

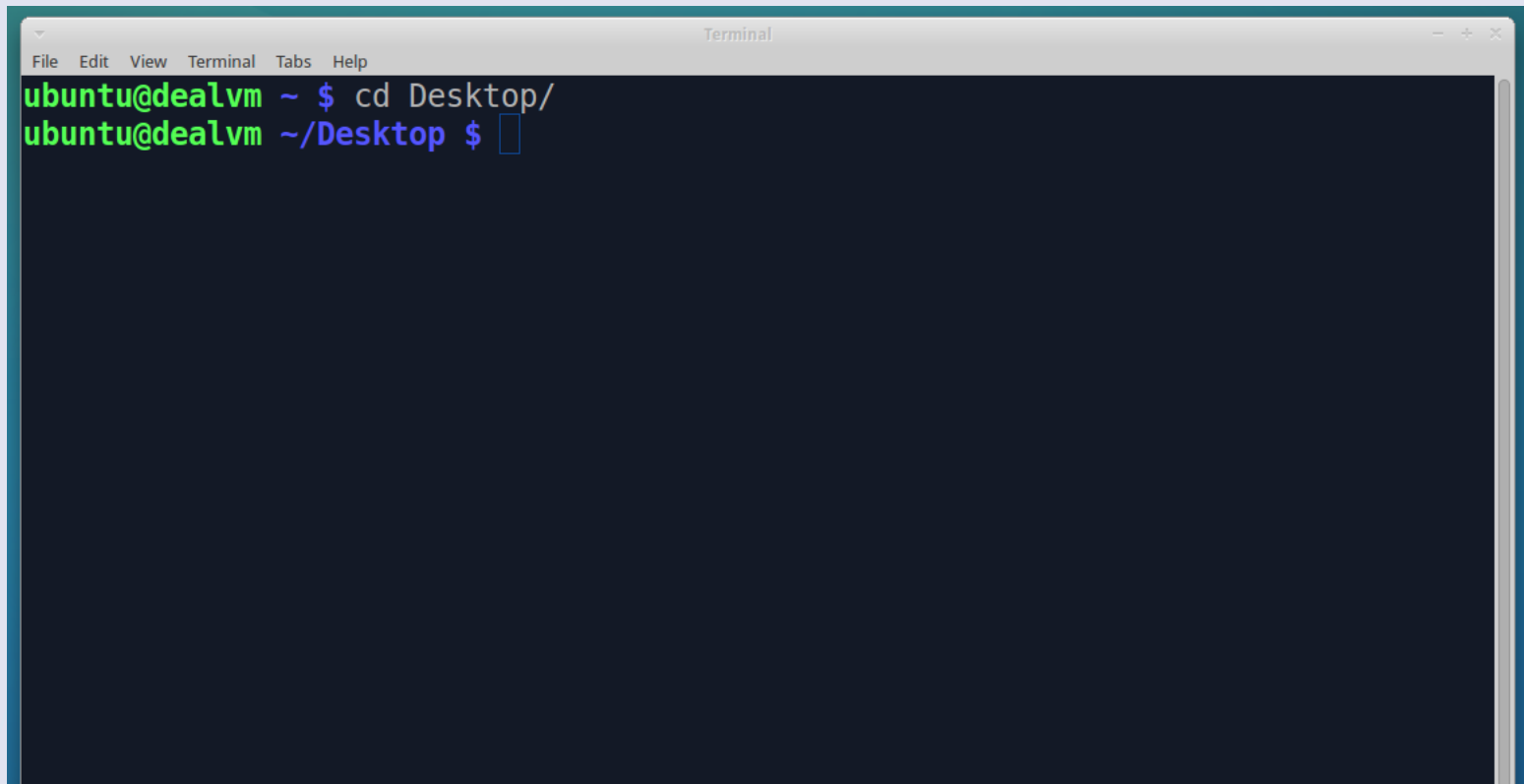
ASPECT tutorial

Part II: Melt transport

Juliane Dannberg,
Rene Gassmöller, John Naliboff

Starting the model...

- This will take a while...
- Start by going to the Desktop directory:
`cd Desktop`



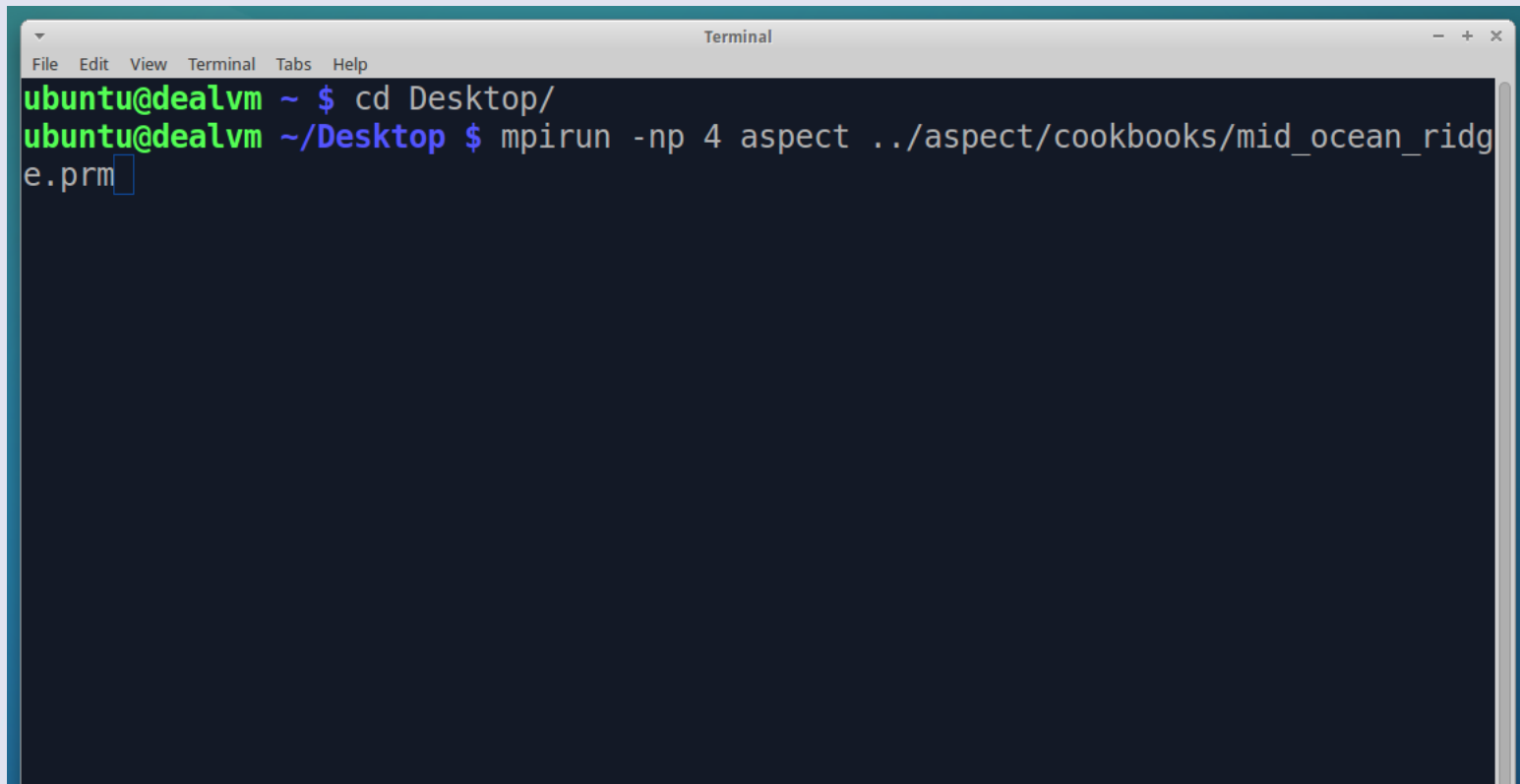
```
Terminal
File Edit View Terminal Tabs Help
ubuntu@dealvm ~ $ cd Desktop/
ubuntu@dealvm ~/Desktop $
```

Starting the model...

- Then start the model by typing:

```
mpirun -np 2 aspect
```

```
../aspect/cookbooks/mid_ocean_ridge.prm
```

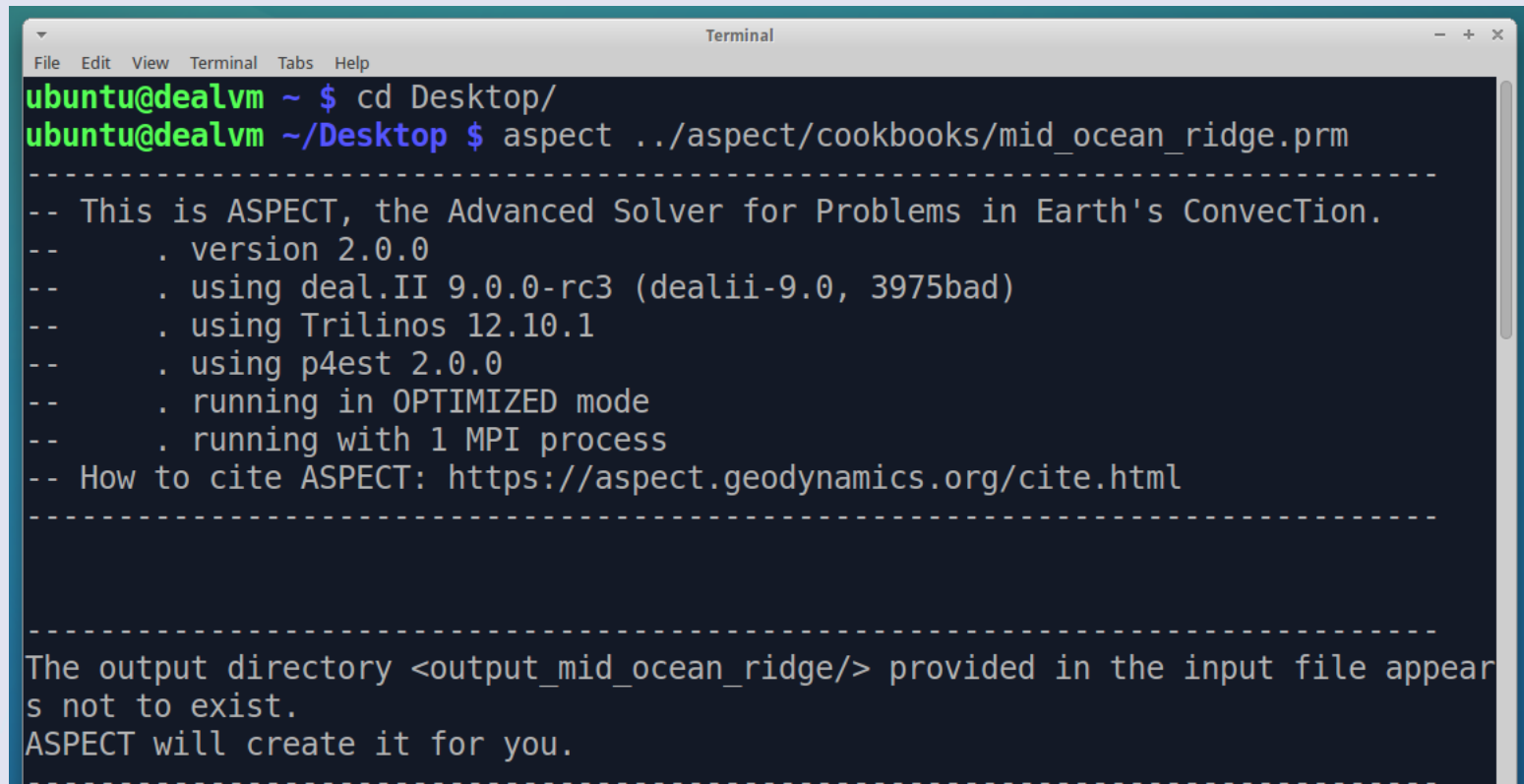


A terminal window titled "Terminal" with a menu bar (File, Edit, View, Terminal, Tabs, Help). The prompt is "ubuntu@dealvm ~". The user enters "cd Desktop/" and the prompt changes to "ubuntu@dealvm ~/Desktop". The user then enters "mpirun -np 4 aspect ../aspect/cookbooks/mid_ocean_ridge.prm" and the cursor is at the end of the command.

```
ubuntu@dealvm ~ $ cd Desktop/  
ubuntu@dealvm ~/Desktop $ mpirun -np 4 aspect ../aspect/cookbooks/mid_ocean_ridge.prm
```

Starting the model...

- This should give you output like this
- We will let this model run and come back later

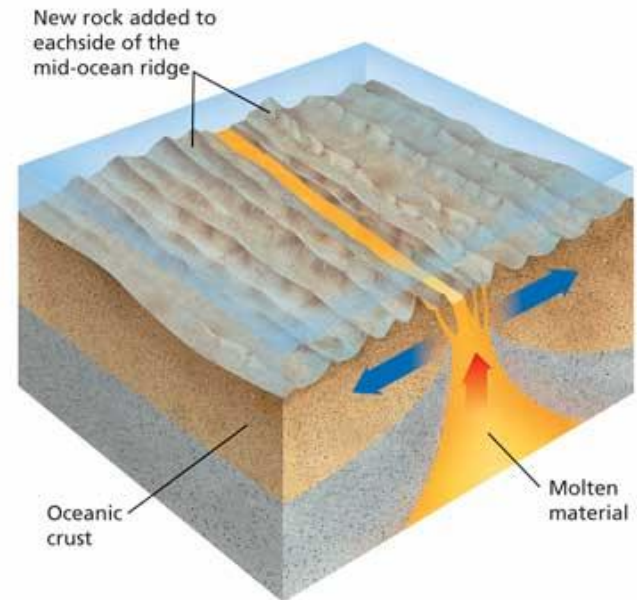
A terminal window titled "Terminal" with a menu bar (File, Edit, View, Terminal, Tabs, Help). The prompt is "ubuntu@dealvm ~ \$". The user enters "cd Desktop/" and then "aspect ../aspect/cookbooks/mid_ocean_ridge.prm". The output shows ASPECT version 2.0.0, using deal.II 9.0.0-rc3, Trilinos 12.10.1, and p4est 2.0.0. It also provides a citation link: https://aspect.geodynamics.org/cite.html. The output ends with a message: "The output directory <output_mid_ocean_ridge/> provided in the input file appears not to exist. ASPECT will create it for you."

```
File Edit View Terminal Tabs Help
ubuntu@dealvm ~ $ cd Desktop/
ubuntu@dealvm ~/Desktop $ aspect ../aspect/cookbooks/mid_ocean_ridge.prm
-----
-- This is ASPECT, the Advanced Solver for Problems in Earth's Convection.
--   . version 2.0.0
--   . using deal.II 9.0.0-rc3 (dealii-9.0, 3975bad)
--   . using Trilinos 12.10.1
--   . using p4est 2.0.0
--   . running in OPTIMIZED mode
--   . running with 1 MPI process
-- How to cite ASPECT: https://aspect.geodynamics.org/cite.html
-----

-----
The output directory <output_mid_ocean_ridge/> provided in the input file appears
not to exist.
ASPECT will create it for you.
-----
```

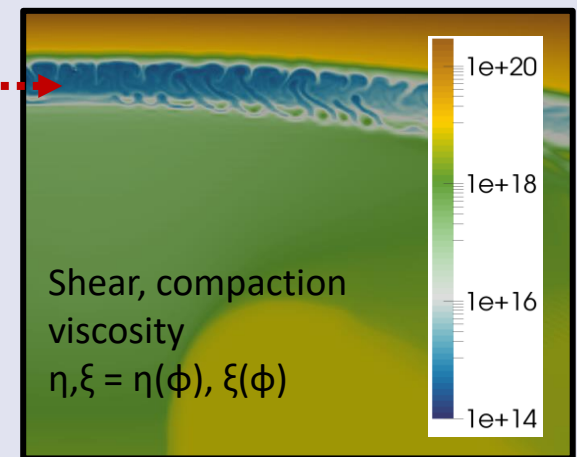
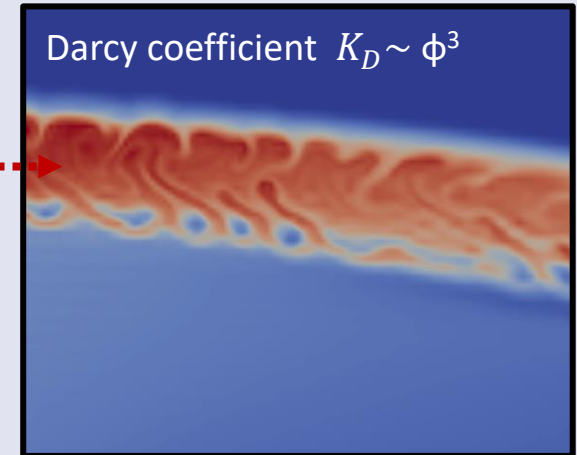
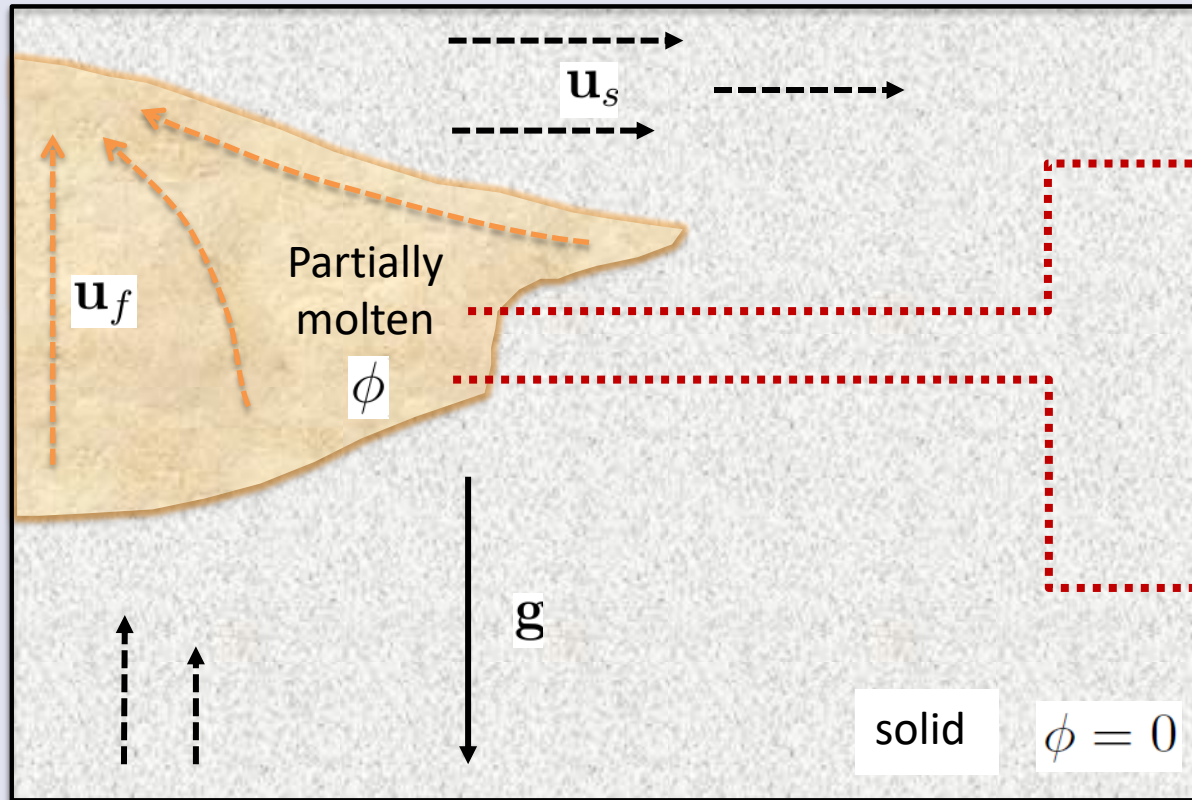
1. Theory
2. Methods
3. Example
4. Playtime

Mid-ocean ridges



From <http://www.phschool.com>

The problem



ρ	density	ξ^*	compaction viscosity
η^*	shear viscosity	K_D	Darcy coefficient

Excellent introduction:

Spiegelman, M., Katz, R., & Simpson, G. (2007). An Introduction and Tutorial to the “McKenzie Equations” for magma migration.

