A real world application
Tête Rousse Glacier

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Tête Rousse Glacier

✓ **Context**

- The history of Tête Rousse Glacier
- The 2010 water filled-cavity
- Analysis of the cavity roof stability (Autumn 2010)

✓ **Step 1**

- Tête Rousse Glacier flow without a water filled-cavity (diagnostic)

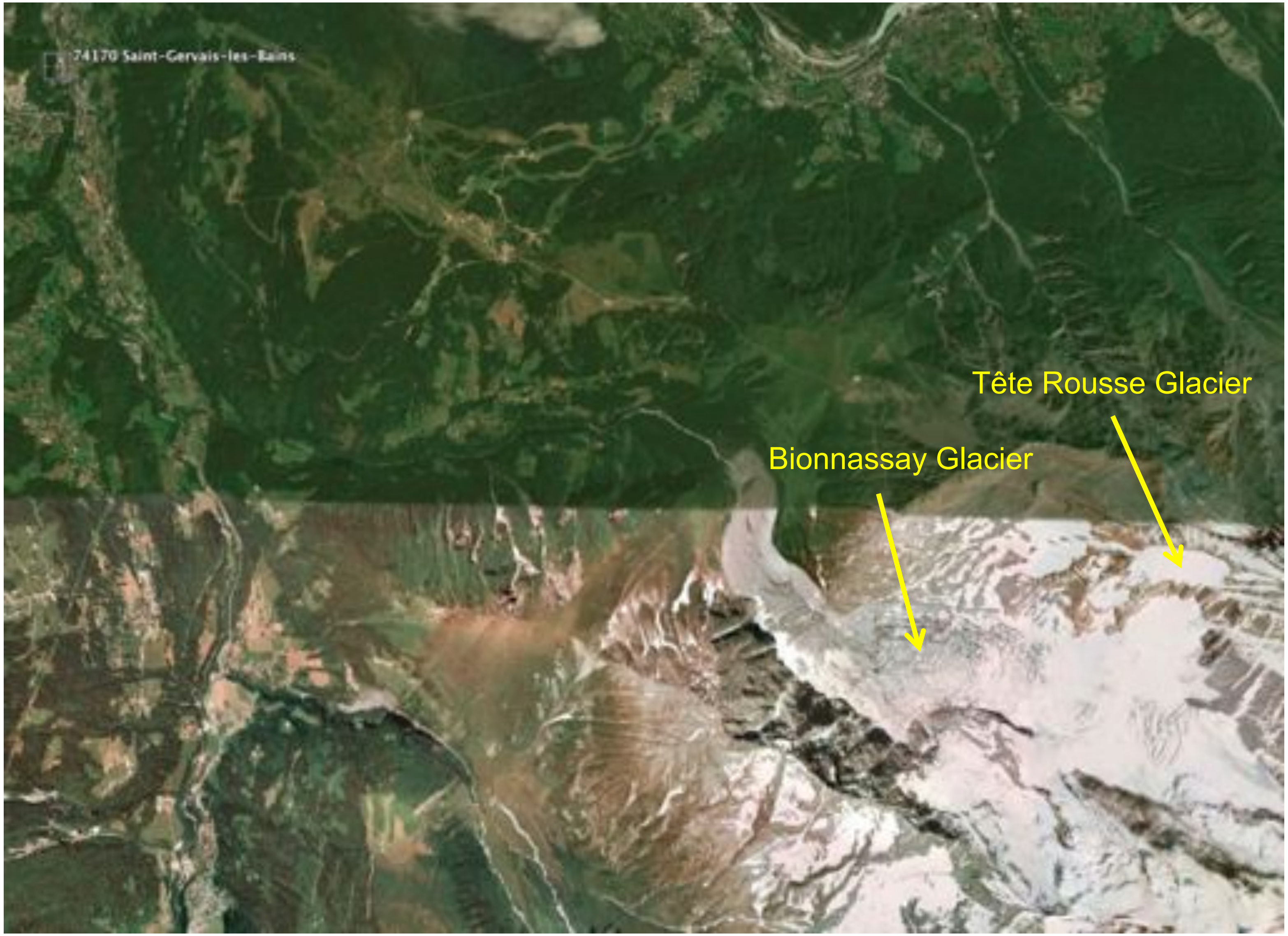
✓ **Step 2**

- Influence of an empty cavity below Tête Rousse Glacier (diagnostic)

✓ **Step 3**

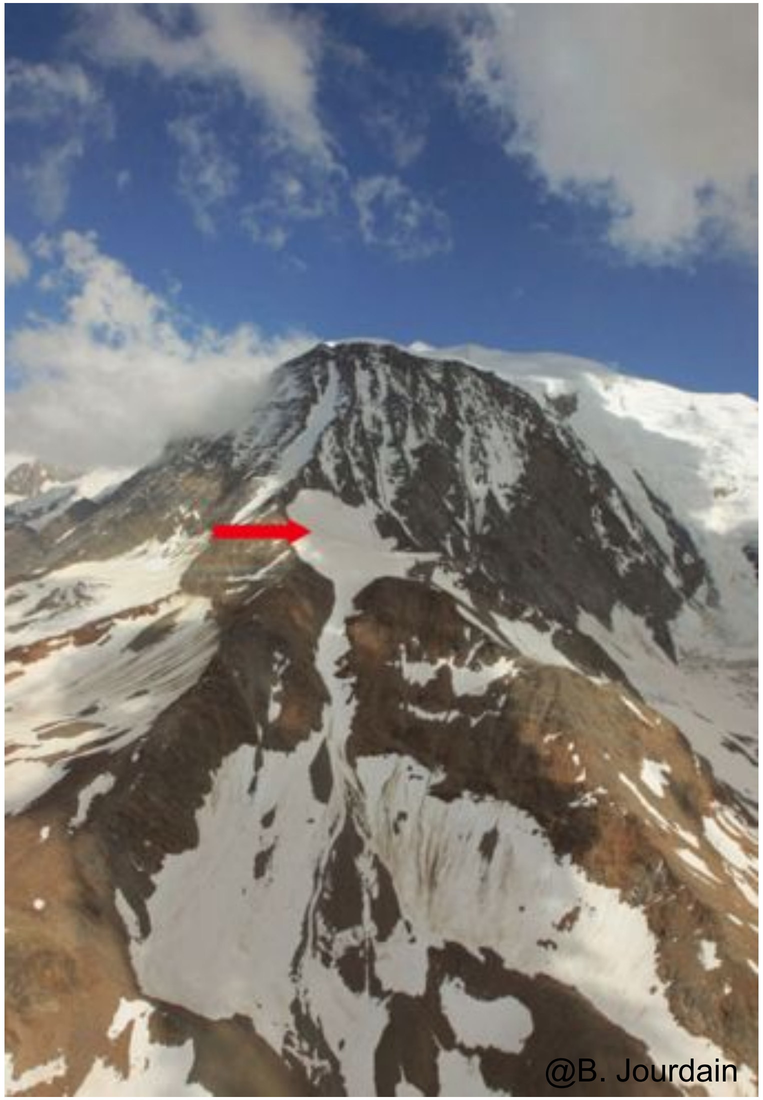
- Rate of closure of the cavity for a given drainage scenario (prognostic)

Location (Mont Blanc Area, France Alps)



Location (Mont Blanc Area, France Alps)

Tête Rousse glacier
3100 to 3300 m
0.08 km^2 (2007)



Chronology

The Past History – The 1892 catastrophe

Contemporary history:

2007-10 - Studies ton answer the question about the necessity to maintain the tunnel

