New Coupled Model
For Ice-Permafrost-Groundwater flow

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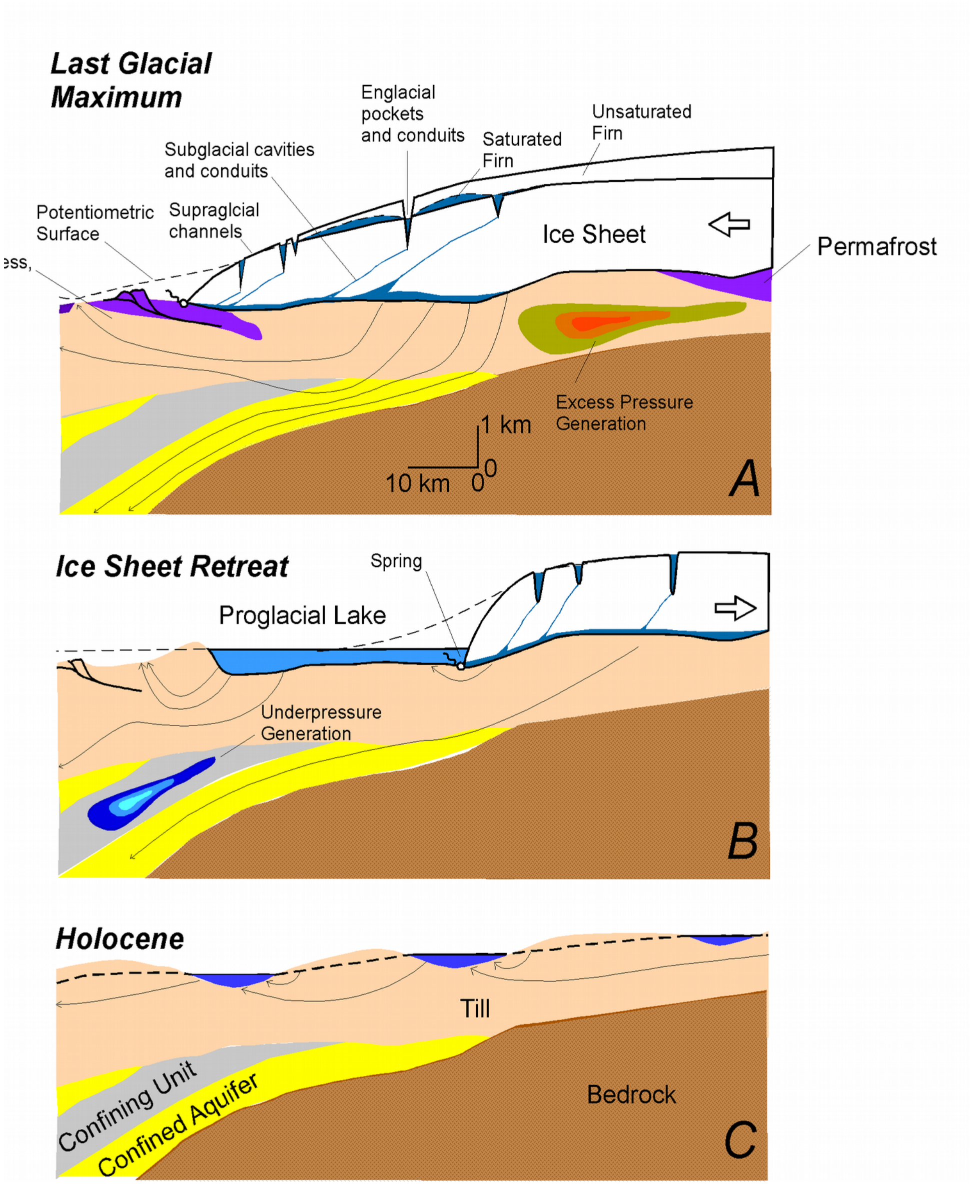
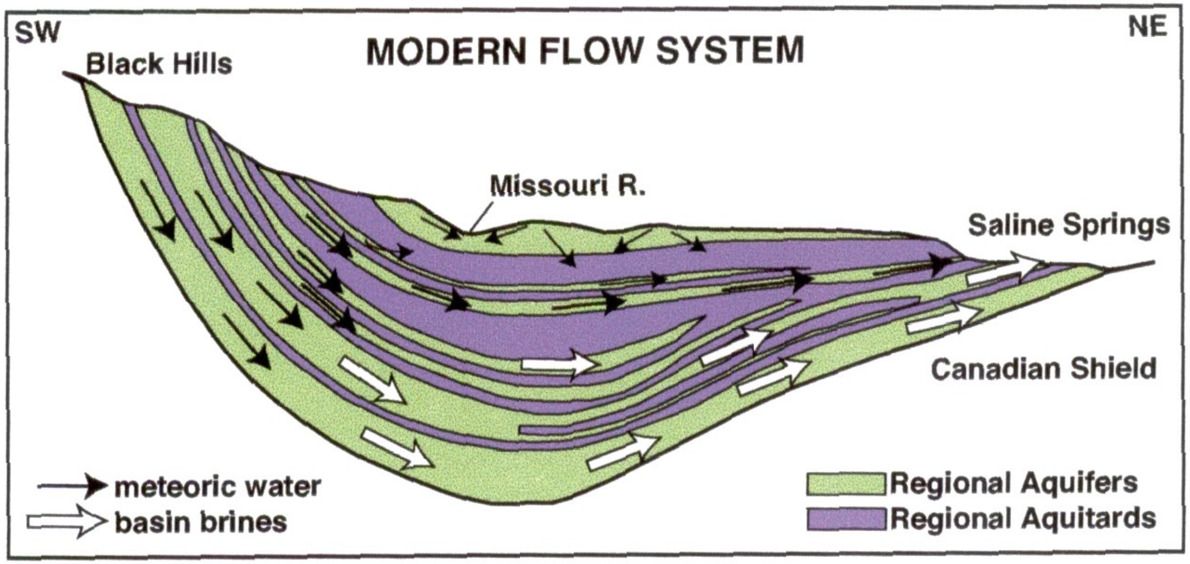
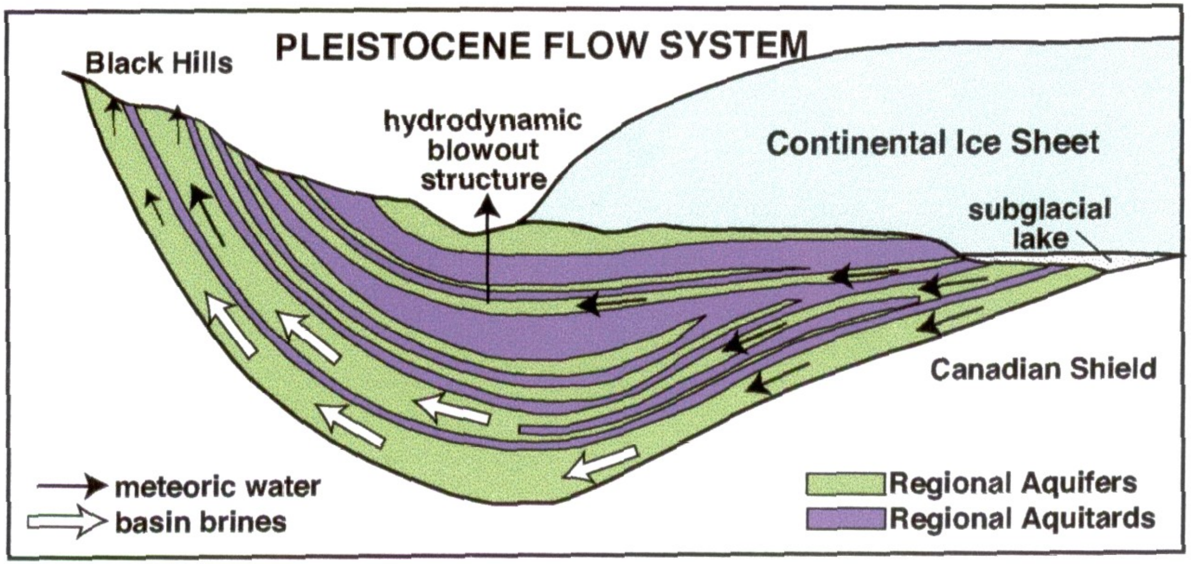
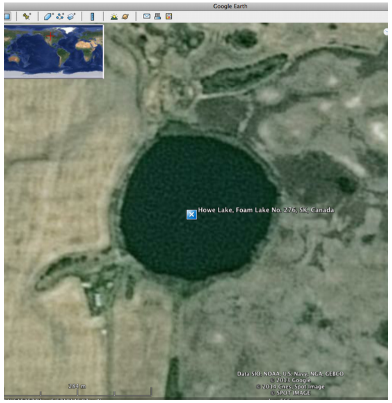
Effects of ice sheet on groundwater flow