<http://www.deep-earth.org/2010/Spiegelman-melt.pdf>

Very comprehensive lecture notes:

Katz, R. F. (2011). An introduction to coupled magma/mantle dynamics.

<http://foalab.earth.ox.ac.uk/files/IntroMagmaLectures.pdf>

Mass conservation

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

Momentum conservation

$$-\nabla \cdot \left[2\eta^* \left(\varepsilon(\mathbf{u}_s) - \frac{1}{3}(\nabla \cdot \mathbf{u}_s)\mathbf{1} \right) \right] + \nabla p = \bar{\rho} \mathbf{g}$$

Energy conservation

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T = \dots \text{ (source terms)}$$

u_s , solid velocity
 p pressure
 ρ density
 \mathbf{g} gravity

Mass conservation

$$\frac{\partial}{\partial t} [\rho_f \phi] + \nabla \cdot [\rho_f \phi \mathbf{u}_f] = \Gamma$$

$$\frac{\partial}{\partial t} [\rho_s (1 - \phi)] + \nabla \cdot [\rho_s (1 - \phi) \mathbf{u}_s] = -\Gamma$$

Momentum conservation

$$\phi (\mathbf{u}_f - \mathbf{u}_s) = -K_D (\nabla p_f - \rho_f \mathbf{g})$$

$$-\nabla \cdot \left[2\eta^* \left(\varepsilon(\mathbf{u}_s) - \frac{1}{3}(\nabla \cdot \mathbf{u}_s) \mathbf{1} \right) + \xi^* (\nabla \cdot \mathbf{u}_s) \mathbf{1} \right] + \nabla p_f = \bar{\rho} \mathbf{g}$$

Melt advection

$$\frac{\partial \phi}{\partial t} + \mathbf{u}_s \cdot \nabla \phi = \frac{\Gamma}{\rho_s} + (1 - \phi)(\nabla \cdot \mathbf{u}_s + \kappa_s \rho_s \mathbf{g} \cdot \mathbf{u}_s)$$

Energy conservation

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T = \dots \text{ (source terms)}$$

$\mathbf{u}_{s,f}$ solid, fluid velocity
 ϕ porosity
 p_f fluid pressure
 p_c compaction pressure
 $\rho_{s,f}$ density
 \mathbf{g} gravity
 Γ melting rate

Mass conservation

$$\frac{\partial}{\partial t} [\rho_f \phi] + \nabla \cdot [\rho_f \phi \mathbf{u}_f] = \Gamma$$

$$\frac{\partial}{\partial t} [\rho_s (1 - \phi)] + \nabla \cdot [\rho_s (1 - \phi) \mathbf{u}_s] = -\Gamma$$

Solid and fluid mass are conserved.

The difference
between solid
and melt velocity

depends on
the
permeability

and pressure
gradients in
the melt.

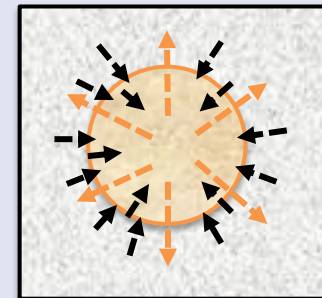
Momentum conservation

$$\phi (\mathbf{u}_f - \mathbf{u}_s) = -K_D (\nabla p_f - \rho_f \mathbf{g})$$

$$-\nabla \cdot \left[2\eta^* \left(\varepsilon(\mathbf{u}_s) - \frac{1}{3}(\nabla \cdot \mathbf{u}_s) \mathbf{1} \right) + \xi^* (\nabla \cdot \mathbf{u}_s) \mathbf{1} \right] + \nabla p_f = \bar{\rho} \mathbf{g}$$

In addition to being sheared...

the solid can also
compact and dilate as
melt flows in and out.



- Compaction length

$$\delta = \sqrt{\frac{(\xi + 4\eta/3)k}{\eta_f}}$$

Describes the intrinsic length scale of melt transport: length scale over which the compaction pressure responds to variations in fluid flux

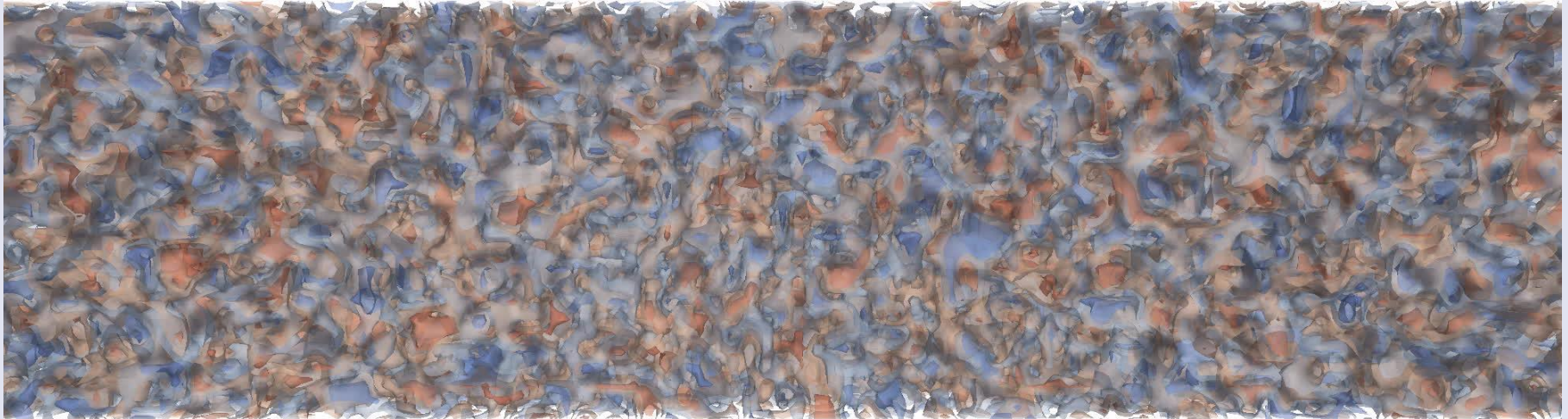
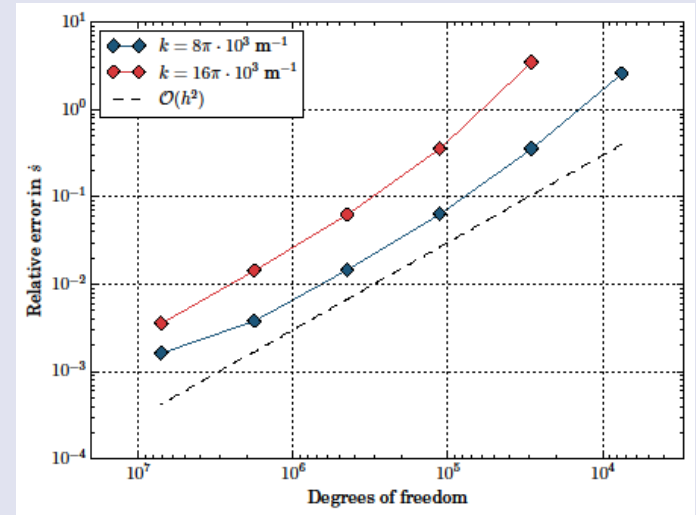
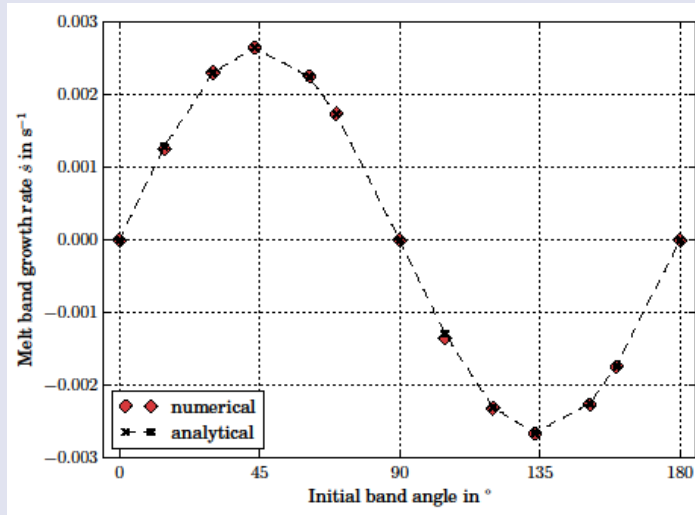
- Separation flux:

$$\phi w = \frac{k\Delta\rho g}{\eta_f}$$

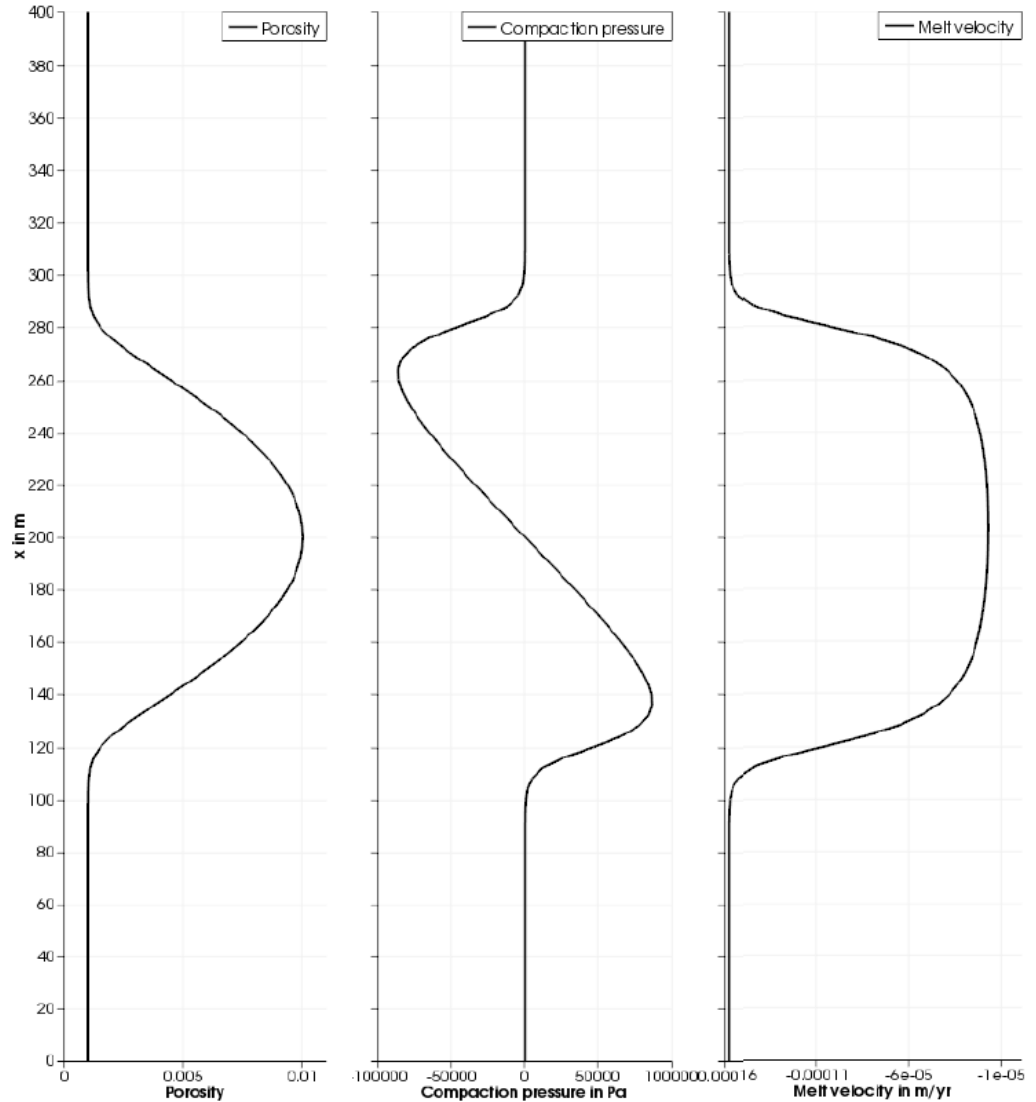
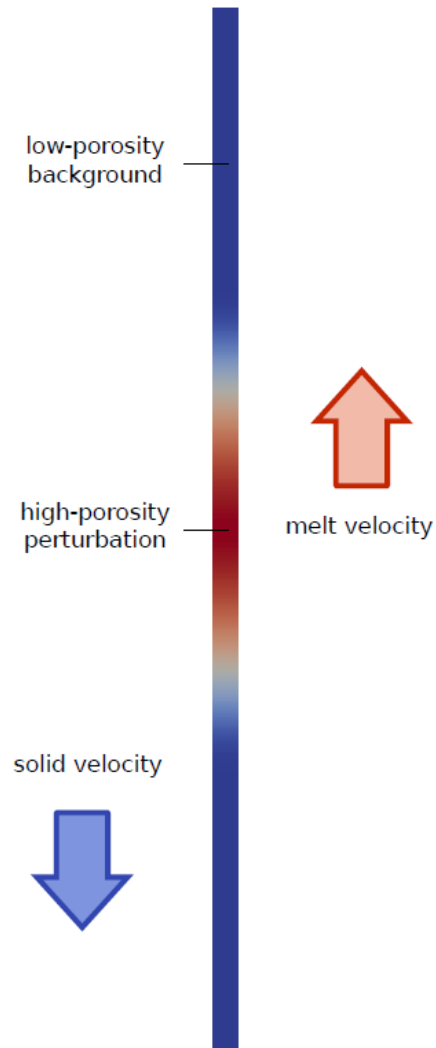
is an estimate of the (gravity drive) melt flux relative to the solid

Shear bands

Magmatic shear bands



Solitary waves



Methods

Eliminating \mathbf{u}_f and introducing the compaction pressure p_c leads to:

$$\begin{aligned}
 -\nabla \cdot \left[2\eta \left(\dot{\boldsymbol{\varepsilon}}(\mathbf{u}_s) - \frac{1}{3}(\nabla \cdot \mathbf{u}_s)\mathbf{1} \right) \right] + \nabla p_f + \nabla p_c &= \bar{\rho}\mathbf{g}, \\
 \nabla \cdot \mathbf{u}_s - \nabla \cdot K_D \nabla p_f - K_D \nabla p_f \cdot \frac{\nabla \rho_f}{\rho_f} &= -\nabla \cdot (K_D \rho_f \mathbf{g}) \\
 &+ \Gamma \left(\frac{1}{\rho_f} - \frac{1}{\rho_s} \right) \\
 &- \frac{\phi}{\rho_f} \mathbf{u}_s \cdot \nabla \rho_f - (\mathbf{u}_s \cdot \mathbf{g})(1 - \phi) \kappa_s \rho_s \\
 &- K_D \mathbf{g} \cdot \nabla \rho_f, \\
 \nabla \cdot \mathbf{u}_s + \frac{p_c}{\xi} &= 0.
 \end{aligned}$$

Melt advection

$$\frac{\partial \phi}{\partial t} + \mathbf{u}_s \cdot \nabla \phi = \frac{\Gamma}{\rho_s} + (1 - \phi)(\nabla \cdot \mathbf{u}_s + \kappa_s \rho_s \mathbf{g} \cdot \mathbf{u}_s)$$

$$-\nabla \cdot \left[2\eta \left(\dot{\varepsilon}(\mathbf{u}_s) - \frac{1}{3}(\nabla \cdot \mathbf{u}_s)\mathbf{1} \right) \right] + \nabla p_f + \nabla p_c = \bar{\rho}\mathbf{g},$$

$$\begin{aligned} \nabla \cdot \mathbf{u}_s - \nabla \cdot K_D \nabla p_f - K_D \nabla p_f \cdot \frac{\nabla \rho_f}{\rho_f} &= -\nabla \cdot (K_D \rho_f \mathbf{g}) \\ &+ \Gamma \left(\frac{1}{\rho_f} - \frac{1}{\rho_s} \right) \\ &- \frac{\phi}{\rho_f} \mathbf{u}_s \cdot \nabla \rho_f - (\mathbf{u}_s \cdot \mathbf{g})(1 - \phi) \kappa_s \rho_s \\ &- K_D \mathbf{g} \cdot \nabla \rho_f, \end{aligned}$$

$$\nabla \cdot \mathbf{u}_s + \frac{p_c}{\xi} = 0.$$

Discretization yields the linear system

$$\begin{pmatrix} \mathbf{A} & \mathbf{B}^T & \mathbf{B}^T \\ \mathbf{B} & \mathbf{N} & \mathbf{0} \\ \mathbf{B} & \mathbf{0} & \mathbf{K} \end{pmatrix} \begin{pmatrix} \mathbf{U}_s \\ \mathbf{P}_f \\ \mathbf{P}_c \end{pmatrix} = \begin{pmatrix} \mathbf{F} \\ \mathbf{G} \\ \mathbf{0} \end{pmatrix}$$

New formulation

$$\begin{pmatrix} \mathbf{A} & \mathbf{B}^T & \mathbf{B}^T \\ \mathbf{B} & \mathbf{N} & \mathbf{0} \\ \mathbf{B} & \mathbf{0} & \mathbf{K} \end{pmatrix} \begin{pmatrix} \mathbf{U}_s \\ \mathbf{P}_f \\ \mathbf{P}_c \end{pmatrix} = \begin{pmatrix} \mathbf{F} \\ \mathbf{G} \\ \mathbf{0} \end{pmatrix}$$

replace p_c with \bar{p}_c ,
where $p_c = \sqrt{K_D} \cdot \bar{p}_c$

$$\begin{pmatrix} \mathbf{A} & \mathbf{B}^T & \sqrt{K_D} \mathbf{B}^T \\ \mathbf{B} & \mathbf{N} & \mathbf{0} \\ \sqrt{K_D} \mathbf{B} & \mathbf{0} & K_D \mathbf{K} \end{pmatrix} \begin{pmatrix} \mathbf{U}_s \\ \mathbf{P}_f \\ \bar{\mathbf{P}}_c \end{pmatrix} = \begin{pmatrix} \mathbf{F} \\ \mathbf{G} \\ \mathbf{0} \end{pmatrix}$$

From R. Grove, PhD thesis

Inspired by:

SIAM J. SCI. COMPUT.
Vol. 39, No. 2, pp. B375–B402

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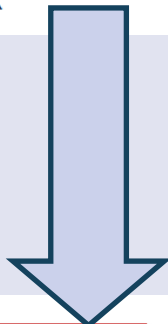
MIXED METHODS FOR TWO-PHASE DARCY–STOKES
MIXTURES OF PARTIALLY MELTED MATERIALS WITH
REGIONS OF ZERO POROSITY*