07/2010 - A water filled cavity under pressure is discovered

- Crisis – Artificial drainage

2011 - Small research program to understand the formation of the cavity

- New crisis – Artificial drainage

2012 - New Artificial drainage needed

The 1892 catastrophe

11 July 1892

175 fatalities

100 000 m^3 of water

Flood produced

800 000 m^3 of sediment

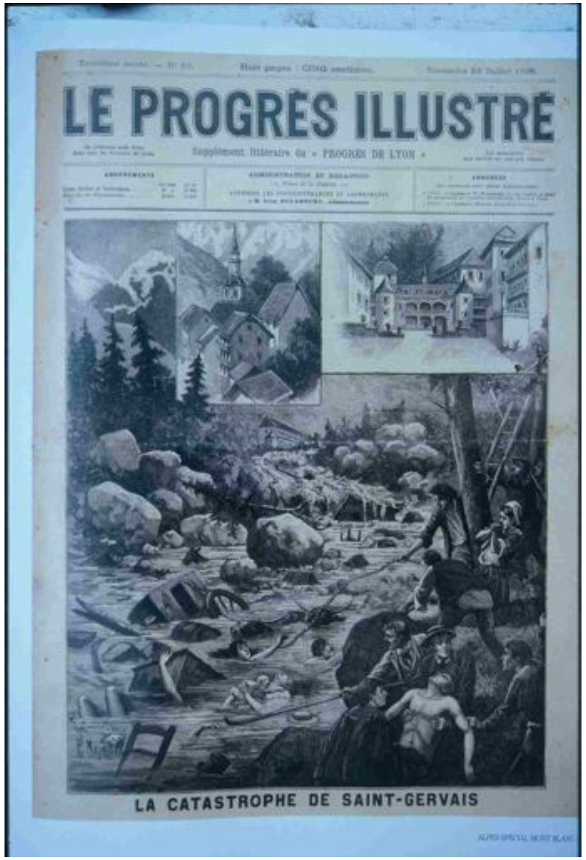
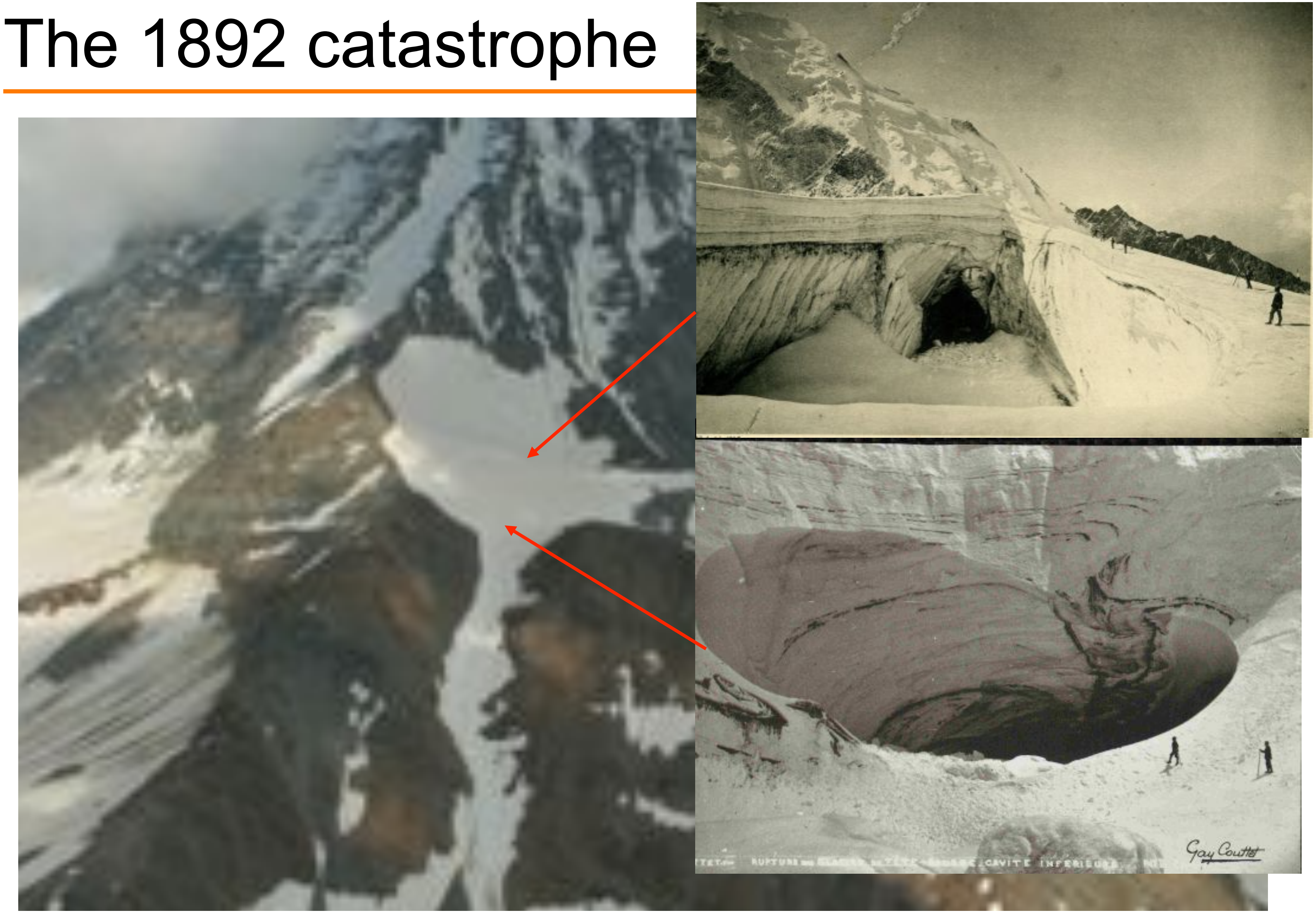


Fig. 22. — Le pont de la route départementale n° à tourné et submergé par la lave.
13 juillet 1892. — Cliché Kuss.

@Vincent, LGGE

The 1892 catastrophe



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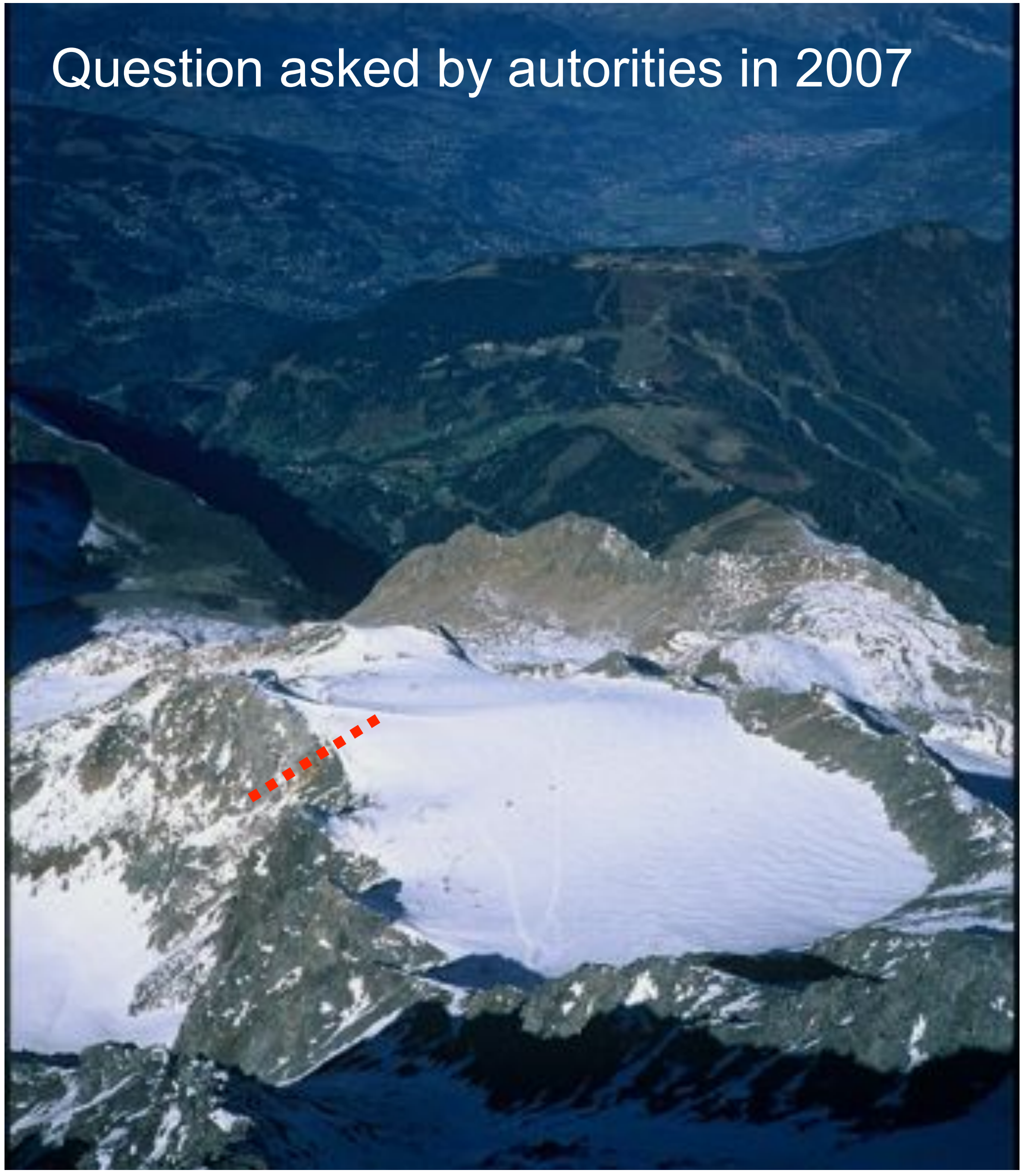
Is there still a risk at Tête Rousse ?