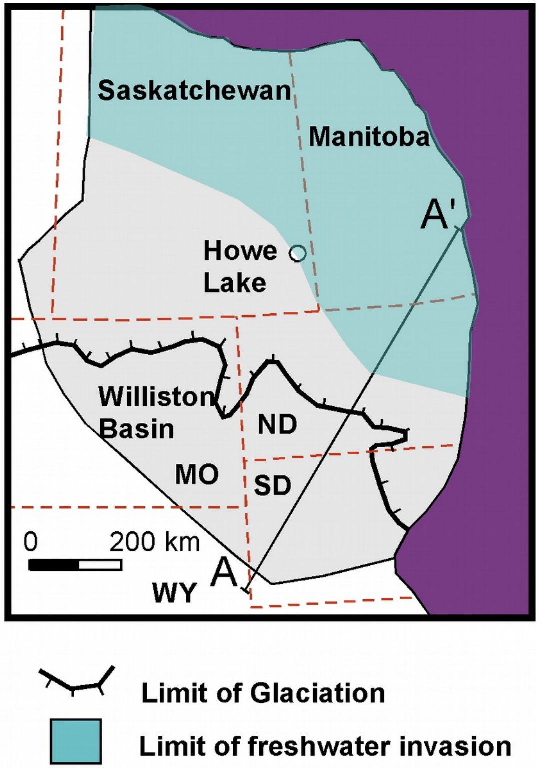


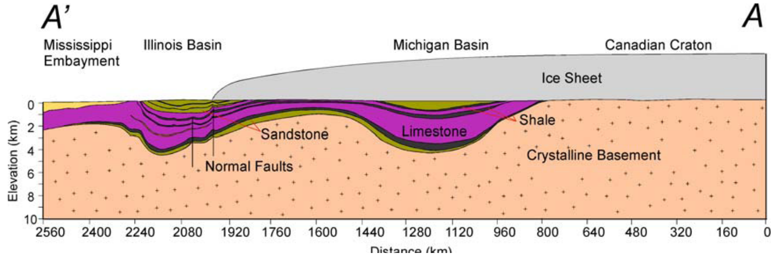
Example of groundwater flow reversal



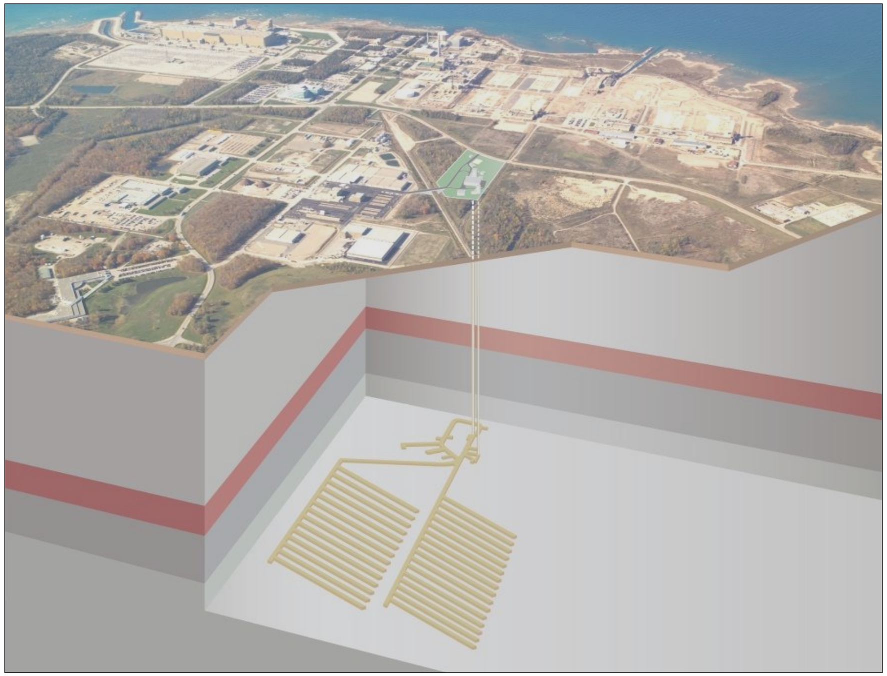






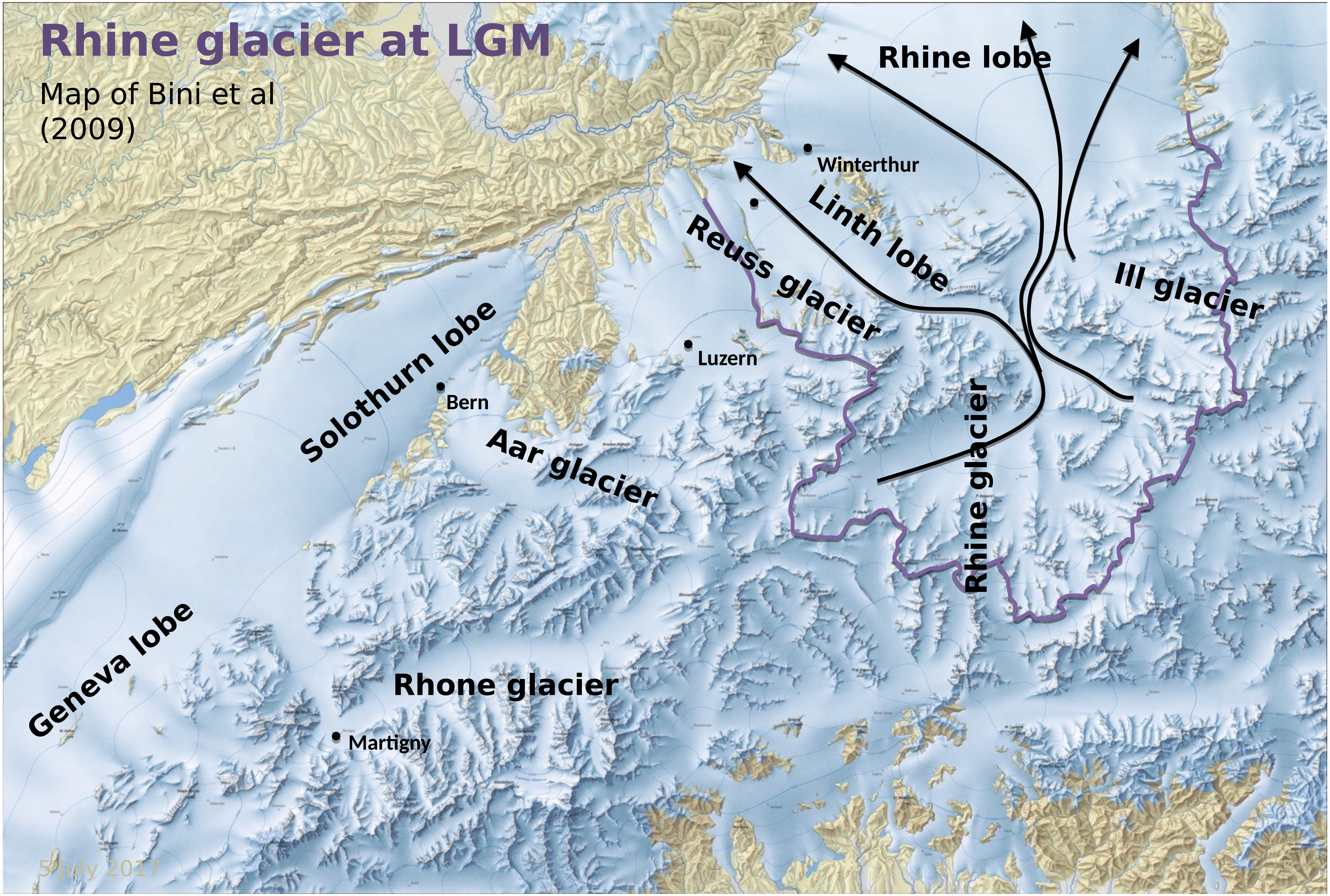


