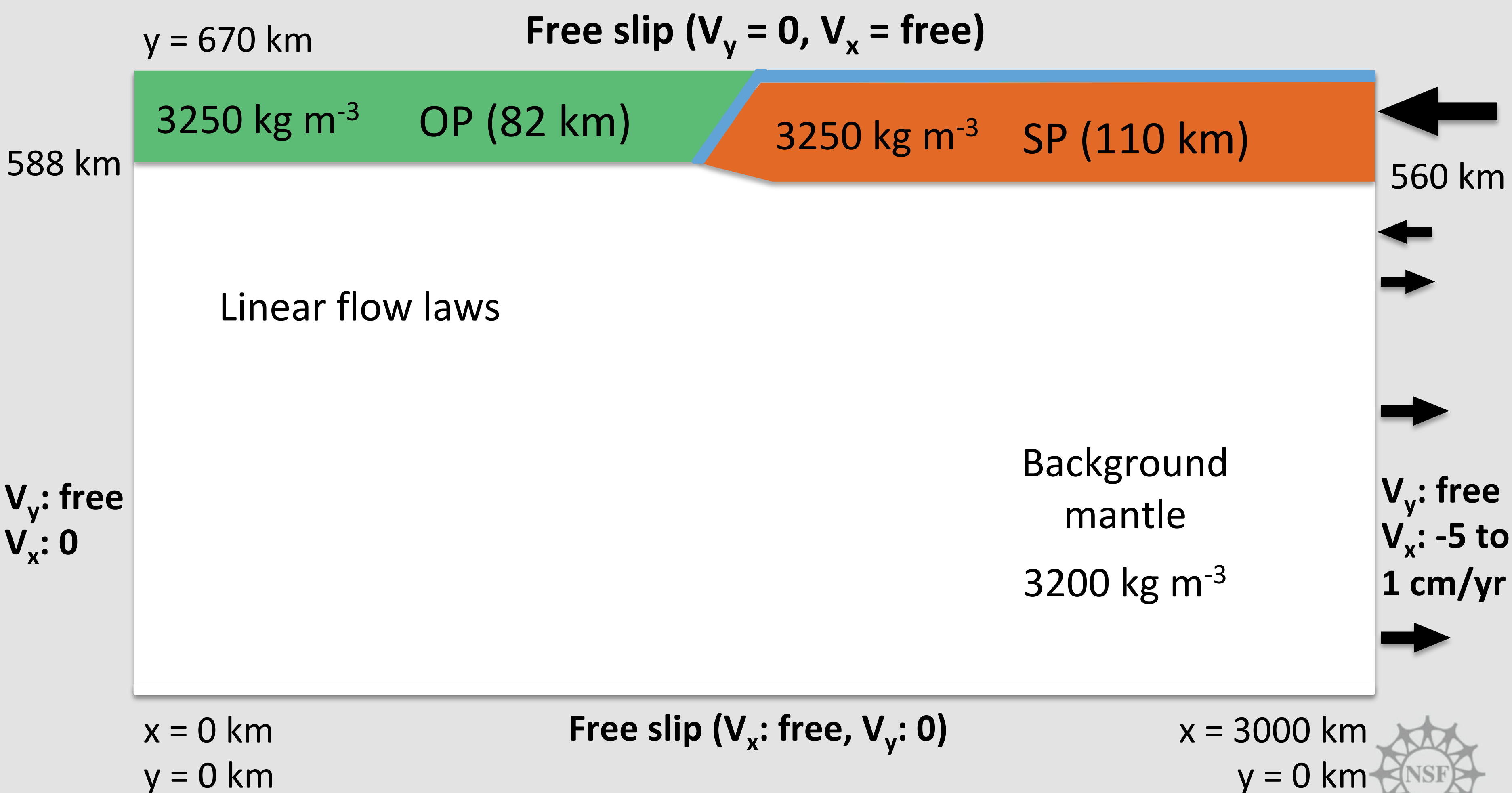
Numerical Model Design

Initial composition & material properties



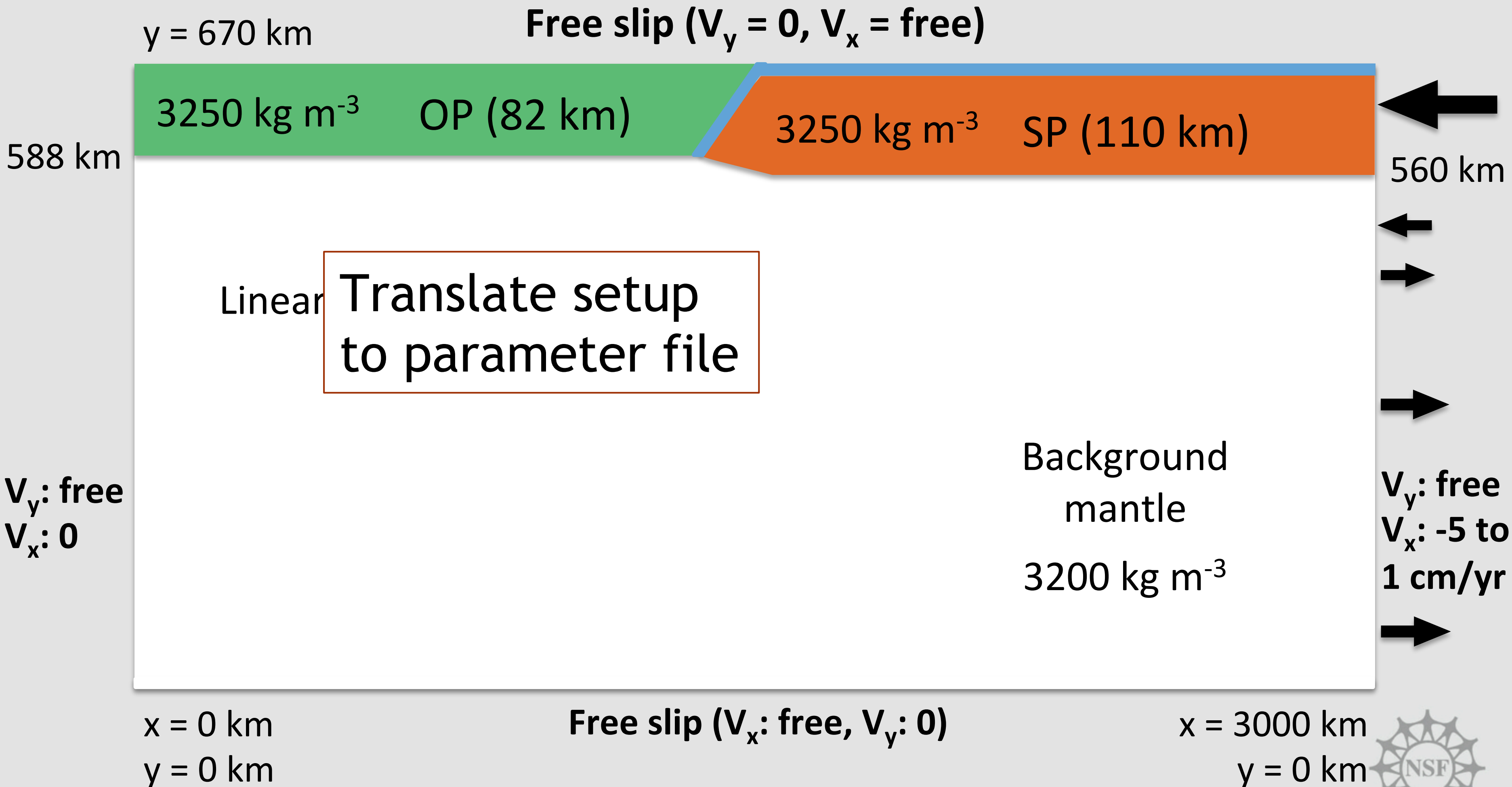
Numerical Model Design

Velocity Boundary Conditions



Numerical Model Design

Velocity Boundary Conditions



Translate setup to parameter file

Parameter file: Global parameters

Open prescribed_subduction.prm with vi or your editor of choice

```
$vi Case1.prm
```

which is an adapted version of the actual Quinquis benchmark.

```
set Dimension                                    = 2
set Start time                                   = 0
set End time                                     = 15e6
set CFL number                                   = 0.01
set Use years in output instead of seconds       = true
set Output directory                             = \
                                    prescribed_subduction/
set Adiabatic surface temperature                = 0
```

[years]

Temperature plays no role in this setup.

Parameter file: Solver settings

```
set Nonlinear solver scheme = single Advection,
                              single Stokes

subsection Solver parameters
  subsection Stokes solver parameters
    set Linear solver tolerance              = 1e-6
    set Number of cheap Stokes solver steps = 200
  end
end
```

Linear viscosities, so no need for an iterative solver scheme

Cheap Stokes preconditioner

Parameter file: Discretization

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

```
subsection Discretization
  set Composition polynomial degree                  = 2
  set Temperature polynomial degree                  = 1
