Elmer/Ice – New Generation Ice Sheet Model

Elmer/Ice – 2D glacier toy model

Thomas Zwinger

CSC

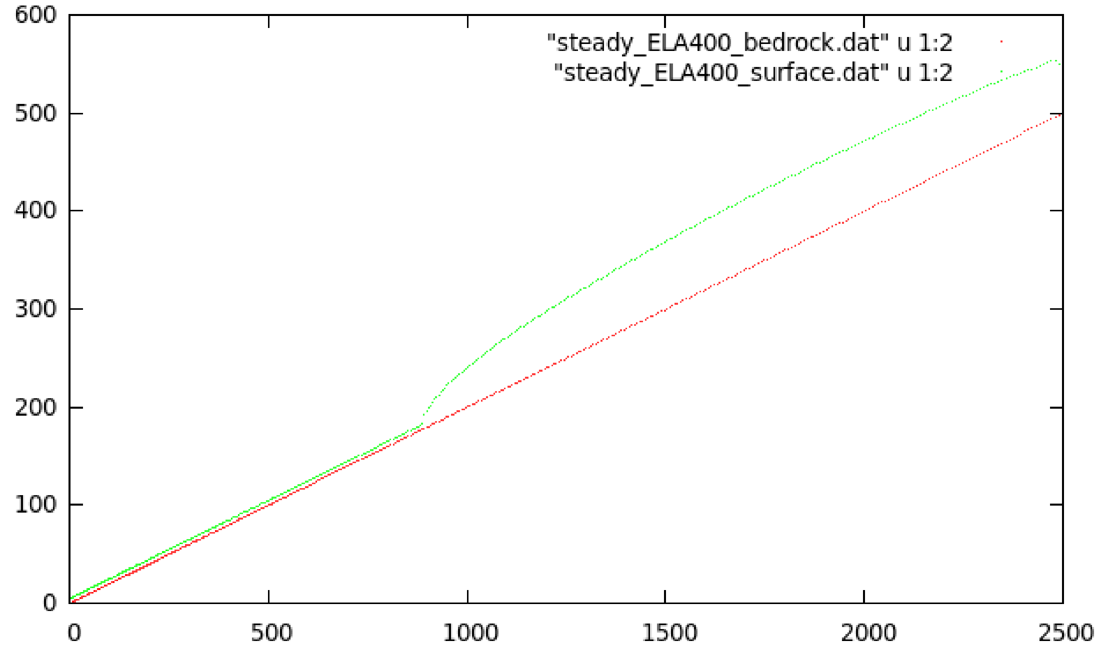
DIAGNOSTIC RUN

Starting from a given point-distribution (DEM) in 2D we show how to

- Build the geometry and mesh it (using Gmsh)
- Set up runs on fixed geometry
- Basic post-processing in ParaView
- Introduce sliding
- Introduce heat transfer (thermo-mechanical coupling)

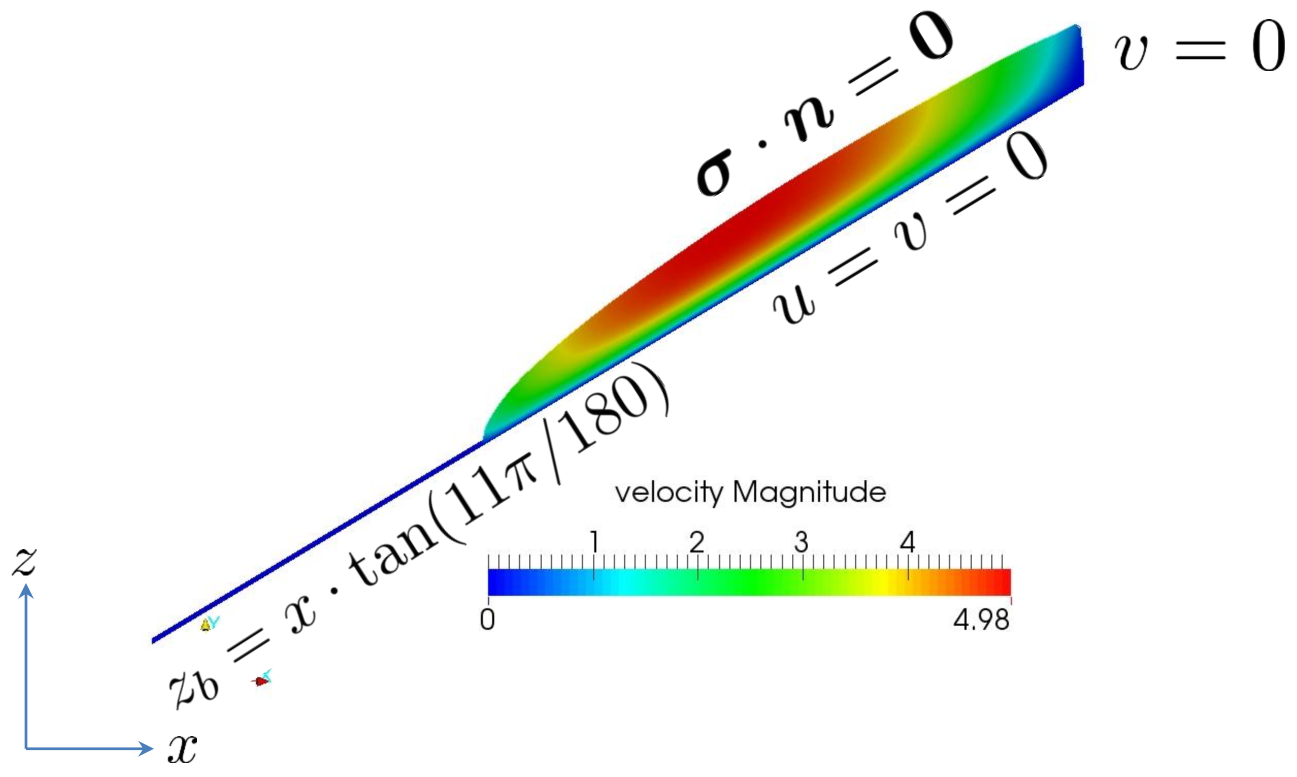
The diagnostic problem

- We start from a distribution of surface and bedrock points that have been created driving a prognostic run into steady state



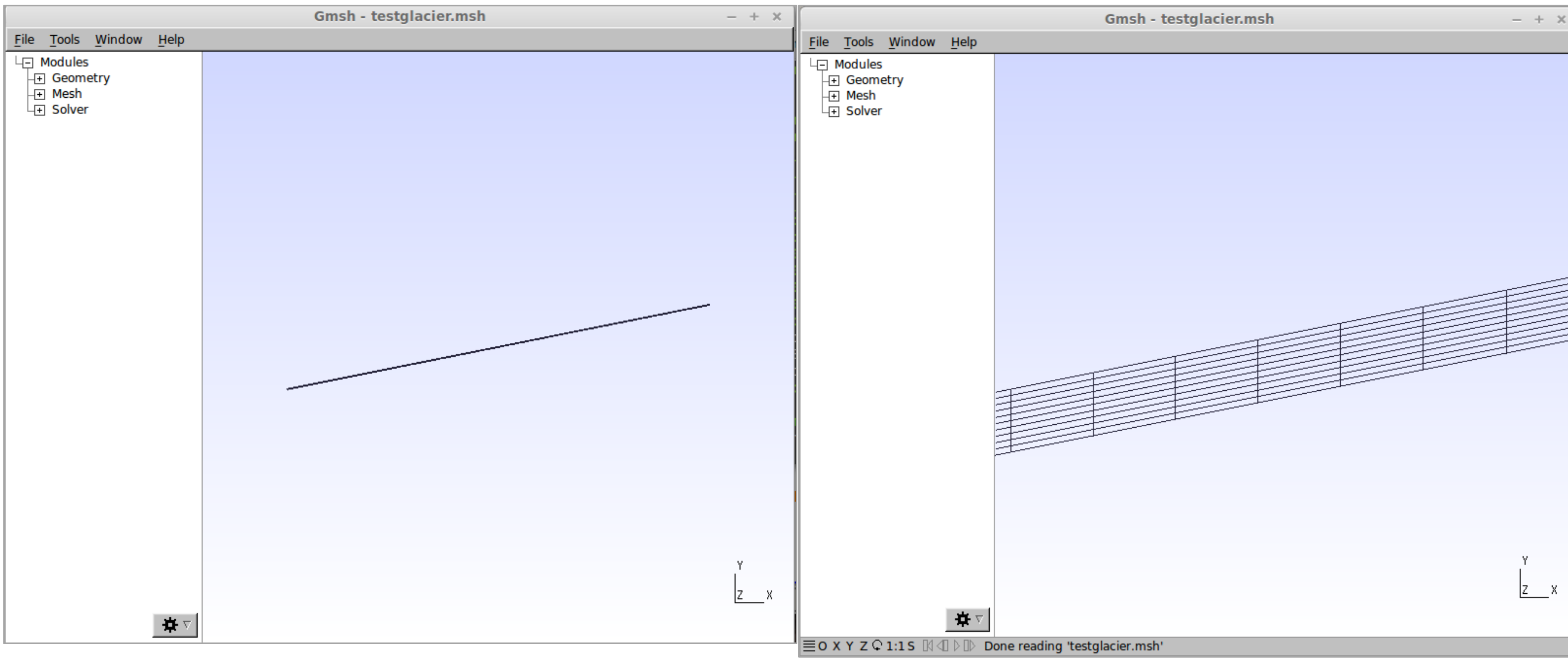
- The distributions are given in the files: **`steady_ELA400_bedrock.dat`**, **`steady_ELA400_surface.dat`**

The diagnostic problem



The diagnostic problem

- We use a 11 deg inclined rectangular mesh (produced with Gmsh) of unit-height



The diagnostic problem

- Open the Gmsh file:

```
$ gmsh testglacier.geo
```

- Go to **Mesh** and press the **2D** button
- **Save** the mesh
- Use ElmerGrid to convert the mesh:

```
> ElmerGrid 14 2 testglacier.msh\
  -autoclean -order 0.1 1.0 0.01
```

Needed to clean up geometry

Orders the numbering in x y z –directions (highest number fastest)