Canadian Bruce Site, Eastern Michigan Basin



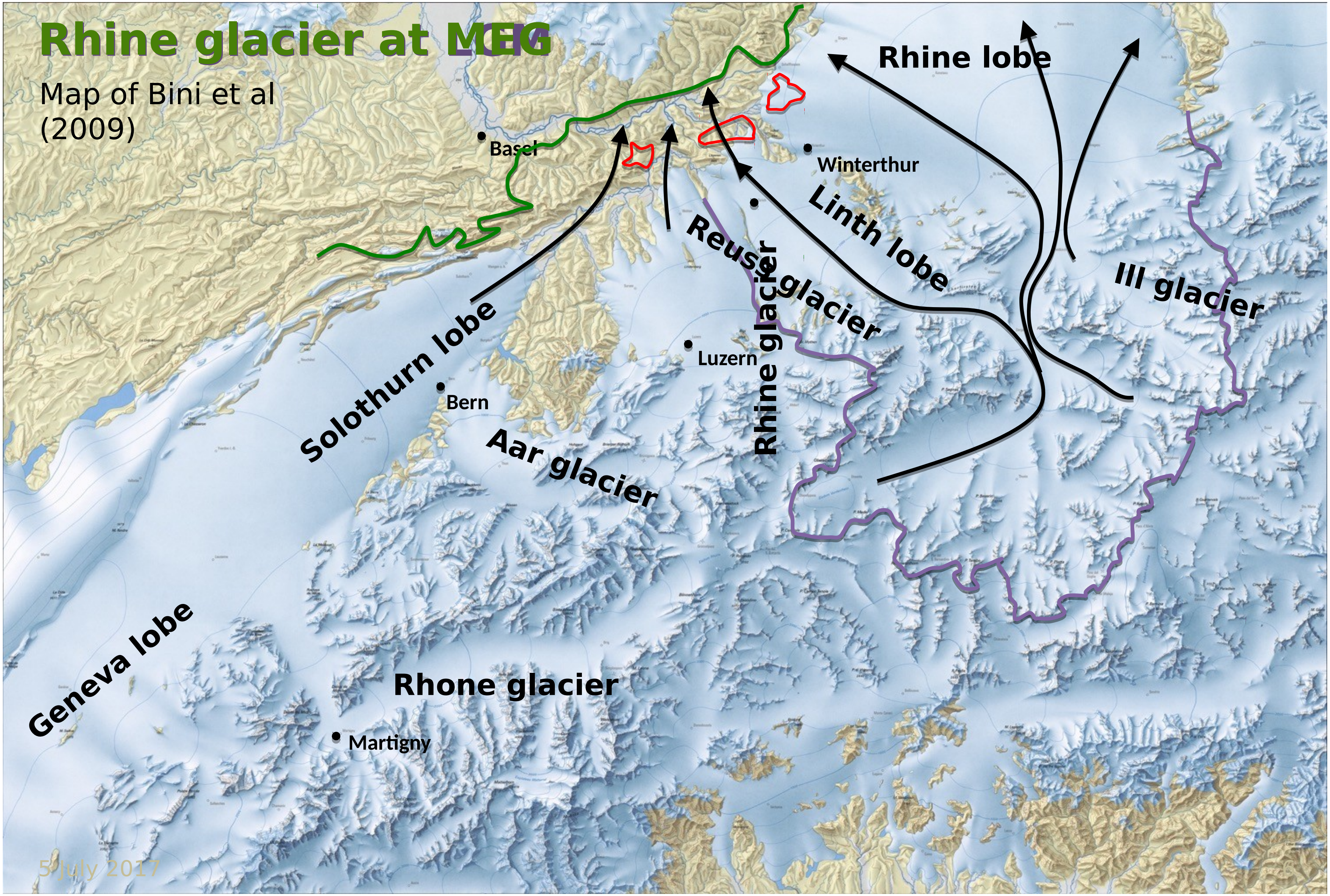
Rhine glacier at LGM

Map of Bini et al (2009)

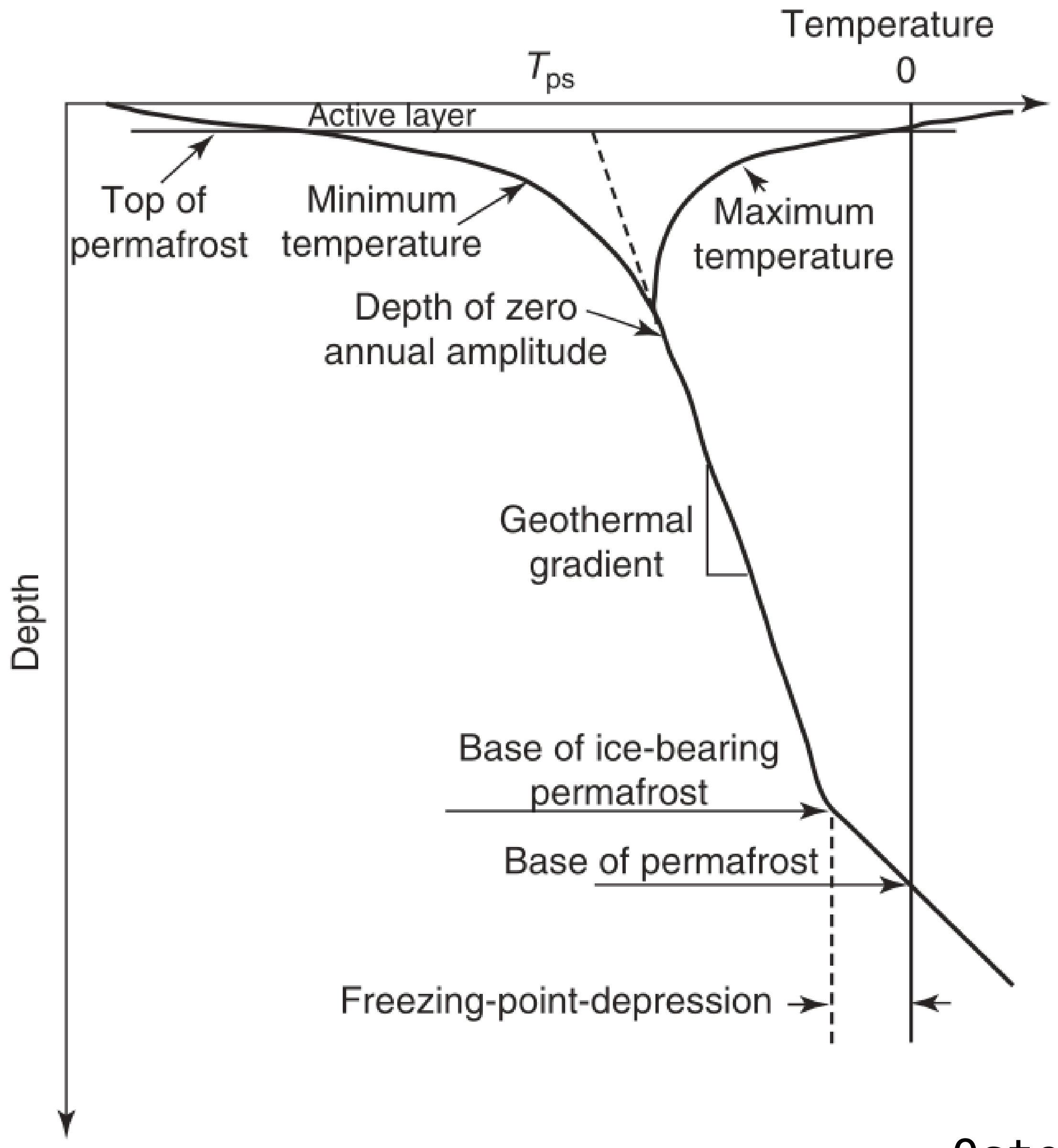


Rhine glacier at MEG

Map of Bini et al (2009)

