Overview and Schedule

Part I. Introduction (Monday)

Part 2. Continental Extension Tutorial (Monday)

Part 3. Melting at Mid-Ocean Ridge Tutorial (Tuesday)

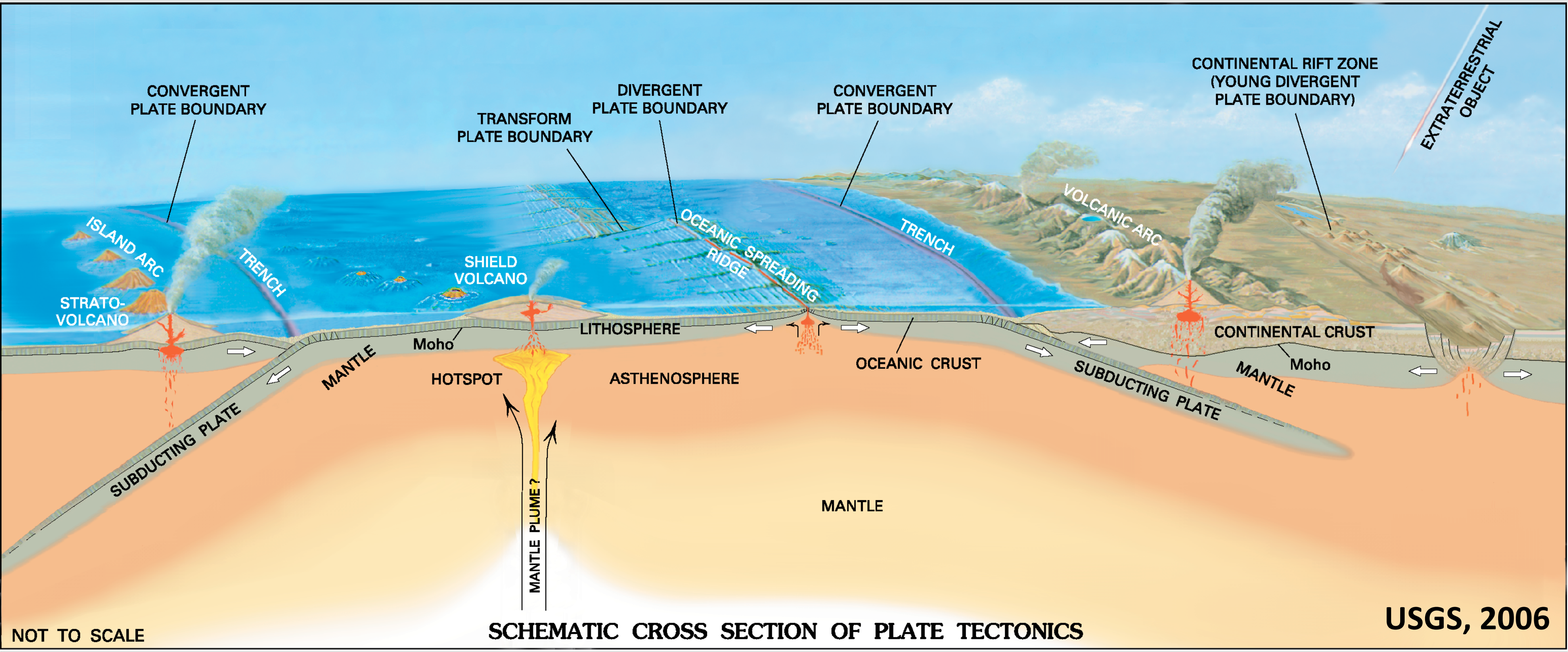
Part 4. Detailed look at ASPECT and Tinker Time (Wednesday)

Numerical Modeling From Start to Finish

1. Define what physical processes to examine
2. Capture the physics through mathematical equations
3. Choose a numerical approximation to solve the equations
4. Design, write and validate software (or validate existing code)
5. Formulate a hypothesis to test
6. Design and run a series of models
7. Verify and interpret results

Physical Processes: Long-Term Tectonics

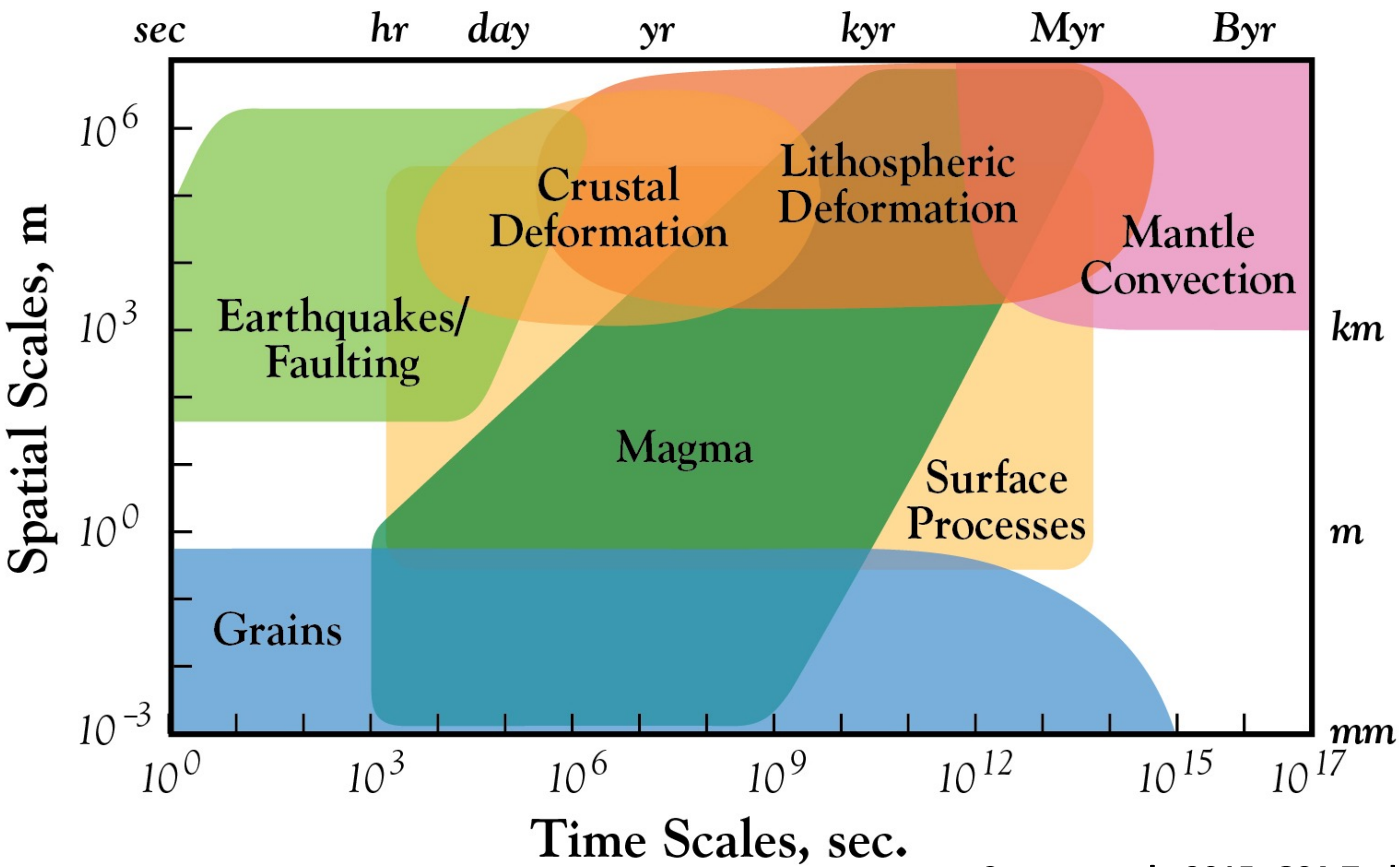
COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS



Crustal Deformation, Lithospheric Deformation, Mantle Convection

- Capture the physical processes through mathematical equations

Relevant Temporal and Spatial Scales



Cooper et al., 2015, GSA Today

Long-Term Tectonics

10^3 to 10^8 years, 10's to 1000's of km

Capture Physics Through Equations

Governing Equations (Incompressible Viscous Flow)

$\nabla \cdot u = 0$ **Conservation of Mass**

$\nabla \cdot \sigma' - \nabla P + \rho g = 0$ **Conservation of Momentum**

$\rho c \left(\frac{\partial T}{\partial t} + u \cdot \nabla T \right) = \nabla \cdot K \nabla T + \mathrm{H}$ **Conservation of Energy**

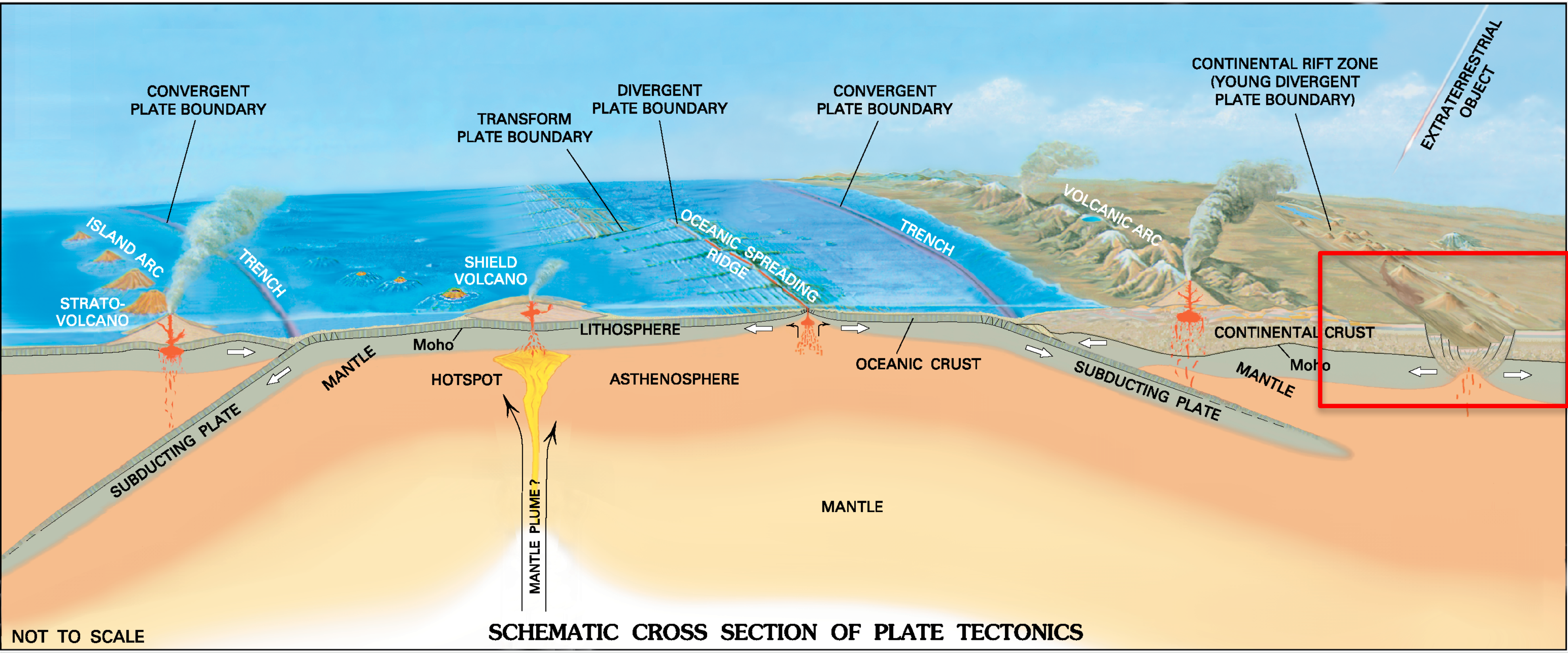
Constitutive Relationships (Rheology)

$\sigma' = A^{-1/n} \dot{\varepsilon}^{-1/n} d^{m/n} e^{\frac{Q+PV}{nRT}}$ **Nonlinear Viscous Flow**

$\sigma' = P \sin\theta + \mathrm{C} \cos\theta$ **Brittle Failure**

Formulate a Hypothesis to Test

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS



Controls on deformation patterns?