The diagnostic problem

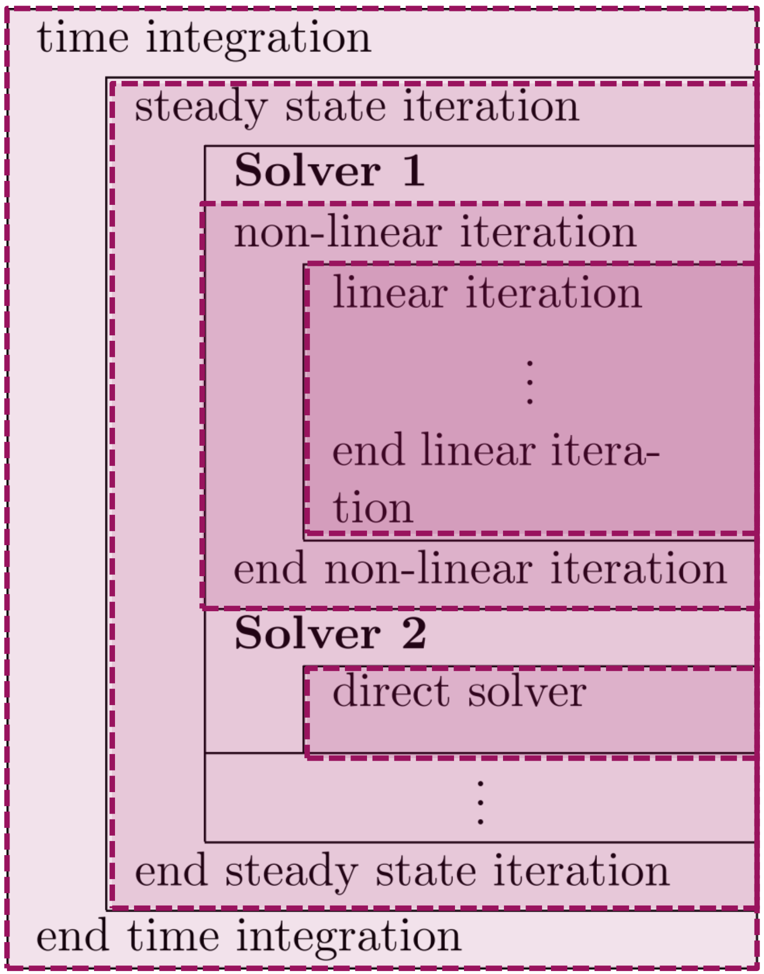
- Open the Solver Input File (SIF)

```
$ emacs Stokes_diagnostic.sif
```

- Steady state simulation = diagnostic

```
Simulation
  Max Output Level = 4
  Coordinate System = "Cartesian 2D"
  Coordinate Mapping(3) = 1 2 3
  Simulation Type = "Steady"
  Steady State Max Iterations = 1
  Output Intervals = 1
  Output File = "Stokes_ELA400_diagnostic.result"
  Post File = "Stokes_ELA400_diagnostic.vtu" ! use .ep suffix for leagcy format
  Initialize Dirichlet Conditions = Logical False
End
```

The diagnostic problem



1. `Timestep Intervals`
2. `Steady State Max Iterations`
3. `Nonlinear Max Iterations`
4. `Linear System Max Iterations`
4. `Linear System Convergence Tolerance`
3. `Nonlinear System Convergence Tolerance`
2. `Steady State Convergence Tolerance`
1.

The diagnostic problem

- Boundary conditions:
  - using array function for reading surfaces
  - **`Real [cubic]`** expects two columned row:

    $x_1 \quad z_1$

    $x_2 \quad z_2$

    …
  - **`include`** just inserts external file (length)
  - Right values interpolated by matching interval of left values for input variable

```
Boundary Condition 1
  Name = "bedrock"
  Target Boundaries = 1
  Compute Normals = Logical True
! include the bedrock DEM, which has two colums
  Bottom Surface = Variable Coordinate 1
  Real cubic
     include  "steady_ELA400_bedrock.dat"
  End
  Velocity 1 = Real 0.0e0
  Velocity 2 = Real 0.0e0
End

Boundary Condition 2
  Name = "sides"
  Target Boundaries(2) = 3 4 ! combine left and right boundary
  Velocity 1 = Real 0.0e0
End

Boundary Condition 3
  Name = "surface"
  Target Boundaries = 2
! include the surface DEM, which has two colums
  Top Surface = Variable Coordinate 1
  Real cubic
     include  "steady_ELA400_surface.dat"
  End
  Depth = Real 0.0
End
```

The diagnostic problem

- Now, run the case:

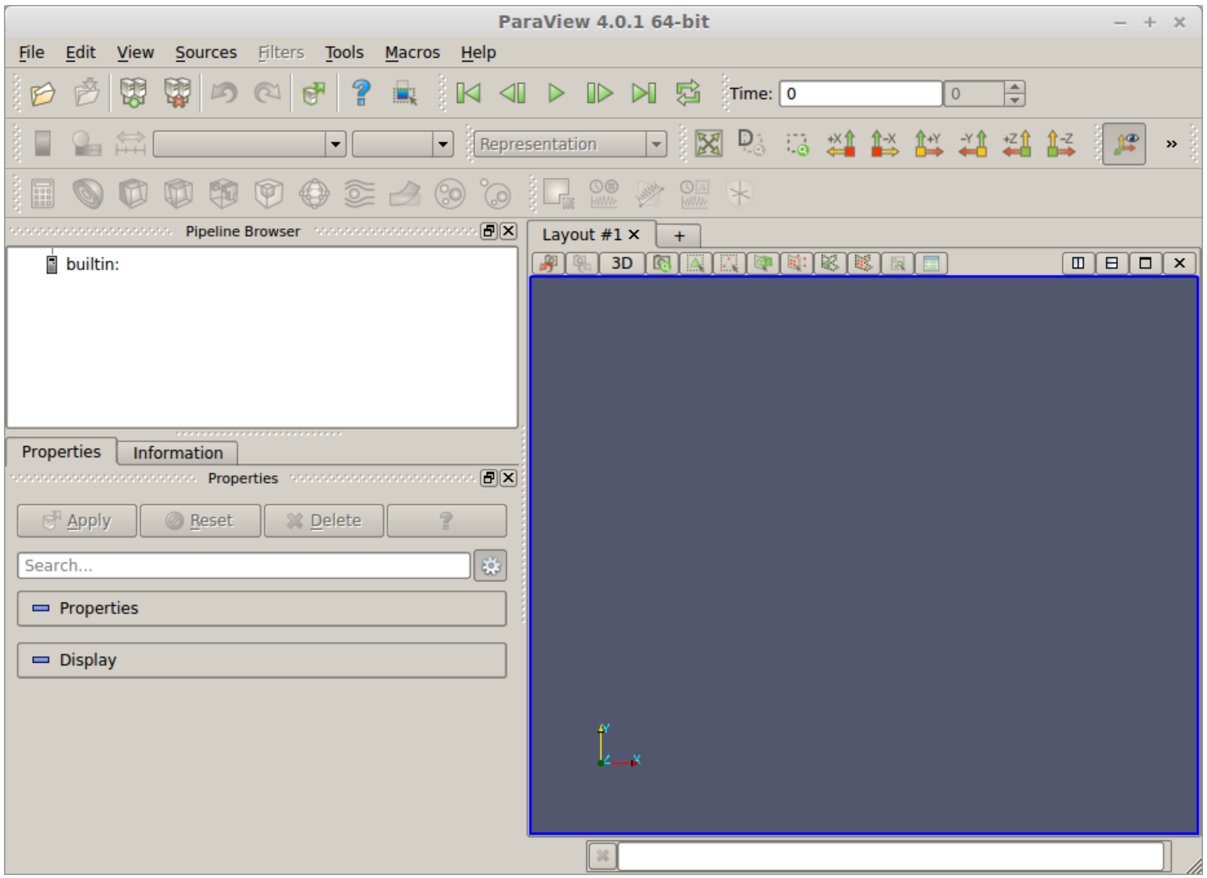
  `$ ElmerSolver Stokes_diagnostic.sif`

  – You will see the convergence history displayed:

```
FlowSolve: --------------------------------------
FlowSolve:  NAVIER-STOKES ITERATION          23
FlowSolve: --------------------------------------
FlowSolve:
FlowSolve: Starting Assembly...
FlowSolve: Assembly done
FlowSolve: Dirichlet conditions done
ComputeChange: NS (ITER=23) (NRM,RELC): (  1.6112696
0.90361030E-03 ) :: navier-stokes
FlowSolve: iter:   23 Assembly: (s)    0.26    6.04
FlowSolve: iter:   23 Solve:    (s)    0.11    2.62
FlowSolve:  Result Norm     :    1.6112695610649261
FlowSolve:  Relative Change :    9.0361030224648782E-004
```