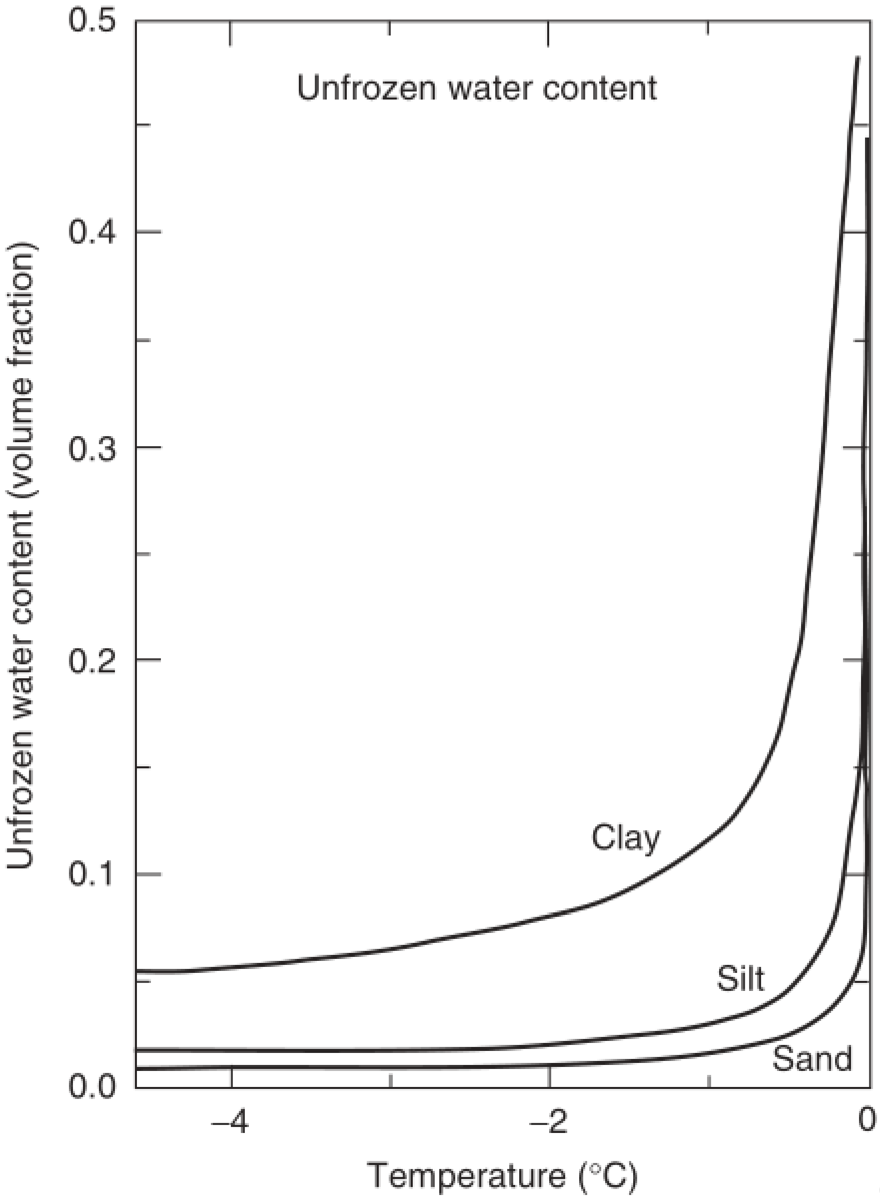


Permafrost



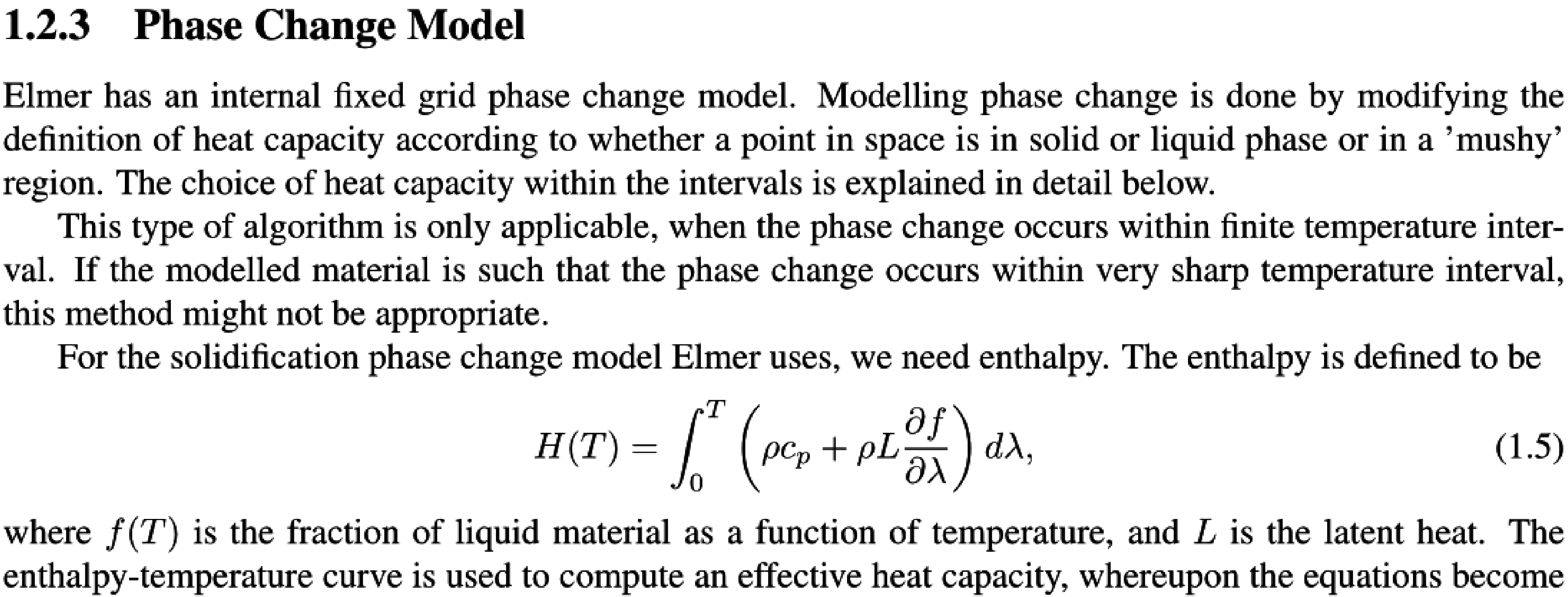
Osterkamp & Burn 2002

Unfrozen water below freezing



Osterkamp & Burn 2002

1. Enthalpy formulation for permafrost



1.2.3 Phase Change Model

Elmer has an internal fixed grid phase change model. Modelling phase change is done by modifying the definition of heat capacity according to whether a point in space is in solid or liquid phase or in a 'mushy' region. The choice of heat capacity within the intervals is explained in detail below.

This type of algorithm is only applicable, when the phase change occurs within finite temperature interval. If the modelled material is such that the phase change occurs within very sharp temperature interval, this method might not be appropriate.

For the solidification phase change model Elmer uses, we need enthalpy. The enthalpy is defined to be

$$H(T) = \int_0^T \left(\rho c_p + \rho L \frac{\partial f}{\partial \lambda} \right) d\lambda, \tag{1.5}$$

where $f(T)$ is the fraction of liquid material as a function of temperature, and L is the latent heat. The enthalpy-temperature curve is used to compute an effective heat capacity, whereupon the equations become

Enthalpy formulation: sif

In Equation section for rock, add:

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   Phase Change Model = Spatial 2”
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In Material section for rock, add:

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   Enthalpy = Variable Temperature
      Real Procedure "MyEnthalpyEquation" "MyEnthalpyEquation"
   Heat Capacity = Real 0.0 ! Already included in enthalpy equation
   Latent Heat = Real 333.5E+03 ! [J/kg]
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MyEnthalpyEquation contains an equation like this:

$$\rho H = \left\{ (1-n)\,\rho_r c_r + (n-\phi_w)\,\rho_i c_i + \phi_w(T)\rho_w c_w \right\} (T - T_o) + \phi_w(T)\rho_w L,$$