Rheology, Rates of Deformation, Inheritance, …

<u>*Continental Extension*</u>

NSF

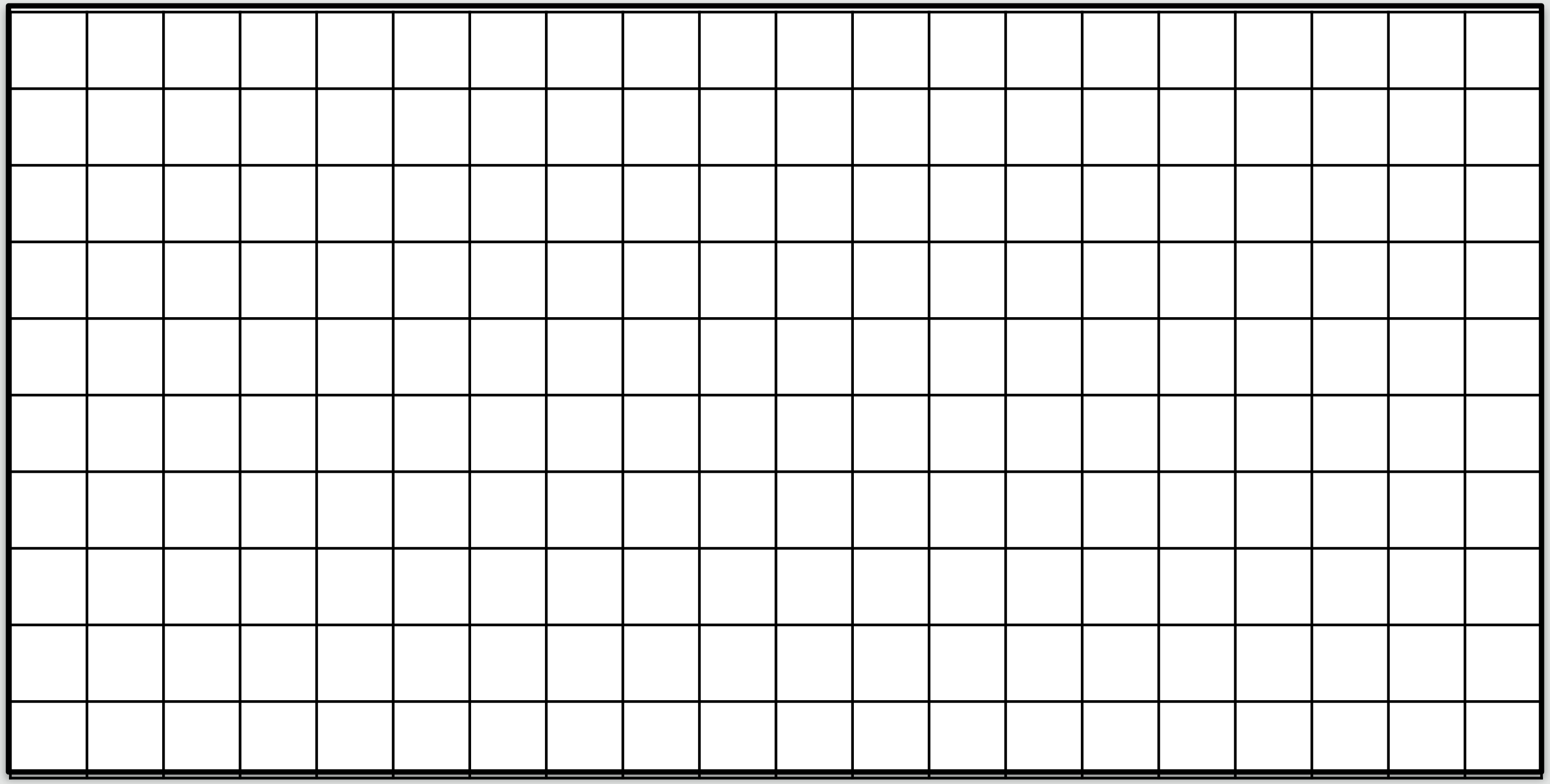
Numerical Model Design

Geometry

Grid Resolution

y = 0 km

10 km Spacing (Coarse Mesh)