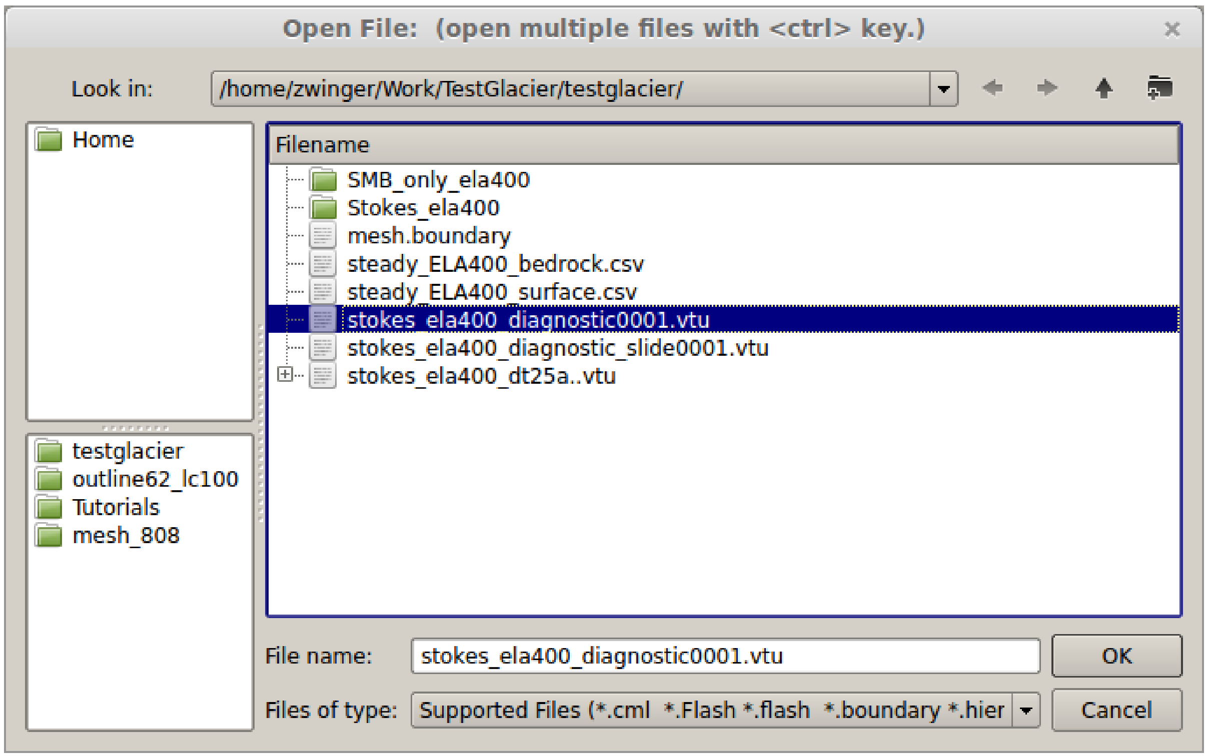
The diagnostic problem

- Post-processing using ParaView: **`$ paraview`**



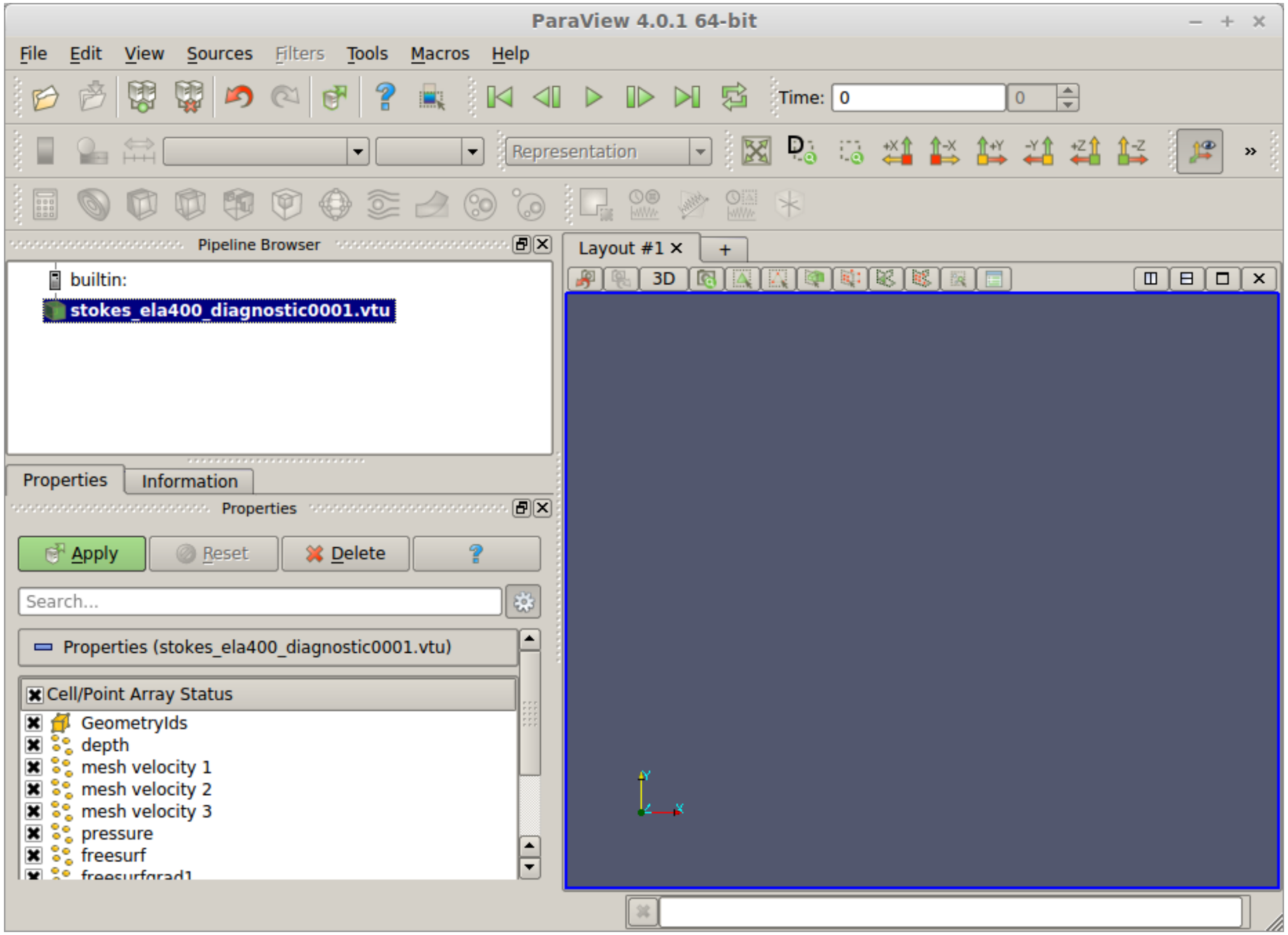
The diagnostic problem

- **File → Open** `stokes_ela400_diagnostic0001.vtu`



The diagnostic problem

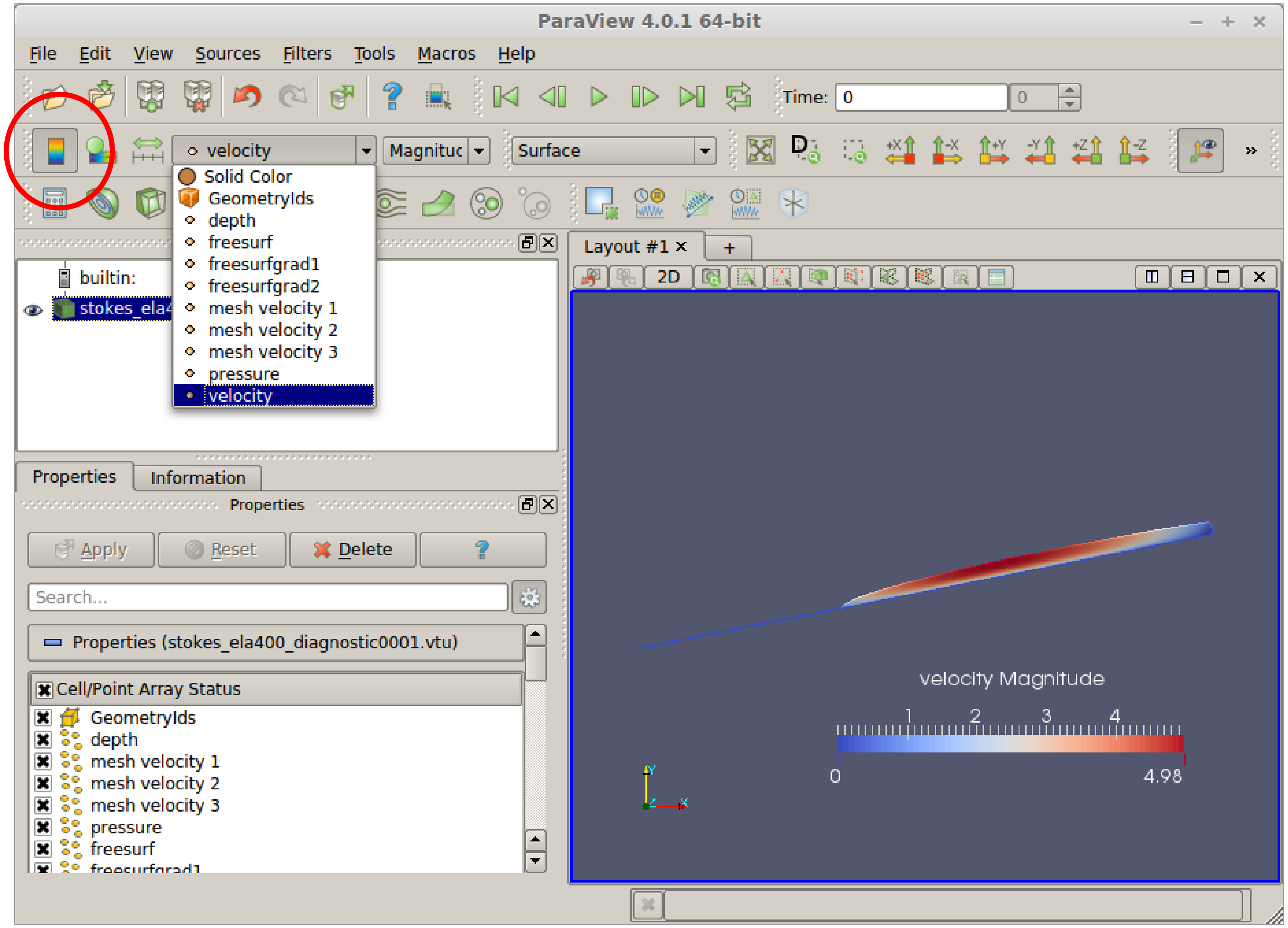
- **Apply**



The diagnostic problem

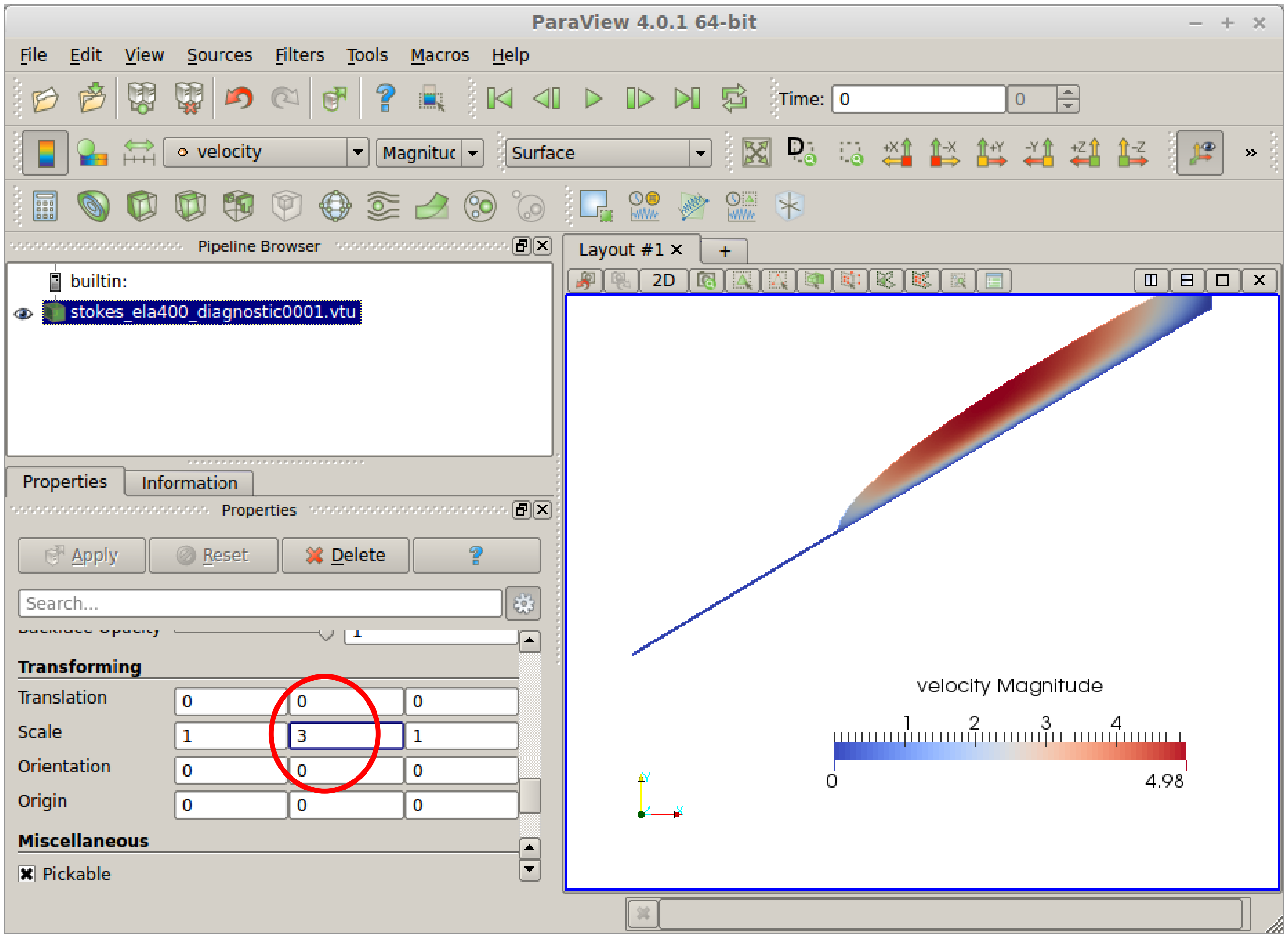
- Change to **velocity**

Press to activate colour bar



The diagnostic problem

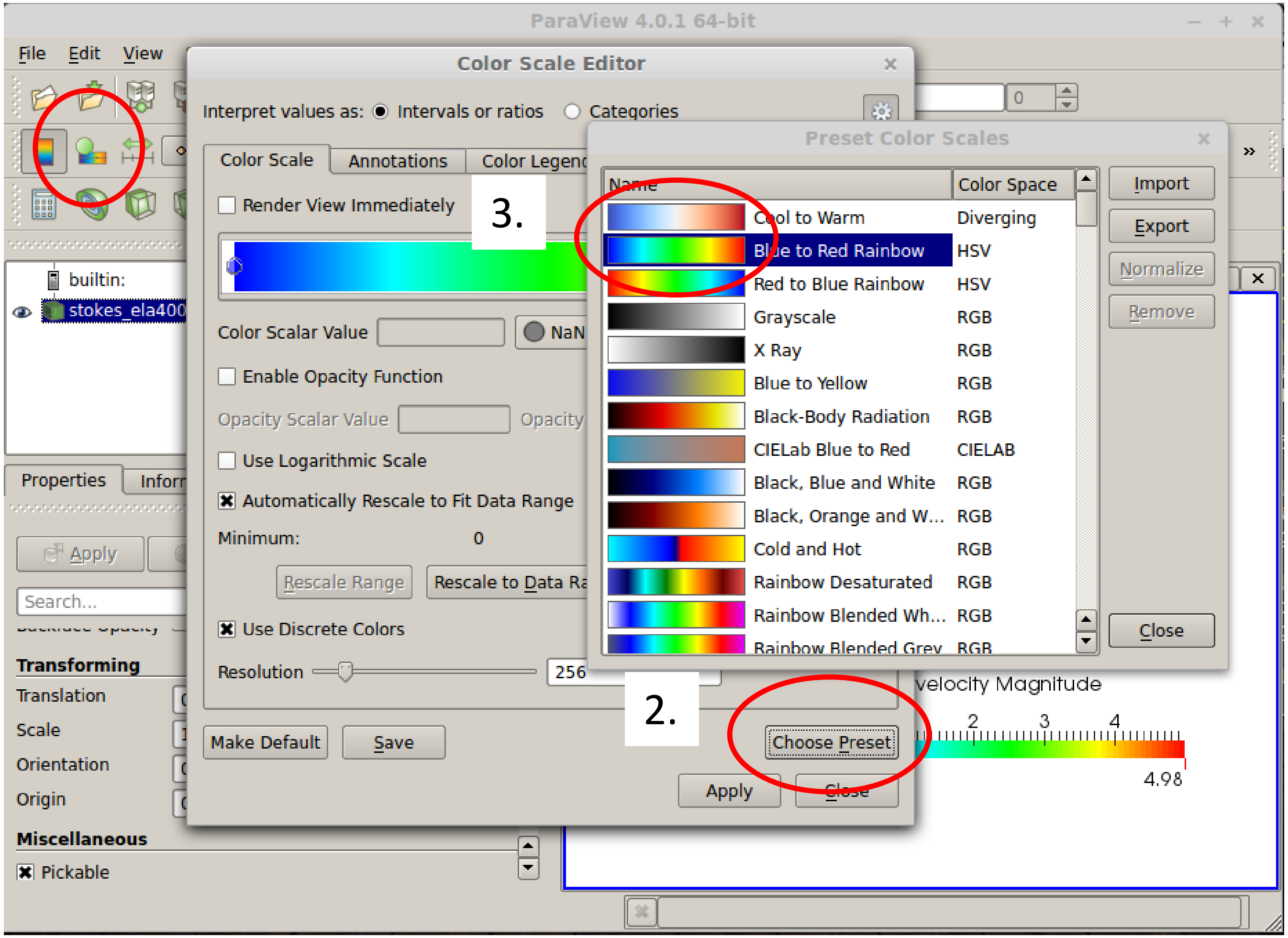
- Scale



The diagnostic problem

- Change colours

1.



Sliding

- Different sliding laws in Elmer
- Simplest: Linear Weertman $\boldsymbol{\tau} = \beta^2 \boldsymbol{u}$
  - This is formulated for the traction $\boldsymbol{\tau}$ and velocity $\boldsymbol{u}$ in tangential plane
- In order to define properties in normal-tangential coordinates: **`Normal-Tangential Velocity = True`**
- β^{-2} is the **`Slip Coefficient {2,3}`** (for the tangential directions 2 and 3)
- Setting normal velocity to zero (no-penetration) **`Velocity 1 = 0.0`**

Sliding

- Now we introduce sliding
  - We deploy a sliding zone between z=300 and 400m

```
Boundary Condition 1