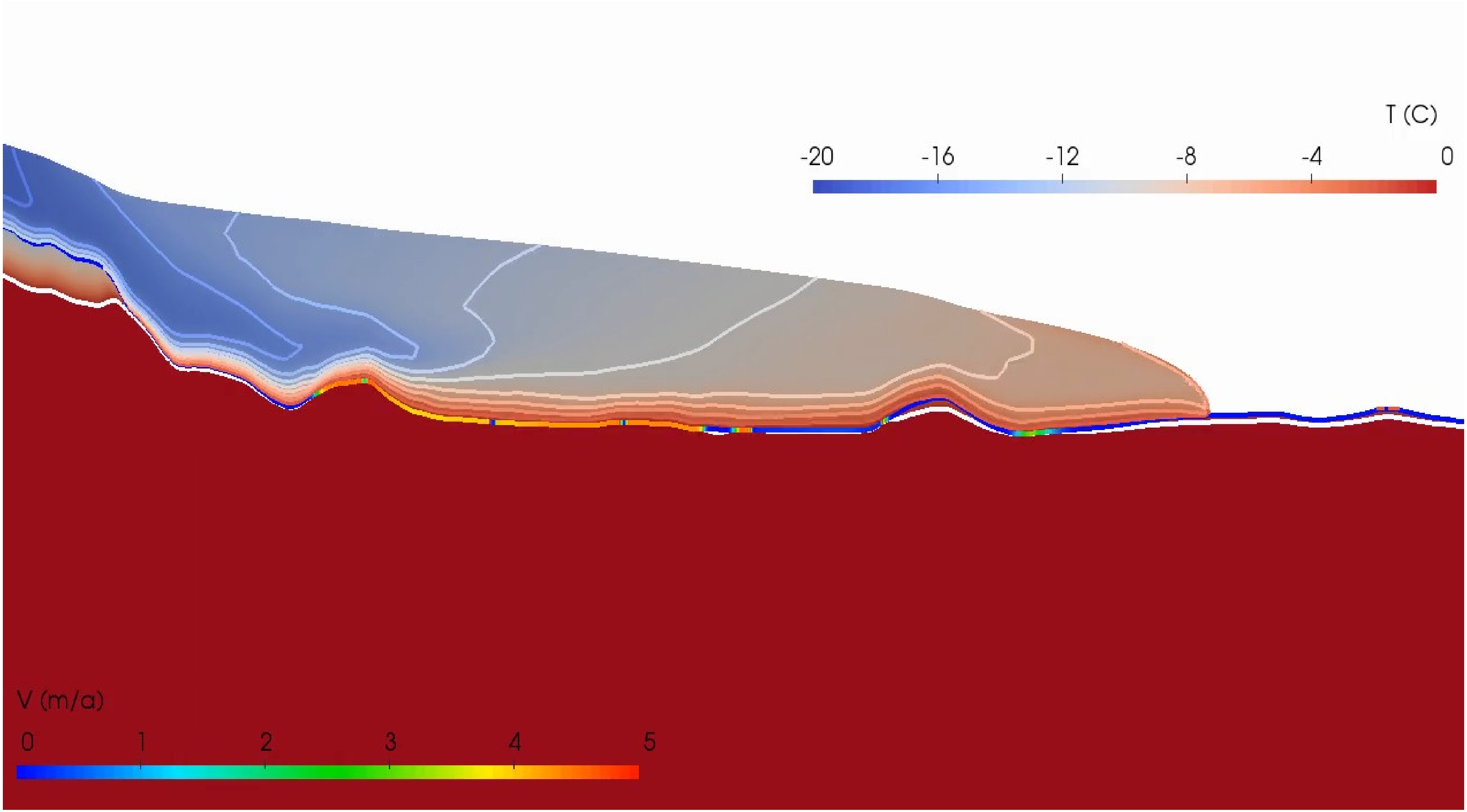
Also write functions for rho (density), K (thermal conductivity of mixture) and C (thermal conductivity) of rock/ice/water mixture

$$K = K_{\mathrm{b}}^{\theta_{\mathrm{b}}} K_{\mathrm{u}}^{\theta_{\mathrm{u}}} K_{\mathrm{i}}^{\theta_{\mathrm{i}}}\,, \qquad C_{\mathrm{v}} = \theta_{\mathrm{i}} C_{\mathrm{i}} + \theta_{\mathrm{u}} C_{\mathrm{u}} + \theta_{\mathrm{b}} C_{\mathrm{b}}\,,$$

Temperature Solver

Use standard “HeatSolver” for both ice and rock.
Use Limiter for ice to limit temperature to Tpmp (a function of pressure)
For boundary condition, nothing special to do. Can add basal sliding and friction as usual

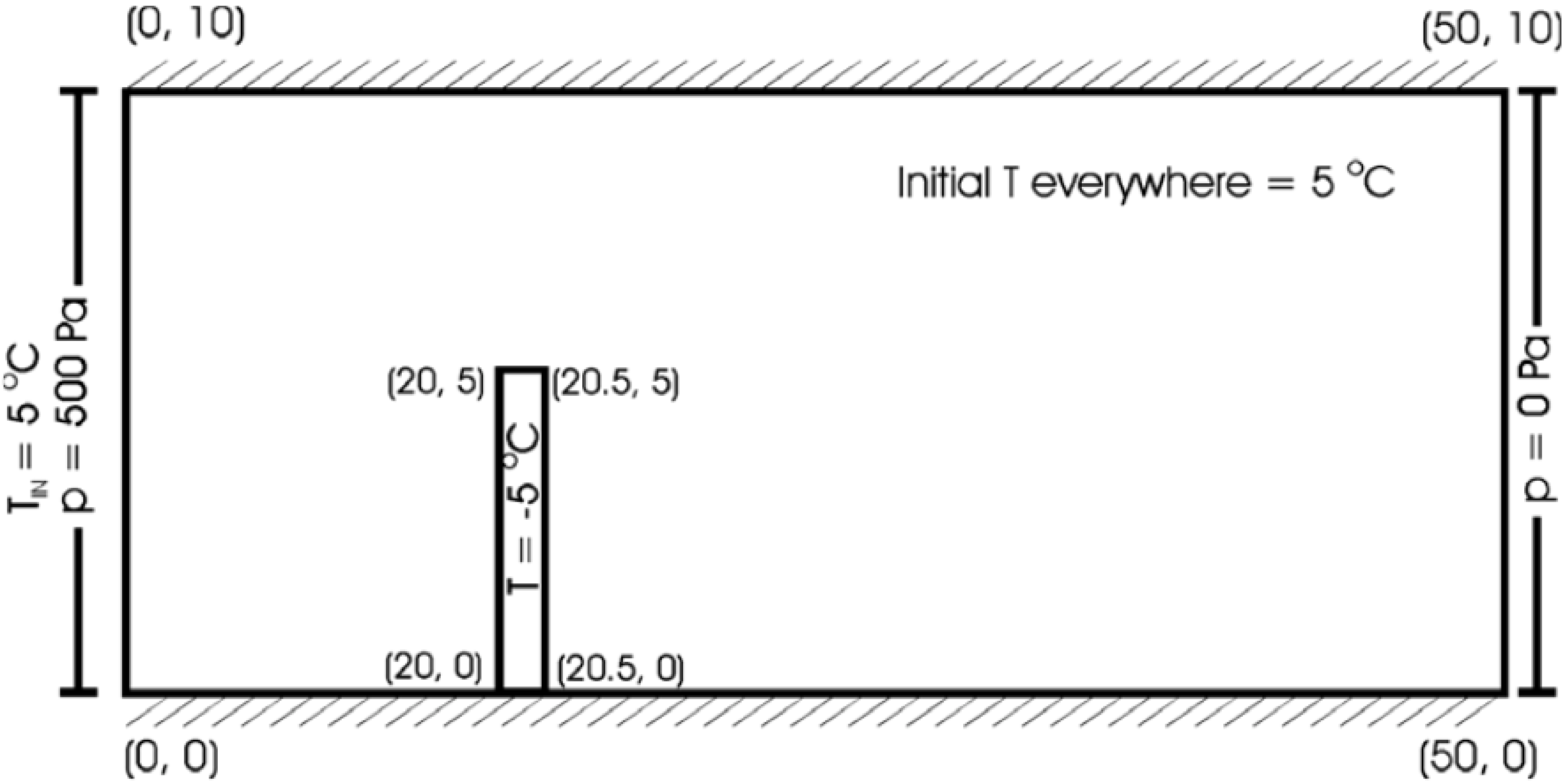
Temperature evolution during ice advance