  set Stokes velocity polynomial degree              = 2
  set Use locally conservative discretization        = false
set Use discontinuous composition discretization     = true

  subsection Stabilization parameters
   set Use limiter for discontinuous composition solution
= true
   set Global composition maximum    = 1, 1, 1, 1, 100
   set Global composition minimum    = 0, 0, 0, 0, 0
   set Stabilization method          = entropy viscosity
  end
end
```

Discontinuous Galerkin for compositional fields → explain

Stabilization of advection

Parameter file: Geometry

```
subsection Geometry model
  set Model name = box

  subsection Box
    set X extent       = 3000e3
    set Y extent       = 670e3
    set X repetitions = 4
  end
end
```

2D box of 3000x670 km

Divide the coarse grid to get better aspect ratio of mesh cells

Parameter file: Composition

```
subsection Compositional fields
  set Number of fields        = 3
  set Names of fields         = OP, ML_SP, crust_SP
end
```

Sublithospheric mantle is background

```
subsection Initial composition model
  set List of model names  = function
  subsection Function
    set Function constants =  Ax=1451200.0, Az=670000.0, ...
    set Function expression = \
   if(z>=Cz&z>=((Az-Cz)/(Ax-Cx)*(x-Cx)+Cz),1,0); \
   if((x>=Ex&z>=Ez&z<Gz)| \
      (x<Ex&z<=((Bz-Dz)/(Bx-Dx)*(x-Dx)+Dz)
       &z<Gz&z>=((Ez-Dz)/(Ex-Dx)*(x-Dx)+Dz)),1,0); \
   if(z>=Cz&z>((Bz-Dz)/(Bx-Dx)*(x-Dx)+Dz)&
      z<((Az-Cz)/(Ax-Cx)*(x-Cx)+Cz)| \
      z>=Gz&z<=((Bz-Dz)/(Bx-Dx)*(x-Dx)+Dz),1,0)
  set Variable names       = x,z
  end
end
```