  Name = "bedrock"
  Target Boundaries = 1
  Conpute Normals = Logical True
! include the bedrock DEM, which has two colums
  Bottom Surface = Variable Coordinate 1
  Real cubic
     include  "steady_ELA400_bedrock.dat"
  End
  Normal-Tangential Velocity = True
  Velocity 1 = Real 0.0e0
  Slip Coefficient 2 = Variable Coordinate 2
     Real MATC "(1.0 - (tx > 300.0)*(tx < 400.0))*1000.0 + 1.0/100.0"
End
```

Use normal-tangential coordinate system

Definition of slip Coefficient

Sliding

- Restart from previous run (improved initial guess)

```
Simulation
  Max Output Level = 4
  Coordinate System = "Cartesian 2D"
  Coordinate Mapping(3) = 1 2 3
  Simulation Type = "Steady"
  Steady State Max Iterations = 1
  Output Intervals = 1
  Output File = "Stokes_ELA400_diagnostic_slide.result"
  Post File = "Stokes_ELA400_diagnostic_slide.vtu"
  Initialize Dirichlet Conditions = Logical False
  ! Restart from previous run
  Restart File = "Stokes_ELA400_diagnostic.result"
  Restart Position = 0
End
```

Take last entry

The diagnostic problem

- Now, run the case:

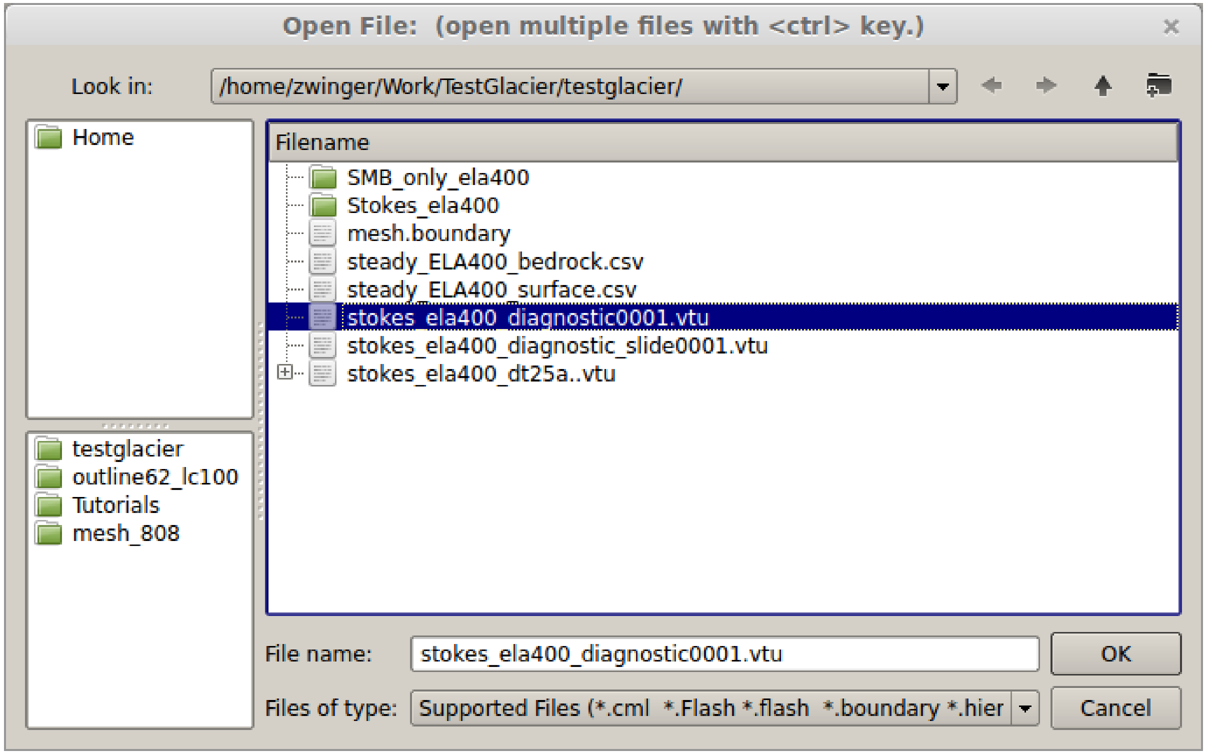
`$ ElmerSolver Stokes_diagnostic_slide.sif`

  – Converged much earlier:

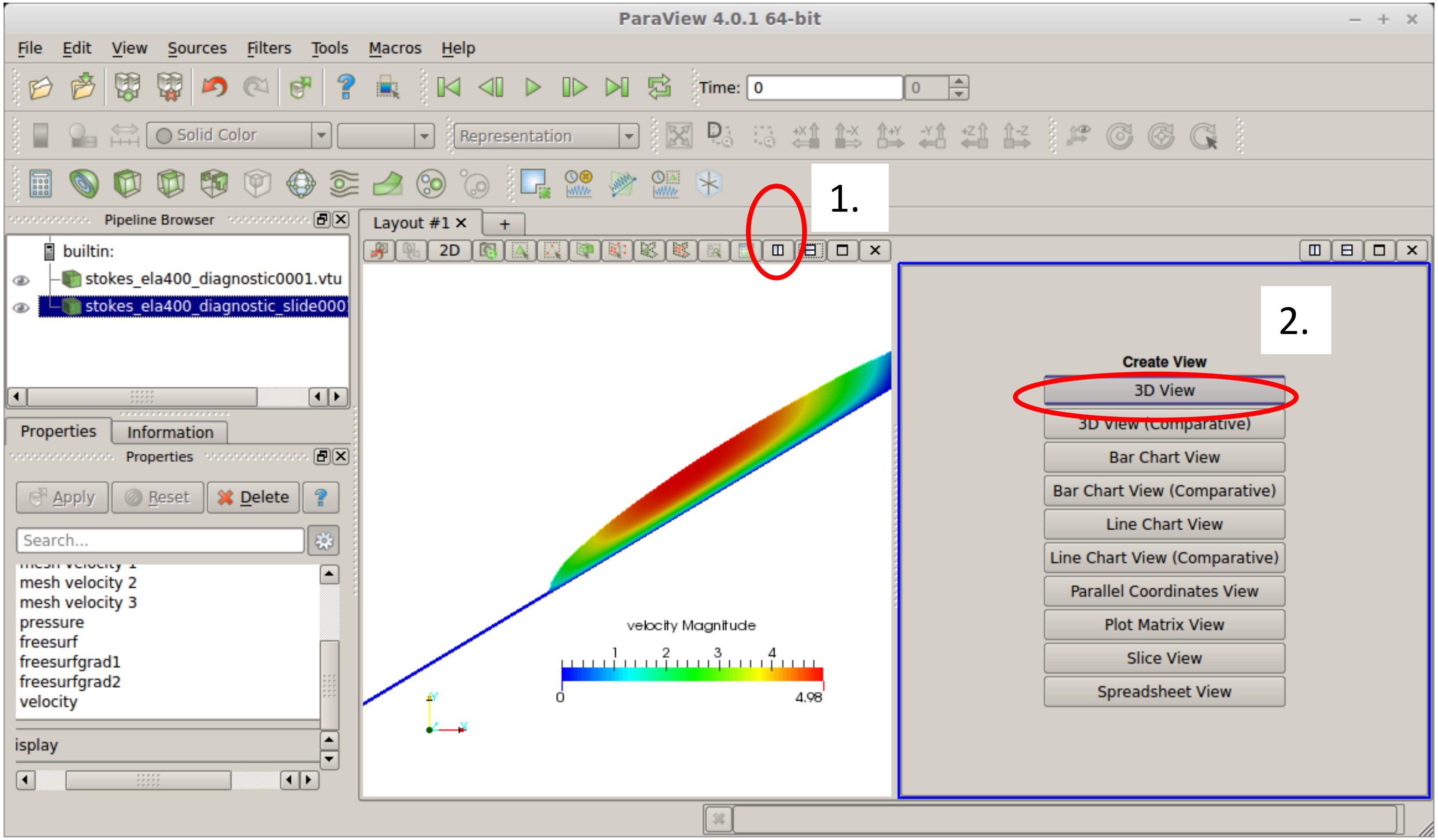
```
FlowSolve: --------------------------------------
FlowSolve:  NAVIER-STOKES ITERATION          12
FlowSolve: --------------------------------------
FlowSolve:
FlowSolve: Starting Assembly...
FlowSolve: Assembly done
FlowSolve: Dirichlet conditions done
ComputeChange: NS (ITER=12) (NRM,RELC): (  3.4915753
0.34732117E-05 ) :: navier-stokes
FlowSolve: iter:   12 Assembly: (s)    0.32    3.53
FlowSolve: iter:   12 Solve:    (s)    0.12    1.38
FlowSolve:  Result Norm     :    3.4915753430899730
FlowSolve:  Relative Change :    3.4732116934487441E-006
ComputeChange: SS (ITER=1) (NRM,RELC): (  3.4915753
2.0000000     ) :: navier-stokes
```

Sliding

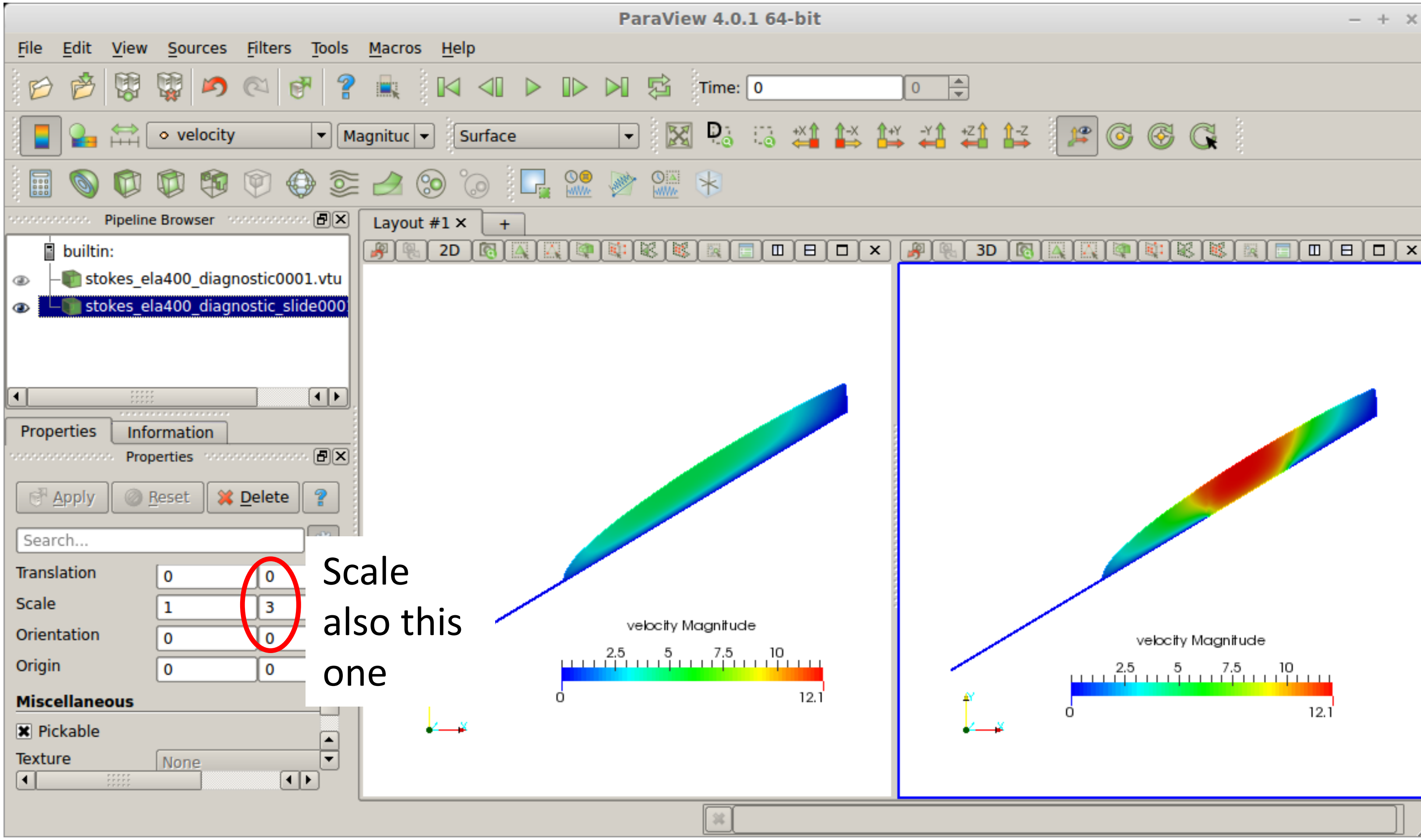
- Load parallel to previous file
- **File → Open**
  `stokes_ela400_diagnostic_slide0001.vtu`



Sliding


ParaView 4.0.1 64-bit
File Edit View Sources Filters Tools Macros Help
Time: 0
Solid Color
Representation
1.
Pipeline Browser
builtin:
stokes_ela400_diagnostic0001.vtu
stokes_ela400_diagnostic_slide000
Layout #1
2D
Properties Information
Apply Reset Delete
Search...
mesh velocity 2
mesh velocity 3
pressure
freesurf
freesurfgrad1
freesurfgrad2
velocity
isplay
velocity Magnitude
0
4.98
2.
Create View
3D View
3D View (Comparative)
Bar Chart View
Bar Chart View (Comparative)
Line Chart View
Line Chart View (Comparative)
Parallel Coordinates View
Plot Matrix View
Slice View
Spreadsheet View

Sliding



Scale also this one

Heat transfer

- Adding heat transfer:
  - Add `ElmerIceSolvers TemperateIceSolver` with variable name `Temp` (see next slide)
  - Surface temperature distribution: linear from 273.15K at z=0m to 263.15K at z=1000m

```
Temp = Variable Coordinate 2
     Real
           0.0   273.15
        1000.0   263.15
     End
```

  - Geothermal heat flux of 200 mW m^{-2} at bedrock

```
Temp Flux BC = Logical True
Temp Heat Flux = Real $ 0.200 * (31556926.0)*1.0E-06
```

Heat transfer

```
Solver 4
  Equation = String "Homologous Temperature Equation"
  Procedure =  File "ElmerIceSolvers" "TemperateIceSolver"
  Variable = String "Temp"
  Variable DOFs = 1
  Stabilize = True
  Optimize Bandwidth = Logical True
  Linear System Solver = "Iterative"
  Linear System Direct Method = UMFPACK
  Linear System Convergence Tolerance = 1.0E-06
  Linear System Abort Not Converged = False
  Linear System Preconditioning = "ILU1"
  Linear System Residual Output = 0
  Nonlinear System Convergence Tolerance = 1.0E-05
  Nonlinear System Max Iterations = 100
  Nonlinear System Relaxation Factor = Real 9.999E-01
  Steady State Convergence Tolerance = 1.0E-04
End
```

Heat transfer

- Material parameters in Material section

```
Material 1
…
 ! Heat transfer stuff
  Temp Heat Capacity = Variable Temp
    Real MATC "capacity(tx)*(31556926.0)^(2.0)"

  Temp Heat Conductivity = Variable Temp
    Real MATC "conductivity(tx)*31556926.0*1.0E-06"
End
```

- Using defined MATC-functions for
  - Capacity: $c(T) = 146.3 + (7.253 \cdot T[\mathrm{K}])$
  - Conductivity: $\kappa(T) = 9.828 \exp\left(-5.7 \times 10^{-3} \cdot T[\mathrm{K}]\right)$

Heat transfer

- Material parameters in Material section

```
!! conductivity
$ function conductivity(T)  { _conductivity=9.828*exp(-5.7E-03*T)}
!! capacity
$ function capacity(T) { _capacity=146.3+(7.253*T)}
```

- Using defined MATC-functions for
  - Capacity: $c(T) = 146.3 + (7.253 \cdot T[\mathrm{K}])$
  - Conductivity: $\kappa(T) = 9.828 \exp\left(-5.7 \times 10^{-3} \cdot T[\mathrm{K}]\right)$