x = 0 km
y = 100 km

x = 200 km
y = 100 km

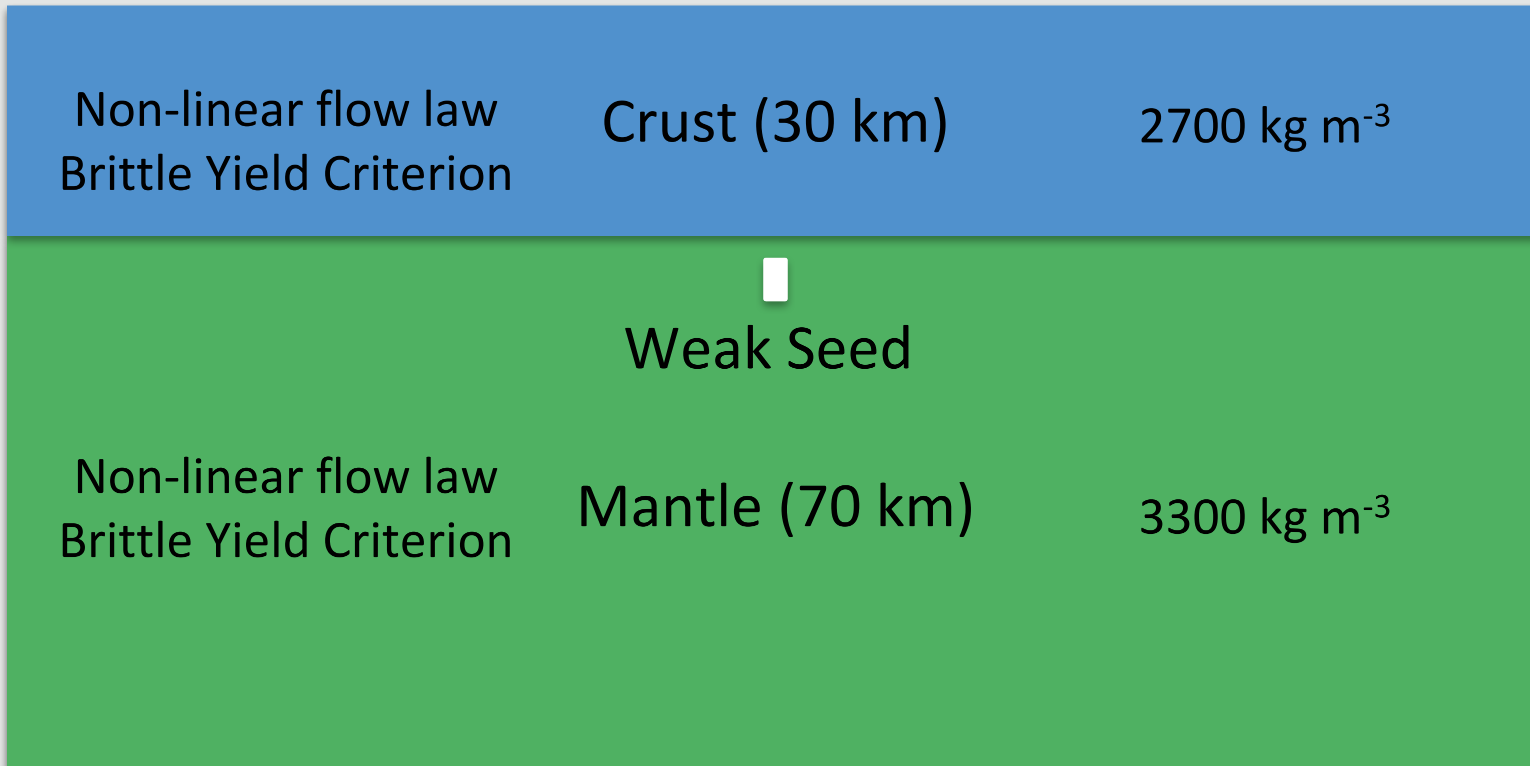
"Appropriate" resolution depends on process

Each study requires a resolution test

Numerical Model Design

Initial Conditions (Lithology)

y = 0 km



x = 0 km
y = 100 km

x = 200 km
y = 100 km

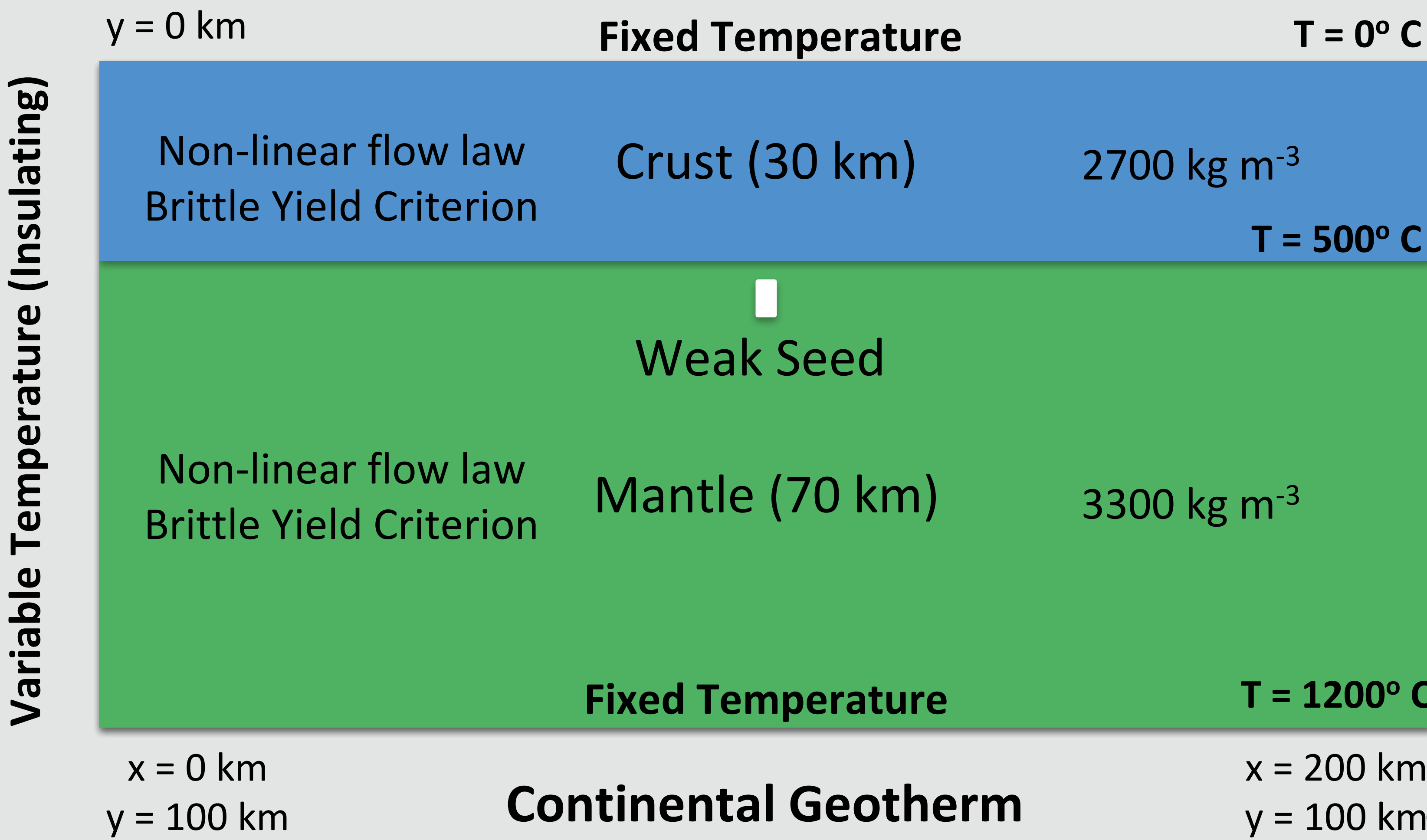
✓ Thermodynamic Properties

✓ Distinct Material Properties

Numerical Model Design

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Initial and Boundary Conditions (Temperature)