Parameter file: Composition

```
subsection Boundary composition model
  set Fixed composition boundary indicators = right
  set List of model names                    = initial composition
end
```

Prescribed inflow on the right,
so fix the composition that comes in

Parameter file: Temperature

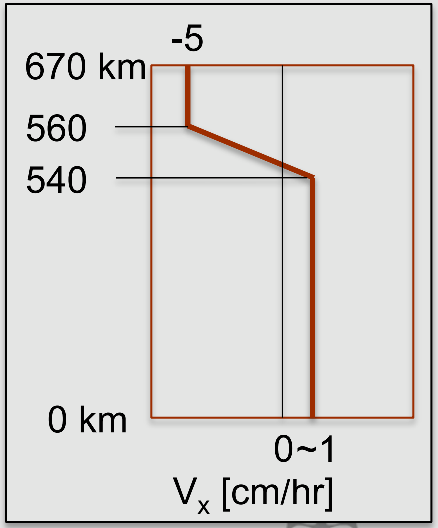
```
subsection Initial temperature model
  set List of model names = function
  subsection Function
    set Function expression = 0
  end
end
subsection Boundary temperature model
  set Fixed temperature boundary indicators = bottom, top,
                                              right
  set List of model names = box
  subsection Box
    set Bottom temperature  = 0
    set Left temperature    = 0
    set Right temperature   = 0
    set Top temperature     = 0
  end
end
```

Temperature plays no role,
but we should set boundary conditions for inflow boundaries.

Parameter file: Velocity BC

```
subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, bottom,top
  set Prescribed velocity boundary indicators = right x:function

  subsection Function
    set Function constants  = cm=100.
    set Function expression = if(z<540000.0,(600.0/550.0)/cm, \
                                 if(z>560000.0, -5.0/cm, \
                                  ((((-600.0/550.0)-5.0)/-20.0)*
                                  ((z/1000.0)-560.0)+5.0)*
                                  (-1.0/cm))); \
                              0
    set Variable names      = x,z
  end
end
```



Prescribe the plate inflow (horizontal component only) and a gradual transition to a compensating outflow of mantle material.

Parameter file: Material parameters

```
subsection Material model
  set Model name = multicomponent

  subsection Multicomponent
    set Reference temperature       = 0.0
    set Viscosity averaging scheme = maximum composition
    # Fields: background, OP, ML SP, crust SP
    set Viscosities                 = 1e20, 1e23, 1e23, 1e20
    set Densities                   = 3200, 3250, 3250, 3250
    set Thermal conductivities      = 1
  end

end

subsection Formulation
  set Formulation                   = Boussinesq approximation
end
```

Take the max composition to compute viscosity to counteract diffusion.

Only density and viscosity vary between all compositions.

Parameter file: Mesh refinement

```
subsection Mesh refinement
  set Initial adaptive refinement                 = 2
  set Initial global refinement                   = 4
  set Minimum refinement level                    = 2
  set Normalize individual refinement criteria = true
  set Refinement criteria merge operation         = plus
  set Coarsening fraction                         = 0.10
  set Refinement fraction                         = 0.9
  set Strategy                                    = minimum refinement
                                        function, viscosity, composition
  set Time steps between mesh refinement          = 10

  subsection Minimum refinement function
    set Coordinate system = cartesian
    set Variable names = x,z,t
    set Function constants = vel=150e3, L=100e3, crust=10e3
    set Function expression = if(x>=1350e3&670e3-z<crust,6,
                              if(670e3-z<L,5,if(670e3-z<vel,4,1)))
  end
end
```

Limit coarsening to level 2

Static and dynamic strategies

Make sure the crustal layer is always well resolved.

Parameter file: Postprocessing

```
subsection Postprocess
  set List of postprocessors               = visualization,
                                             velocity statistics
```

Track the RMS velocity

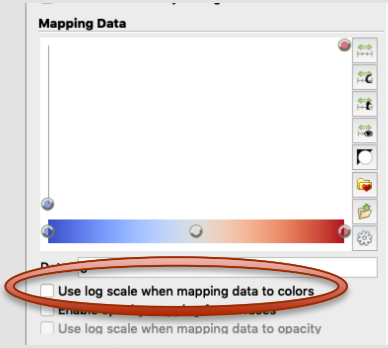
```
  subsection Visualization
    set List of output variables           = density, viscosity,
                                             strain rate,
                                             error indicator
    set Time between graphical output = 5e5
  end

end
```

Output graphics every 0.5 My (since `set Use years in output instead of seconds = true`)