Heat transfer

- Now, run the case:

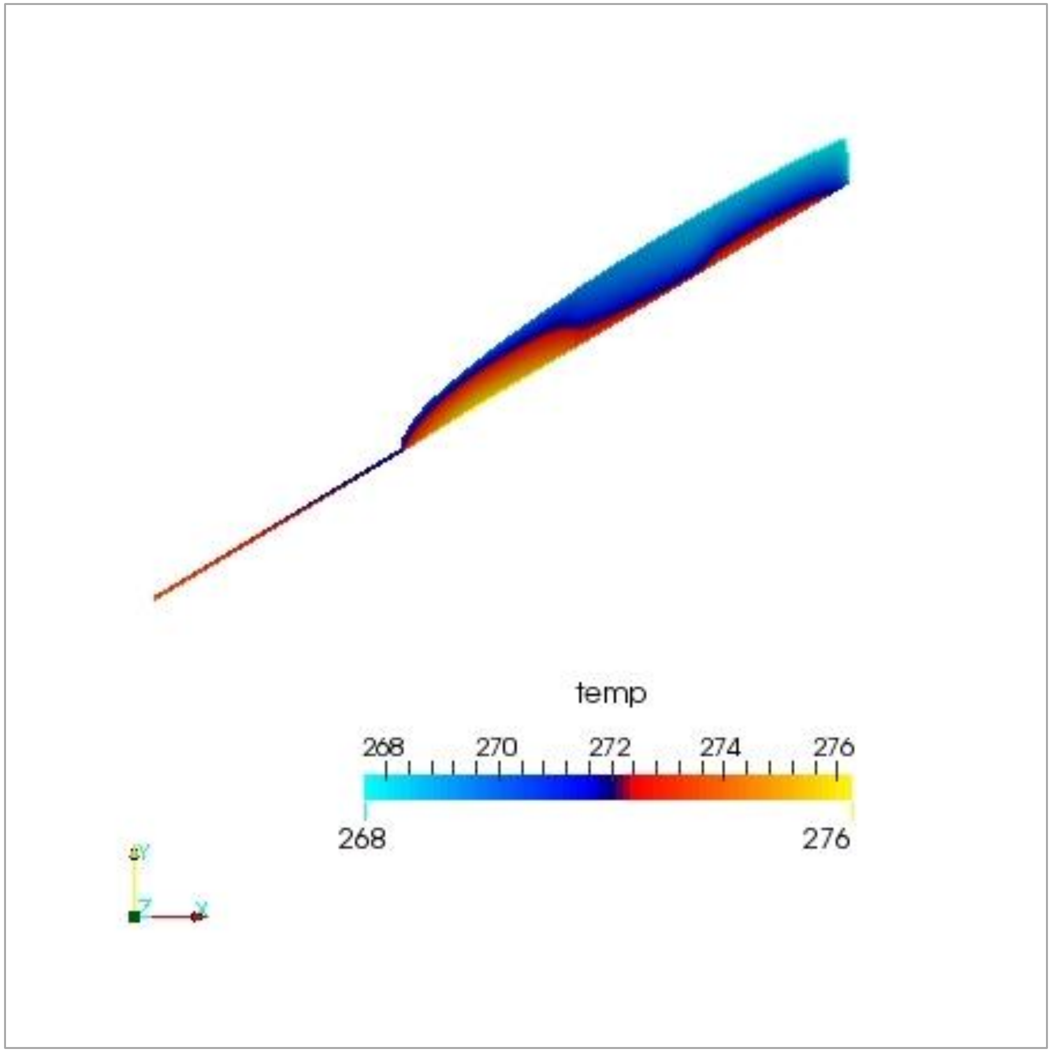
```
$ ElmerSolver Stokes_diagnostic_temp.sif
```

- It goes pretty quick, as we only have one-way coupling and hence don’t even execute the Stokes solver

```
Solver 3
  Exec Solver = "Never" ! we have a solution from previous case
  Equation = "Navier-Stokes"
```

Heat transfer

Heat transfer



- Due to high geothermal heatflux we have areas above pressure melting point
- We have to account for this

Heat transfer

- Constrained heat transfer:
  - Including following lines in Solver section
    `ElmerIceSolvers TemperateIce`

```
 ! the contact algorithm (aka Dirichlet algorithm)
 !-----------------------------------------------------
  Apply Dirichlet = Logical True
 ! those two variables are needed in order to store
 ! the relative or homologous temperature as well
 ! as the residual
 !-------------------------------------------------
Exported Variable 1 = String "Temp Homologous"
Exported Variable 1 DOFs = 1
Exported Variable 2 = String "Temp Residual"
Exported Variable 2 DOFs = 1
```

Heat transfer

- Constrained heat transfer:
  - Also introduce the upper limit for the temperature (a.k.a. pressure melting point) in the Material section

```
Temp Upper Limit = Variable Depth
         Real MATC "273.15 - 9.8E-08 * tx * 910.0 * 9.81"
```

$$T_{\mathrm{pm}} = T_0 + \beta_{\mathrm{c}} p \qquad\qquad p \approx \rho_{\mathrm{ice}} g d$$

Heat transfer

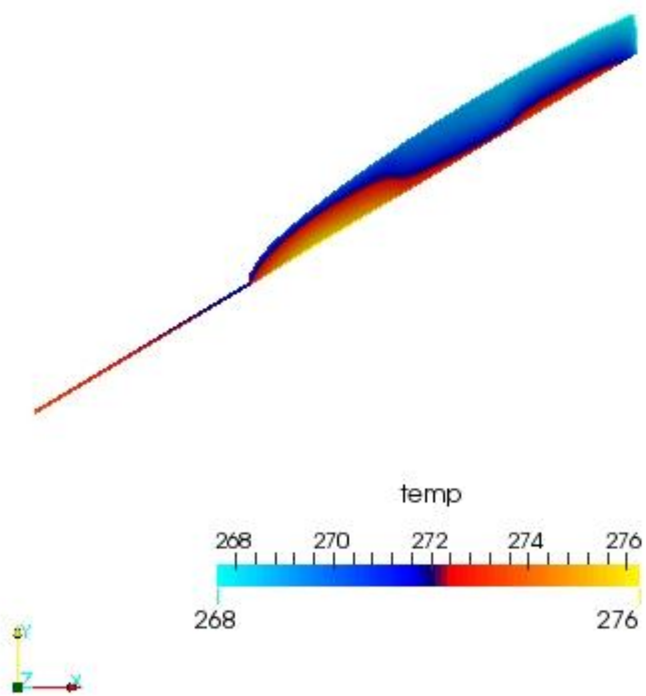
- Now, run the case:

```
$ ElmerSolver \
    Stokes_diagnostic_temp_constrained.sif
```

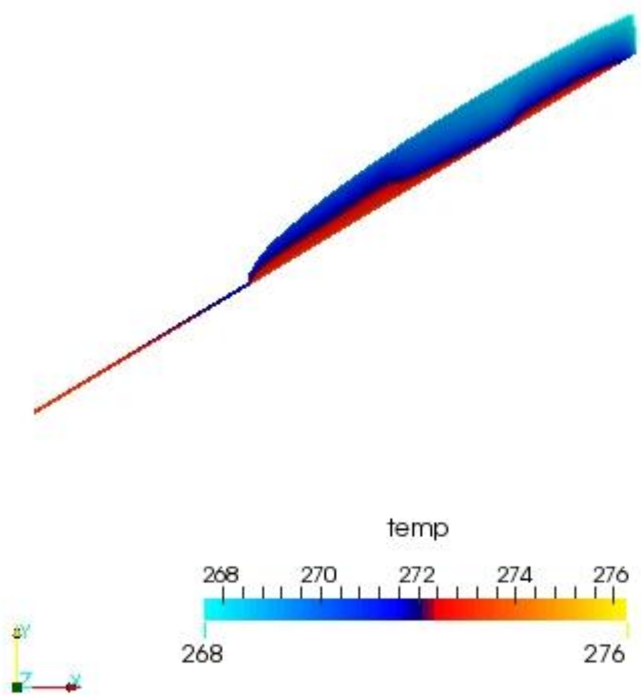
- Already from the norm (~ averaged nodal values) it comes clear that values are in general now lower

```
TemperateIceSolver (temp): iter:    5 Assembly: (s)    1.36    6.77
TemperateIceSolver (temp): iter:    5 Solve:    (s)    0.00    0.01
TemperateIceSolver (temp):  Result Norm   :    271.78121462656480
TemperateIceSolver (temp):  Relative Change :
5.0215061382786350E-006
ComputeChange: SS (ITER=1) (NRM,RELC): (  271.78121      2.0000000
) :: homologous temperature equation
```

Heat transfer



Unconstrained



Constrained

Heat transfer

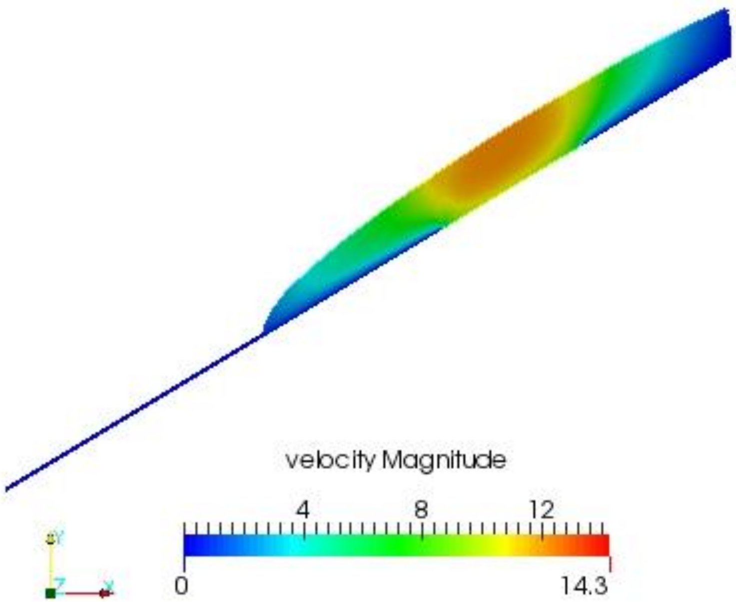
- Thermo-mechanically coupled simulation:
  - We have to iterate between Stokes and HTEq.