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Glaciological studies

. Topographic measurements

. Radar measurements

. Temperature measurements

. Mass balance measurements

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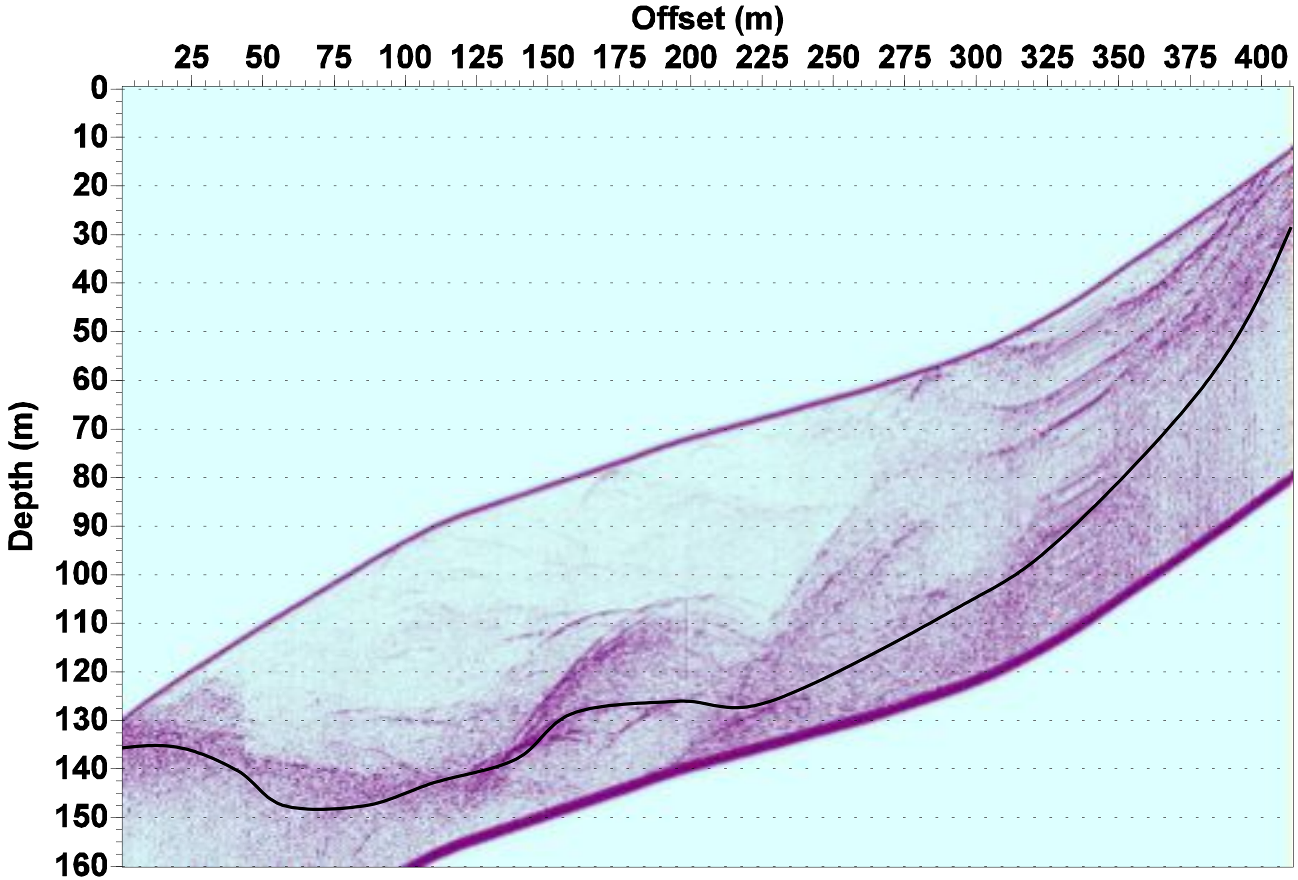
Glaciological studies



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The radar measurements showed a zone (volume) with an anomaly.

Glaciological studies

In Sept 2009, geophysical survey using the

Magnetic Resonance Imaging (LTHE, Grenoble)

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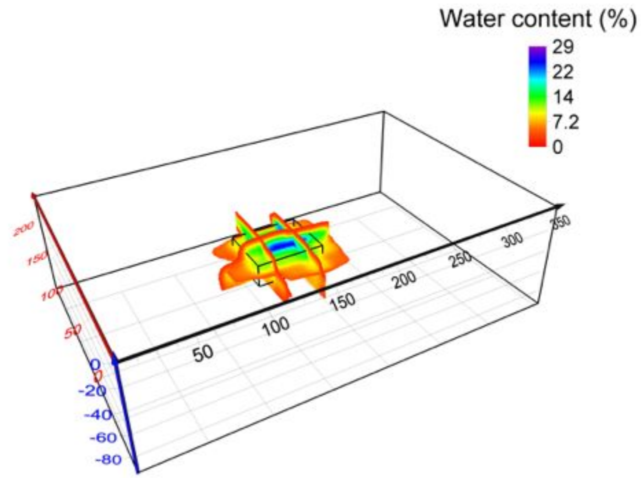
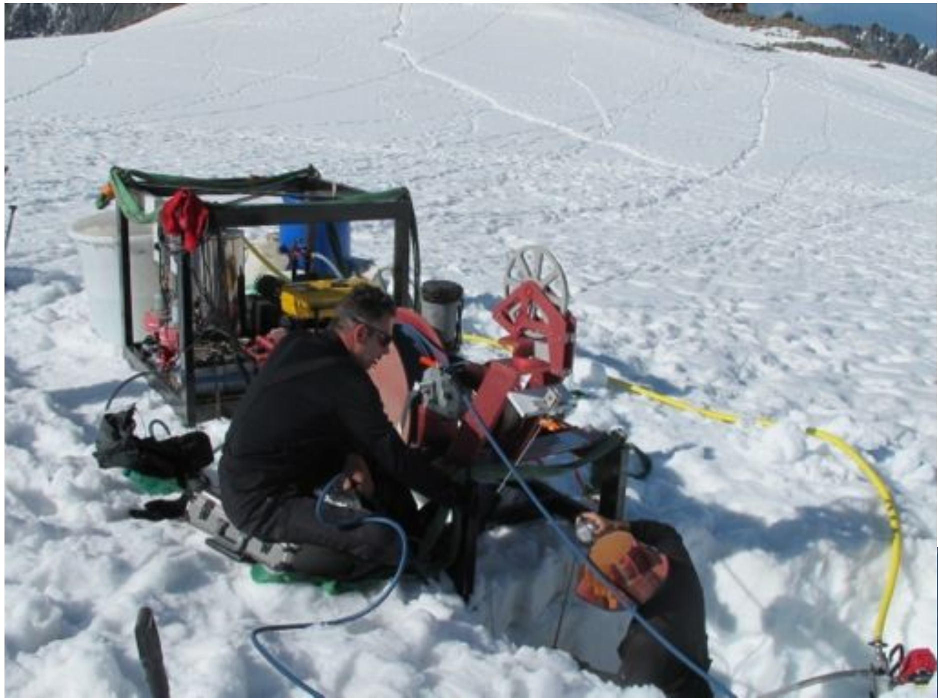
Glaciological studies



Water volume of 65 000 m^3

Report given to public authorities in March 2010

Pressure measurements



20 hot-water drillings performed from 29 June to 8 July 2010

Confirm the presence of a cavity

and that

the cavity is under pressure!