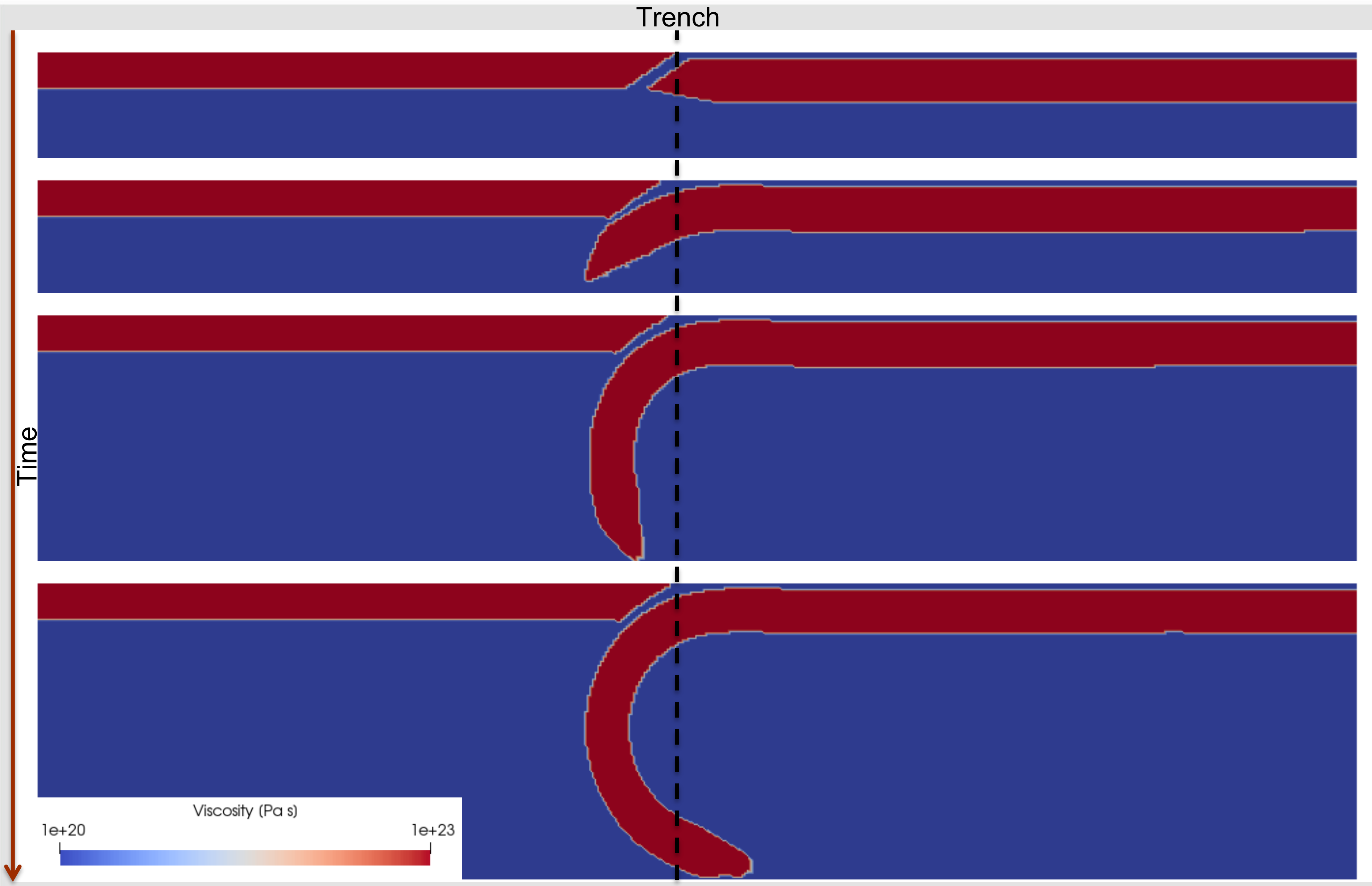
Visualizing the results

1. Start ParaView by typing `paraview &` in the terminal
2. Load the solution.pvd file
3. Display the viscosty and set the colorbar to log scale:
    1. Click *Edit color map*
    2. Select log scale