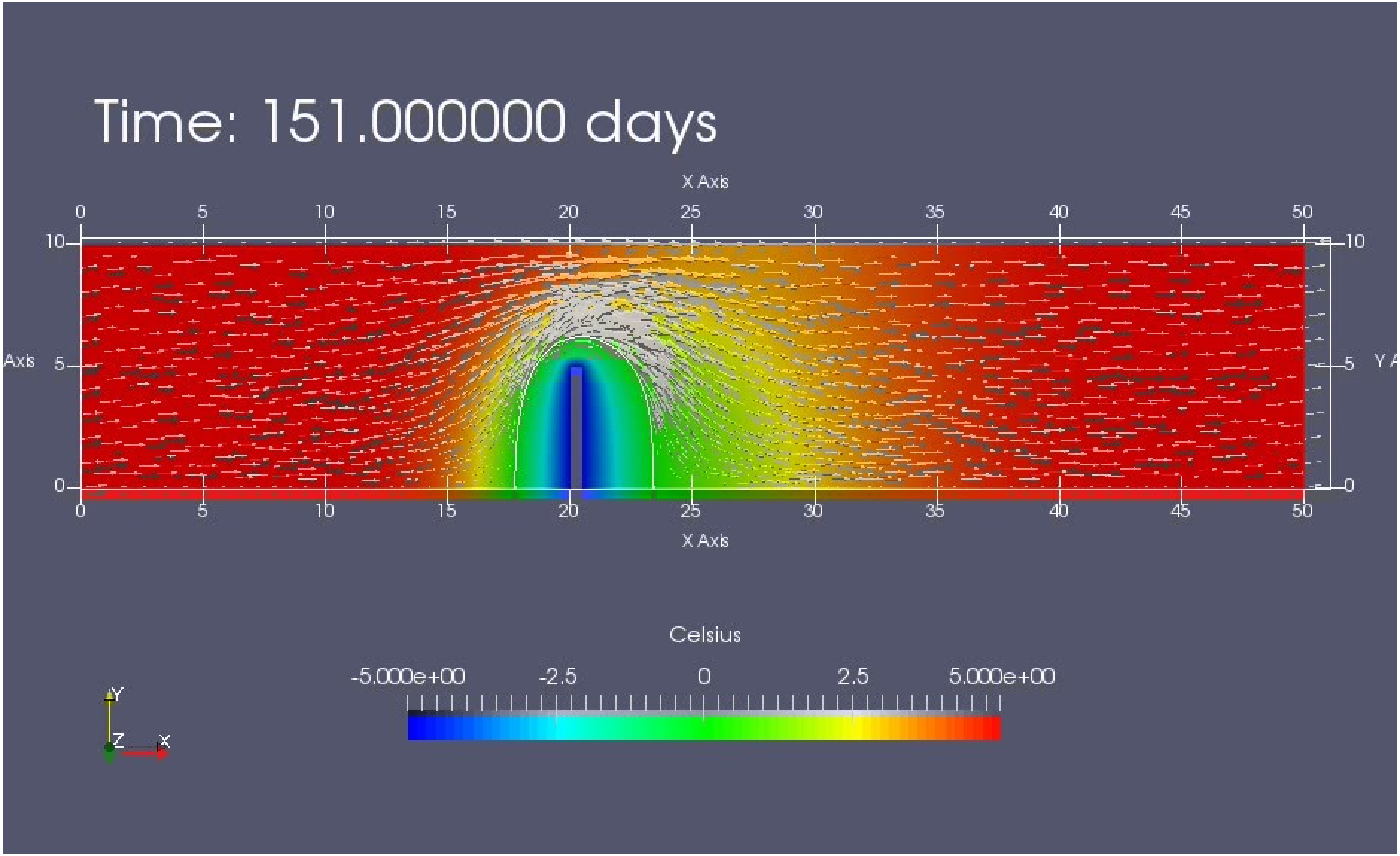
2. Fully coupled Darcy-permafrost-ice flow model

- Groundwater flow with heat transfer including phase change
- Thermodynamically consistent formulation. No empirical relation
- New Darcy solver
- New Permafrost solver
- Temperature dependent rock permeability