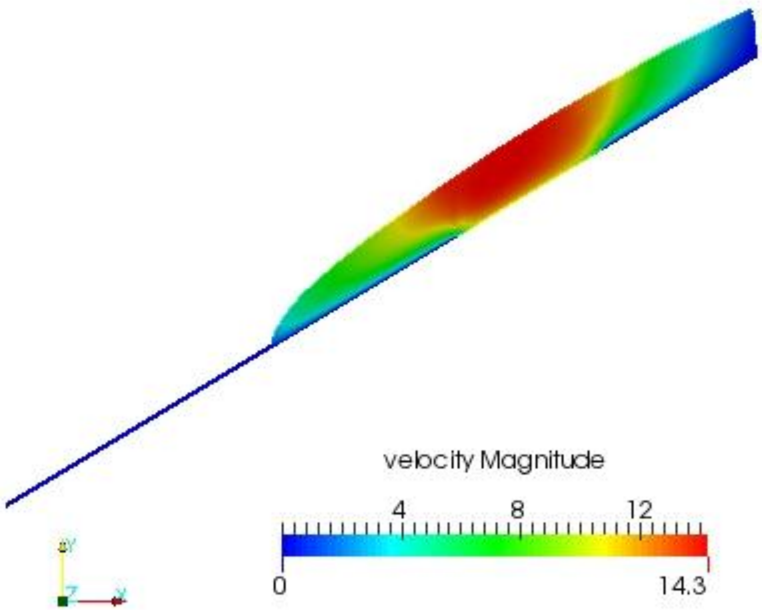
```
Steady State Max Iterations = 20
```

  - Coupling to viscosity in Material section

```
! the variable taken to evaluate the Arrhenius law
! in general this should be the temperature relative
! to pressure melting point. The suggestion below plugs
! in the correct value obtained with TemperateIceSolver
Temperature Field Variable = String "Temp Homologous"
```

Heat transfer





Uncoupled (constant T)

Thermo-mechanically coupled

PROGNOSTIC RUN

Starting from a flat mesh (resembling ice-free conditions) we will

- Set up a transient run
- Introduce the kinematic free surface condition (run on surface)
- Couple it to the climatic mass balance
- Introduce vertically aligned mesh adaption
- Show, how to do transient post-processing in ParaView

The prognostic problem

- Glacier with ~11 deg constant inclination
- Standard accumulation/ablation function

$$a(z) = \lambda\, z + a(z = 0)$$

- Or in terms of ELA (equilibrium line altitude):

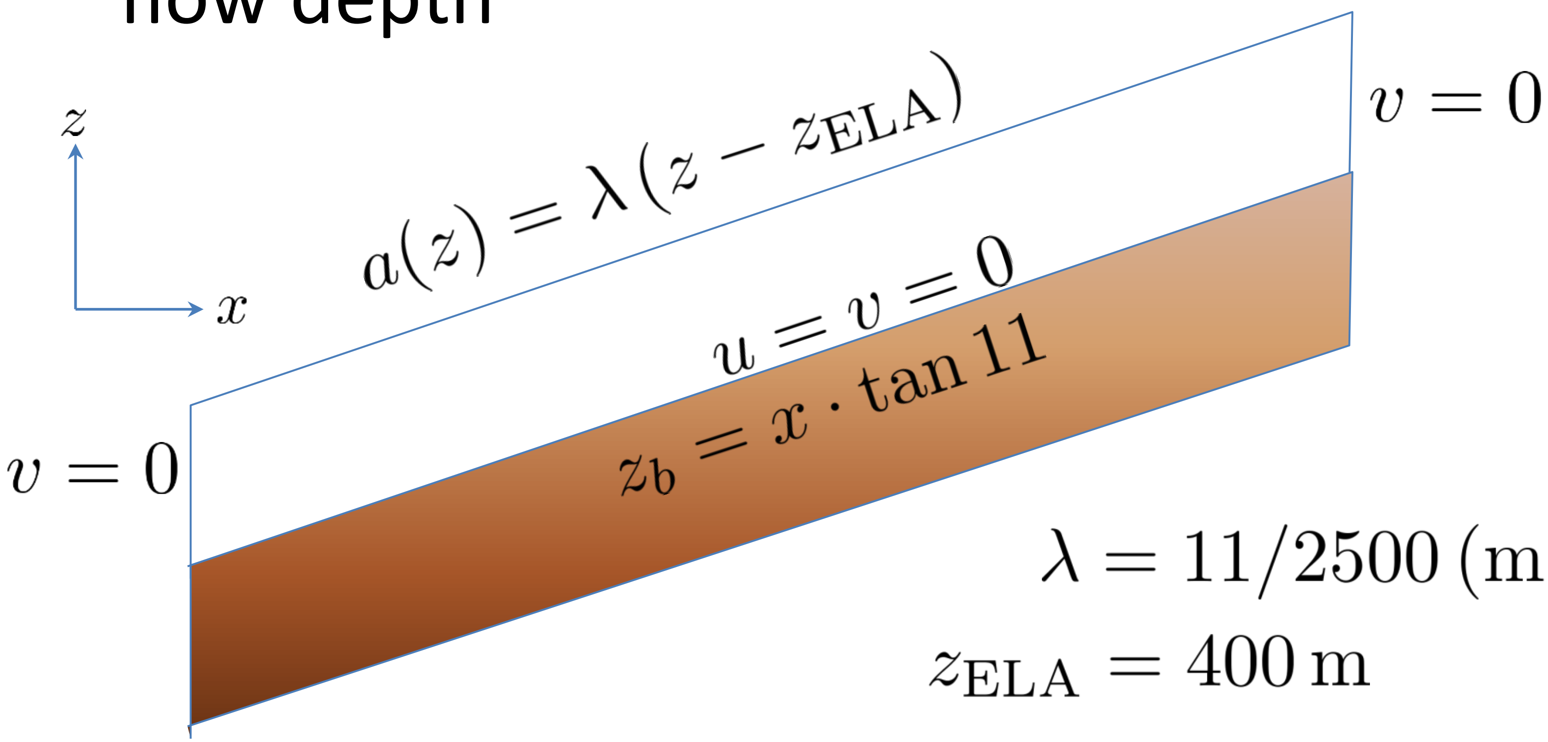
$$a_{\mathrm{ELA}} = \lambda\, z_{\mathrm{ELA}} + a_0 = 0$$

- We know lapserate, λ, and z_{ELA} and have to define

$$a_0 = -\lambda\, z_{\mathrm{ELA}}$$

The prognostic problem

- From x=[0 :2500], z=[0:500]
- Setting mesh with 10 vertical levels with 5m flow depth

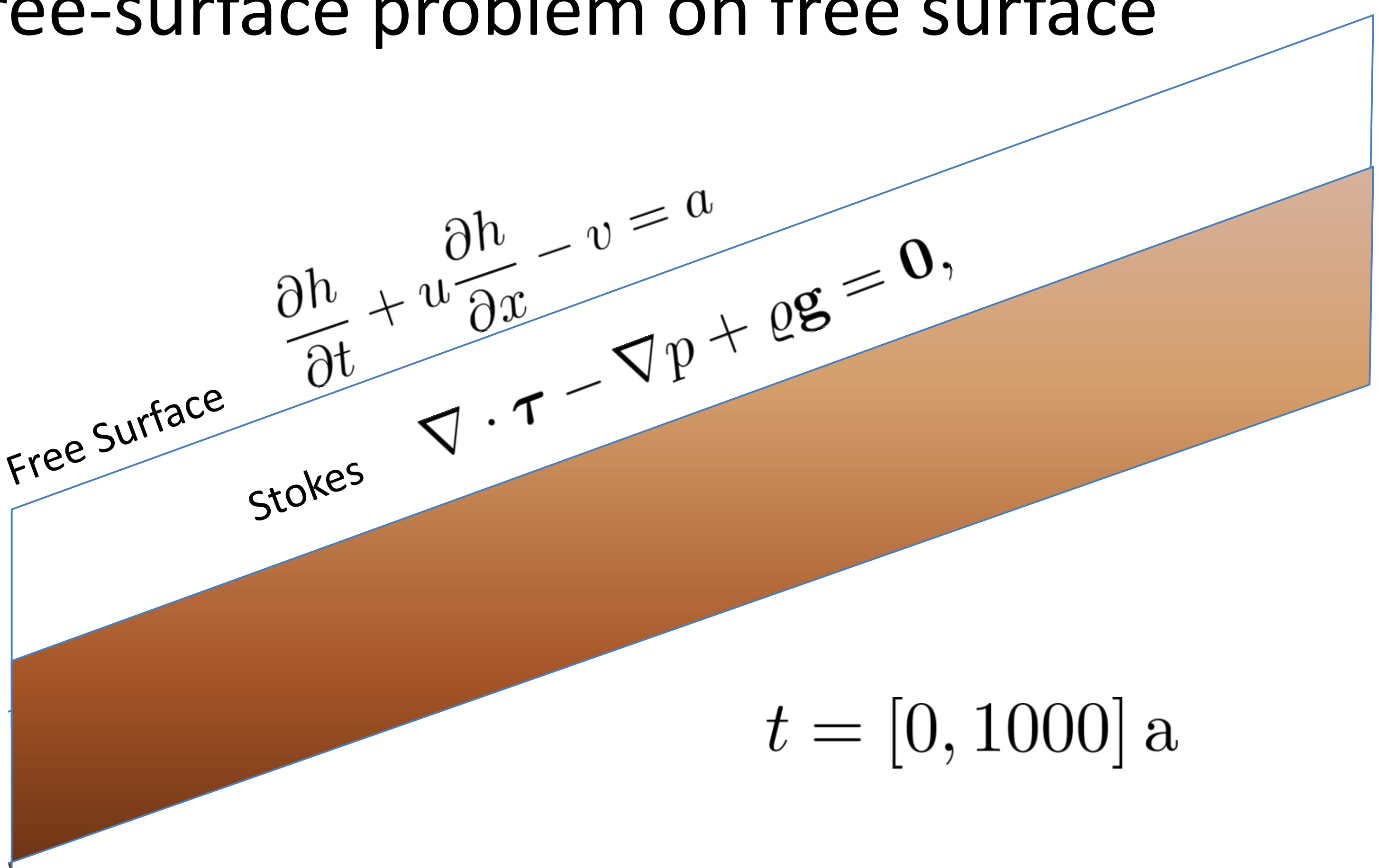


$$\lambda = 11/2500\,(\text{m/a})\,\text{m}^{-1}$$

$$z_{\text{ELA}} = 400\,\text{m}$$

The prognostic problem

- Flow problem (Navier-Stokes) in ice
- Free-surface problem on free surface



$$t = [0, 1000]\,\mathrm{a}$$

The prognostic problem

- Changing to transient case (`Stokes_prognostic.sif`)

```
Simulation
  …
  Simulation Type = "Transient"
  …
End
```

- MATC function for accumulation/ablation

```
$ function accum(X) {\
  lapserate = (11.0/2750.0);\
  ela = 400.0;\
  asl = -ela*lapserate;\
  _accum = lapserate*X(1) + asl;\
}
```