Decisions

The hydrostatic pressure exceeded the ice pressure due to the weight of the ice column

We could expect that the water contained in the glacier would be released suddenly

The public authorities have been warned immediately (13 July, 2010)

It has been decided to drain the subglacial lake as soon as possible, because 3000 people were threatened in the valley.

A difficult field work

Drainage of the cavity

A new risk ?

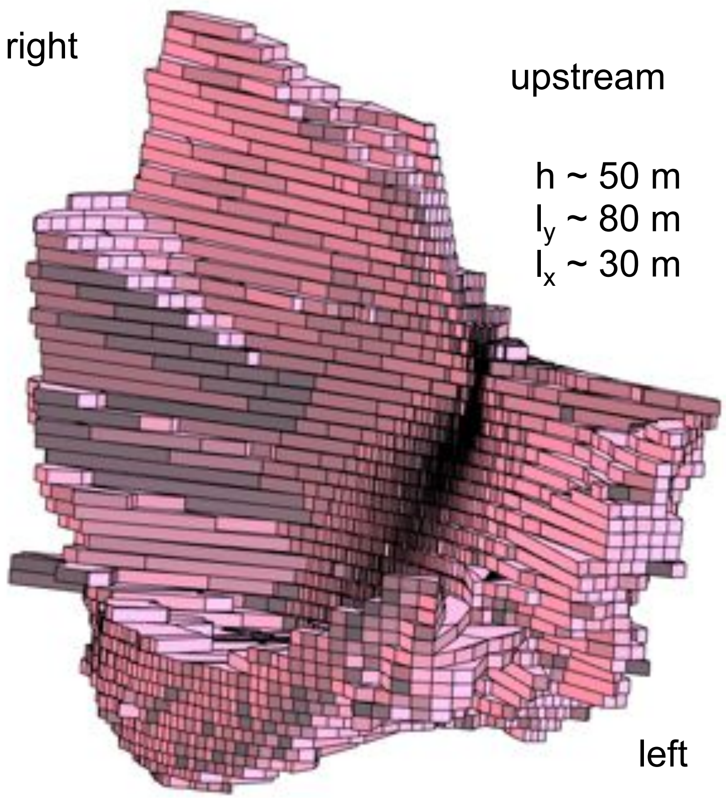
But was stopped the 1st September :

What was the risk of breakout of the cavity roof induced by the artificial drainage?

The 2010 cavity

Pumping of 47 700 m^3 from 25 August to 8 October 2010

Question (addressed end of August 2010):
What is the risk of break-up during the pumping phase?



Timing for answering

Sonar data

Septembre

D	L	M	E	J	V	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

Meeting with the mayor of St Gervais

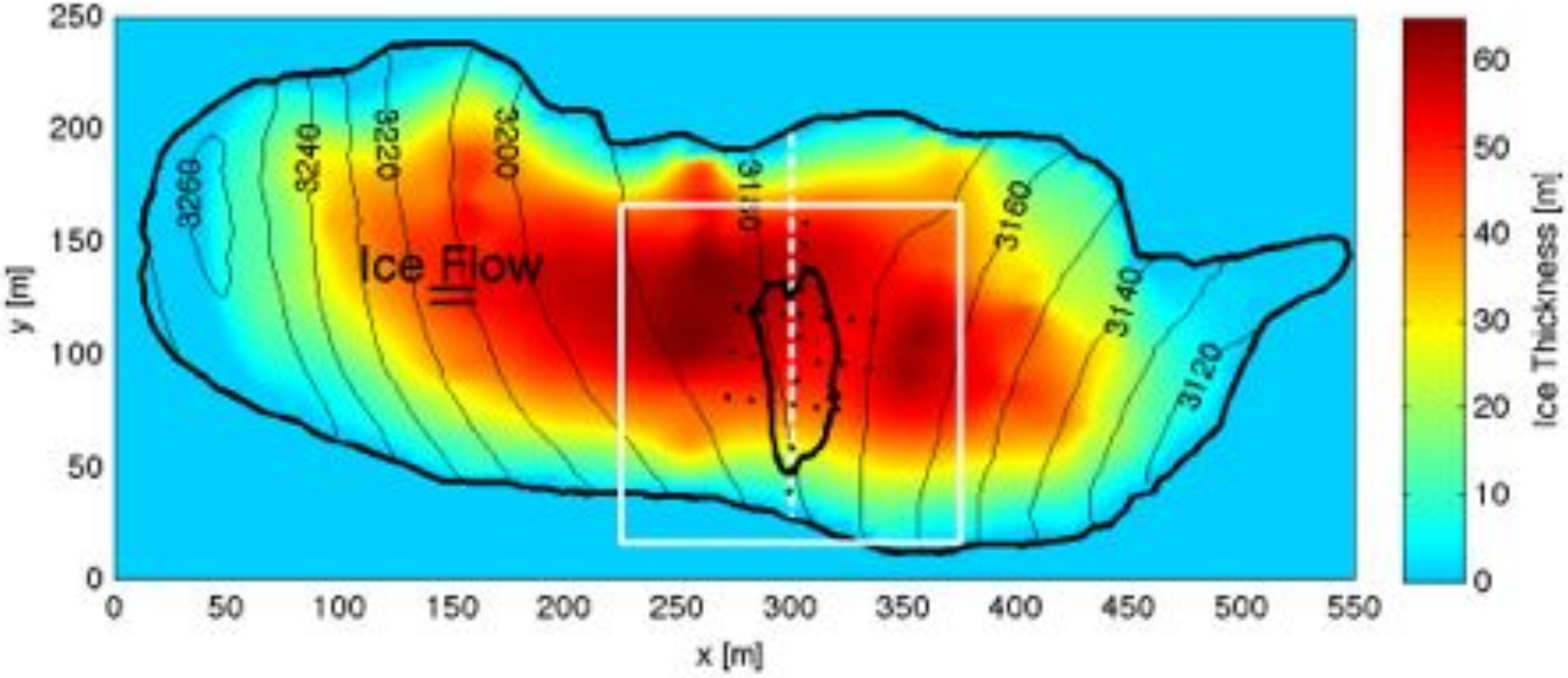
Proposed application

Construct a model of the flow of Tête Rousse Glacier

- Step 1: Without the cavity (normal state)
- Step 2: Add an empty cavity (stress analysis)
- Step 3: Rate of closure of the cavity (surface deformation analysis)

Data for ice flow modelling

- Bedrock DEM
- 2007 Surface DEM
- Cavity topography from sonar measurements
- Few surface velocities, without the cavity (0.6 m/a at the centre of the glacier)
- 27 Stakes to measure surface displacement during drainage



Material:

Data: Contour_TR_cavity.dat, Contour_TR_glacier.dat, DEM_TR_bed.dat, DEM_TR_cavity.dat, DEM_TR_surf.dat

PROG: USF_TR.f90

Step1a: Makegeo.m, teterousse.geo, teterousse1a.sif

Step1b: teterousse1b.sif

Step2a: Makegeo_2.m, teterousse.geo, teterousse2a.sif

Step2b: teterousse2b.sif

Step3a: teterousse3a.sif

Step3b: teterousse3b.sif

Modelling Tête Rousse Glacier

- ✓ **Step 1**
  - 1a Tête Rousse Glacier flow without a water filled-cavity (diagnostic)
  - 1b Add Stress Solver to get the stress
    Compute the Eigenvalues of the stress tensor