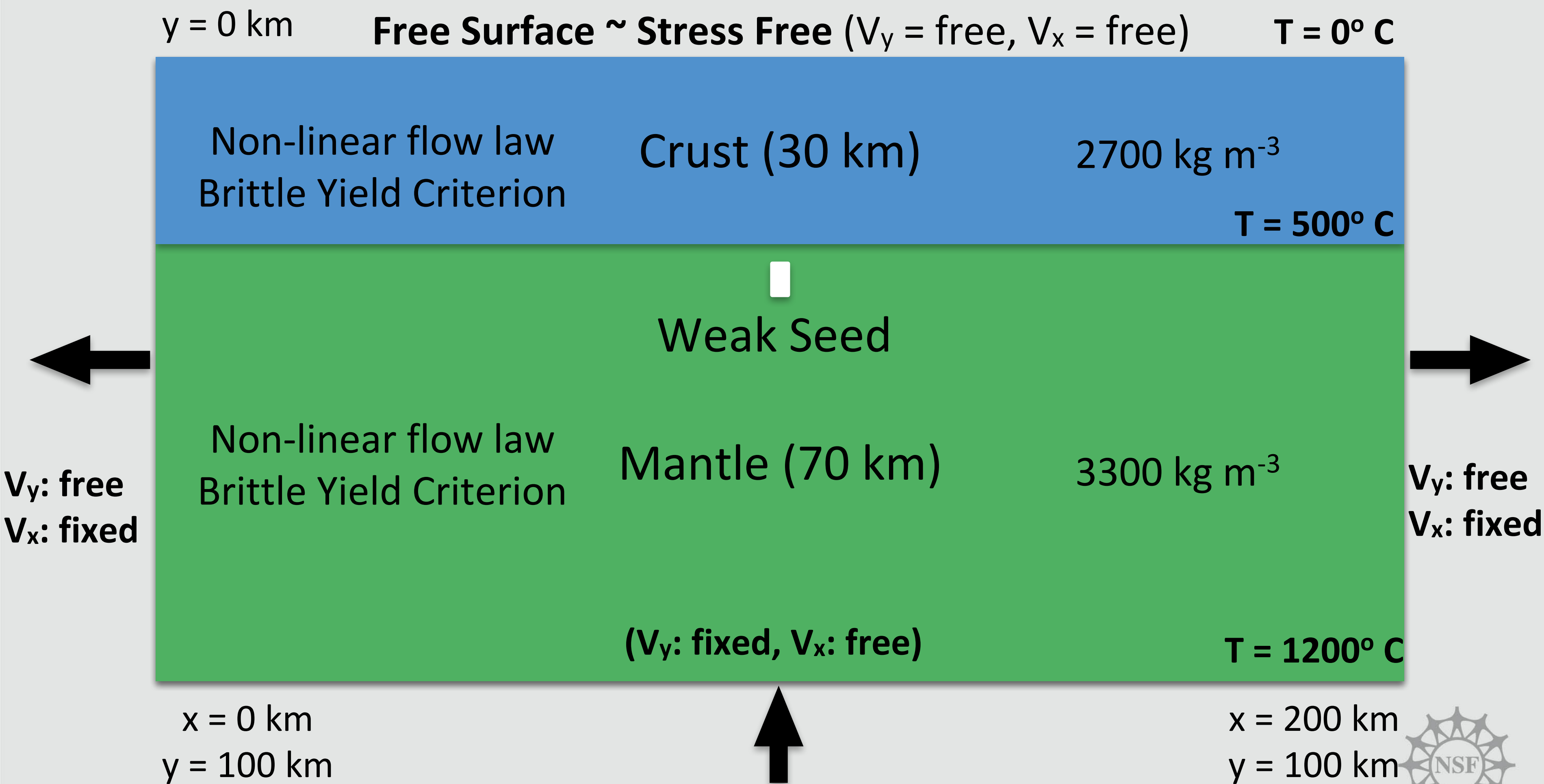
Continental Geotherm

Chapman, 1986, Geol. Soc. Lon. Spec. Pub.