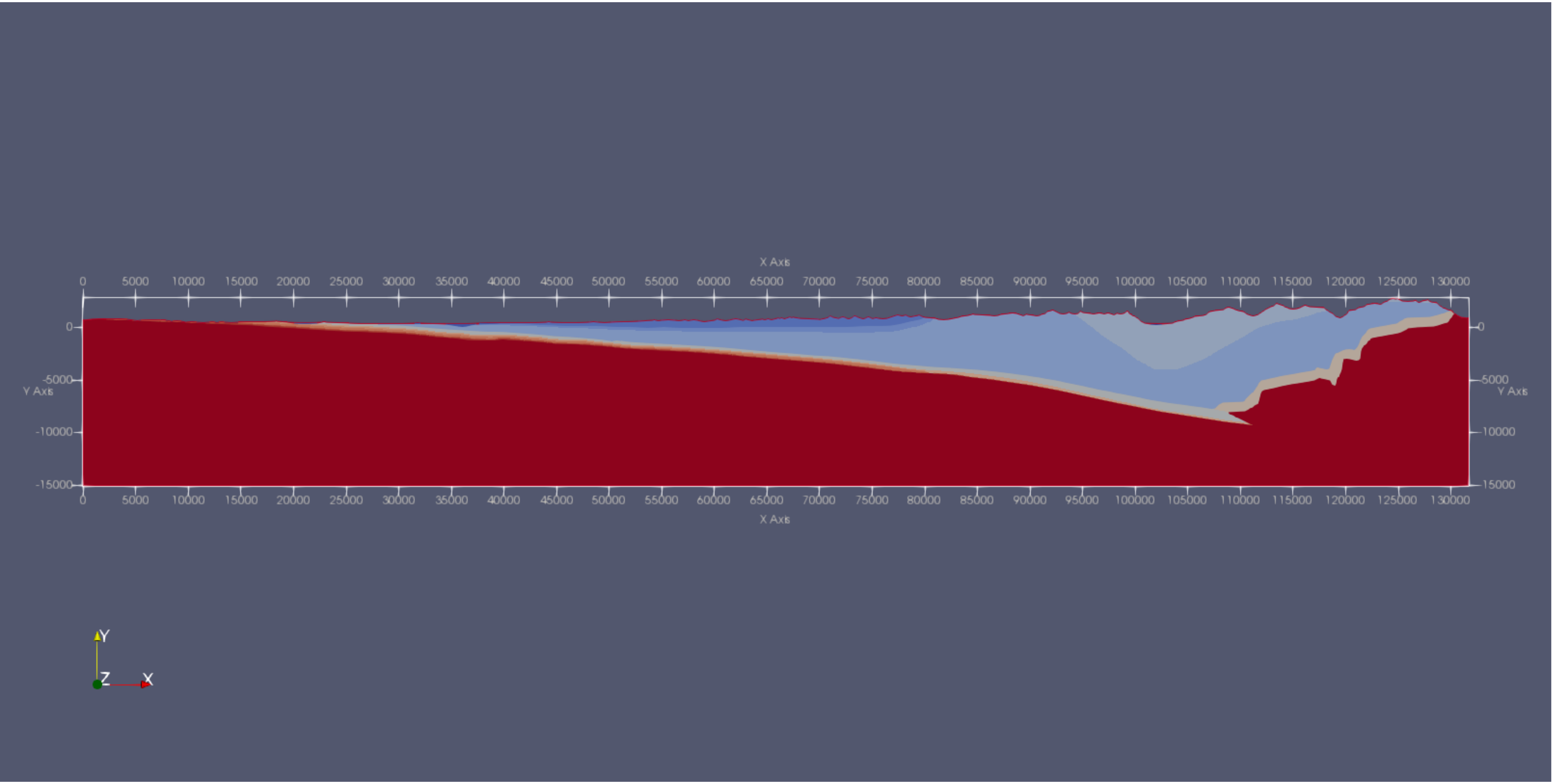
Frozen wall problem



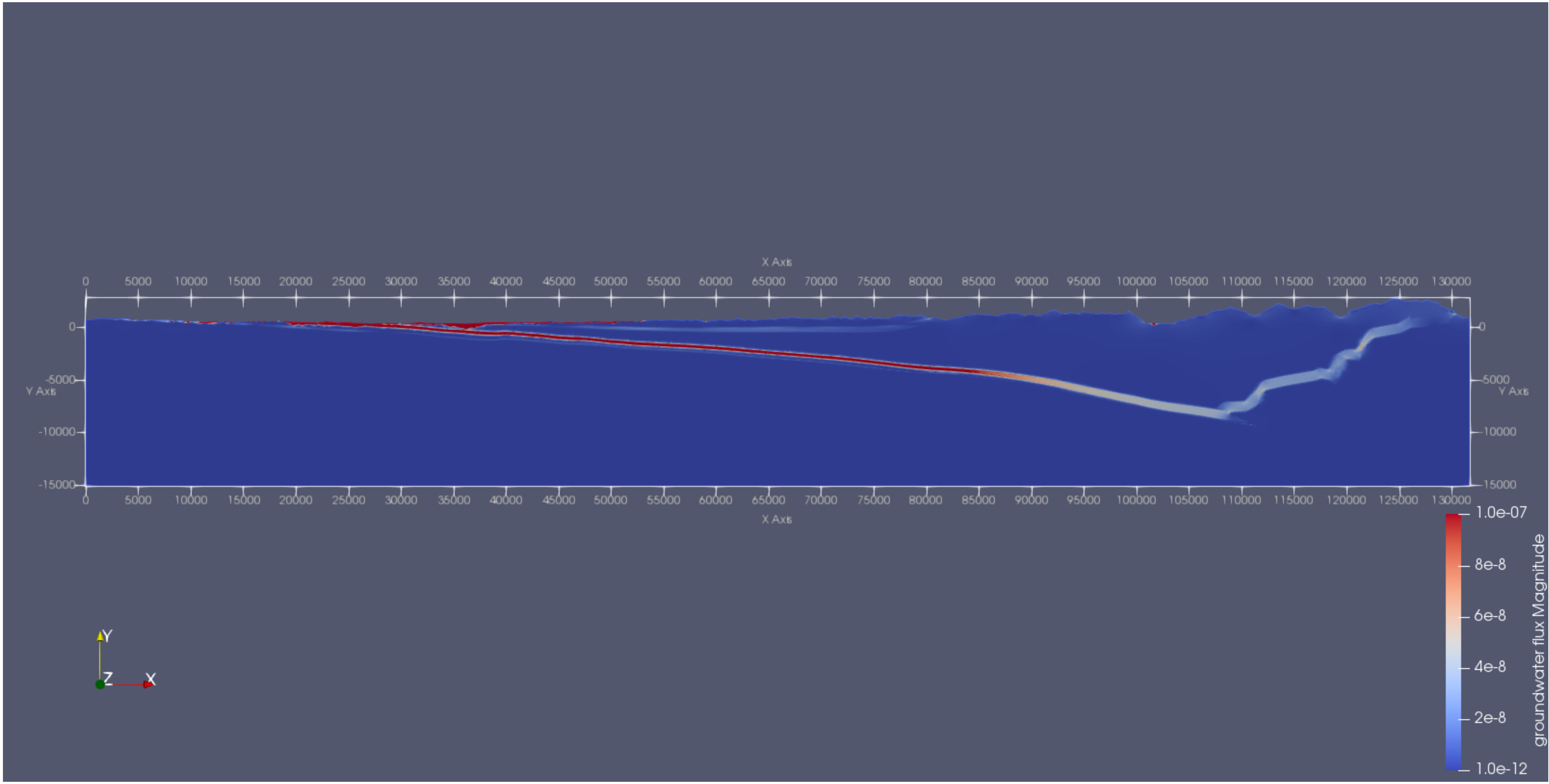
Frozen wall


Time: 151.000000 days
X Axis
0
5
10
15
20
25
30
35
40
45
50
Y Axis
10
5
0
Celsius
-5.000e+00
-2.5
0
2.5
5.000e+00
Y
Z
X