- ✓ **Step 2**
  - 2a Influence of an empty cavity below Tête Rousse Glacier (diagnostic)
  - 2b Apply a water pressure in the cavity

- ✓ **Step 3**
  - 3a Rate of closure of the cavity for a given drainage scenario (prognostic)
  - 3b Add a drainage scenario

Step 1a: Work to do

- create the mesh
- impose the boundary conditions in the SIF file
- test other BCs on the lateral boundary
- test sliding at the base of the glacier

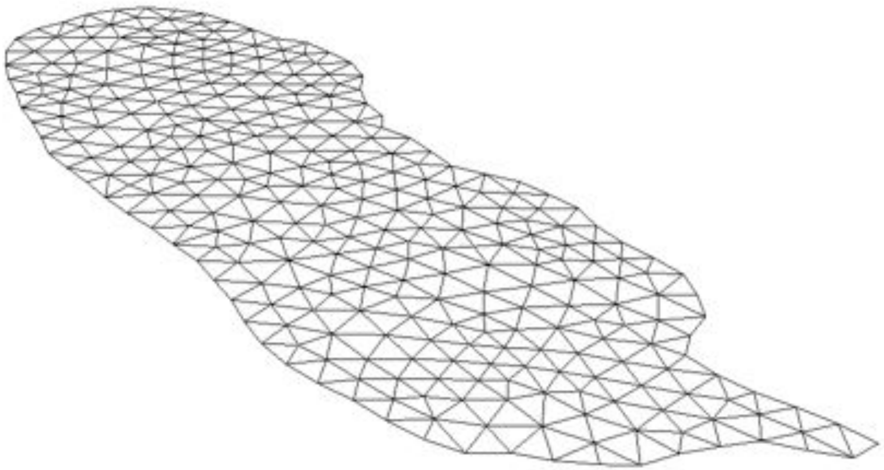
Step 1a: steps to make the mesh

1/ build the teterousse.geo file (input file of gmsh, footprint of the glacier)

2/ gmsh to get teterousse.msh (still footprint of the glacier)

3/ ElmerGrid to transform into Elmer format (still footprint of the glacier)

4/ we will use the internal extrusion feature in Elmer to create a volume from this footprint

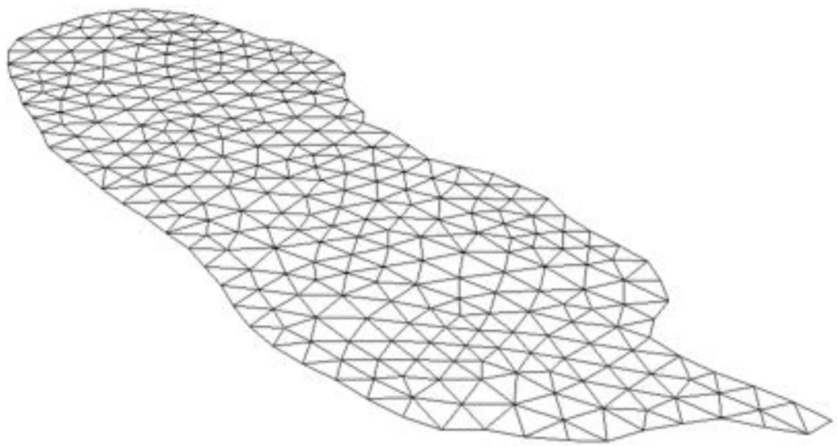


Step 1a: `Makegeo.m` (create a .geo file)

```
clear;
lc_out=18.0;            (size of the element in the plane)

A=dlmread('Contour_TR_glacier.dat');      (Read contour points)
fid1=fopen('teterousse.geo','w');
fprintf(fid1,'Mesh.Algorithm=5; \n');   (delaunay algorithm)

As=size(A,1);

np=0;
for ii=1:As
    np=np+1;
    fprintf(fid1,'Point(%g)={%14.7e,%14.7e,0.0,%g}; \n',np,A(ii,1),A(ii,2),lc_out);
end

fprintf(fid1,'Spline(1)={');
for ii=1:As
  fprintf(fid1,'%g,',ii);
end
fprintf(fid1,'%g}; \n',1);

fprintf(fid1,'Line Loop(2)={1}; \n');
fprintf(fid1,'Plane Surface(3) = {2}; \n');
fprintf(fid1,'Physical Line(4) = {1}; \n');
fprintf(fid1,'Physical Surface(5) = {3}; \n');

fclose(fid1)
```

Step 1a: `Makegeo.m`

```
% create teterousse.msh using gmsh
!gmsh teterousse.geo -1 -2

% convert teterousse.gmsh in an Elmer type mesh
!ElmerGrid 14 2 teterousse.msh —autoclean
```



Step 1a: `gmsh` (create a .msh file)

gmsh teterousse.geo -1 -2

help: http://www.geuz.org/gmsh/

line commands:
`"-1 -2"` performs 1D and 2D mesh generation and then exit

Step 1a: `In the sif file`

Define the number of vertical layers (Simulation section):

```
Simulation
  Coordinate System  =  Cartesian 3D
  Simulation Type = Steady
  Extruded Mesh Levels = Integer 16
  …
End
```

The first solver to be executed is the StructuredMeshMapper

```
Solver 1
  Equation = "MapCoordinate"
  Procedure = "StructuredMeshMapper" "StructuredMeshMapper"
  Active Coordinate = Integer 3
  Mesh Velocity Variable = String "dSdt"
  Mesh Update Variable = String "dS"
  Mesh Velocity First Zero = Logical True
End
```

Step 1a: `In the sif file`

Define the top and bottom surfaces (BC section):

```
! cavity roof and Bedrock
Boundary Condition 2
Bottom Surface = Variable Coordinate 1
    Real Procedure "./USF_TR" "BottomSurface"
End

! Upper Surface
Boundary Condition 3
  Top Surface = Variable Coordinate 1
    Real Procedure "./USF_TR" "TopSurface"
End
```

`BottomSurface` and `TopSurface` are two user functions (in USF_TR.f90) that read the bottom and top DEM and interpolate for each node the altitude.

Step 1a: User Function USF_TR.f90

BottomSurface:

- load the file `DEM_TR_bed.dat` in ../Data
- for each node, use InterpolateDEM to get the altitude(x,y) of the bedrock

TopSurface:

- load the file `DEM_TR_surf.dat` in ../Data
- for each node, use InterpolateDEM to get the altitude(x,y) of the upper surface