TODD ARBOGAST[†], MARC A. HESSE[‡], AND ABRAHAM L. TAICHER[§]

- linearly dependent for $\phi \rightarrow 0$
- $K_D \rightarrow 0$ for $\phi \rightarrow 0$
($K_D \propto \phi^n, n = 2 \text{ or } 3$)
- Last equation vanishes for $\phi \rightarrow 0$
- $P_c \rightarrow 0$ for $\phi \rightarrow 0$

New formulation: $\phi \rightarrow 0$

$$\begin{pmatrix} \mathbf{A} & \mathbf{B}^T & \mathbf{B}^T \\ \mathbf{B} & \mathbf{N} & \mathbf{0} \\ \mathbf{B} & \mathbf{0} & \mathbf{K} \end{pmatrix} \begin{pmatrix} \mathbf{U}_s \\ \mathbf{P}_f \\ \mathbf{P}_c \end{pmatrix} = \begin{pmatrix} \mathbf{F} \\ \mathbf{G} \\ \mathbf{0} \end{pmatrix}$$



Stokes system

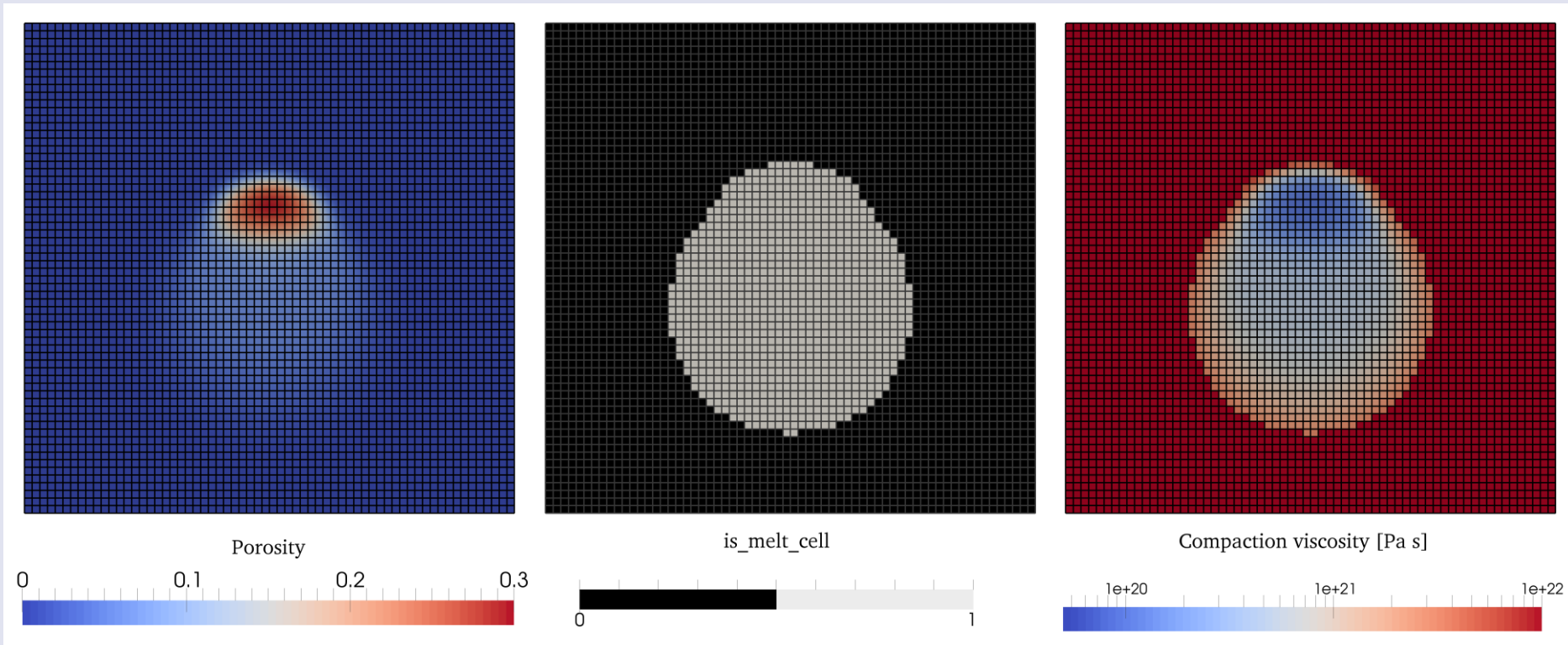
$$\begin{pmatrix} \mathbf{A} & \mathbf{B}^T & \sqrt{K_D} \mathbf{B}^T \\ \mathbf{B} & \mathbf{N} & \mathbf{0} \\ \sqrt{K_D} \mathbf{B} & \mathbf{0} & K_D \mathbf{K} \end{pmatrix} \begin{pmatrix} \mathbf{U}_s \\ \mathbf{P}_f \\ \bar{\mathbf{P}}_c \end{pmatrix} = \begin{pmatrix} \mathbf{F} \\ \mathbf{G} \\ \mathbf{0} \end{pmatrix}$$

➤ linearly dependent for $\phi \rightarrow 0$

➤ $K_D \rightarrow 0$ for $\phi \rightarrow 0$
($K_D \propto \phi^n, n = 2 \text{ or } 3$)

➤ Last equation vanishes for $\phi \rightarrow 0$

➤ Do not solve last equation if $\phi < \phi_{\min_{18}}$



1. Reformulate equations
 2. Only solve the two-phase flow equations if the porosity is above a given limit, otherwise solve Stokes flow with one phase
- ⊙ Advantage: faster solver + recovery of Stokes solution for $\phi \rightarrow 0$ ¹⁹

- ⊙ Mantle melting can be described as “reaction” between the solid and the fluid phase
- ⊙ Thermodynamics: assumption of equilibrium (very fast reactions)
- ⊙ Geodynamics: reaction rates q

$$\frac{\partial \mathbf{c}(t)}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c}(t) = q(\mathbf{c}(t)),$$

where \mathbf{c} is a vector of compositions or phases.

- Problems with accuracy/convergence of the non-linear solver, in particular if there is a threshold for melt transport

- Solution: operator split, allows for different time steps

Instead of solving
$$\frac{\partial \mathbf{c}(t)}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c}(t) = q(\mathbf{c}(t)),$$

we first solve the advection equation without reactions

$$\frac{\partial \mathbf{c}(t)}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c}(t) = 0, \text{ obtaining } \Delta \mathbf{c}_A(t^{n+1}) \text{ from } \mathbf{c}(t^n),$$

and then resolve the reactions as a series of coupled ODEs, potentially with a different time step:

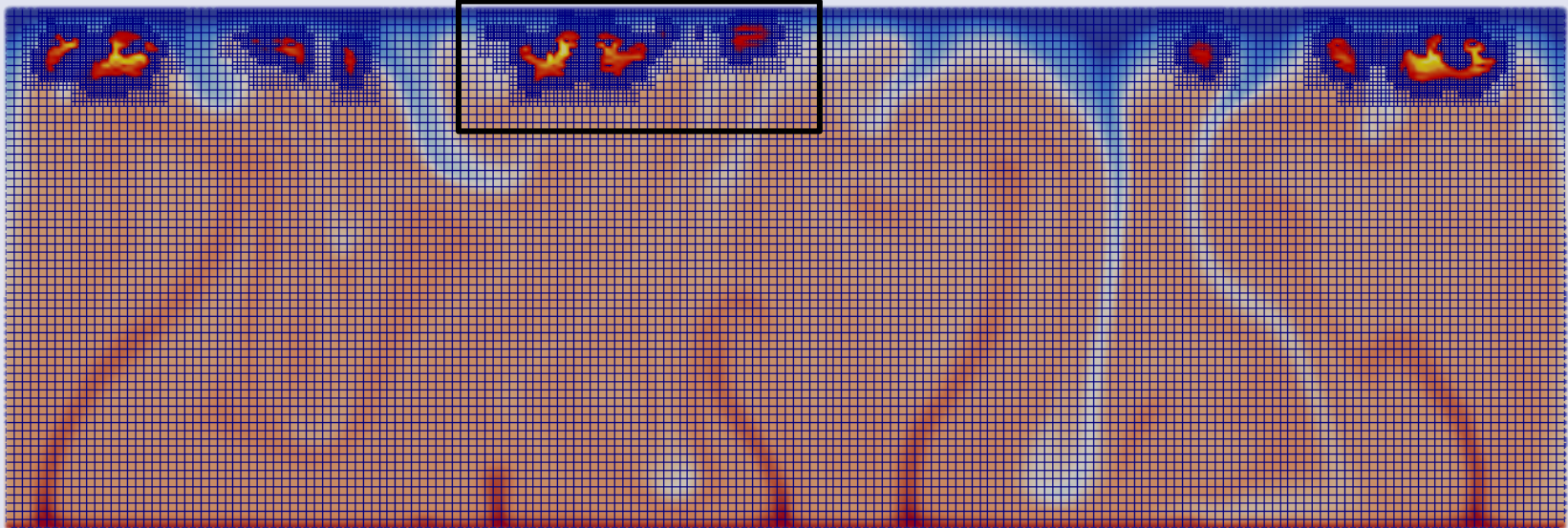
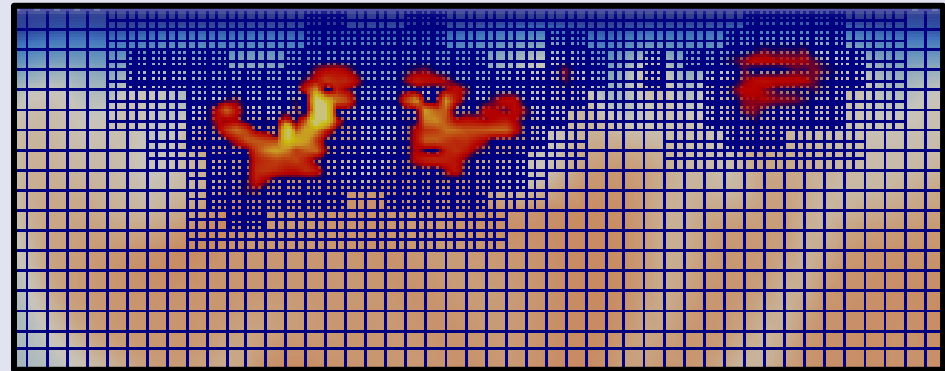
$$\frac{\partial \mathbf{c}(t)}{\partial t} = q(\mathbf{c}(t^n) + \Delta \mathbf{c}_A(t^{n+1}))$$

obtaining $\Delta \mathbf{c}_R(t^{n+1})$ from $\mathbf{c}(t^n) + \Delta \mathbf{c}_A(t^{n+1})$.

➤ Allows for
equilibrium &
disequilibrium
melting

Adaptive mesh refinement

Refine the mesh where
melt is present



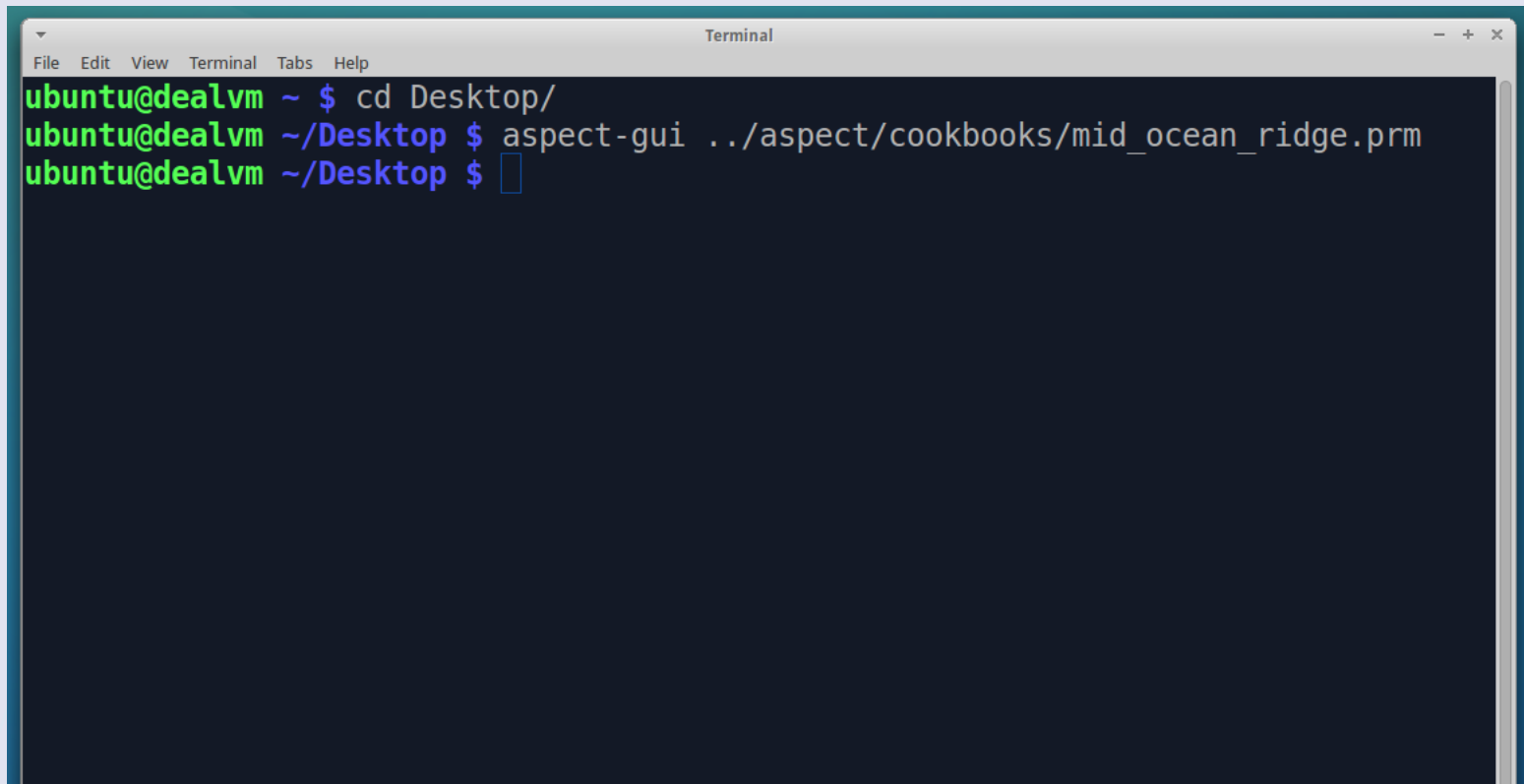
Model setup

Motivation: What is the question we want to answer?

- Equations ✓
- Geometry: Which region is part of the model?
- Mesh
- Material properties
 - ❖ How does the material deform?
 - ❖ What is the density?
- Initial conditions
- Boundary conditions: Can material/energy flow in and out?
- Solvers
- Postprocessing

Using the ASPECT GUI...

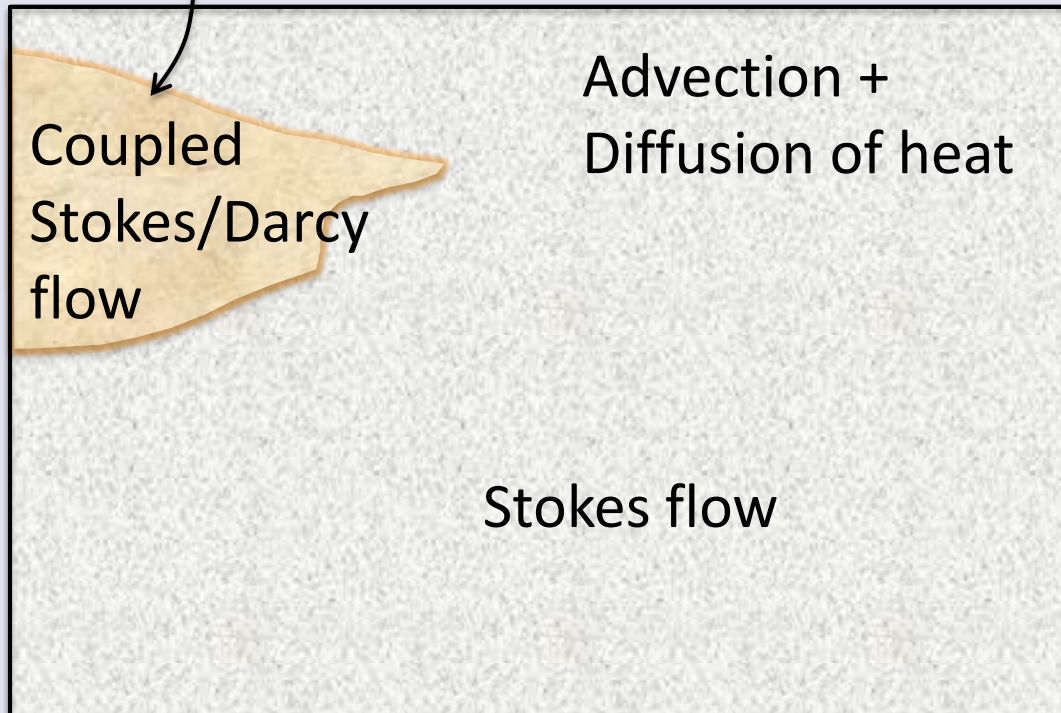
- We will look at the input file in the ASPECT-GUI
`aspect-gui`
`../aspect/cookbooks/mid_ocean_ridge.prm`