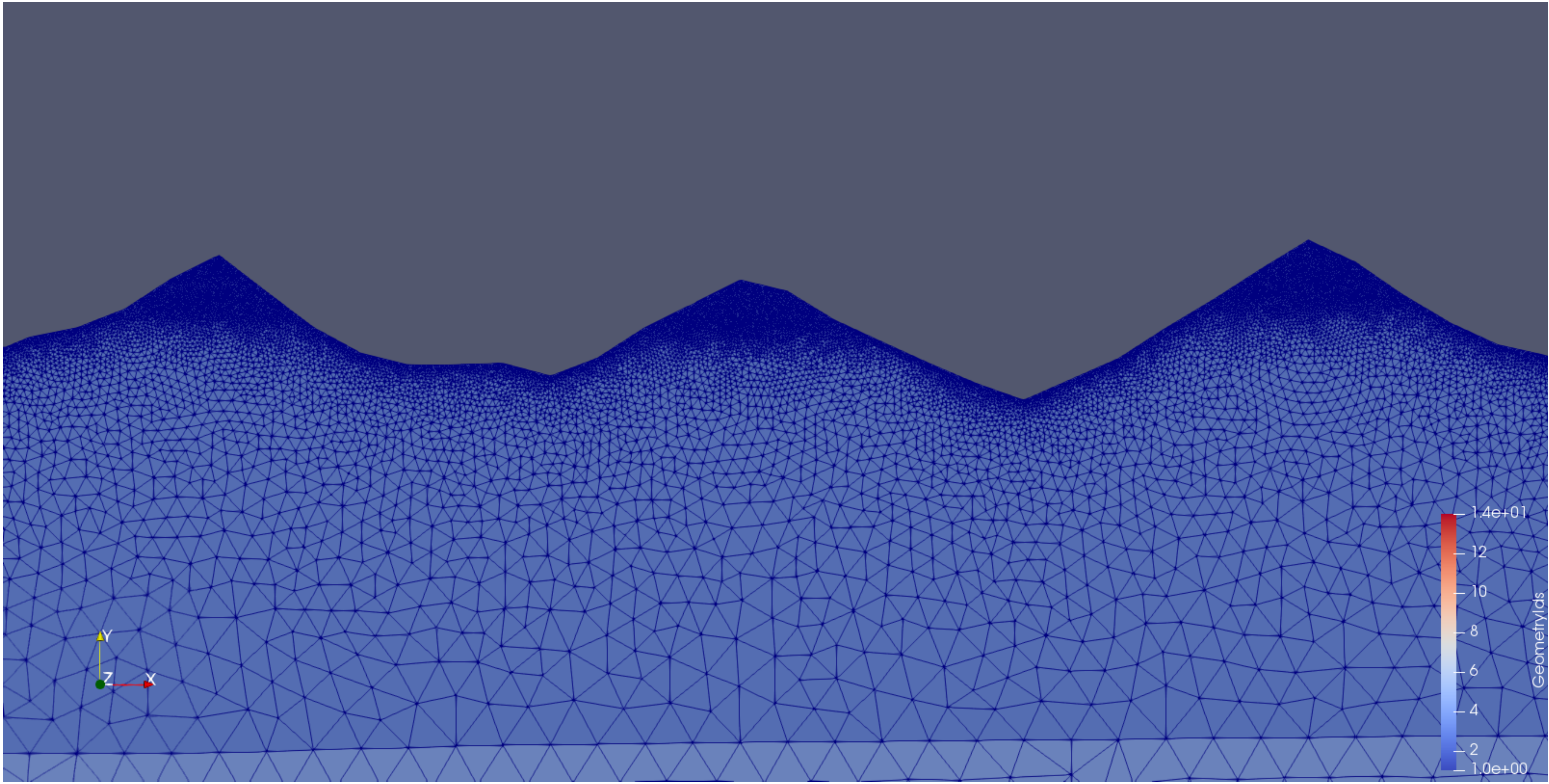
Large scale groundwater flow problem



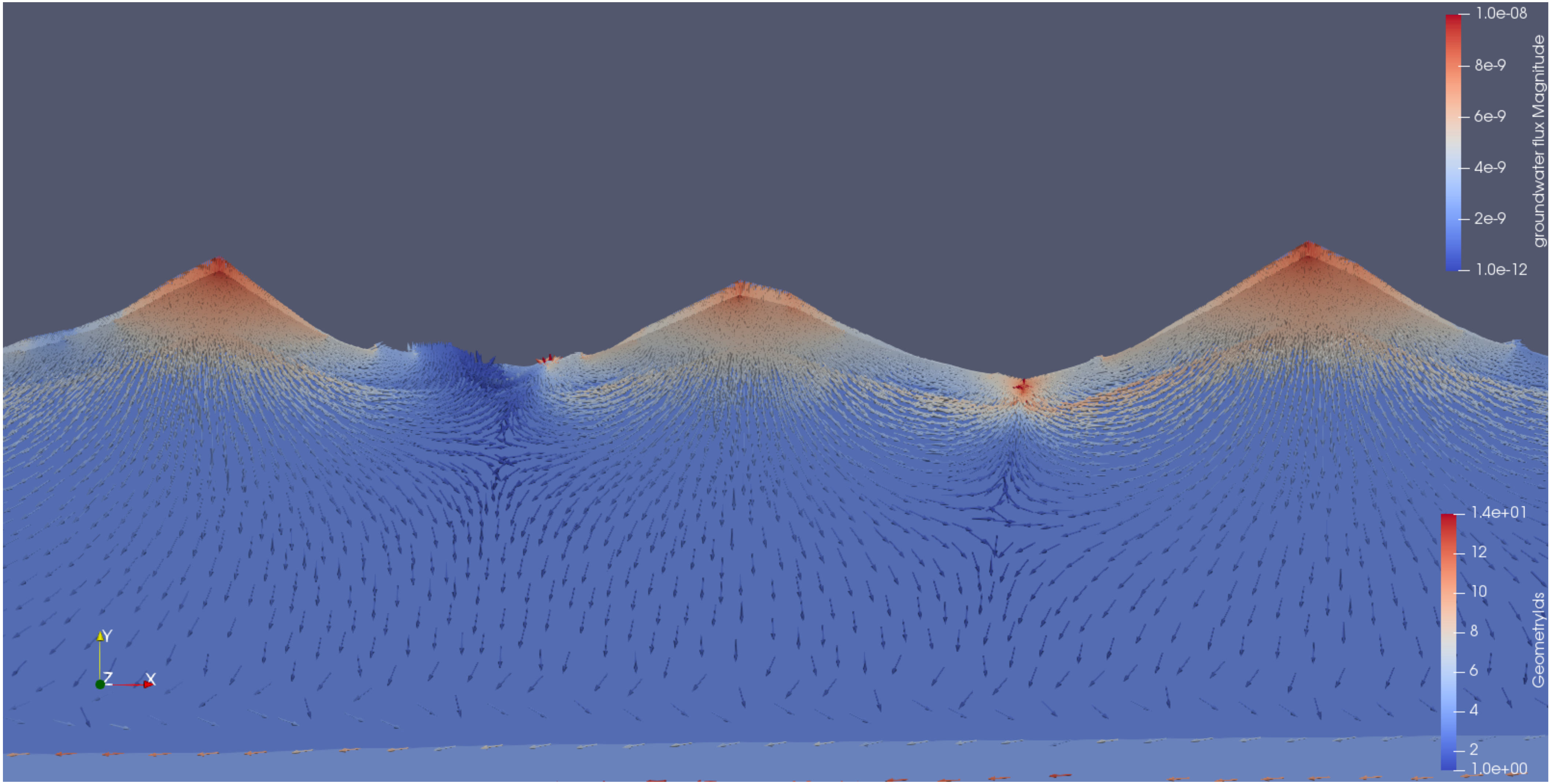
Groundwater flux



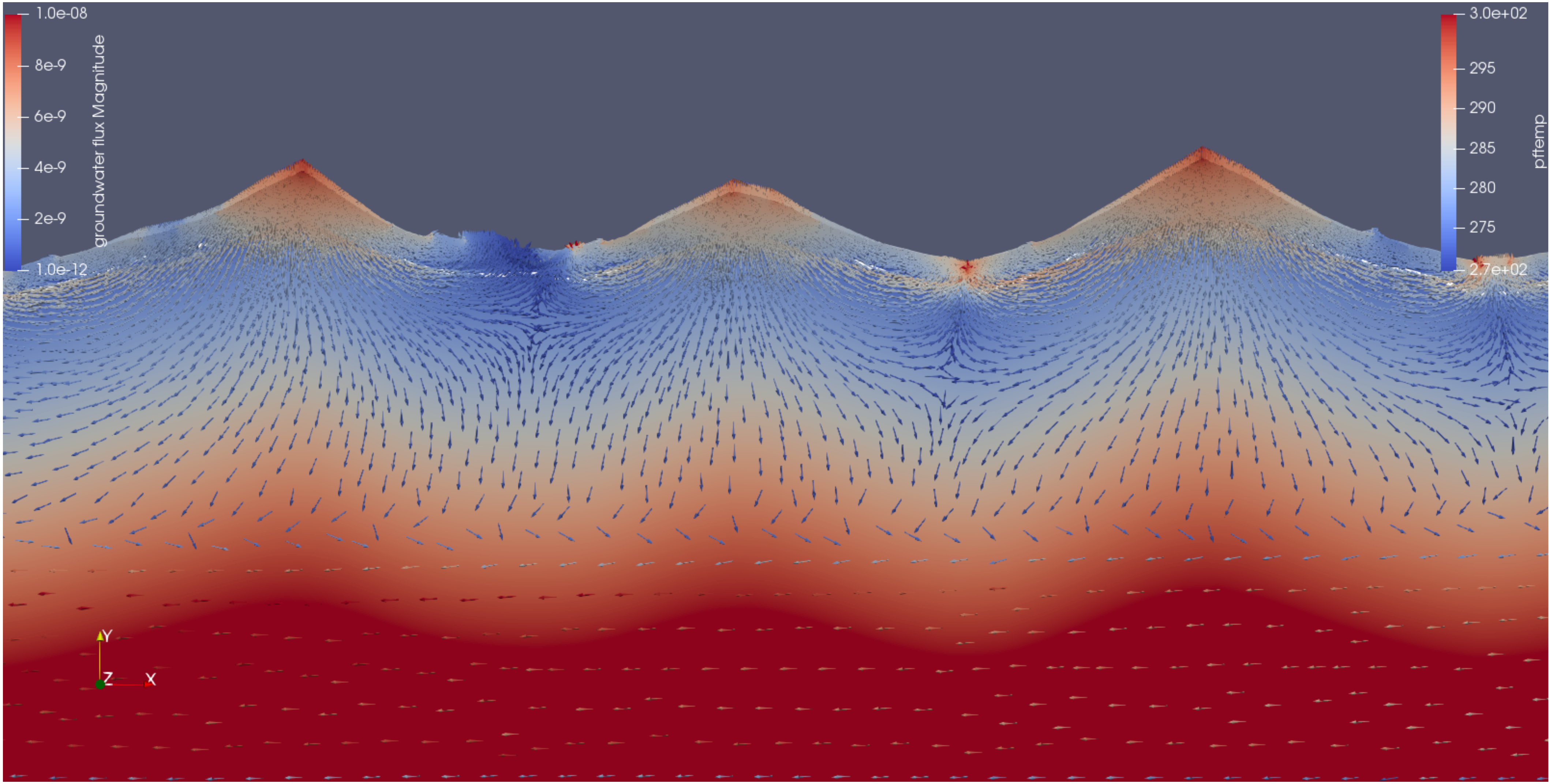
Mesh resolution: down to ~5 m



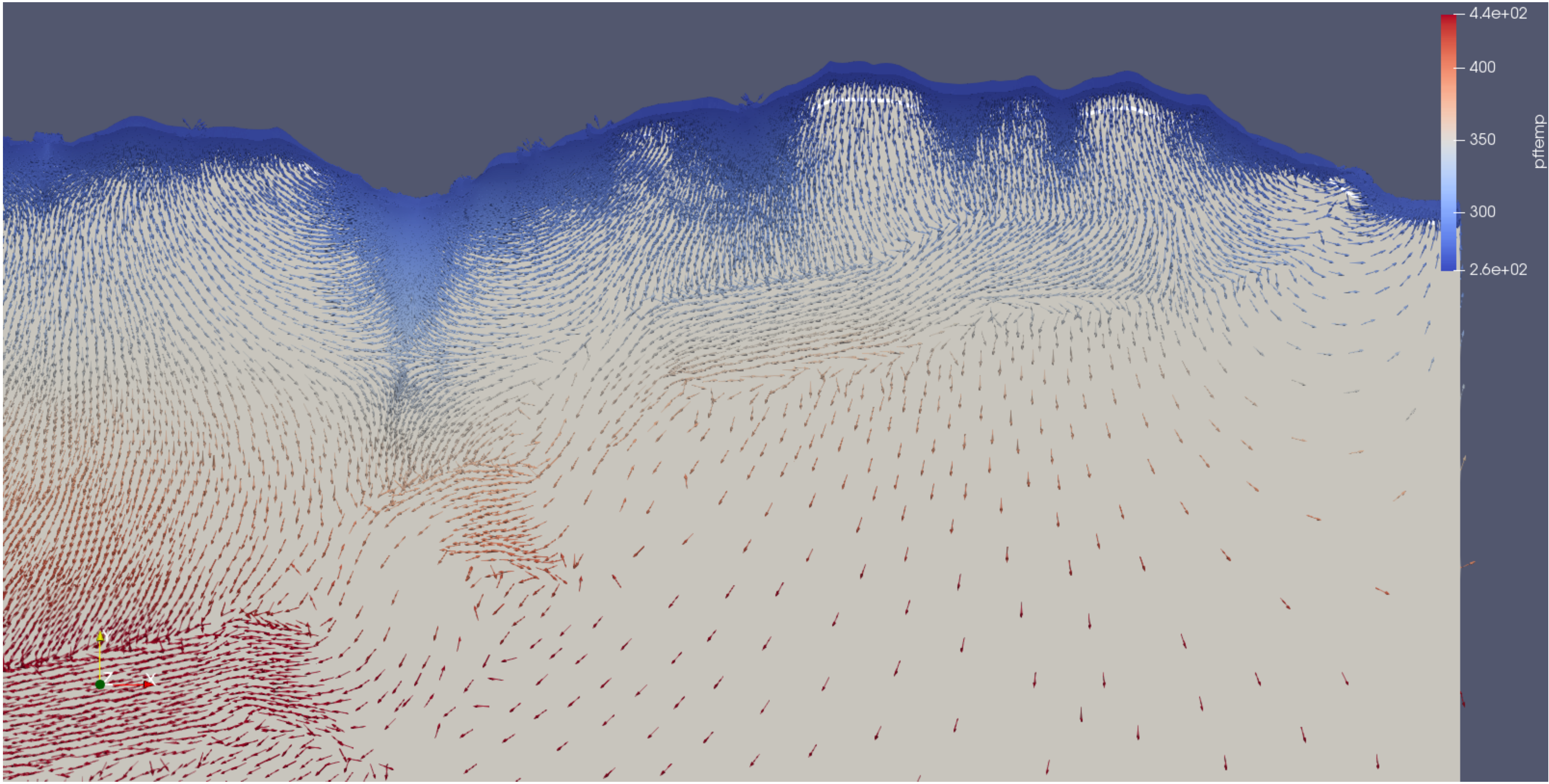
GW flux vector



Temperature



Flux + temperature



Transient coupled simulation