Compilation: `elmerf90 ../PROG/USF_TR.f90 –o USF_TR`

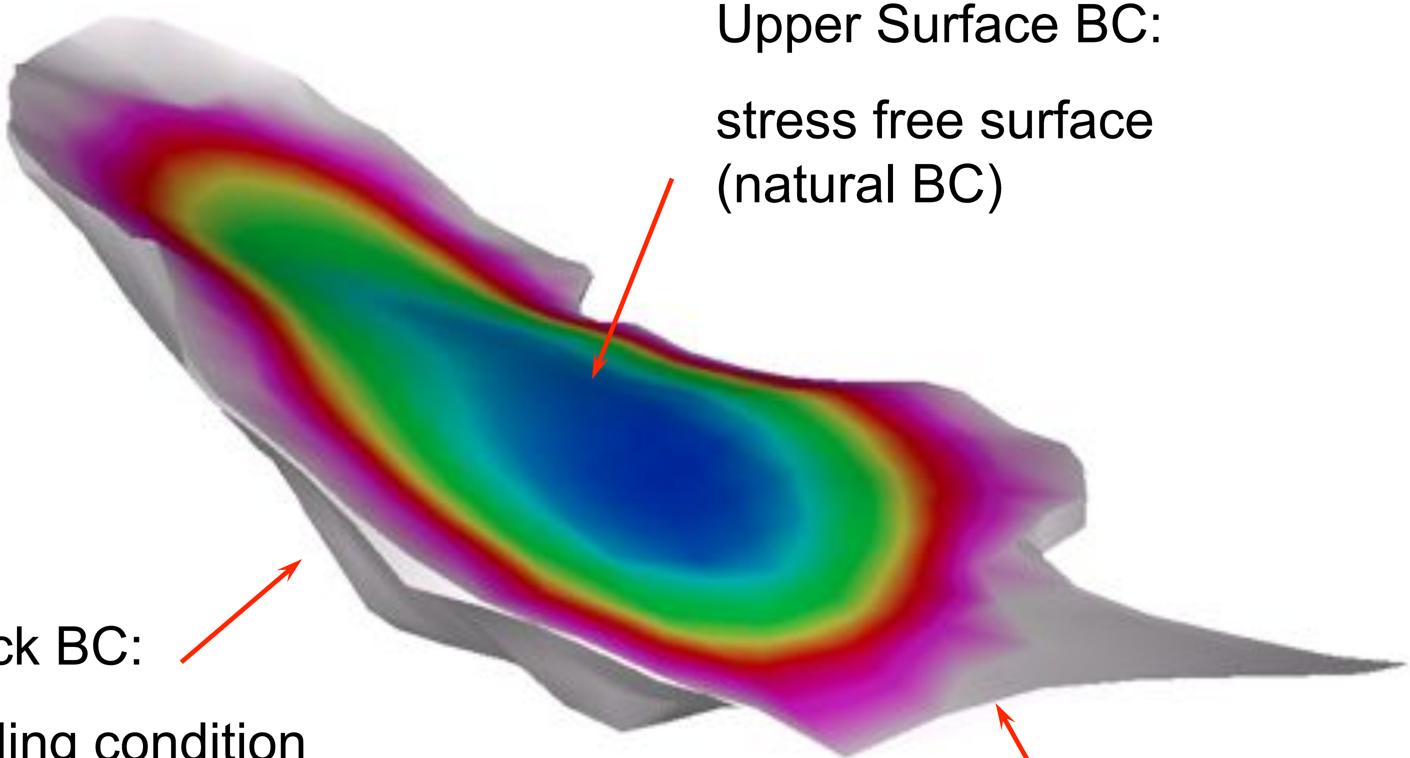
Step 1a: Hypothesis of the modelling

Solve only the Stokes equation in a diagnostic way

3 boundary conditions

Upper Surface BC:

stress free surface
(natural BC)



Bedrock BC:

No sliding condition

Lateral BC:

zero horizontal velocities

Step 1a: use Glen's law

$$D_{ij} = A\tau_e^{n-1} S_{ij} \quad ; \quad S_{ij} = A^{-1/n} I_{D_2}^{(1-n)/n} D_{ij}$$

$$A = A(T^{'}) = A_0 \exp^{-Q/RT^{'}}$$

$$A = A_1 = 2.89 \times 10^{-13} \text{ s}^{-1}\text{Pa}^{-3} \text{ if } T \leq -10°\text{C}$$
$$A = A_2 = 2.43 \times 10^{-2} \text{ s}^{-1}\text{Pa}^{-3} \text{ if } T \geq -10°\text{C}$$

$$Q = Q_1 = 60 \text{ kJ mol}^{-1} \text{ if } T \leq -10°\text{C}$$
$$Q = Q_2 = 115 \text{ kJ mol}^{-1} \text{ if } T \geq -10°\text{C}$$

Cuffey and Paterson (2010)

Paterson 2010

A* =	3.50000E-25	s^-1 Pa^-3
A1 =	2.89165E-13	s^-1 Pa^-3
A2 =	2.42736E-02	s^-1 Pa^-3
Q1 =	60000	J/mol
Q2 =	115000	J/mol

T [°C]	A [s^-1 Pa^-3]	A [a^-1 MPa^-3]
0	2.4029E-24	75.830
-1	1.9945E-24	62.942
-2	1.6533E-24	52.173
-3	1.3685E-24	43.186
-4	1.1312E-24	35.698
-5	9.3370E-25	29.465
-6	7.6958E-25	24.286
-7	6.3339E-25	19.988
-8	5.2054E-25	16.427
-9	4.2716E-25	13.480
-10	3.5000E-25	11.045
-10	3.5000E-25	11.045
-11	3.1520E-25	9.947
-12	2.8363E-25	8.951
-13	2.5501E-25	8.048
-14	2.2910E-25	7.230
-15	2.0564E-25	6.490
-16	1.8444E-25	5.820
-17	1.6528E-25	5.216
-18	1.4798E-25	4.670
-19	1.3238E-25	4.177
-20	1.1831E-25	3.734
-21	1.0565E-25	3.334
-22	9.4260E-26	2.975
-23	8.4019E-26	2.651
-24	7.4822E-26	2.361
-25	6.6570E-26	2.101
-30	3.6580E-26	1.154
-35	1.9601E-26	0.619
-40	1.0225E-26	0.323
-45	5.1843E-27	0.164
-50	2.5496E-27	0.080

assume a constant temperature of -1°C

Step 1a: use Glen's law

```
$yearinsec = 365.25*24*60*60
$rhoi = 900.0/(1.0e6*yearinsec^2)
$rhow = 1000.0/(1.0e6*yearinsec^2)
! Prefactor from Paterson (1994) in MPa^{-3} a^{-1}
$A1 = 3.985e-13*yearinsec*1.0e18
$A2 = 1.916e3*yearinsec*1.0e18
$gravity = -9.81*yearinsec^2

Material 1
  Density = Real $rhoi

  Viscosity Model = String "glen"
  Viscosity = 1.0 ! Dummy but avoid warning output
  Glen Exponent = Real 3.0
  Limit Temperature = Real -10.0
  Rate Factor 1 = Real $A1
  Rate Factor 2 = Real $A2
  Activation Energy 1 = Real 60e3
  Activation Energy 2 = Real 139e3
  Glen Enhancement Factor = Real 1.0
  Critical Shear Rate = Real 1.0e-10

  Constant Temperature = Real -1.0
End
```

Step 1a: Boundary Conditions

```
! lateral side of the glacier
Boundary Condition 1
  Target Boundaries = 1
  Velocity 1 = real 0.0
  Velocity 2 = real 0.0
End

! Bedrock
Boundary Condition 2
  Bottom Surface = Variable Coordinate 1
    Real Procedure "./USF_TR" "BottomSurface"
  Velocity 1 = Real 0.0
  Velocity 2 = Real 0.0
  Velocity 3 = Real 0.0
End

! Upper Surface
Boundary Condition 3
  Top Surface = Variable Coordinate 1
    Real Procedure "./USF_TR" "TopSurface"
End
```

Null horizontal velocities

No sliding

Natural BC, nothing to do!

Step 1a: Other BCs for the lateral boundary

```
! lateral side of the glacier
Boundary Condition 1
  Target Boundaries = 1
End
```

Natural BC

```
! lateral side of the glacier
Boundary Condition 1
  Target Boundaries = 1
  Velocity 1 = real 0.0
  Velocity 2 = real 0.0
  Velocity 3 = real 0.0
End
```

zero velocity

Conclusion ?

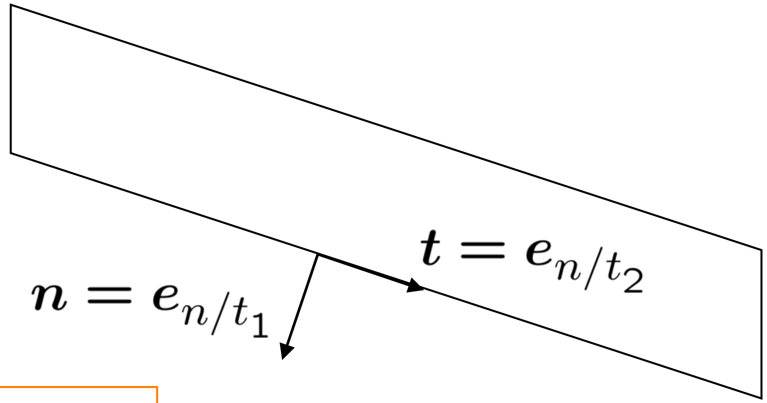
Step 1a: Add sliding on the bedrock

Friction law in Elmer:

$$C_i u_i = \sigma_{ij} n_j \;\; (i = 1, 2)$$

$$\Rightarrow \quad C_t u_t = \sigma_{nt} \; ; \; C_n u_n = \sigma_{nn}$$

where $\boldsymbol{n}$ is the surface normal vector




```
! Bedrock BC
Boundary Condition 2
  . . .

  Flow Force BC = Logical True
  Normal-Tangential Velocity = Logical True

  Velocity 1 = Real 0.0e0
  Slip Coefficient 2 = Real 0.1
  Slip Coefficient 3 = Real 0.1
End
```

How to evaluate the Slip Coefficient ?