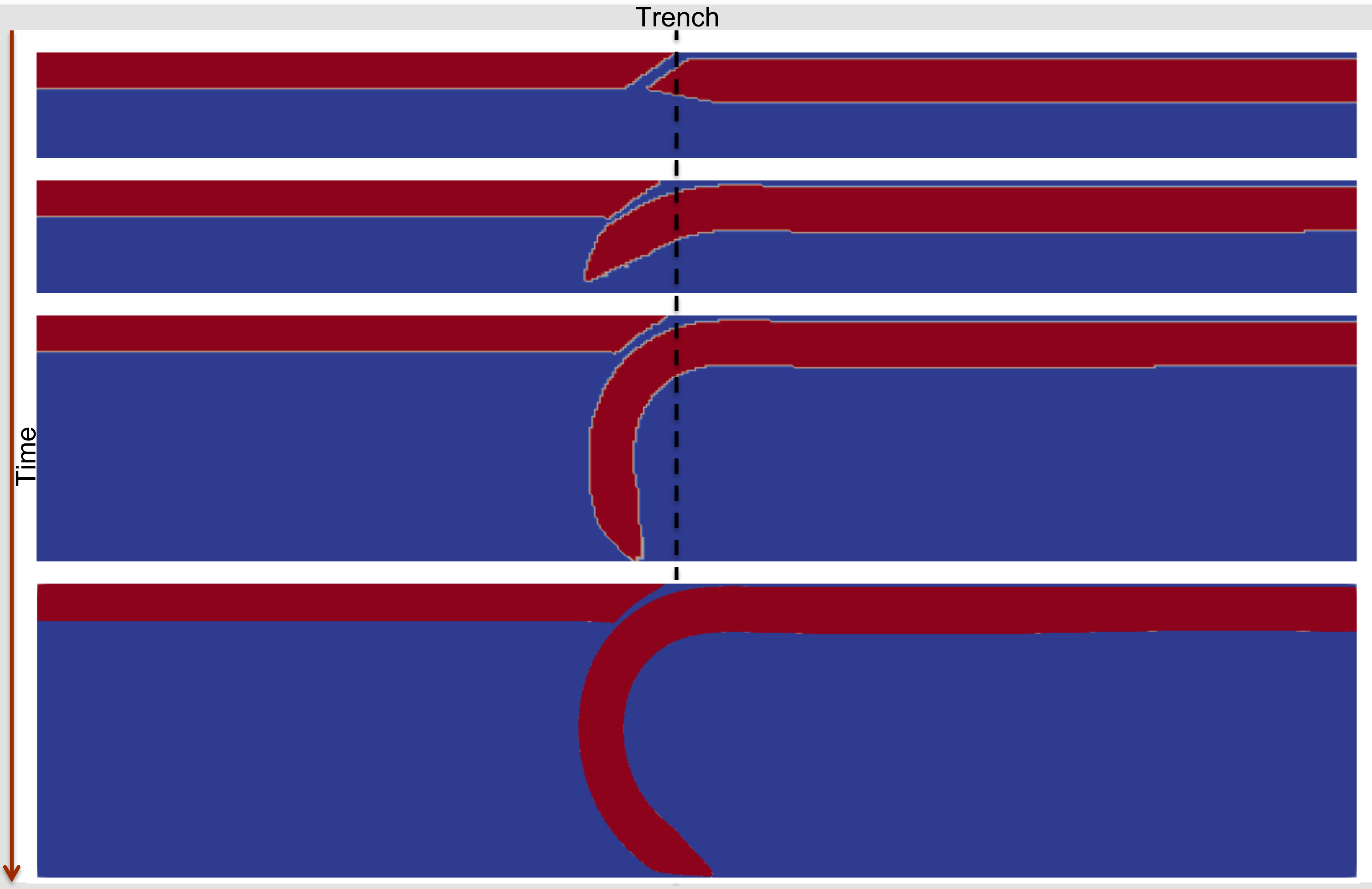


3. Press play!
4. What does the slab do? E.g. advance, retreat, slide along the 660…
5. Look at the strain rate, where is it highest?
6. Does the mesh refinement follow the slab?
7. Add velocity vectors:
    1. Glick *Glyphs*
    2. Set *Active Attributes* → *Vectors* to **velocity**
    3. Set *Scaling* → *Scale mode* to **vector** and press the reset button
    4. How would the boundary conditions affect the flow field?