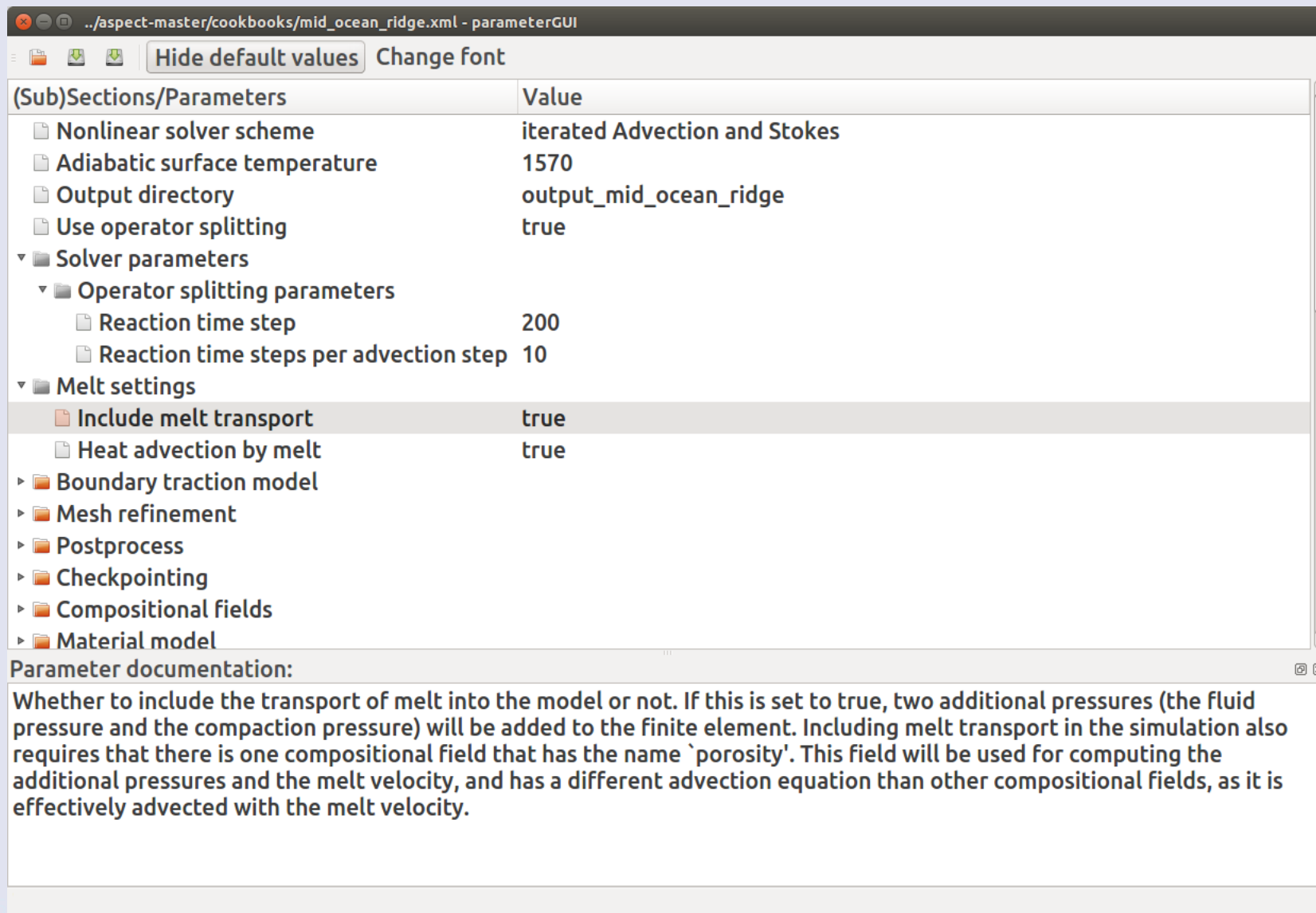
```
Terminal
File Edit View Terminal Tabs Help
ubuntu@dealvm ~ $ cd Desktop/
ubuntu@dealvm ~/Desktop $ aspect-gui ../aspect/cookbooks/mid_ocean_ridge.prm
ubuntu@dealvm ~/Desktop $
```

Equations

Melting and freezing
reactions + latent heat



Equations



../aspect-master/cookbooks/mid_ocean_ridge.xml - parameterGUI

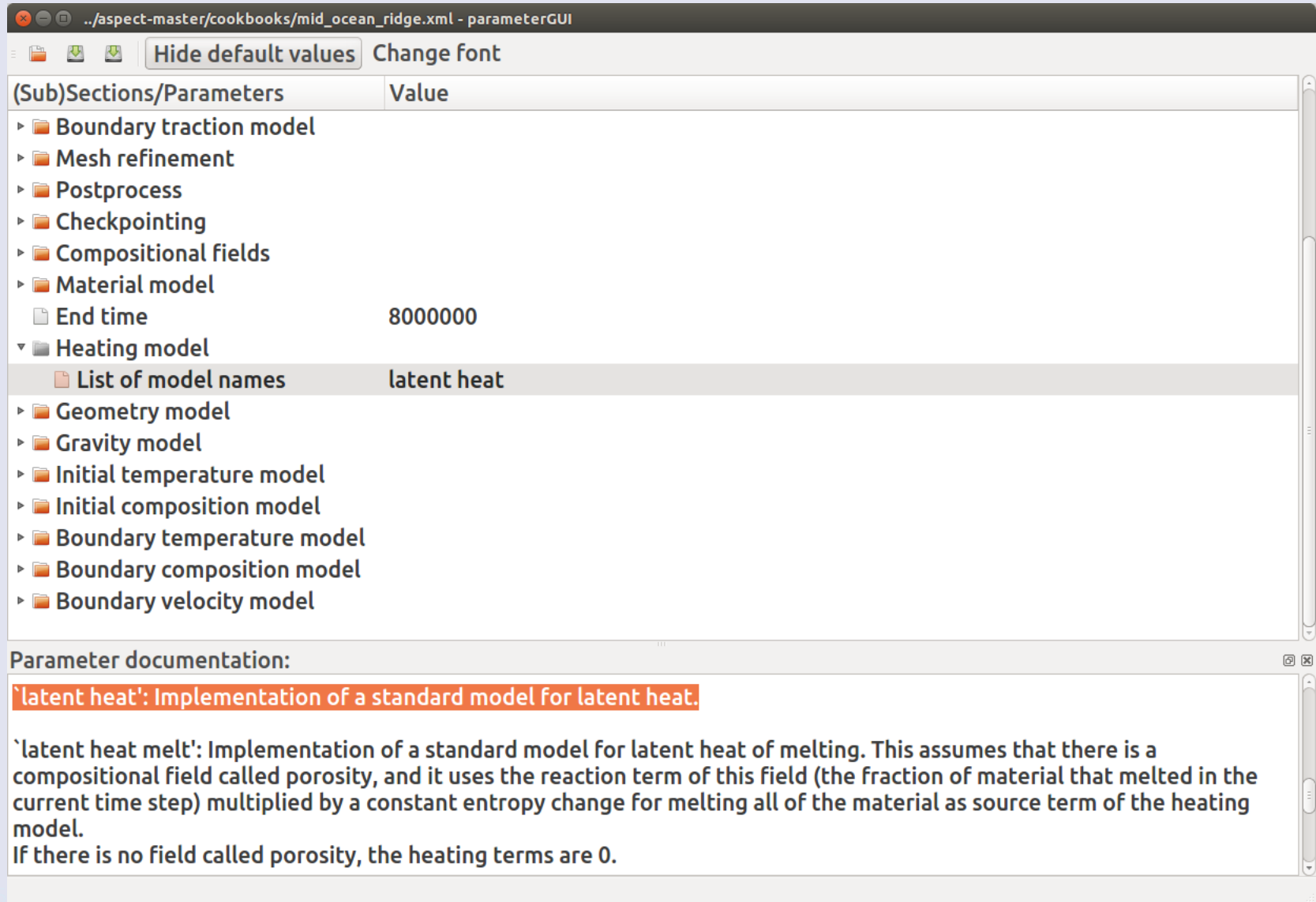
Hide default values Change font

(Sub)Sections/Parameters	Value
Nonlinear solver scheme	iterated Advection and Stokes
Adiabatic surface temperature	1570
Output directory	output_mid_ocean_ridge
Use operator splitting	true
▼ Solver parameters	
▼ Operator splitting parameters	
Reaction time step	200
Reaction time steps per advection step	10
▼ Melt settings	
Include melt transport	true
Heat advection by melt	true
▶ Boundary traction model	
▶ Mesh refinement	
▶ Postprocess	
▶ Checkpointing	
▶ Compositional fields	
▶ Material model	

Parameter documentation:

Whether to include the transport of melt into the model or not. If this is set to true, two additional pressures (the fluid pressure and the compaction pressure) will be added to the finite element. Including melt transport in the simulation also requires that there is one compositional field that has the name `porosity'. This field will be used for computing the additional pressures and the melt velocity, and has a different advection equation than other compositional fields, as it is effectively advected with the melt velocity.

Equations



The screenshot shows a window titled `../aspect-master/cookbooks/mid_ocean_ridge.xml - parameterGUI`. The window contains a tree view of model sections and a documentation panel.

(Sub)Sections/Parameters	Value
▶ Boundary traction model	
▶ Mesh refinement	
▶ Postprocess	
▶ Checkpointing	
▶ Compositional fields	
▶ Material model	
End time	8000000
▼ Heating model	
List of model names	latent heat
▶ Geometry model	
▶ Gravity model	
▶ Initial temperature model	
▶ Initial composition model	
▶ Boundary temperature model	
▶ Boundary composition model	
▶ Boundary velocity model	

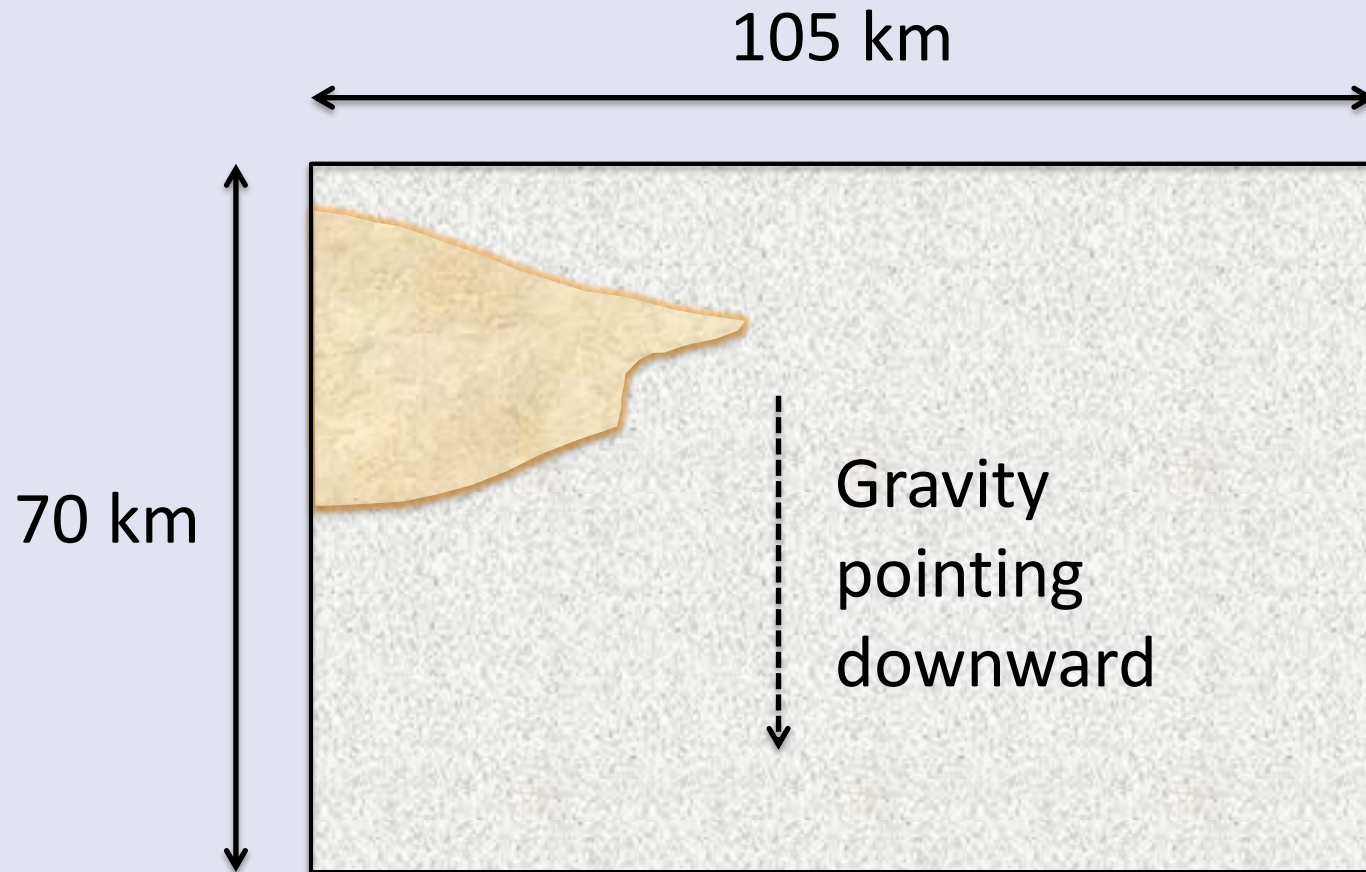
Parameter documentation:

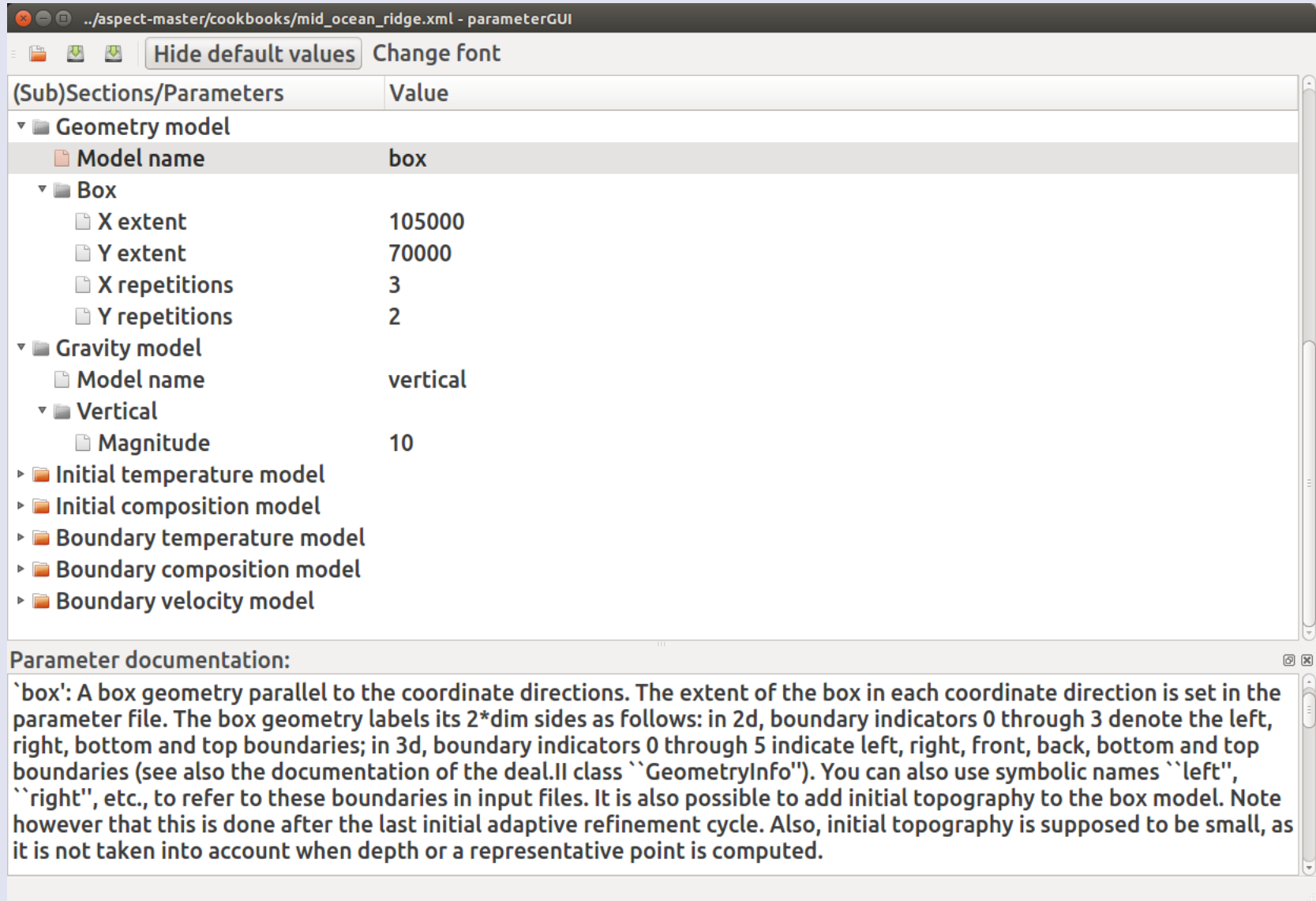
'latent heat': Implementation of a standard model for latent heat.

'latent heat melt': Implementation of a standard model for latent heat of melting. This assumes that there is a compositional field called porosity, and it uses the reaction term of this field (the fraction of material that melted in the current time step) multiplied by a constant entropy change for melting all of the material as source term of the heating model.

If there is no field called porosity, the heating terms are 0.

Model geometry





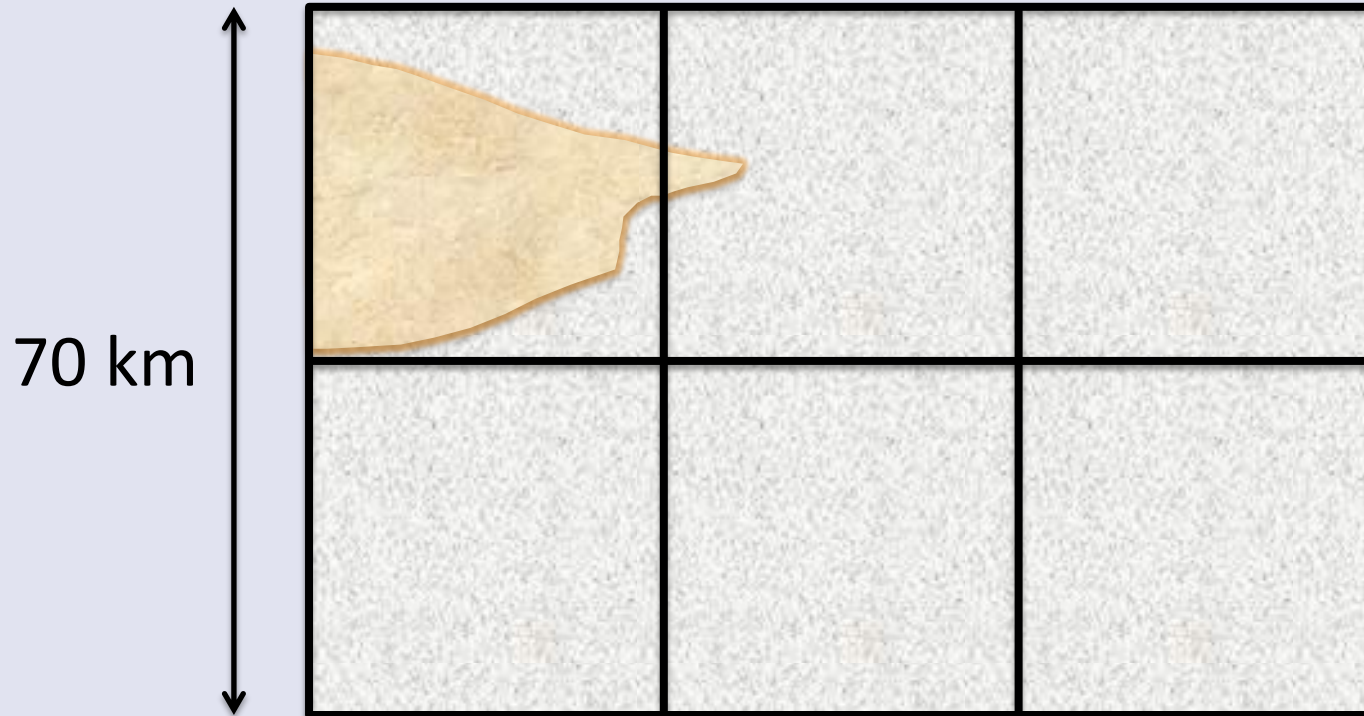
The screenshot shows a window titled `../aspect-master/cookbooks/mid_ocean_ridge.xml - parameterGUI`. The window contains a tree view of parameters and a documentation pane at the bottom.