Modelling Tête Rousse Glacier

✓ **Step 1**

- 1a Tête Rousse Glacier flow without a water filled-cavity (diagnostic)
- 1b Add Stress Solver to get the stress
  Compute the Eigenvalues of the stress tensor

✓ **Step 2**

- 2a Influence of an empty cavity below Tête Rousse Glacier (diagnostic)
- 2b Apply a water pressure in the cavity

✓ **Step 3**

- 3a Rate of closure of the cavity for a given drainage scenario (prognostic)
- 3b Add a drainage scenario

Step 1b: Add the Stress Solver

Objective: compute the stress field as

$$\int_V S_{ij}\Phi \, \mathrm{d}V = 2\int_V \eta D_{ij}\Phi \, \mathrm{d}V$$

where D_{ij} and η are calculated from the nodal velocities using the derivative of the basis functions

- Add a Solver

```
Solver 3
  Equation = Sij
  Procedure = "ElmerIceSolvers" "ComputeDevStress"
  Variable = -nooutput "Sij"
  Variable DOFs = 1
  Exported Variable 1 = Stress
  Exported Variable 1 DOFs = 6

  Flow Solver Name = String "Flow Solution"

  Linear System Solver = Direct
  Linear System Direct Method = umfpack
End
```

Step 1b: Add the Stress Solver

- Add this solver in the Equation Section

```
Active Solvers(3) = 1 2 3
```

- Tell you want the Cauchy stress to be computed (Material Section)

```
Material 1
  Cauchy Stress = Logical True
End
```

- Output : negative stress = Compressive stress
  positive stress = Tensile stress

`Stress.1`	→	S_{xx}	`Stress.4`	→	S_{xy}
`Stress.2`	→	S_{yy}	`Stress.5`	→	S_{yz}
`Stress.3`	→	S_{zz}	`Stress.6`	→	S_{xz}

Step 1b: Add the Eigenvalues Solver

Objective: compute the eigenvalues of the Cauchy stress tensor

- Add a Solver

```
Solver 4
   Equation = "EigenStresses"
   Procedure = ″ElmerIceSolvers" "ComputeEigenValues"
   Variable = -nooutput dumy
   Variable DOFs = 1

   ! The 3 eigenvalues
   Exported Variable 1 = EigenStress
   Exported Variable 1 DOFS = 3

  ! The 3 eigenvectors (Option)
   Exported Variable 2 = EigenVector1
   Exported Variable 2 DOFS = 3
   Exported Variable 3 = EigenVector2
   Exported Variable 3 DOFS =  3
   Exported Variable 4 = EigenVector3
   Exported Variable 4 DOFS = 3
End
```

Step 1.3: Add the Eigenvalues Solver

- Add this solver in the Equation Section

```
Active Solvers(4) = 1 2 3 4
```

- Output : negative stress = Compressive stress
positive stress = Tensile stress
ordered → `Eigenstress.3` gives the maximal tensile stress

`Eigenstress.1` → S_1
`Eigenstress.2` → S_2
`Eigenstress.3` → S_3

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  - 3a Rate of closure of the cavity for a given drainage scenario (prognostic)
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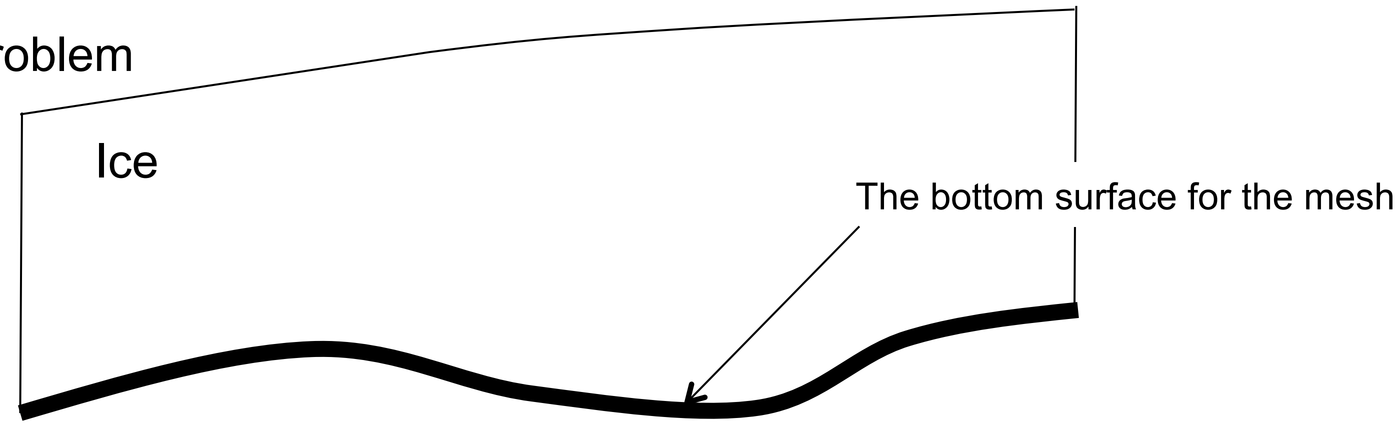
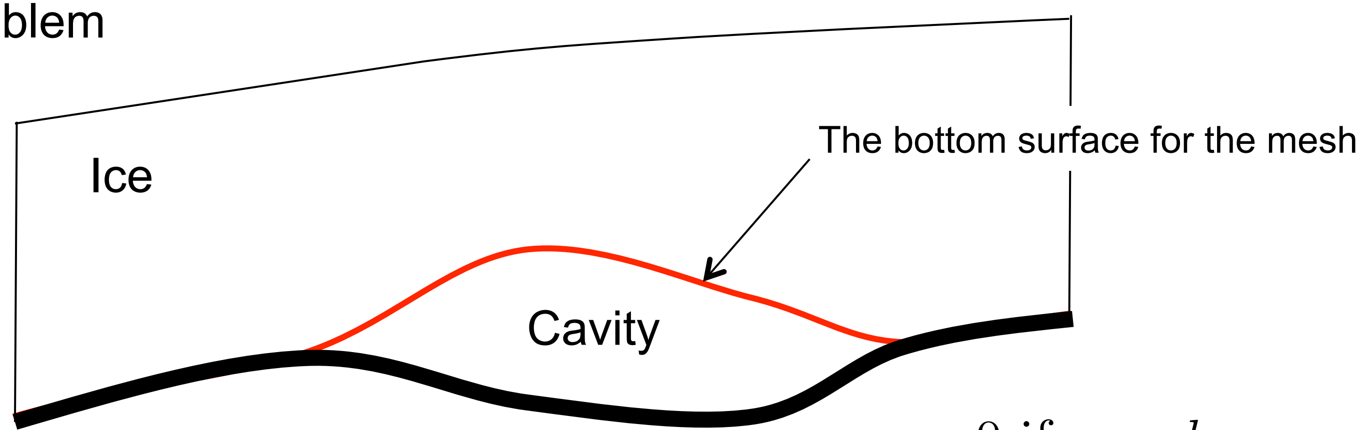
Step 2a: Add the cavity (empty)

The initial problem



Only one BC for the base: no sliding

The new problem



!!! The ice bottom surface is not anymore given by the bedrock DEM !!!