Numerical Model Design

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

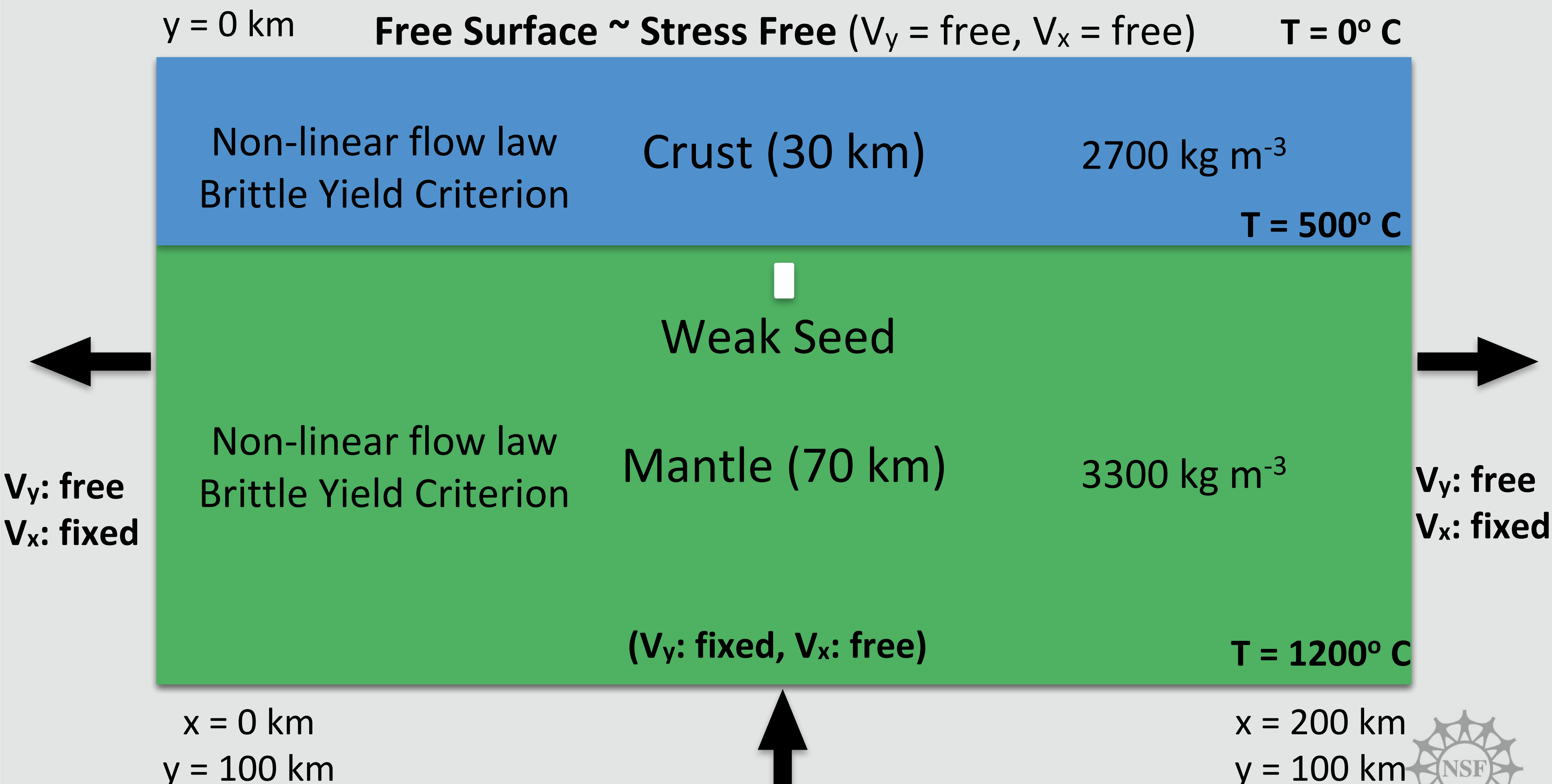
Temporal Constrains, Discretization, Solver Settings



How long will the model run, time step-size, element type, solver tolerance?

Numerical Model Design

Velocity Boundary Conditions



Options: free-slip, free surface, fixed (no-slip), periodic

Continental Extension Cookbook

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Instructions

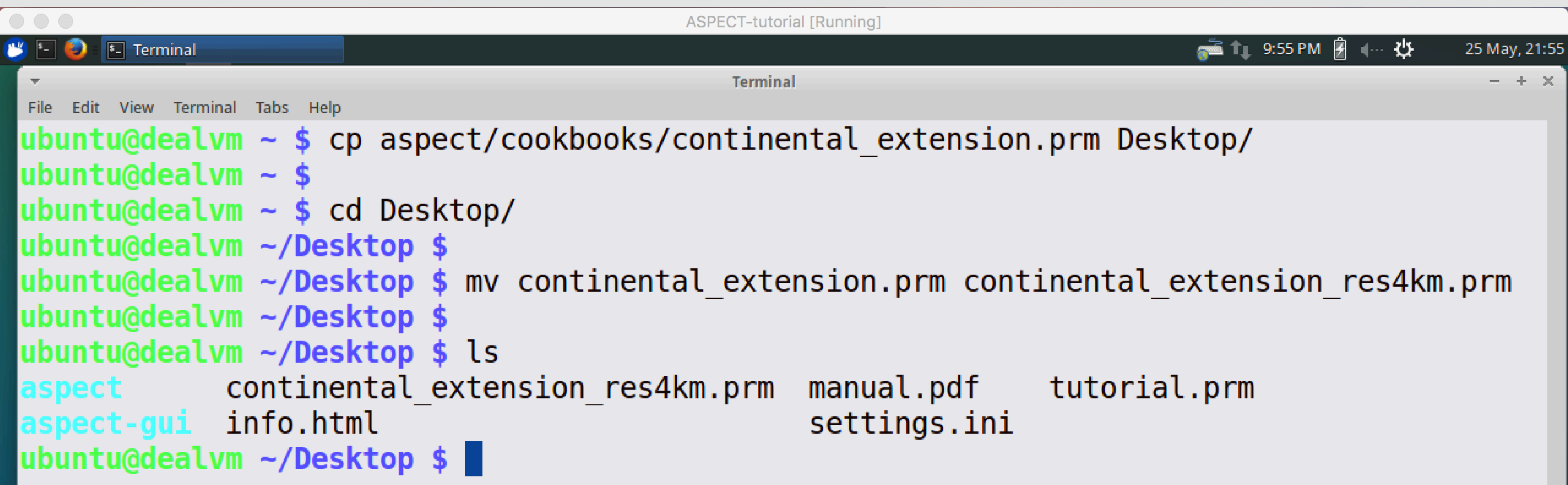
1. Open a terminal in the virtual machine

2. Copy the continental extension cookbook file to the Desktop

cp aspect/cookbooks/continental_extension.prm Desktop/

3. Rename the file to continental_extension_res4km.prm

mv continental_extension.prm continental_extension_res4km.prm



Instructions continued

4. Open continental_extension_res4km.prm in a text editor (double click file)

5. Change the grid resolution from 2 km to 4 km (see images below)

Change the value of X repetitions from 200 to 100

Change the value of Y repetitions from 50 to 25

```
# Model geometry (400x100 km, 2 km spacing)
subsection Geometry model
  set Model name = box
  subsection Box
    set X repetitions = 200
    set Y repetitions = 50
    set X extent      = 400e3
    set Y extent      = 100e3
  end
end
```