- As `BodyForce` for `FreeSurfaceSolver`

The prognostic problem

```
Solver 3
   Exec Solver = always
   Equation = "Free Surface"
   Variable = String "Zs"
   Variable DOFs =  1
   Exported Variable 1 = -dofs 1 "Zs Residual"
   Exported Variable 2 = -dofs 1 "RefZs"
   Procedure = "FreeSurfaceSolver" "FreeSurfaceSolver"
   Linear System Solver = Iterative
   Linear System Max Iterations = 1500
   Linear System Iterative Method = BiCGStab
   Linear System Preconditioning = ILU0
   Linear System Convergence Tolerance = Real 1.0e-7
   Linear System Abort Not Converged = False
   Linear System Residual Output = 1
   Nonlinear System Max Iterations = 100
   Nonlinear System Convergence Tolerance  = 1.0e-6
   Nonlinear System Relaxation Factor = 0.60
   Steady State Convergence Tolerance = 1.0e-03
   Stabilization Method = Bubbles
   Apply Dirichlet = Logical True
End
```

The prognostic problem

- Set initial z-values

```
Initial Condition 2
   …
   Zs = Equals Coordinate 2
   RefZs = Equals Coordinate 2
   …
End
```

- Accumulation in Body Force

```
Body Force 2
    Zs Accumulation Flux 1 = Real 0.0e0
    Zs Accumulation Flux 2 = Variable Coordinate 1, Coordinate 2
         Real MATC "accum(tx)"
End
```

- Maximum and minimum value

```
Material 2
 Min Zs = Variable RefZs
    Real MATC "tx - 0.1"
 Max Zs = Variable RefZs
      Real MATC "tx + 600.0"
End
```

The prognostic problem

- Need a solver to move the mesh
  - This one uses the structured extruded mesh

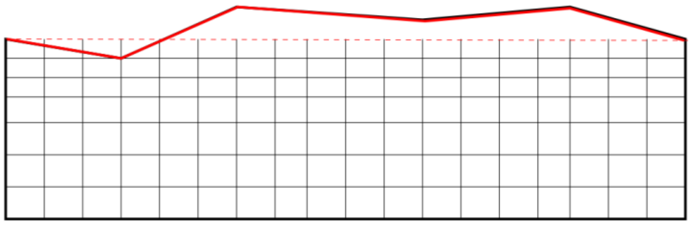
```
Solver 4
   Exec Solver = "after timestep"
   Equation = "MapCoordinate"
   Procedure = "StructuredMeshMapper" "StructuredMeshMapper"
   Active Coordinate = Integer 2
   ! the mesh-update is y-direction
   ! For time being this is currently externally allocated
   Mesh Velocity Variable = String "Mesh Velocity 2"
   ! The 1st value is special as the mesh velocity
   ! could be unrelistically high
   Mesh Velocity First Zero = Logical True
   Dot Product Tolerance = Real 0.01
End
```

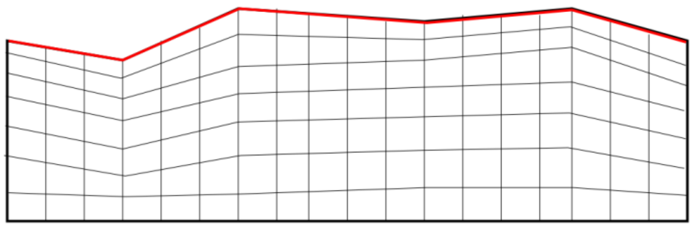
The prognostic problem

- Coupling of free surface

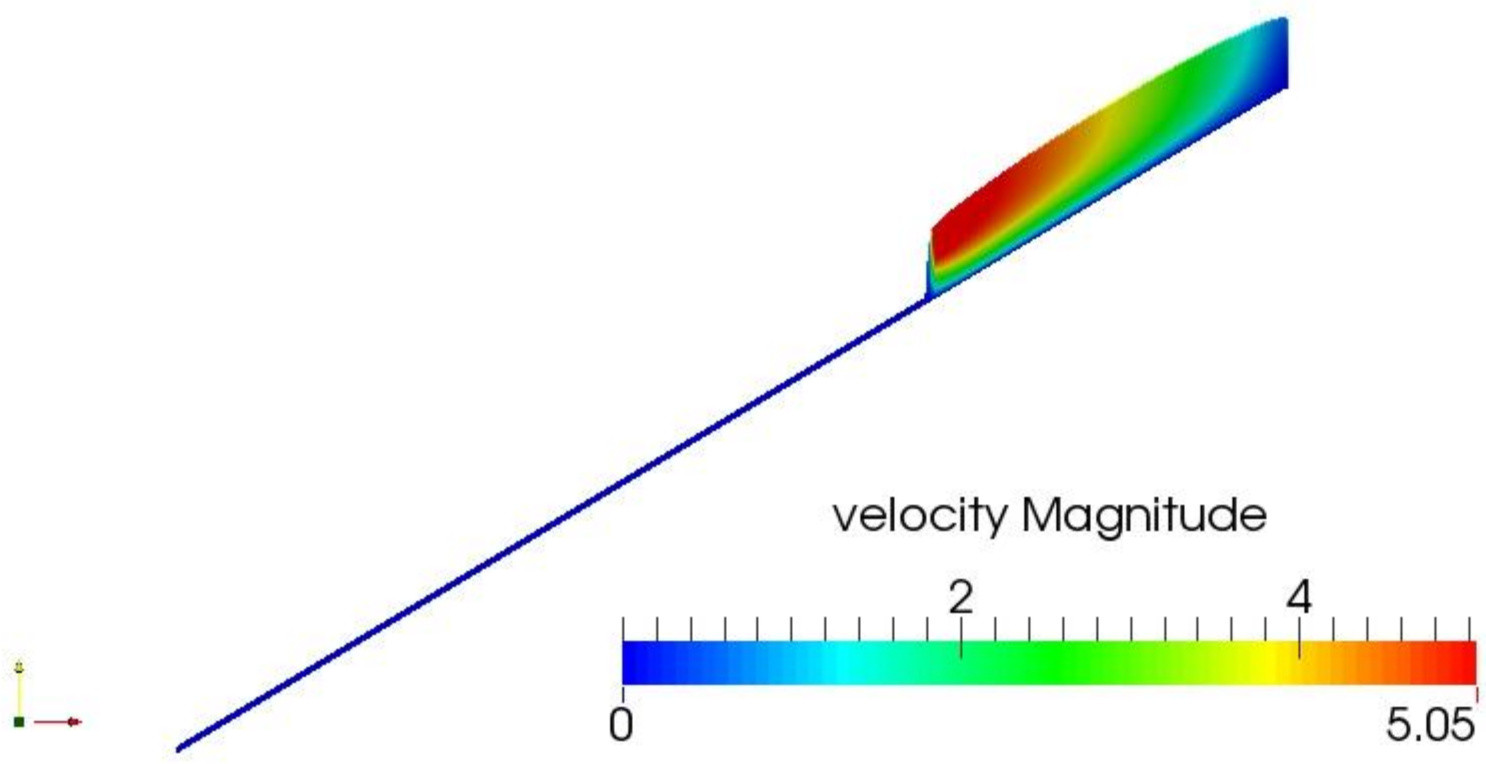
```
Boundary Condition 3
  Name = "surface"
  Top Surface = Equals "Zs"
  Target Boundaries = 2
  Body ID = 2
  Depth = Real 0.0
End
```

- Bodies on surfaces
  - Free surface condition is a dimension-1 PDE
  - Need to run it on body defined on surface





The prognostic problem



Time dependent boundary conditions

- Adding time-dependent ELA to show retreat (`Stokes_prognostic_change.sif`)

```
$ function accum(X) {\
  lapserate = (11.0/2750.0);\
  ela = 400.0 + (0.5*X(2));\
  asl = -ela*lapserate;\
  if (X(0) > 2500)\
    {_accum = 0.0;}\
  else\
   { _accum = lapserate*X(1) + asl;}\
}

Body Force 2
  Name = "BodyForce1"
  Zs Accumulation Flux 1 = Real 0.0e0
  Zs Accumulation Flux 2 = Variable Coordinate 1, Coordinate 2,\
                           Time
    Real MATC "accum(tx)"
End
```

Time dependent boundary conditions

- Similar exercise, but with user defined function (`Stokes_prognostic_changeUDF.sif`)

```
Body Force 2
  Name = "BodyForce1"
  Zs Accumulation Flux 1 = Real 0.0e0
  !Zs Accumulation Flux 2 = Variable Coordinate 1, Coordinate 2,\
                           Time
  !  Real MATC "accum(tx)"
  Zs Accumulation Flux 2 = Variable Coordinate 2, Time
     Real Procedure "accumulation" "getAccumulation"
End
```

- Also introducing a cut-off value of the accumulation above a certain elevation
- Compile the file `accumulation.f90`

```
$ elmerf90 accumulation.f90 -o accumulation.so
```

Time dependent boundary conditions

emacs@zwinger-VM

File Edit Options Buffers Tools F90 Help

Save Undo

```
FUNCTION getAccumulation(  Model, Node, InputArray)RESULT(accum)
  ! provides you with most Elmer functionality
  USE DefUtils
  ! saves you from stupid errors
  IMPLICIT NONE
  ! the external variables
  !----------------------------------------------------------------------
  TYPE(Model_t) :: Model     ! the access point to everything about the model
  INTEGER :: Node            ! the current Node number
  REAL(KIND=dp) :: InputArray(2) ! Contains the arguments passed to the function
  REAL(KIND=dp) :: accum      ! the result
  !----------------------------------------------------------------------
  ! internal variables
  !----------------------------------------------------------------------
  REAL(KIND=dp) :: lapserate, ela0, dElaDt, elaT, asl,&
       inittime, time, elevation, cutoff
  LOGICAL :: FirstTime=.TRUE.
  ! Remember this value
  SAVE FirstTime, inittime

  ! lets hard-code our values
```

-:--- accumulation.f90   Top L20   (F90)

Time dependent boundary conditions

emacs@zwinger-VM

File Edit Options Buffers Tools F90 Help

Save Undo

```
! lets hard-code our values
lapserate = 11.0_dp/2750.0_dp
ela0 = 400.0_dp
dElaDt = 0.5_dp
cutoff = 600.0_dp

! copy input
elevation = InputArray(1)
time = InputArray(2)
WRITE (Message, '(A,E10.2,A,E10.2)')  "elevation=", elevation, "time=", time
CALL INFO("getAccumulation", Message, Level=9)

! store the initial time, to be sure to have relative times
IF (FirstTime) THEN
   inittime = time
   FirstTime = .FALSE.
END IF

! get change of ELA with time
elaT = ela0 + dElaDt * (time - inittime)
```

-:--- **accumulation.f90** 57% L22 (F90)

Time dependent boundary conditions

emacs@zwinger-VM

File Edit Options Buffers Tools F90 Help

Save Undo

```
  IF (FirstTime) THEN
     inittime = time
     FirstTime = .FALSE.
  END IF

  ! get change of ELA with time
  elaT = ela0 + dElaDt * (time - inittime)

  ! lets do the math
  asl = -elaT*lapserate
  IF (elevation > cutoff) elevation = cutoff
  accum = lapserate*elevation + asl

  RETURN

END FUNCTION getAccumulation
```

-:--- **accumulation.f90** Bot L45 (F90)