(Sub)Sections/Parameters	Value
▼ Geometry model	
Model name	box
▼ Box	
X extent	105000
Y extent	70000
X repetitions	3
Y repetitions	2
▼ Gravity model	
Model name	vertical
▼ Vertical	
Magnitude	10
▶ Initial temperature model	
▶ Initial composition model	
▶ Boundary temperature model	
▶ Boundary composition model	
▶ Boundary velocity model	

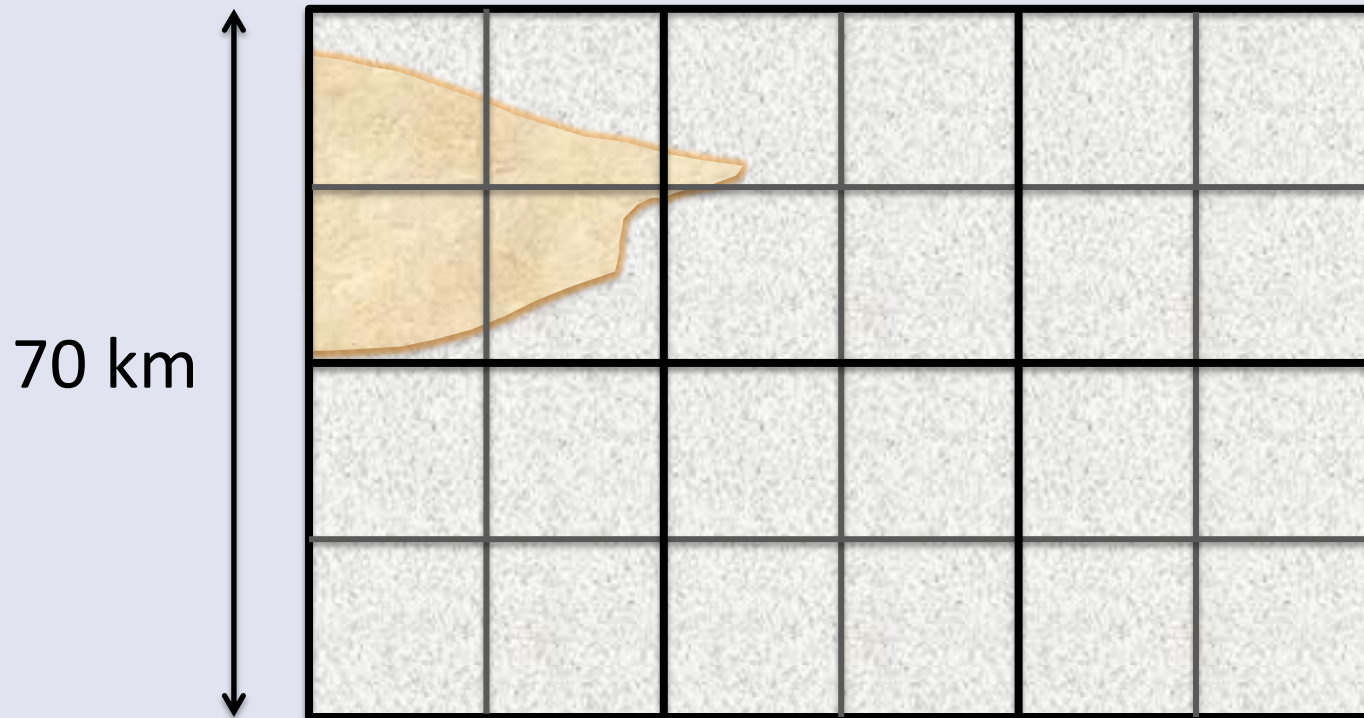
Parameter documentation:

``box'`: A box geometry parallel to the coordinate directions. The extent of the box in each coordinate direction is set in the parameter file. The box geometry labels its 2*dim sides as follows: in 2d, boundary indicators 0 through 3 denote the left, right, bottom and top boundaries; in 3d, boundary indicators 0 through 5 indicate left, right, front, back, bottom and top boundaries (see also the documentation of the deal.II class `GeometryInfo`). You can also use symbolic names ```left```, ```right```, etc., to refer to these boundaries in input files. It is also possible to add initial topography to the box model. Note however that this is done after the last initial adaptive refinement cycle. Also, initial topography is supposed to be small, as it is not taken into account when depth or a representative point is computed.

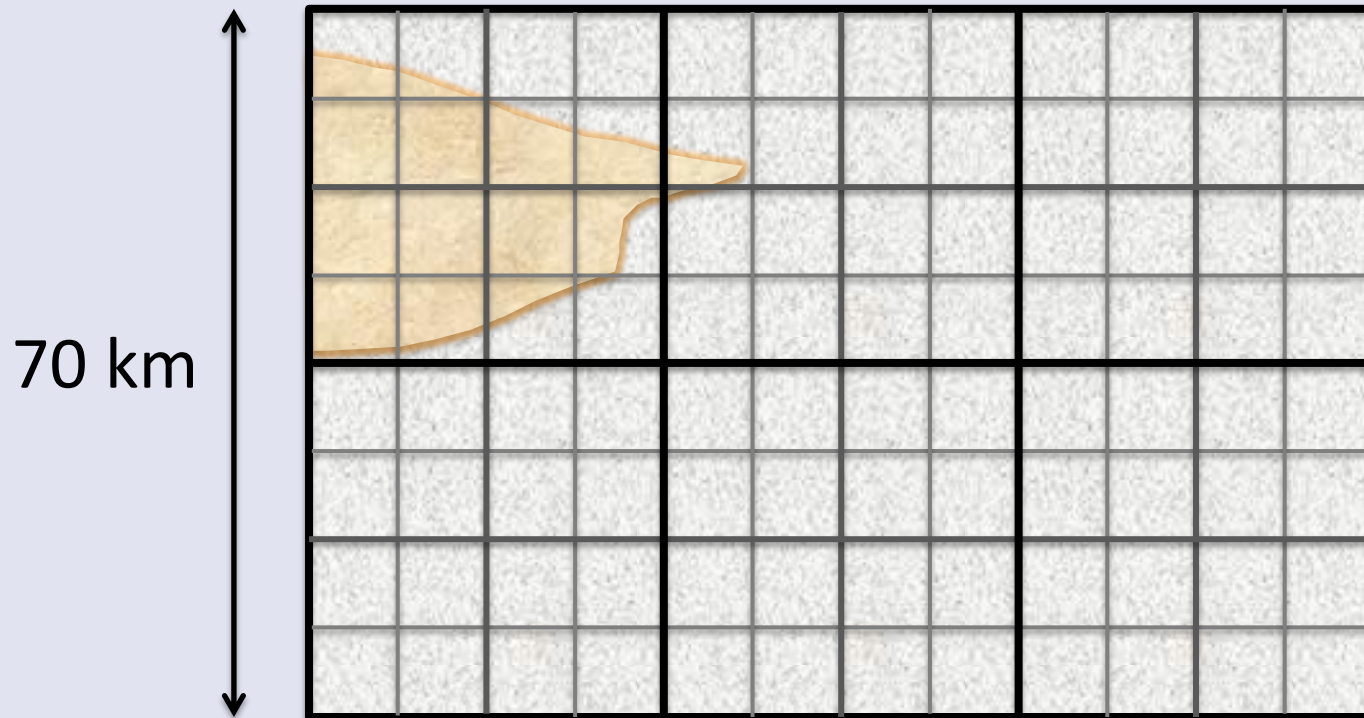
Coarse grid (X repetitions, Y repetitions)



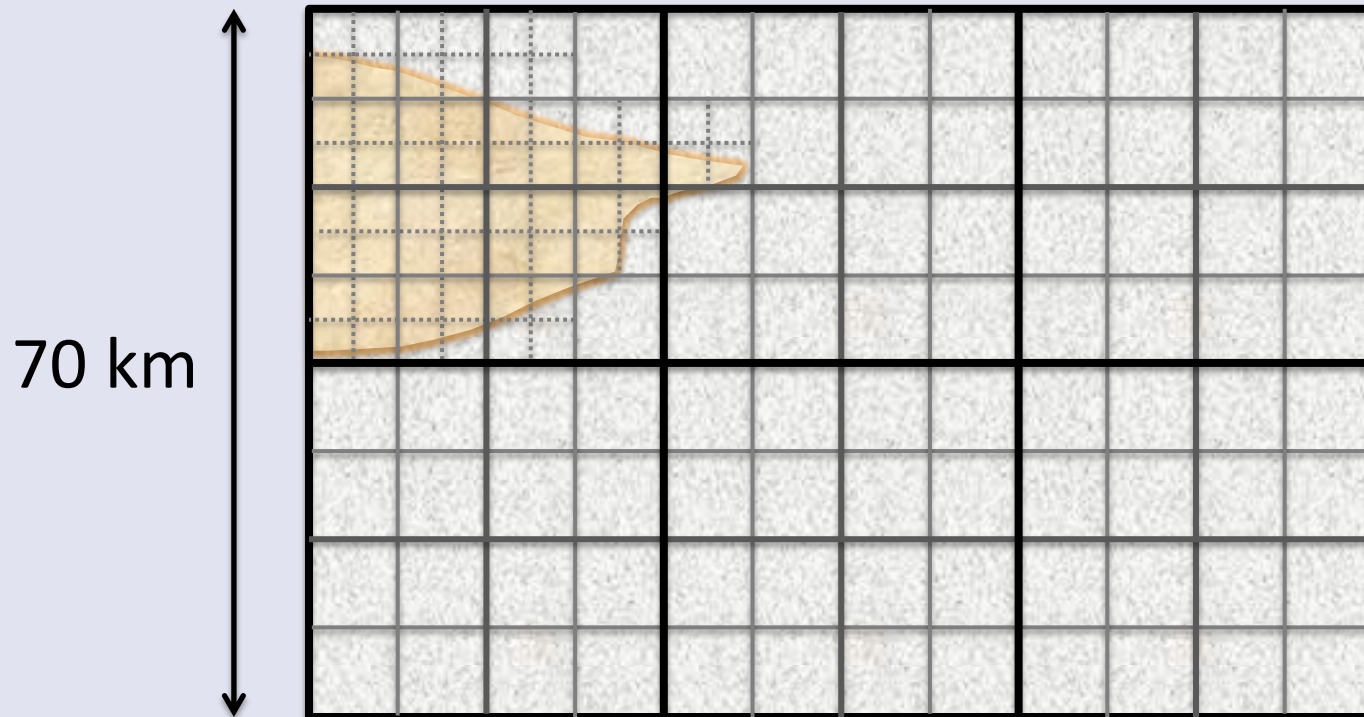
Coarse grid (X repetitions, Y repetitions)
1 global refinement



Coarse grid (X repetitions, Y repetitions)
2 global refinements



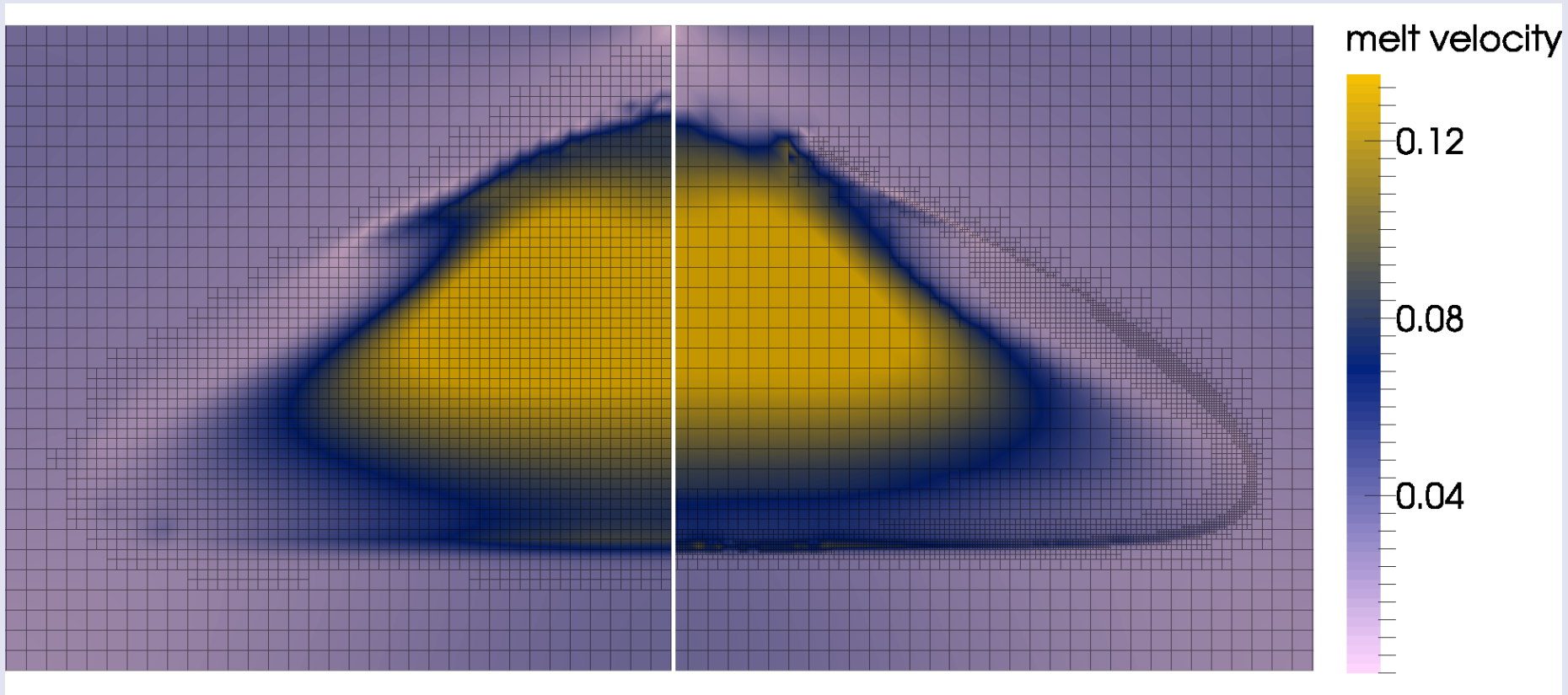
Coarse grid (X repetitions, Y repetitions)
2 global refinements + 1 adaptive refinement



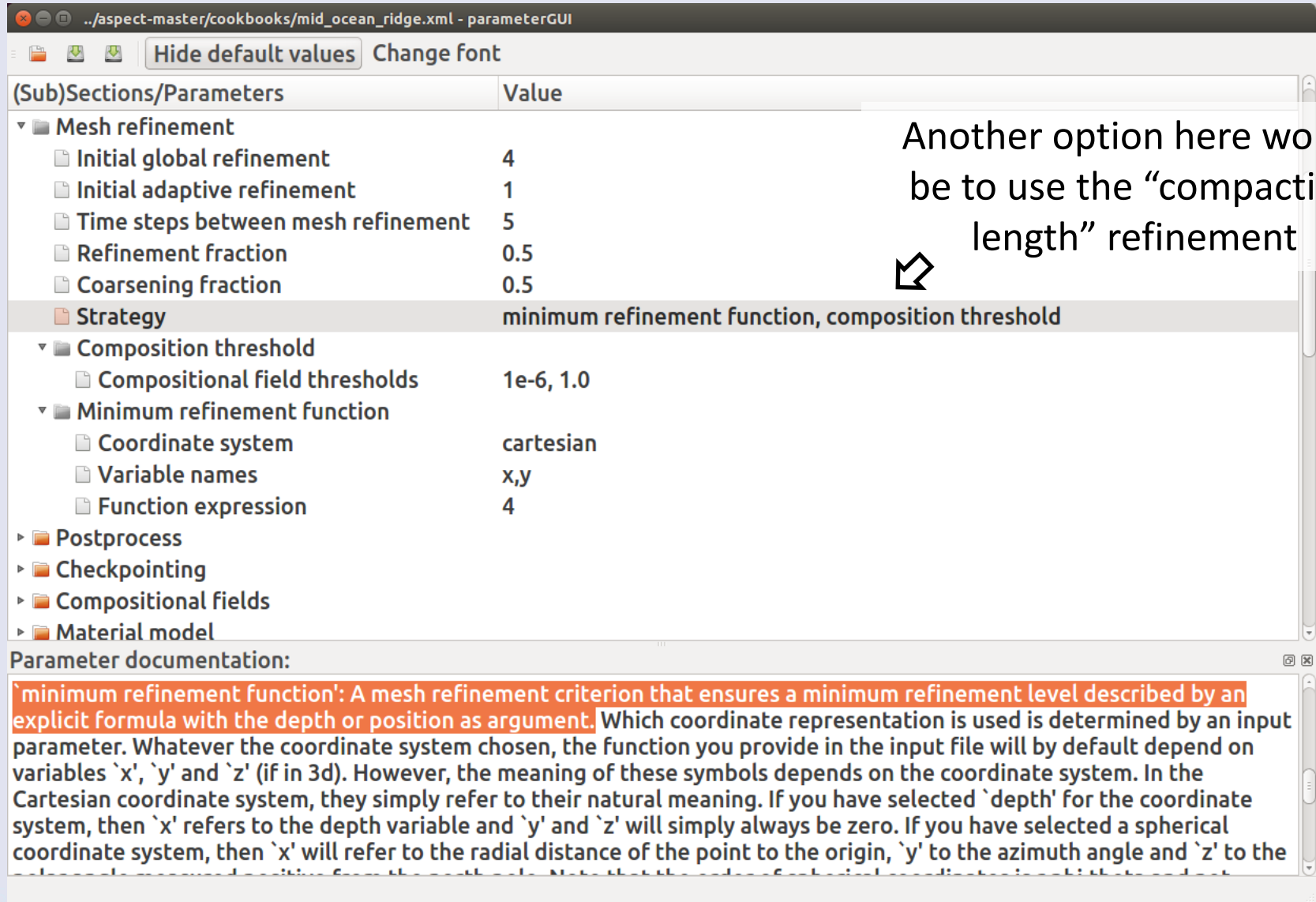
Mesh refinement

Choose the resolution based on:

The presence of melt | the compaction length



Mesh refinement



The screenshot shows a window titled "parameterGUI" with a tree view of parameters. The "Mesh refinement" section is expanded, showing several sub-parameters. A callout box points to the "Strategy" parameter, suggesting an alternative refinement method.

(Sub)Sections/Parameters	Value
Mesh refinement	
Initial global refinement	4
Initial adaptive refinement	1
Time steps between mesh refinement	5
Refinement fraction	0.5
Coarsening fraction	0.5
Strategy	minimum refinement function, composition threshold
Composition threshold	
Compositional field thresholds	1e-6, 1.0
Minimum refinement function	
Coordinate system	cartesian
Variable names	x,y
Function expression	4

Another option here would be to use the “compaction length” refinement

Parameter documentation:
`minimum refinement function': A mesh refinement criterion that ensures a minimum refinement level described by an explicit formula with the depth or position as argument. Which coordinate representation is used is determined by an input parameter. Whatever the coordinate system chosen, the function you provide in the input file will by default depend on variables `x`, `y` and `z` (if in 3d). However, the meaning of these symbols depends on the coordinate system. In the Cartesian coordinate system, they simply refer to their natural meaning. If you have selected `depth` for the coordinate system, then `x` refers to the depth variable and `y` and `z` will simply always be zero. If you have selected a spherical coordinate system, then `x` will refer to the radial distance of the point to the origin, `y` to the azimuth angle and `z` to the elevation angle.