Visualizing the results

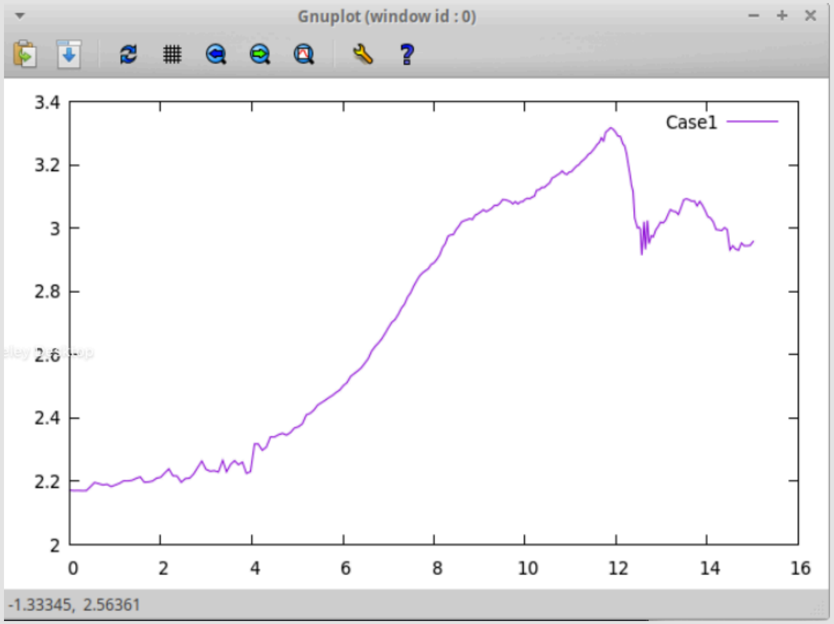


Visualizing the results



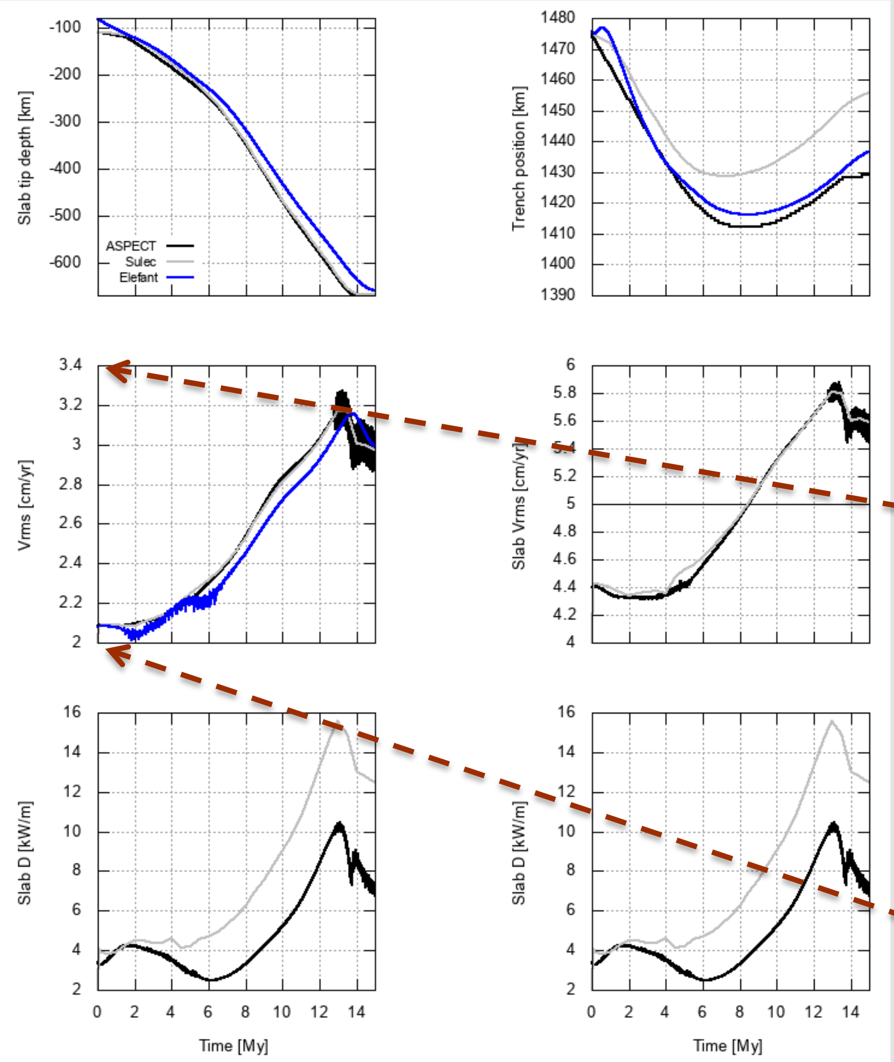
Plotting the statistics

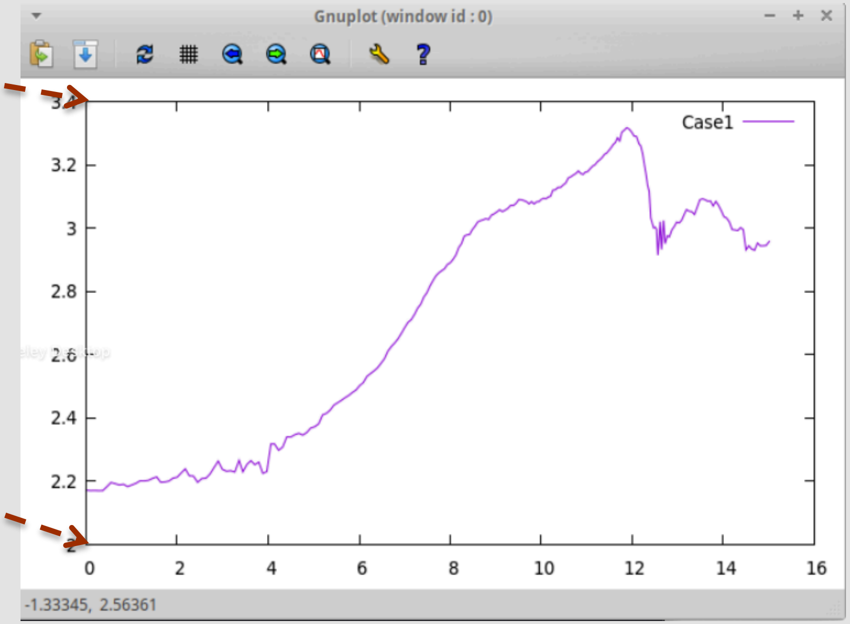
1. In the terminal, go to the directory with the statistics file:
```
$ cd prescribed_subduction/
```
2. Start gnuplot:
```
$ gnuplot
```
3. Plot the root-mean-square velocity [cm/yr] over time [My]:
```
$ plot 'statistics' u ($2/1e6):($16*100) w l
```
4. Can you correlate the trends in the velocity with what you see in ParaView?



Comparing to other codes

High resolution results:





Model Extension

- ✓Grid resolution
- ✓Temperature advection and dependency (Case 2)
- ✓Additional layering of the lithosphere
- ✓Visco-plastic rheology (Case 3&4)
- ✓Phase changes
- ✓Free surface
- ✓Self-consistent subduction
- ✓3D

Model Extension

✓Grid resolution

✓Temperature advection and dependency (Case 2)

✓Additional layering of the lithosphere

✓Visco-plastic rheology (Case 3&4)