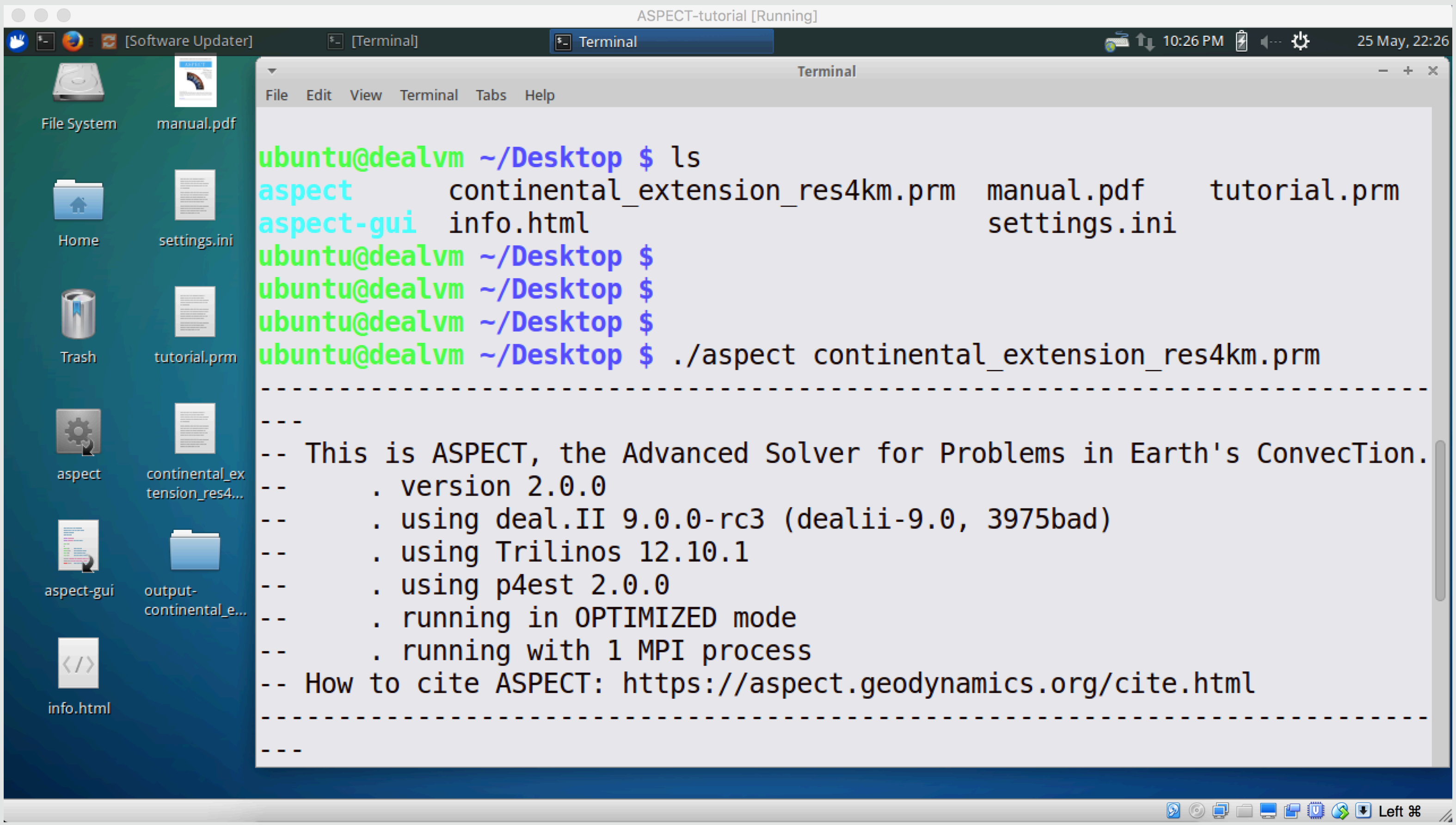
```
# Model geometry (400x100 km, 4 km spacing)
subsection Geometry model
  set Model name = box
  subsection Box
    set X repetitions = 100
    set Y repetitions = 25
    set X extent      = 400e3
    set Y extent      = 100e3
  end
end
```

Continental Extension Cookbook

Instructions continued

6. Run the modified continental extension cookbook

./aspect continental_extension_res4km.prm



Parameter File: Global, Geometry & Mesh

```
set Dimension  = 2

set Start time  = 0

set End time  = 5e6

set Use years in output instead of
seconds = true

set Nonlinear solver scheme = single
Advection, iterated Stokes

set Nonlinear solver tolerance  = 1e-4

set Max nonlinear iterations  = 10

set CFL number = 0.5
```

```
subsection Geometry model
  set Model name = box

  subsection Box
    set X repetitions = 200
    set Y repetitions = 50
    set X extent       = 400e3
    set Y extent       = 100e3
  end

end

subsection Mesh refinement
  set Initial adaptive refinement              = 0
  set Initial global refinement                = 0
  set Time steps between mesh refinement = 0
end
```

Parameter File: Boundary Velocity

```
subsection Free surface
  set Free surface boundary indicators  = top
end

subsection Boundary velocity model

  set Prescribed velocity boundary indicators = left x: function, right x: function, \
                                                  bottom y: function

  subsection Function
    set Variable names  = x,y
    set Function constants  = cm=0.01, year=1
    set Function expression = if (x<200e3 , -0.25*cm/year, 0.25*cm/year) ; 0.125*cm/year;
  end

end
```

Parameter File: Initial Temperature

```
subsection Initial temperature model

  set Model name = function

  subsection Function

    set Variable names = x,y

    set Function constants = h=100e3,ts1=273,ts2=681.5714,ts3=823., \
                             k1=2.5,k2=2.5,k3=3.3,A=1.5e-6, \
                             qs1=0.0653571,qs2=0.035357,qs3=0.035357,qb3=0.035357

    set Function expression = if( (h-y)<=20.e3, \
                              ts1 + (qs1/k1)*(h-y) - (A*(h-y)*(h-y))/(2.0*k1), \
                              if((h-y)>20.e3 && (h-y)<=30.e3, ts2 + (qs2/k2)*(h-y-20.e3),\
                              ts3 + (qs3/k3)*(h-y-30.e3)));

  end

end
```

Parameter File: Boundary Temperature

```
subsection Boundary temperature model

  set Fixed temperature boundary indicators = bottom, top
  set List of model names = box

  subsection Box

    set Bottom temperature = 1573
    set Top temperature     =  273

  end

end
```