Melting and freezing are
faster than advection

Peridotite
melting

(after Katz et al.,
2003)

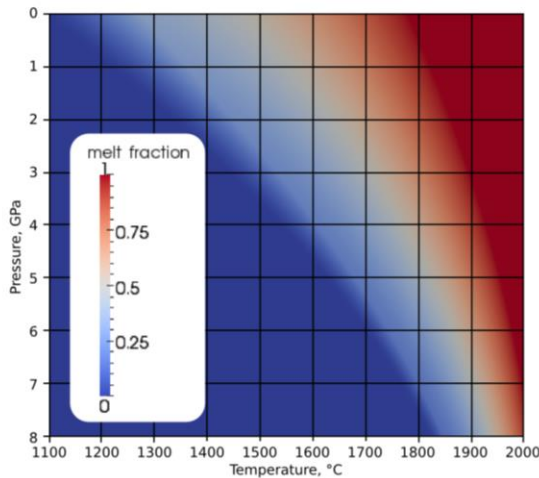
Melt is less dense than the solid

$$k_{\phi} = k_0 \phi^3$$

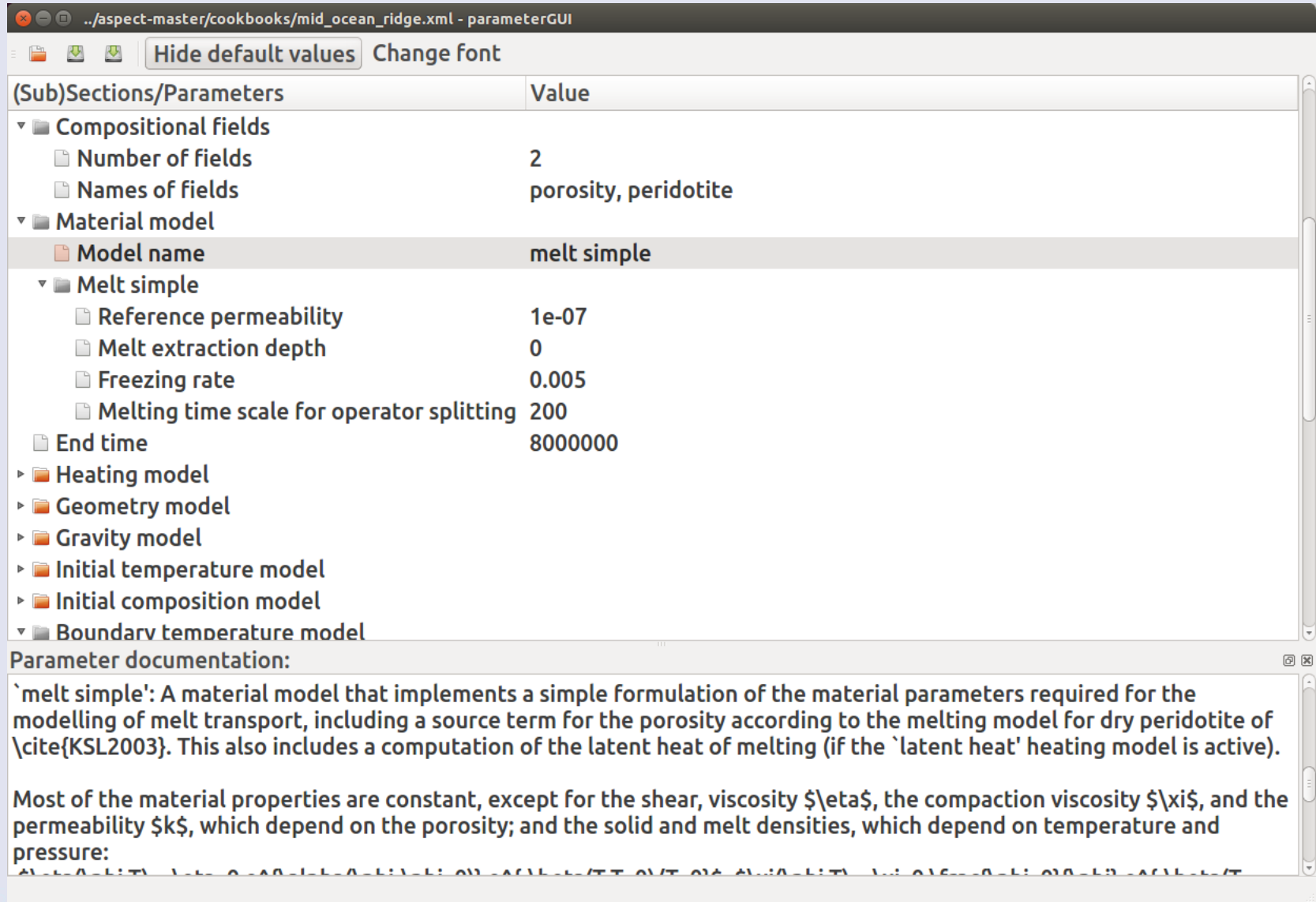
$$\eta(\phi, T) = \eta_0 e^{\alpha(\phi - \phi_0)}$$

$$\xi(\phi, T) = \xi_0 \frac{\phi_0}{\phi}$$

Permeability, shear and
compaction viscosities
depend on the porosity



Material properties



The screenshot shows a window titled "parameterGUI" with a file path "mid_ocean_ridge.xml". It features a tree view of parameters and a documentation pane at the bottom.

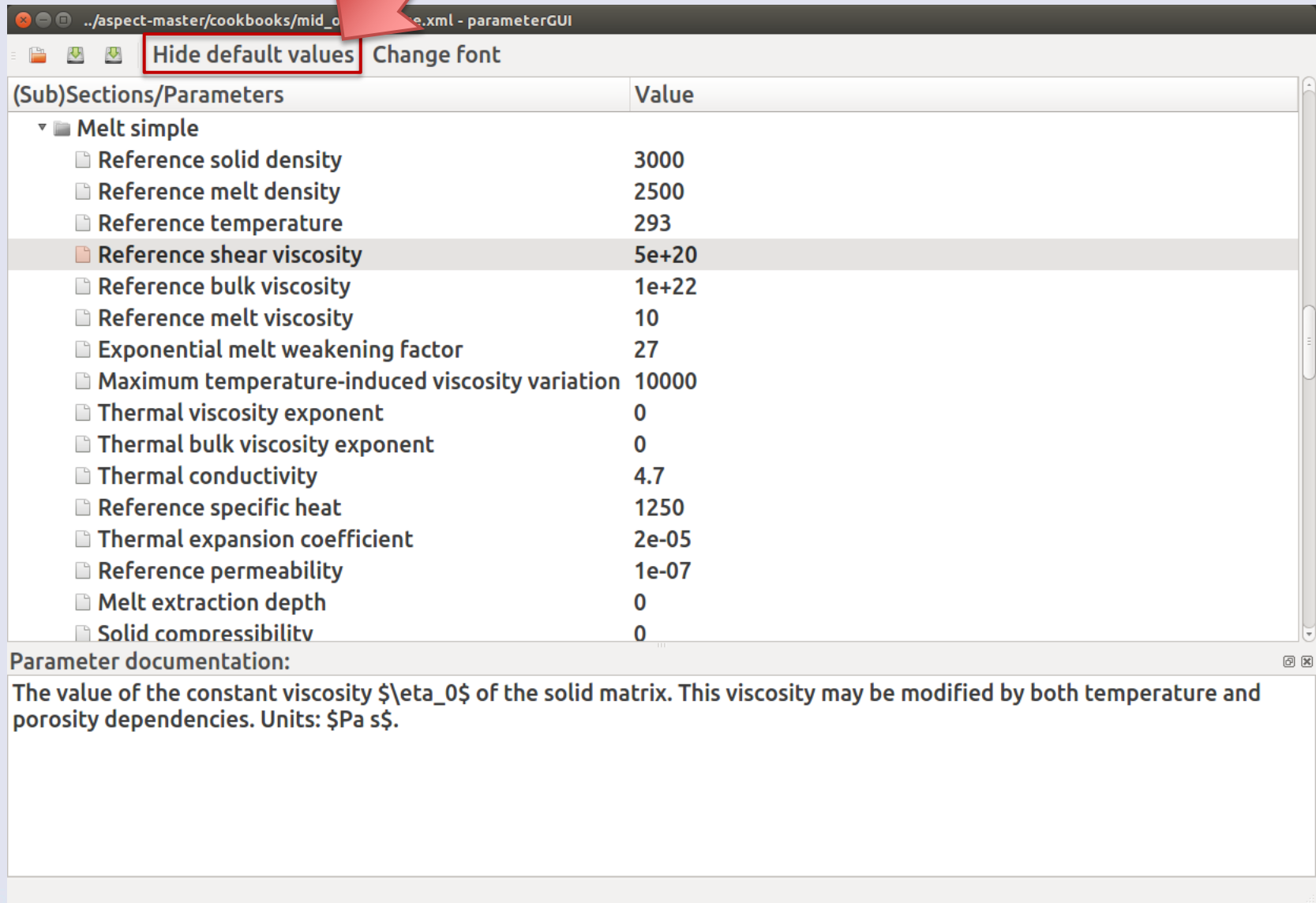
(Sub)Sections/Parameters	Value
Compositional fields	
Number of fields	2
Names of fields	porosity, peridotite
Material model	
Model name	melt simple
Melt simple	
Reference permeability	1e-07
Melt extraction depth	0
Freezing rate	0.005
Melting time scale for operator splitting	200
End time	8000000
Heating model	
Geometry model	
Gravity model	
Initial temperature model	
Initial composition model	
Boundary temperature model	

Parameter documentation:

``melt simple'`: A material model that implements a simple formulation of the material parameters required for the modelling of melt transport, including a source term for the porosity according to the melting model for dry peridotite of [\cite{KSL2003}](#). This also includes a computation of the latent heat of melting (if the ``latent heat'` heating model is active).

Most of the material properties are constant, except for the shear, viscosity η , the compaction viscosity ξ , and the permeability k , which depend on the porosity; and the solid and melt densities, which depend on temperature and pressure:

Material properties



.. /aspect-master/cookbooks/mid_o...e.xml - parameterGUI

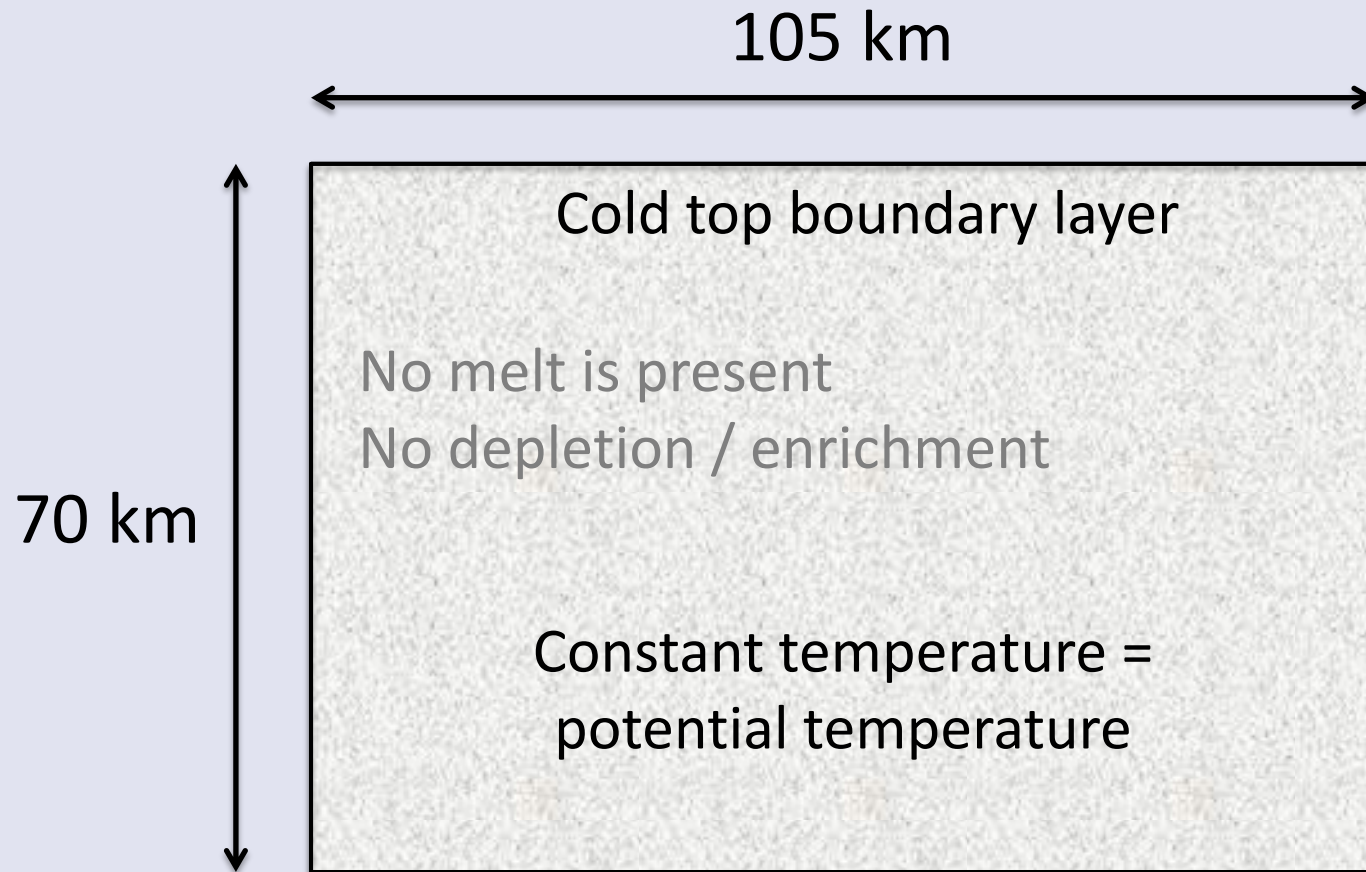
Hide default values Change font

(Sub)Sections/Parameters	Value
▼ Melt simple	
Reference solid density	3000
Reference melt density	2500
Reference temperature	293
Reference shear viscosity	5e+20
Reference bulk viscosity	1e+22
Reference melt viscosity	10
Exponential melt weakening factor	27
Maximum temperature-induced viscosity variation	10000
Thermal viscosity exponent	0
Thermal bulk viscosity exponent	0
Thermal conductivity	4.7
Reference specific heat	1250
Thermal expansion coefficient	2e-05
Reference permeability	1e-07
Melt extraction depth	0
Solid compressibility	0

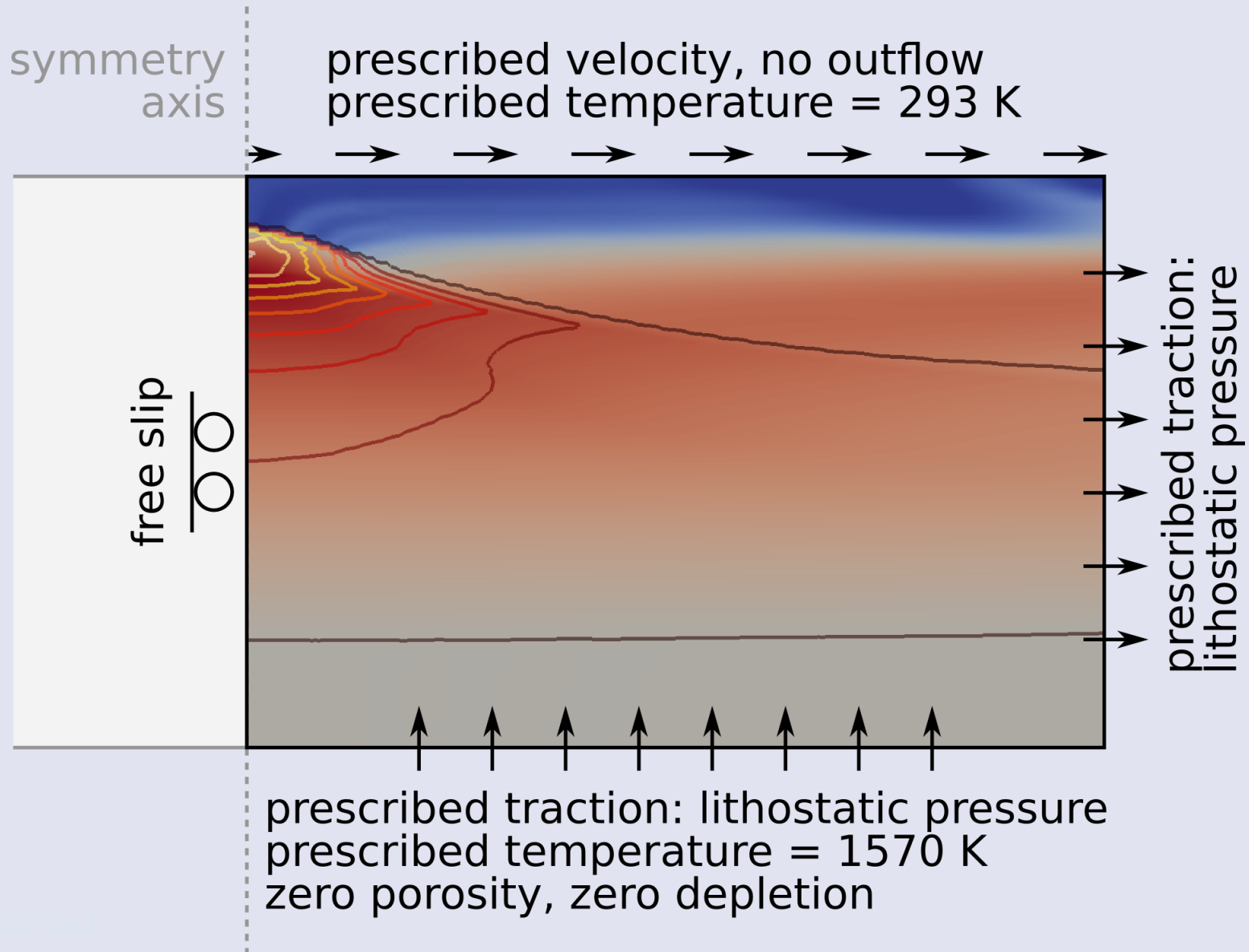
Parameter documentation:

The value of the constant viscosity η_0 of the solid matrix. This viscosity may be modified by both temperature and porosity dependencies. Units: Pa s.