✓Phase changes

✓Free surface

✓Self-consistent subduction

✓3D

~70 publications with ASPECT:
https://aspect.geodynamics.org/publications.html

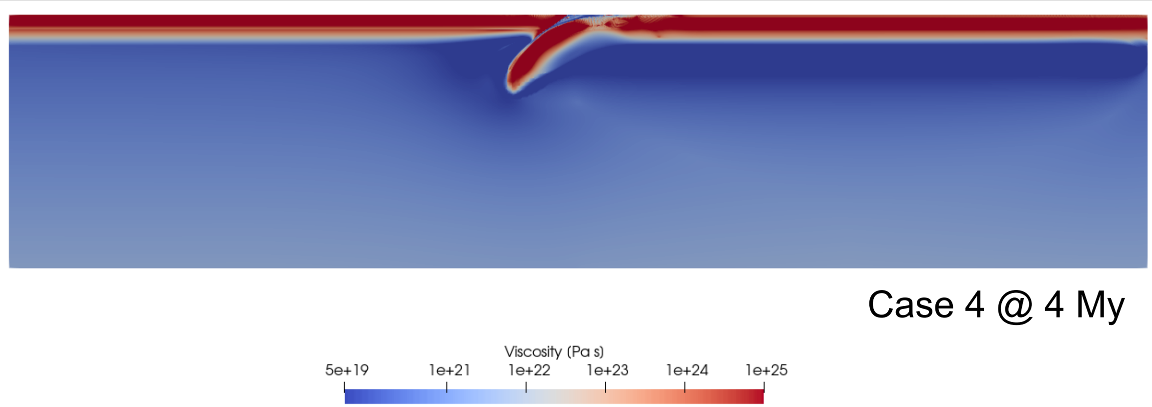
Model Extension

✓Grid resolution

✓Temperature advection and dependency (Case 2)

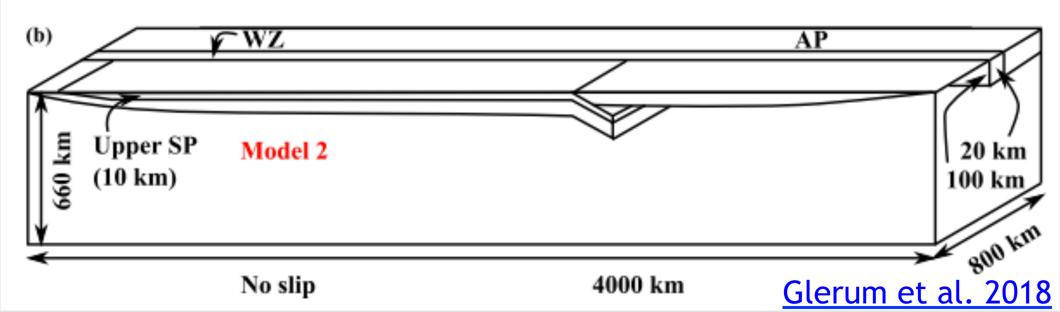
✓Additional layering of the lithosphere

✓Visco-plastic rheology (Case 3&4)

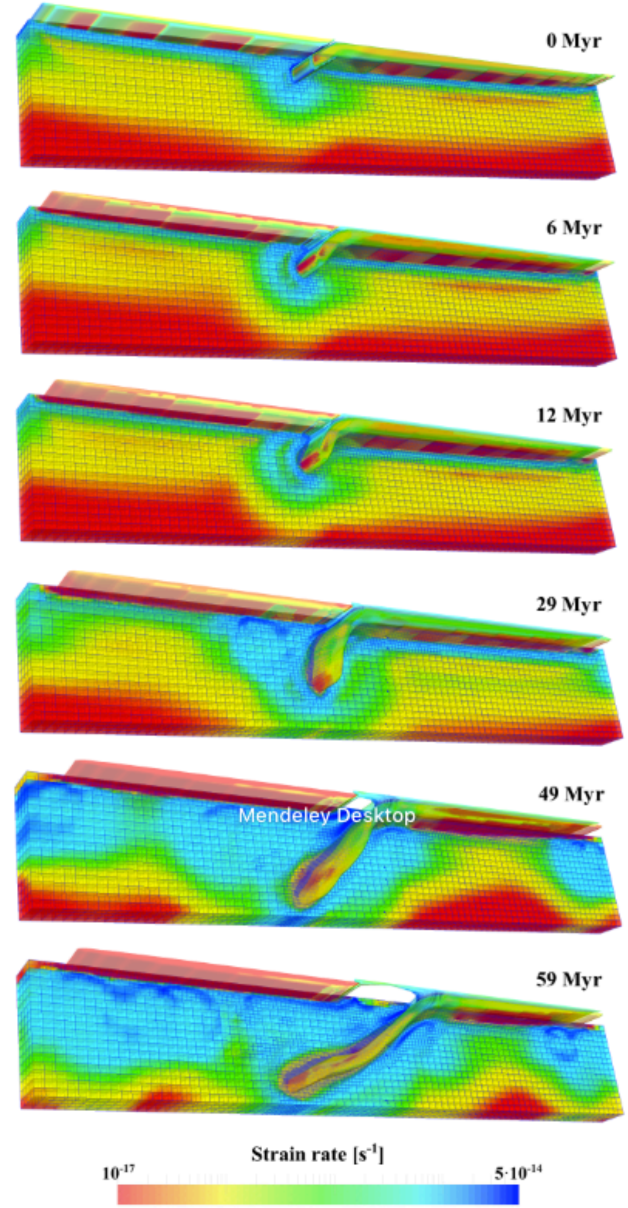


Model Extension

- ✓Grid resolution
- ✓Temperature advection and dependency
- ✓Additional layering of the lithosphere
- ✓Visco-plastic rheology
- ✓Self-consistent subduction
- ✓3D