Parameter File: Composition

```
subsection Compositional fields
  set Number of fields = 4
  set Names of fields = upper, lower, mantle, seed
end

subsection Initial composition model
  set Model name = function
  subsection Function
    set Variable names  = x,y
    set Function expression = if(y>=80.e3, 1, 0); \
                              if(y<80.e3 && y>=70.e3, 1, 0); \
                              if(y<70.e3 && y>-100.e3,1, 0); \
                              if(y<68.e3 && y>60.e3 && x>=198.e3 && x<=202.e3 , 1, 0);
  end
end

subsection Boundary composition model
  set Fixed composition boundary indicators  = bottom
end
```

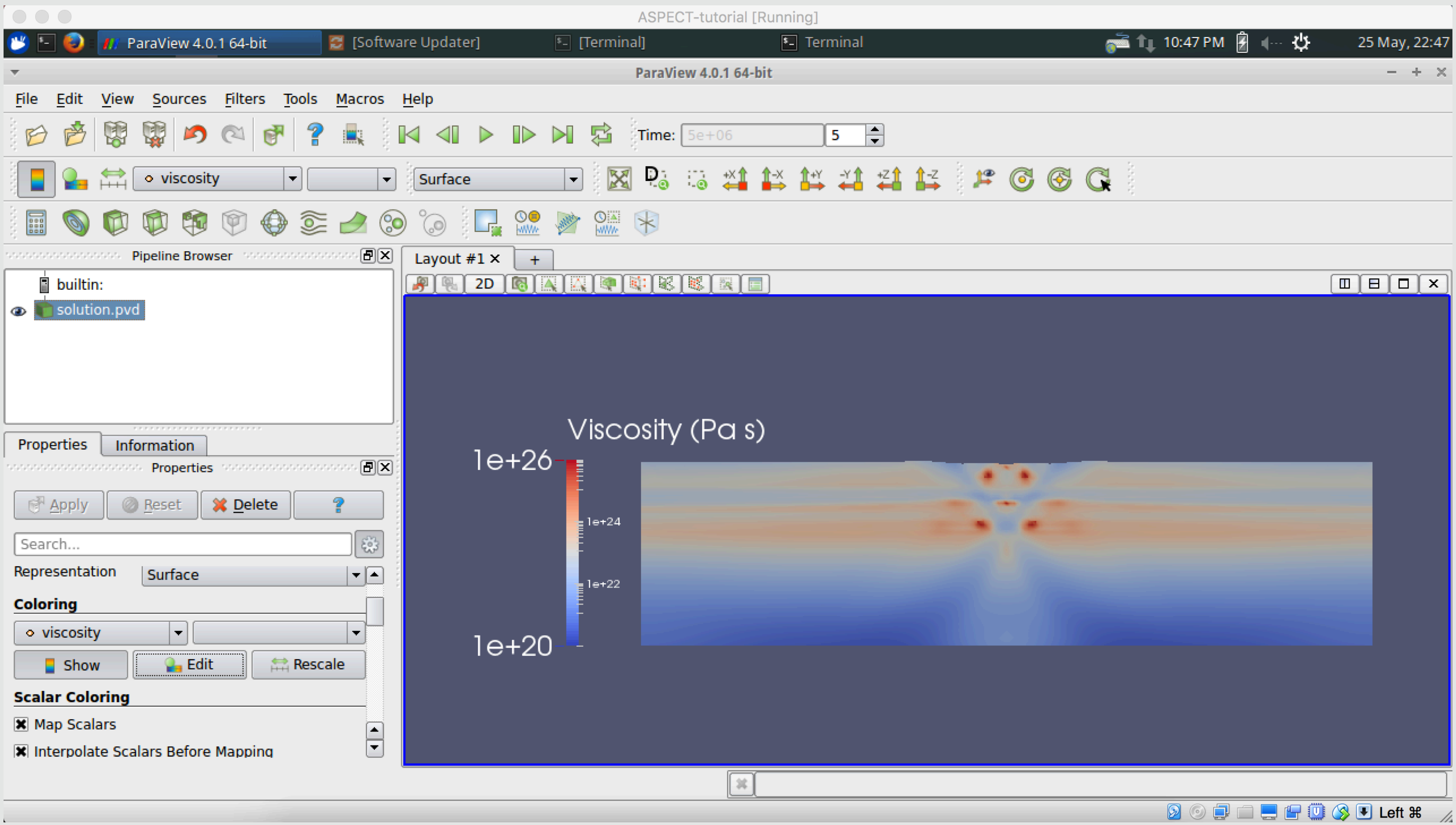
Parameter File: Material Properties

```
subsection Material model
  set Model name = visco plastic

   subsection   Visco Plastic

    set Minimum viscosity = 1e18
    set Maximum viscosity = 1e26

    set Densities  =   3300,   2800,    2900,  3300,   300

    set Prefactors for dislocation creep                = 6.52e-16, 8.57e-28, 7.13e-18, 6.52e-16, 7.13e-18
    set Stress exponents for dislocation creep     =          3.5,          4.0,          3.0,          3.5,          3.0
    set Activation energies for dislocation creep =     530.e3,     223.e3,     345.e3,   530.e3,     345.e3
    set Activation volumes for dislocation creep  =     18.e-6,             0.,             0.,    18.e-6,              0.


    # Plasticity parameters
    set Angles of internal friction =      20.,     20.,     20.,     20.,     20.
    set Cohesions                              = 20.e6, 20.e6, 20.e6, 20.e6, 20.e6
```

Model Postprocessing

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Visualize the model results with Paraview



Model Verification and Interpretation

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Sensitivity Analysis Parameters

- ✓ Grid Resolution
- ✓ Particles-Per-Cell
- ✓ Time-Step Size
- ✓ Model Geometry
- ✓ Initial Lithology
- ✓ Initial Temperature
- ✓ Boundary Conditions
- ✓ Solver convergence settings
- ✓ Viscous flow law
- ✓ Brittle Yield Mechanism
- ✓ Brittle parameters
- ✓ Strain-weakening (magnitude, rate)
- ✓ Elastic Constants

As an exercise, try varying some these parameters in the continental extension cookbook!