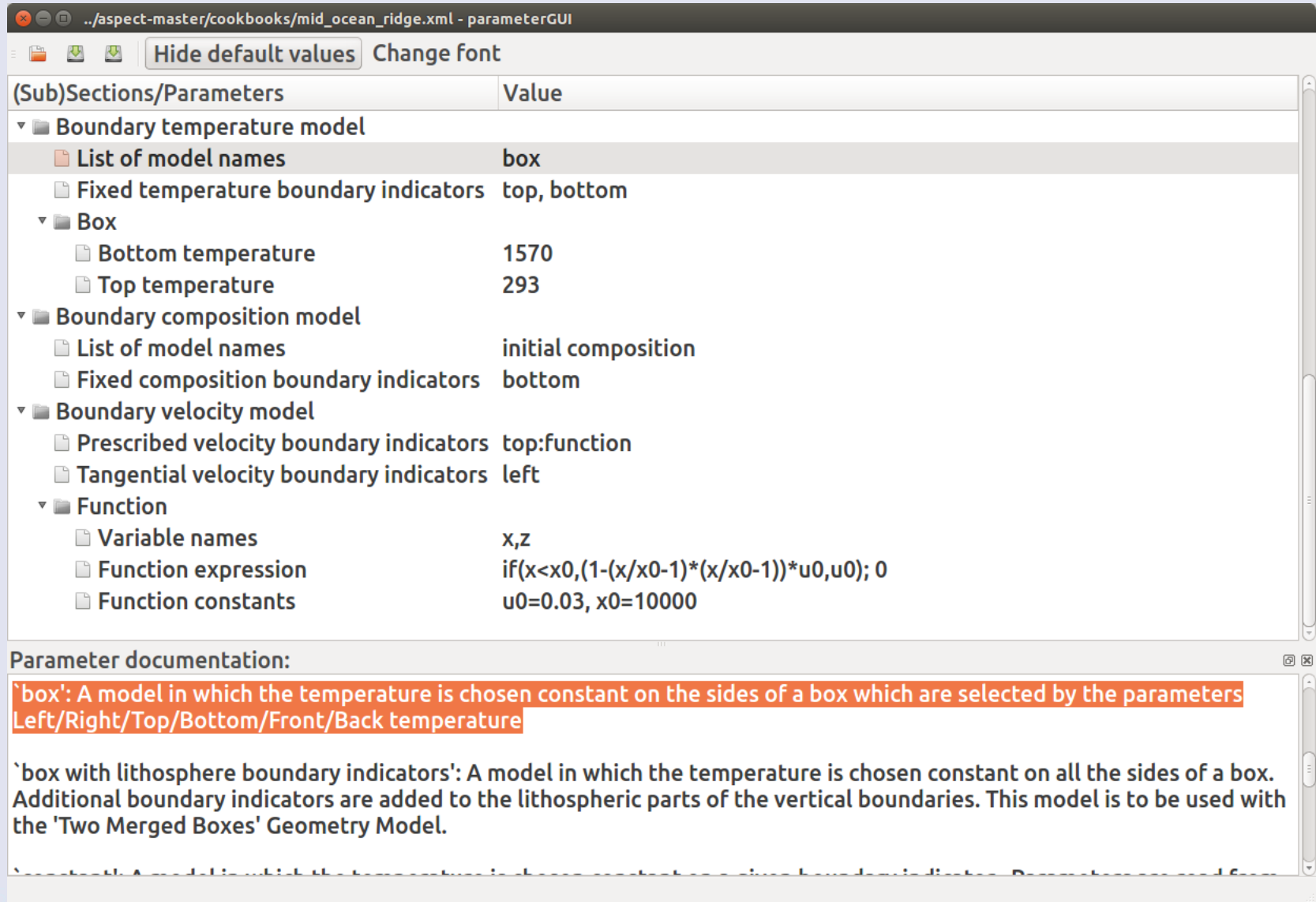
Initial conditions



Boundary conditions



Boundary conditions



The screenshot shows a window titled `../aspect-master/cookbooks/mid_ocean_ridge.xml - parameterGUI`. The window contains a table of parameters and a documentation section.

(Sub)Sections/Parameters	Value
▼ Boundary temperature model	
List of model names	box
Fixed temperature boundary indicators	top, bottom
▼ Box	
Bottom temperature	1570
Top temperature	293
▼ Boundary composition model	
List of model names	initial composition
Fixed composition boundary indicators	bottom
▼ Boundary velocity model	
Prescribed velocity boundary indicators	top:function
Tangential velocity boundary indicators	left
▼ Function	
Variable names	x,z
Function expression	<code>if(x<x0,(1-(x/x0-1)*(x/x0-1))*u0,u0); 0</code>
Function constants	<code>u0=0.03, x0=10000</code>

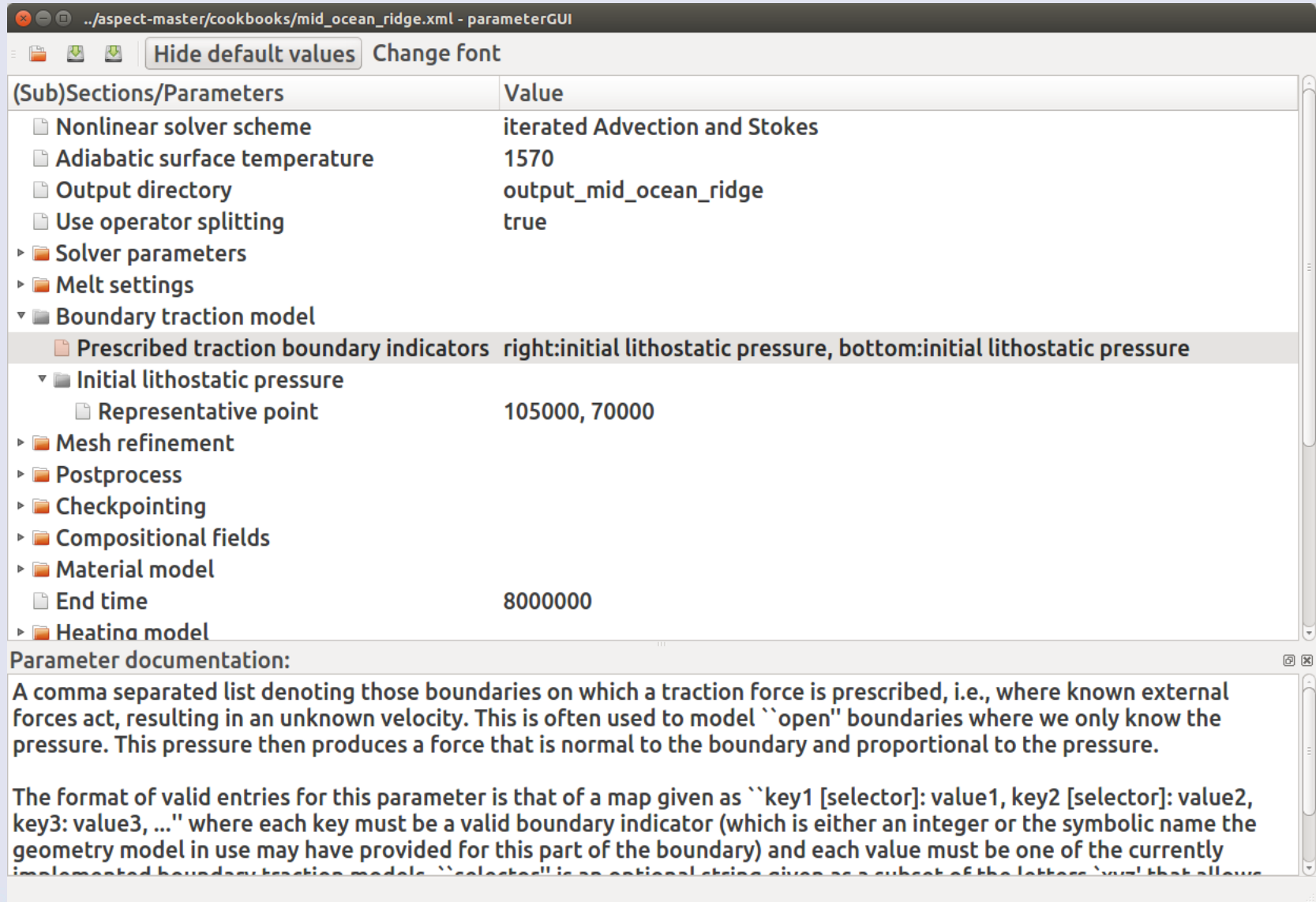
Parameter documentation:

'box': A model in which the temperature is chosen constant on the sides of a box which are selected by the parameters Left/Right/Top/Bottom/Front/Back temperature

'box with lithosphere boundary indicators': A model in which the temperature is chosen constant on all the sides of a box. Additional boundary indicators are added to the lithospheric parts of the vertical boundaries. This model is to be used with the 'Two Merged Boxes' Geometry Model.

'...': A model in which the temperature is chosen constant on the sides of a box which are selected by the parameters Left/Right/Top/Bottom/Front/Back temperature

Boundary conditions



(Sub)Sections/Parameters	Value
Nonlinear solver scheme	iterated Advection and Stokes
Adiabatic surface temperature	1570
Output directory	output_mid_ocean_ridge
Use operator splitting	true
Solver parameters	
Melt settings	
Boundary traction model	
Prescribed traction boundary indicators	right:initial lithostatic pressure, bottom:initial lithostatic pressure
Initial lithostatic pressure	
Representative point	105000, 70000
Mesh refinement	
Postprocess	
Checkpointing	
Compositional fields	
Material model	
End time	8000000
Heating model	

Parameter documentation:

A comma separated list denoting those boundaries on which a traction force is prescribed, i.e., where known external forces act, resulting in an unknown velocity. This is often used to model "open" boundaries where we only know the pressure. This pressure then produces a force that is normal to the boundary and proportional to the pressure.

The format of valid entries for this parameter is that of a map given as "key1 [selector]: value1, key2 [selector]: value2, key3: value3, ..." where each key must be a valid boundary indicator (which is either an integer or the symbolic name the geometry model in use may have provided for this part of the boundary) and each value must be one of the currently implemented boundary traction models. "selector" is an optional string given as a subset of the letters 'xyz' that allows

../aspect-master/cookbooks/mid_ocean_ridge.xml - parameterGUI

Hide default values Change font

(Sub)Sections/Parameters	Value
Nonlinear solver scheme	iterated Advection and Stokes
Adiabatic surface temperature	1570
Output directory	output_mid_ocean_ridge
Use operator splitting	true
Solver parameters	
Operator splitting parameters	
Reaction time step	200
Reaction time steps per advection step	10
Melt settings	
Boundary traction model	
Mesh refinement	
Postprocess	
Checkpointing	
Compositional fields	
Material model	
End time	8000000
Heating model	

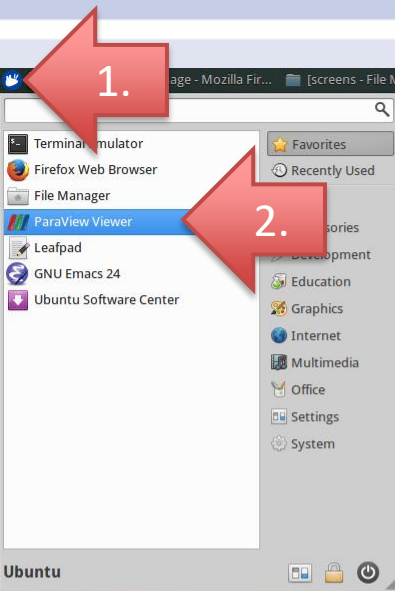
Parameter documentation:

If set to true, the advection and reactions of compositional fields and temperature are solved separately, and can use different time steps. Note that this will only work if the material/heating model fills the reaction_rates/heating_reaction_rates structures. Operator splitting can be used with any existing solver schemes that solve the temperature/composition equations.

We have to iterate between Stokes and advection system!

We want to solve reactions separately because they are much faster

Paraview

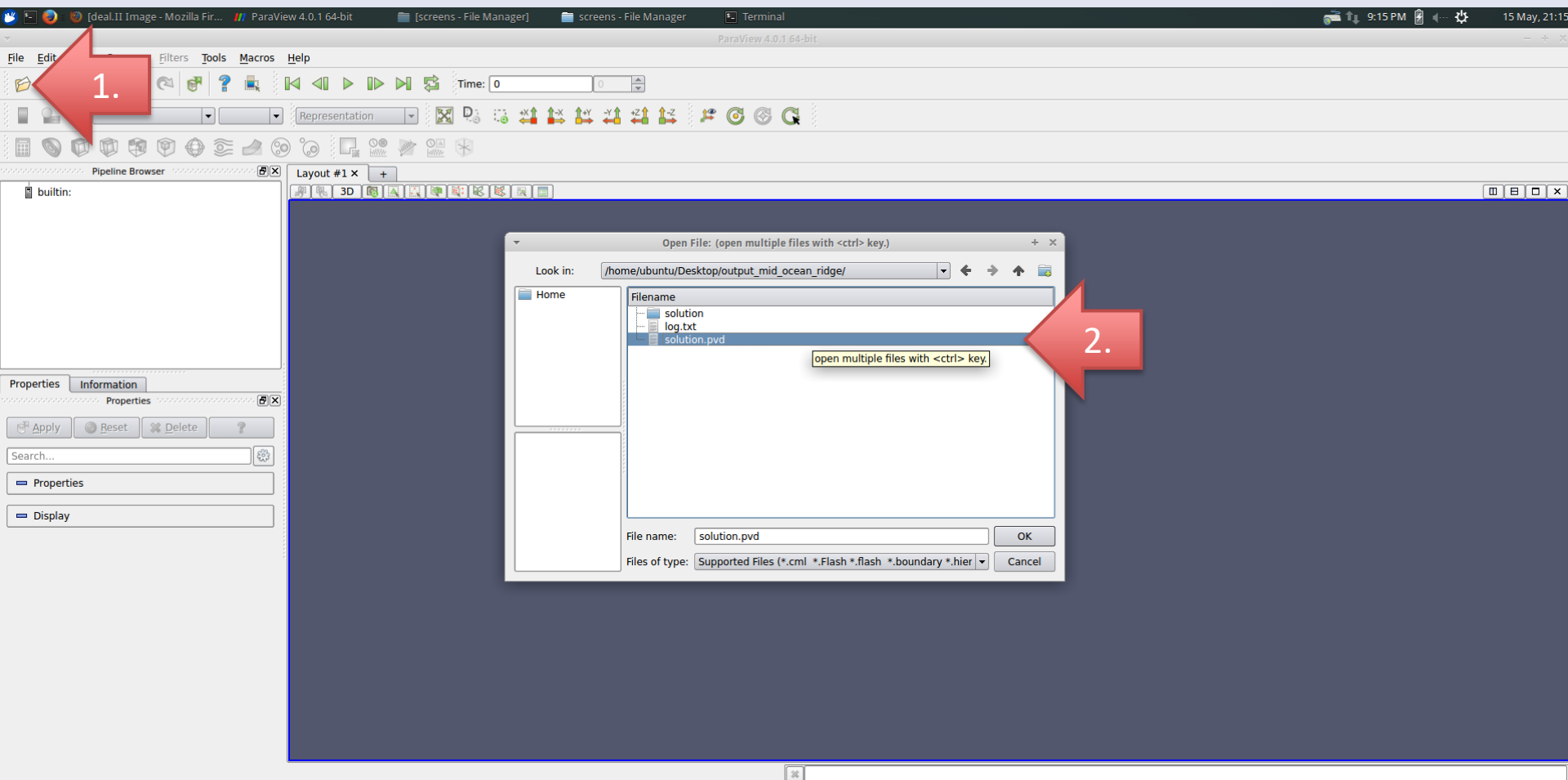


```
File Edit View Terminal Tabs Help
Solving for u f in 11 iterations.
  Relative nonlinear residuals (temperature, compositional fields, Stokes sy
stem): 0.0210364, 0, 0, 0.000153361
  Relative nonlinear residual (total system) after nonlinear iteration 1: 0.
0210364

  Solving temperature system... 12 iterations.
  Skipping porosity composition solve because RHS is zero.
  ...Skipping peridotite composition solve because RHS is zero.

  Solving temperature system... 8 iterations.
  Skipping porosity composition solve because RHS is zero.
  Skipping peridotite composition solve because RHS is zero.
  Rebuilding Stokes preconditioner...
  Solving Stokes system... 0+0 iterations.
  Solving for u f in 11 iterations.
  Relative nonlinear residuals (temperature, compositional fields, Stokes sy
stem): 6.43405e-07, 0, 0, 9.58873e-08
  Relative nonlinear residual (total system) after nonlinear iteration 3: 6.
43405e-07

  Postprocessing:
```



- The output file is located in:
/home/ubuntu/Desktop/output_mid_ocean_ridge

Paraview: Plot contours

The screenshot illustrates the Paraview 4.0.1 64-bit interface for plotting contours. The main window shows a 3D visualization of a porous medium with blue contour lines overlaid on a red-to-white color gradient. The interface includes a top toolbar, a Pipeline Browser on the left, and two Properties panels on the right. Red arrows highlight the 'Contour' filter icon in the toolbar, the 'Contour By' dropdown menu, and the 'Add Value' button in the Properties panel.

Toolbar: The top toolbar contains various icons for file operations, navigation, and visualization. The 'Contour' filter icon is highlighted with a red arrow.

Pipeline Browser: The Pipeline Browser on the left shows the data source 'solution.pvd' and the filter 'Contour1'.

Properties Panel (Left): The Properties panel for 'Contour1' shows the 'Contour By' dropdown set to 'porosity'. The 'Generate Triangles' checkbox is checked. A tooltip explains: "This property specifies the name of the scalar array from which the contour filter will compute isolines and/or isosurfaces."

Properties Panel (Right): The Properties panel for 'Contour1' shows the 'Contour By' dropdown set to 'porosity'. The 'Generate Triangles' checkbox is checked. A tooltip explains: "This property specifies the name of the scalar array from which the contour filter will compute isolines and/or isosurfaces." The 'Isosurfaces' section shows a 'Value Range' of [-0.00667116, 0.168953] and a list of values: 0.1, 0.01, 0.05, and 0.15. The 'Add Value' button is highlighted with a red arrow.

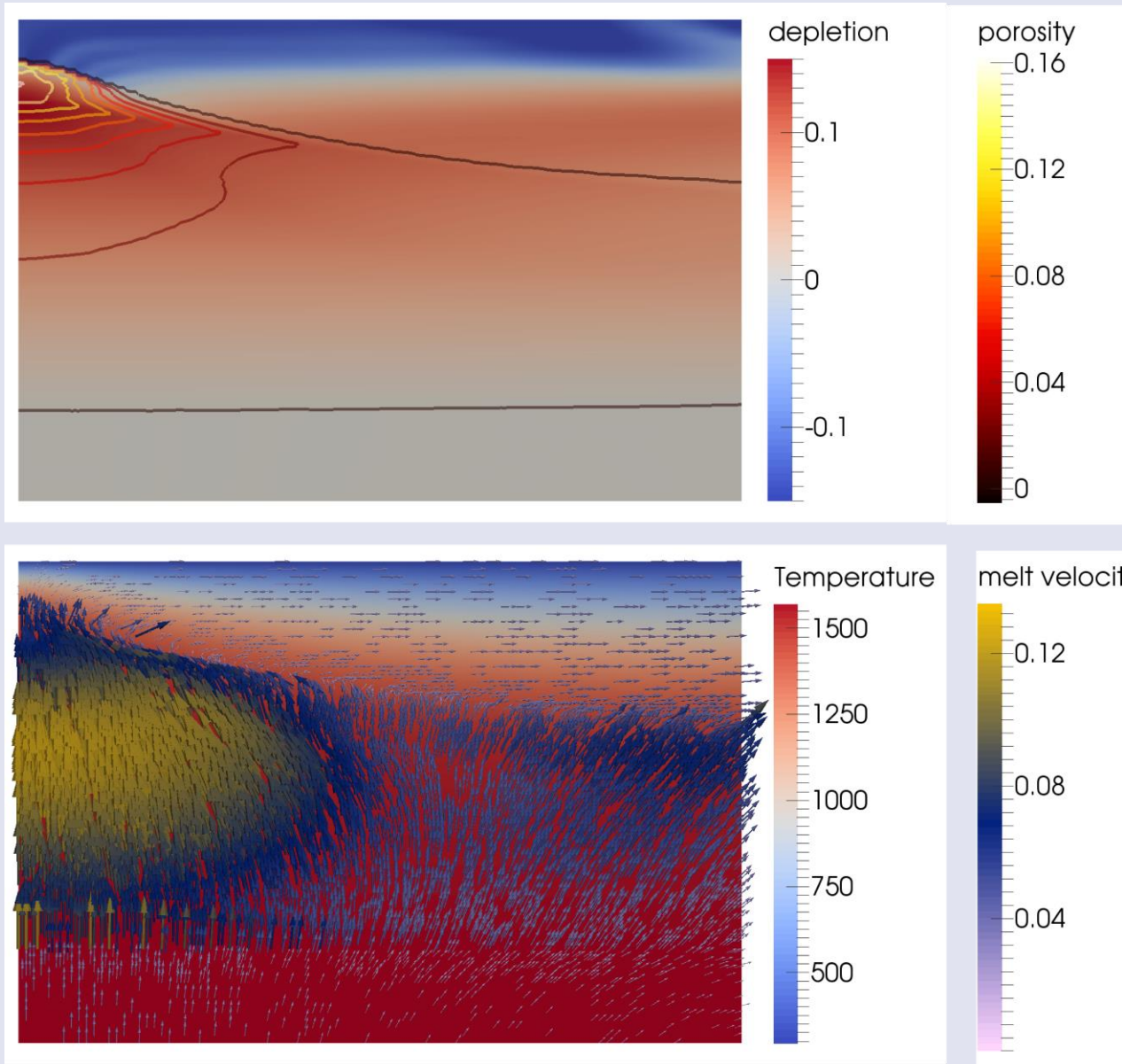
Paraview: Plot glyphs

The image displays the Paraview 4.0.1 64-bit software interface. The main window shows a 3D visualization of a vector field (glyphs) overlaid on a surface plot. The glyphs are represented as arrows pointing downwards, colored in a gradient from blue to red. The surface plot is a top-down view of a geological structure.