Glerum et al. 2018



Model Extension

✓ Grid resolution

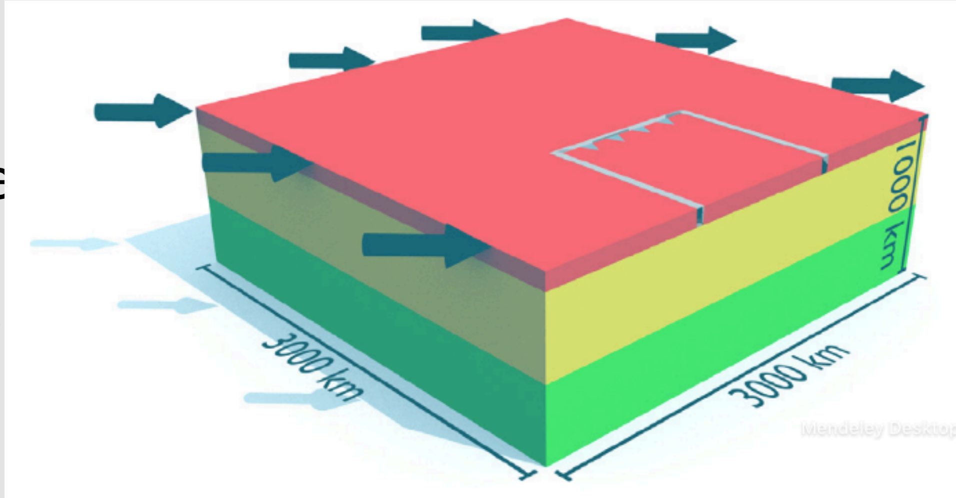
✓ Temperature advection and depe

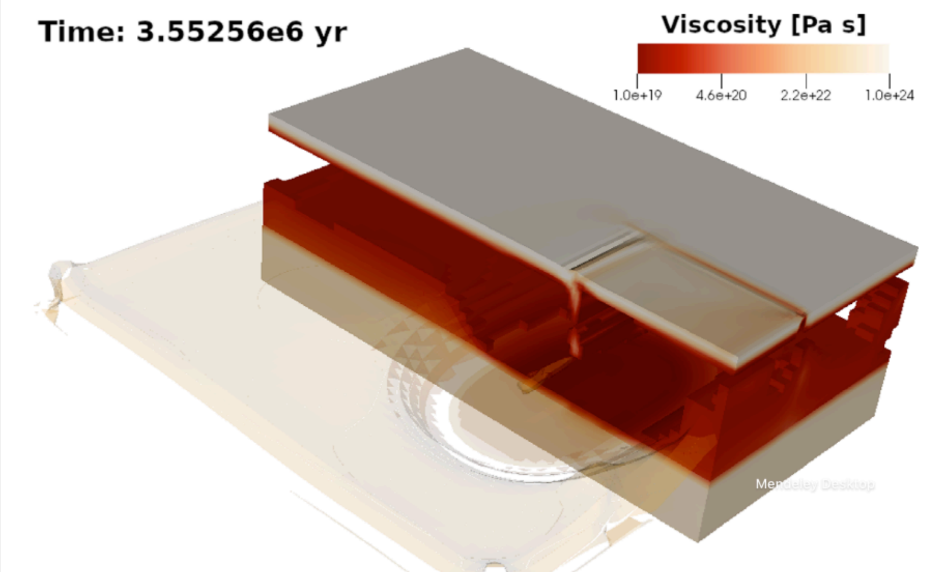
✓ Additional layering of the lithosp

✓ Visco-plastic rheology

✓ Oblique subduction

✓ 3D





[Fraters et al. 2019]

Model Extension

✓Temperature advection and dependency (Case 2)

Try to add an initial temperature field consisting of:

1. A linear increase in the lithosphere from 293 K at the surface to 1600 K at the LAB.

2. A smaller increase (0.4 K/km) in the sublithospheric mantle.

Use the Function expression in line 90.

Model Extension

✓Temperature advection and dependency (Case 2)

Try to add an initial temperature field, for example:

```
subsection Function
  set Function constants  = Ts=473.25, Tm=1573.25,             \
                            yl_OP=84e3, yl_SP=110e3,           \
                            Dy=670e3
  set Function expression = if(x<1500e3,                       \
                               if(Dy-y<yl_OP,                  \
                                  Ts+(Tm-Ts)*((Dy-y)/yl_OP),   \
                                  Tm+(Dy-yl_OP-y)/1000.*0.25), \
                               if(Dy-y<yl_SP,                  \
                                  Ts+(Tm-Ts)*((Dy-y)/yl_SP),   \
                                  Tm+(Dy-yl_SP-y)/1000.*0.25)) \
  set Variable names      = x, y, t
end
```

Model Extension

✓Temperature advection and dependency (Case 2)

Try to add an initial temperature field, for example:

```
subsection Function
  set Function constants  = Ts=473.25, Tm=1573.25,            \
                            yl_OP=84e3, yl_SP=110e3,          \
                            Dy=670e3
  set Function expression = if(x<1500e3,                      \
                               if(Dy-y<yl_OP,                 \
                                  Ts+(Tm-Ts)*((Dy-y)/yl_OP),  \
                                  Tm+(Dy-yl_OP-y)/1000.*0.25), \
                               if(Dy-y<yl_SP,                 \
                                  Ts+(Tm-Ts)*((Dy-y)/yl_SP),  \
                                  Tm+(Dy-yl_SP-y)/1000.*0.25)) \
  set Variable names      = x, y, t
end
```