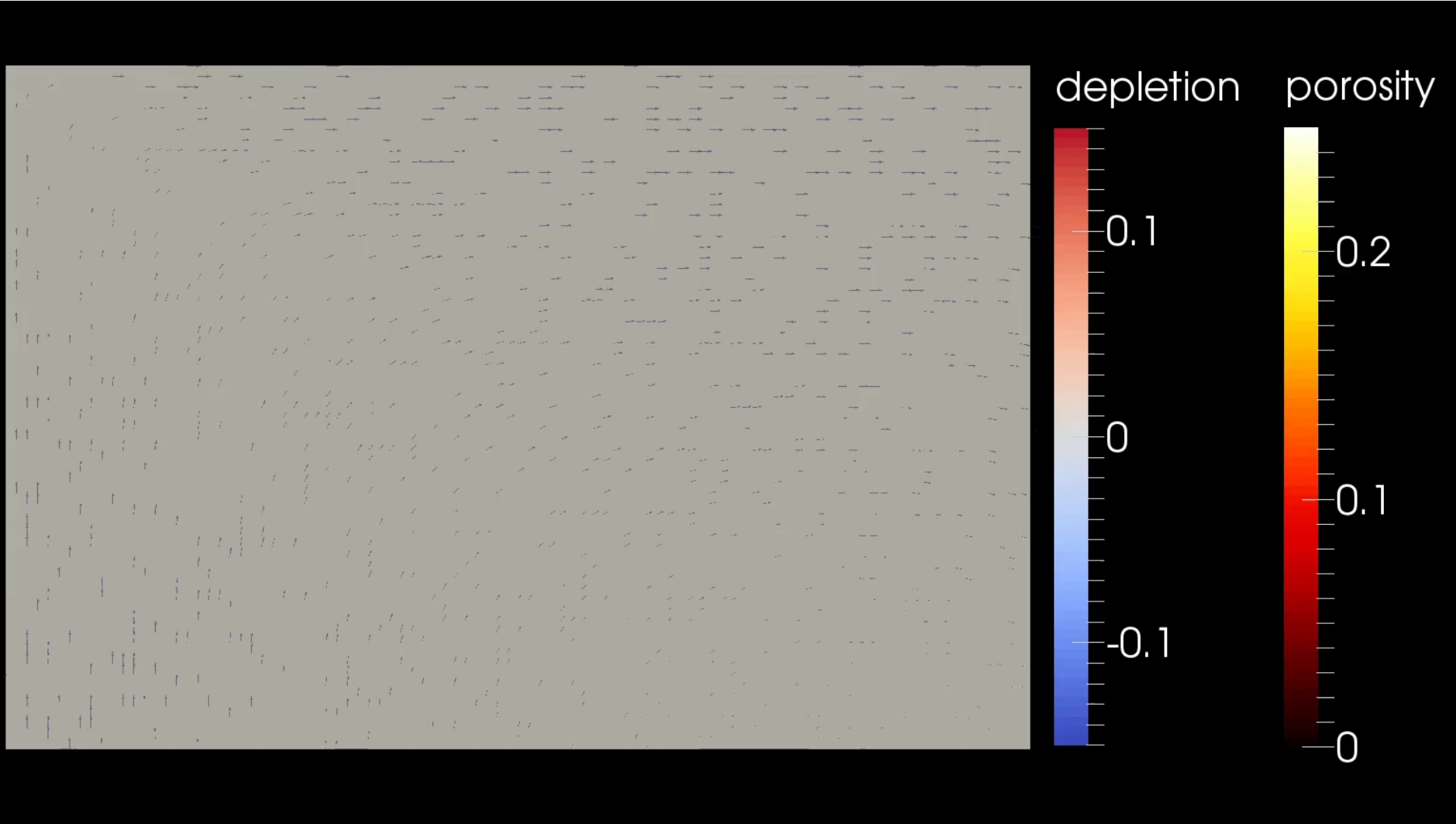
Key interface elements and their configurations are highlighted:

- Toolbar:** The top toolbar includes navigation and visualization icons. A red arrow points to the 'Glyphs' icon (a globe with arrows).
- Properties Panel (Right):** The 'Properties' panel for 'Glyph1' is shown. It includes:
 - Scalars:** Set to 'compaction_viscosity'.
 - Vectors:** Set to 'u_f'.
 - Glyph Type:** Set to 'Arrow'.
 - Tip Resolution:** 6
 - Tip Radius:** 0.1
 - Tip Length:** 0.35
 - Shaft Resolution:** 6
 - Shaft Radius:** 0.03
 - Glyph Transform:** Set to 'Transform2'.
 - Translate:** 0, 0, 0
 - Rotate:** 0, 0, 0
 - Scale:** 1, 1, 1
 - Orientation:** Checked.
- Properties Panel (Left):** A smaller version of the 'Properties' panel for 'Glyph1' is shown, mirroring the settings in the right panel. A red arrow points from the 'u_f' vector selection in this panel to the 'u_f' vector selection in the right panel.
- Callout Box:** A yellow callout box with a red arrow pointing to the 'u_f' vector selection in the right panel contains the text: "This property indicates the name of the vector array on which to operate. The indicated array may be used for scaling and/or orienting the glyphs. (See the SetScaleMode and SetOrient properties.)"

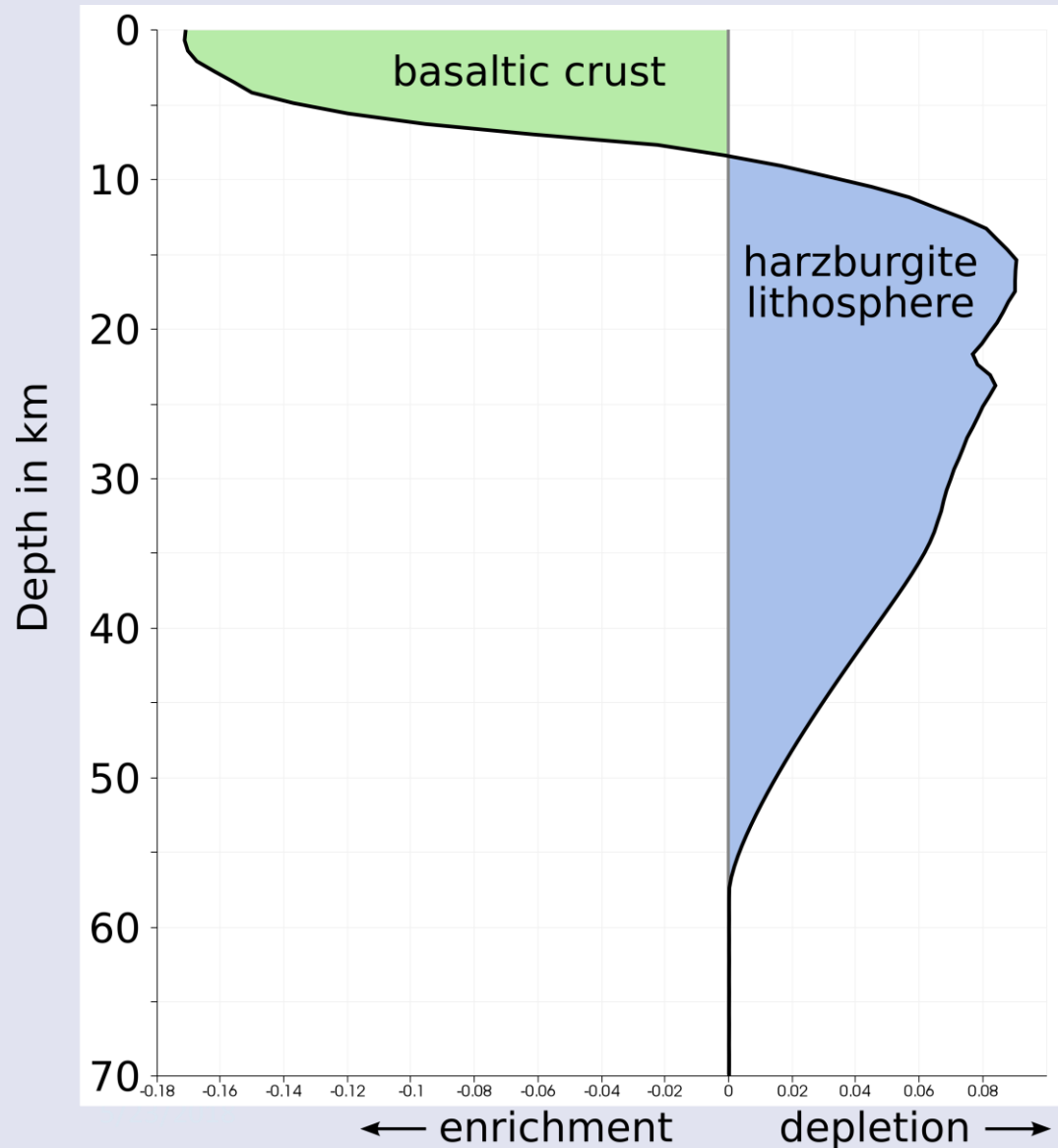
Results



Model evolution



Results: chemical composition

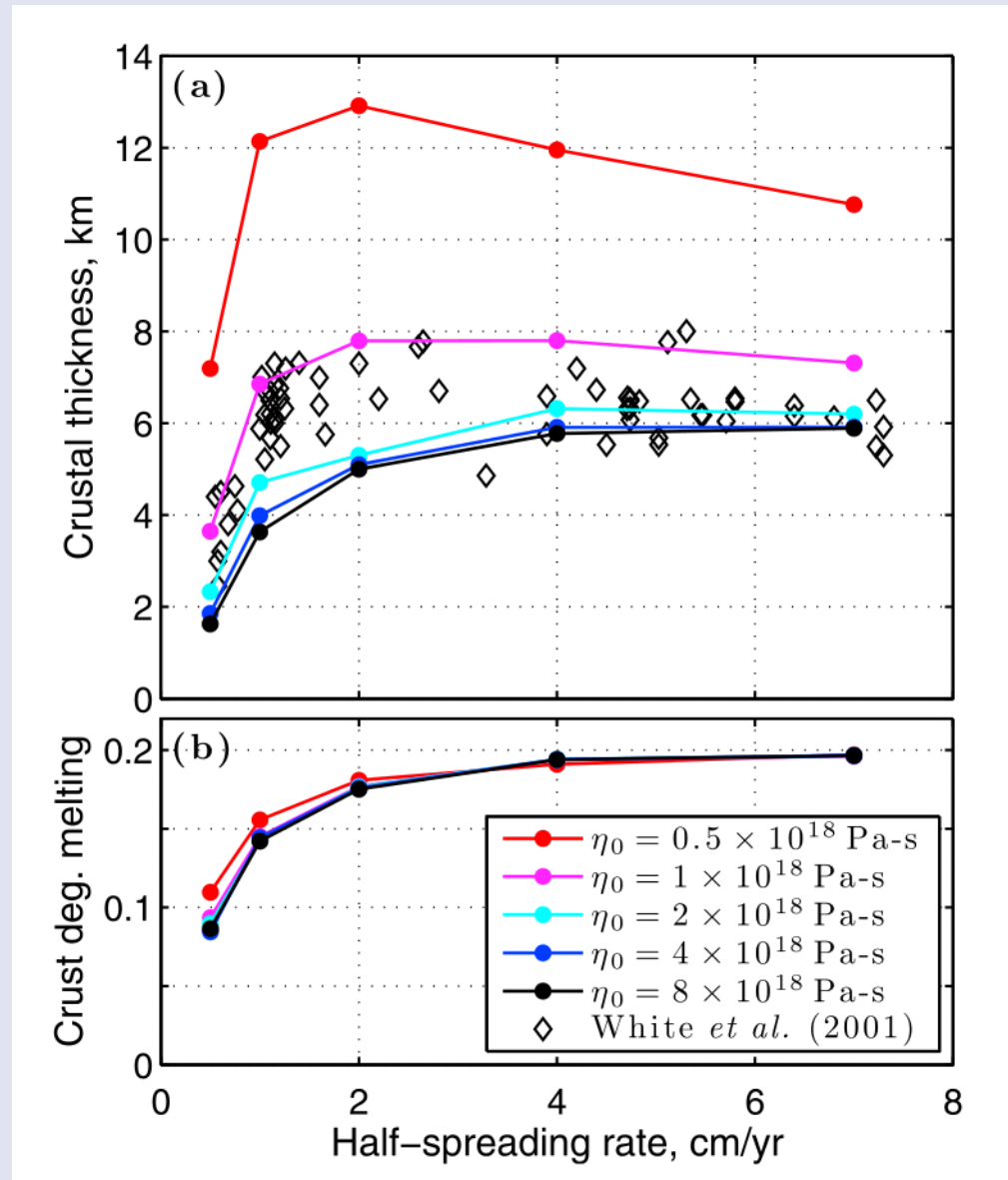


- Vertical profile through the model (*Paraview: Filters* ⇒ *Plot over line*)
- Enriched crust
- Depleted lithosphere
- Crustal thickness: ~8 km

Things to play with

Vary:

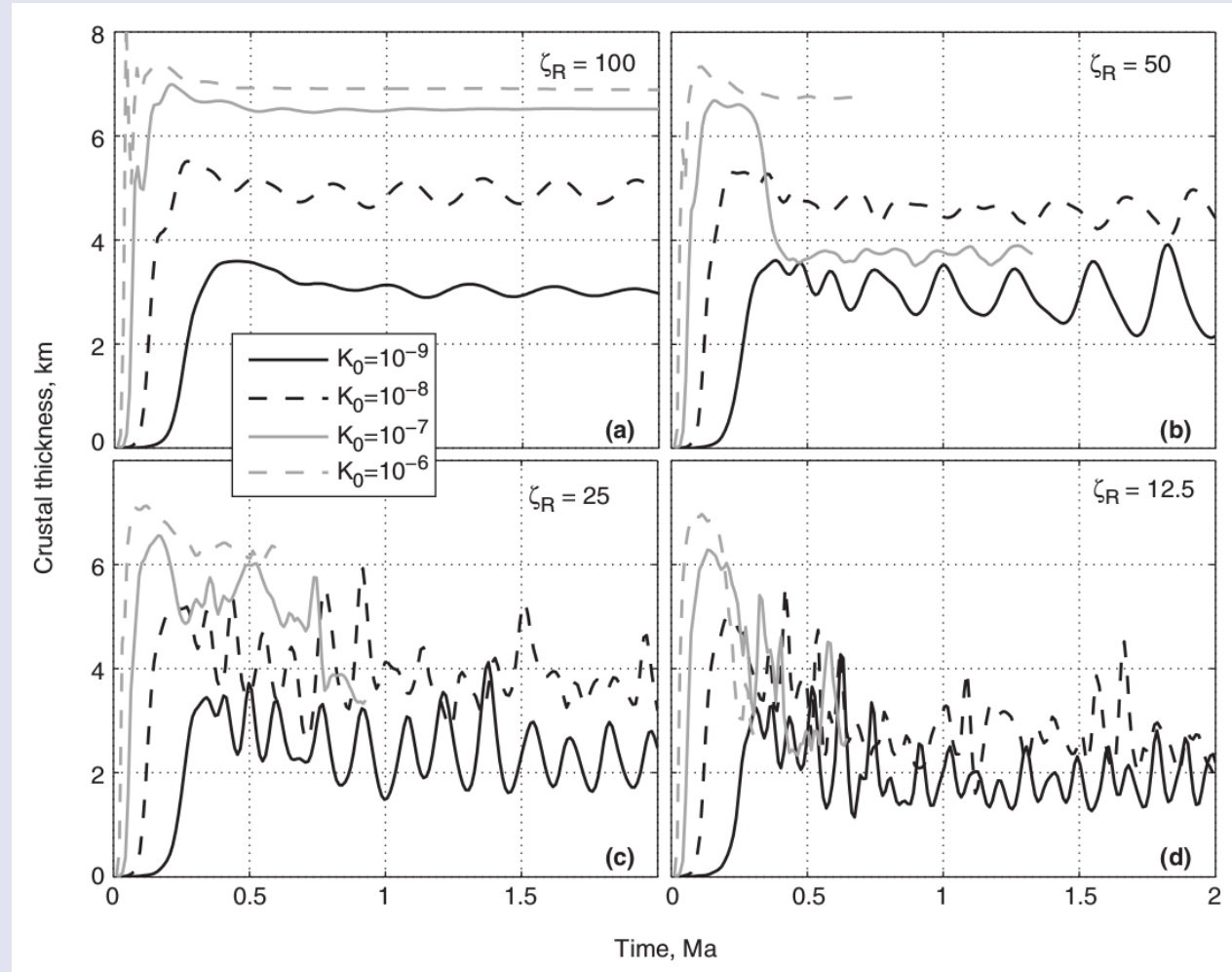
- Spreading rate
- Shear viscosity
- Permeability
- Compaction viscosity



Things to play with

Vary:

- Spreading rate
- Shear viscosity
- Permeability
- Compaction viscosity



Katz, 2008

Ideas: Making the model more realistic

- Temperature-dependent rheology
- Dislocation creep & brittle failure
- Free surface
- Prescribe force on the sides instead of surface velocity
- Other heating processes (Adiabatic heating, shear heating, ...)
- Melting parametrization: use thermodynamics software?

- ASPECT manual:
<http://www.math.clemson.edu/~heister/manual.pdf>
- Methods: Dannberg, J., & Heister, T. (2016). Compressible magma/mantle dynamics: 3-D, adaptive simulations in ASPECT. *Geophysical Journal International*, 207(3), 1343-1366.
<https://doi.org/10.1093/gji/ggw329>
- Ask on the mailing list:
<http://lists.geodynamics.org/cgi-bin/mailman/listinfo/aspect-devel>