Two BCs for the base:

$$\boldsymbol{u} = 0 \text{ if } z_b = b$$
$$\sigma_{nn} = p_w \text{ if } z_b > b$$

$p_w = 0$ if the cavity is empty of water

Step 2a: new Bottom Surface definition

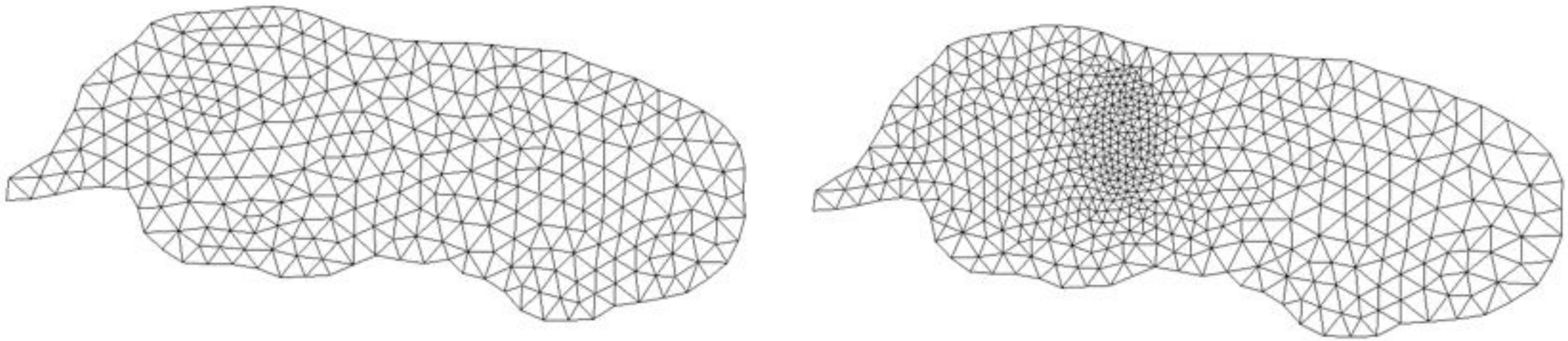
The bottom surface is now given by the `BottomSurface` function in `USF_TR.f90` (and not anymore the bedrock function)

Change the boundary condition 2:

```
Boundary Condition 2
  Bottom Surface = Variable Coordinate 1
    Real Procedure "./USF_TR" "BottomSurface"
End
```

Step 2a: Make a new mesh

We will use the cavity contour to have smaller size elements in the vicinity of the cavity



Work to do : modify the Makegeo.m file to create this new mesh.

Step 2: Make a new mesh (Makegeo_2.m) 1/2

```
clear;
lc_out=18.0;
lc_in=6.0;
A=dlmread('Contour_TR_glacier.dat');
B=dlmread('Contour_TR_cavity.dat');
fid1=fopen('teterousse.geo','w');
As=size(A,1);
Bs=size(B,1);
np=0;
for ii=1:As
    np=np+1;
    fprintf(fid1,'Point(%g)={%14.7e,%14.7e,0.0,%g}; \n',np,A(ii,1),A(ii,2),lc_out);
end
for ii=1:Bs
    np=np+1;
    fprintf(fid1,'Point(%g)={%14.7e,%14.7e,0.0,%g}; \n',np,B(ii,1),B(ii,2),lc_in);
end

fprintf(fid1,'Spline(1)={');
for ii=1:As
  fprintf(fid1,'%g,',ii);
end
fprintf(fid1,'%g}; \n',1);

fprintf(fid1,'Spline(2)={');
for ii=1:Bs
  fprintf(fid1,'%g,',As+ii);
end
fprintf(fid1,'%g}; \n',As+1);
```

Step 2a: Make a new mesh (Makegeo_2.m) 2/2

```
fprintf(fid1,'Line Loop(3)={1}; \n');
fprintf(fid1,'Line Loop(4) = {2}; \n');
fprintf(fid1,'Plane Surface(5) = {3, 4}; \n');
fprintf(fid1,'Plane Surface(6) = {4}; \n');
fprintf(fid1,'Physical Line(7) = {1}; \n');
fprintf(fid1,'Physical Surface(8) = {5,6}; \n');
fclose(fid1)


% create teterousse.msh using gmsh
!gmsh teterousse.geo -1 -2

% convert teterousse.gmsh in an Elmer type mesh
!ElmerGrid 14 2 teterousse.msh –autoclean
```

Step 2a: Change in the basal BC

The basal BC will be of the form:

```
Velocity 1 = Real 0.0
Velocity 1 Condition = Variable Coordinate 1
  Real Procedure "./USF_TR" "MaskCavity"
```

And the same for `Velocity 2` and `Velocity 3`.

The user function MaskCavity returns +1 where z_b=b, -1 where z_b>b
z_b is the node altitude, b is given by the bedrock DEM

use the same interpolation function (`InterpolateDEM`) than the other DEM functions

Visualize the results in ElmerPost.
What does it change in term of velocity and stress?

Modelling Tête Rousse Glacier

✓ **Step 1**

- 1a Tête Rousse Glacier flow without a water filled-cavity (diagnostic)
- 1b Add Stress Solver to get the stress
  Compute the Eigenvalues of the stress tensor

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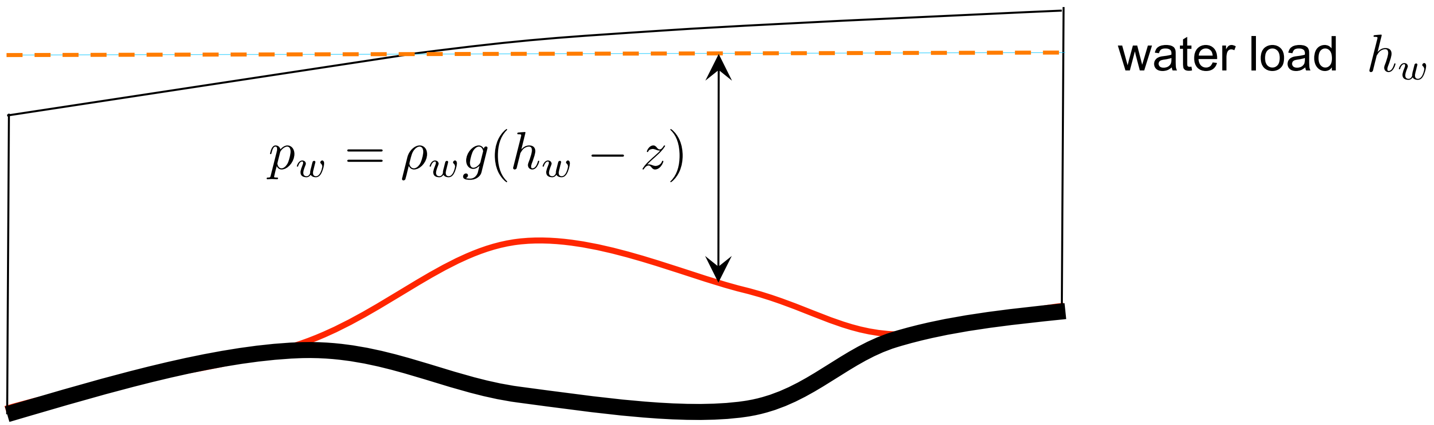
- 3b Add a drainage scenario

Step 2.1: Add a water pressure

Modify the SIF to add a water pressure




```
$hw = 3170.0
```

the water load

In the bedrock BC

```
 Flow Force BC = Logical True
 External Pressure = Variable Coordinate 3
   Real MATC "-rhow*gravity*(hw-tx)
```

will only apply where a Dirichlet BC is not applied

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Step 3a: Move to prognostic

Will do it in two steps

- Move to prognostic assuming the cavity is empty of water at t=0
  (big step, need 2 new solvers!)

- Prescribe the observed drainage scenario for the water pressure

To move from a diagnostic to a prognostic simulations:

- Add the FreeSurface solver (here 2 times, since we have 2 FS)
- Add one body per FS (new Initial Condition and Equation Sections)
- Modifications in the Simulation and Boundary Condition Sections

Only shown for the upper free surface here

Step 3a – Steady to transient

The simulation Section has to be modified:

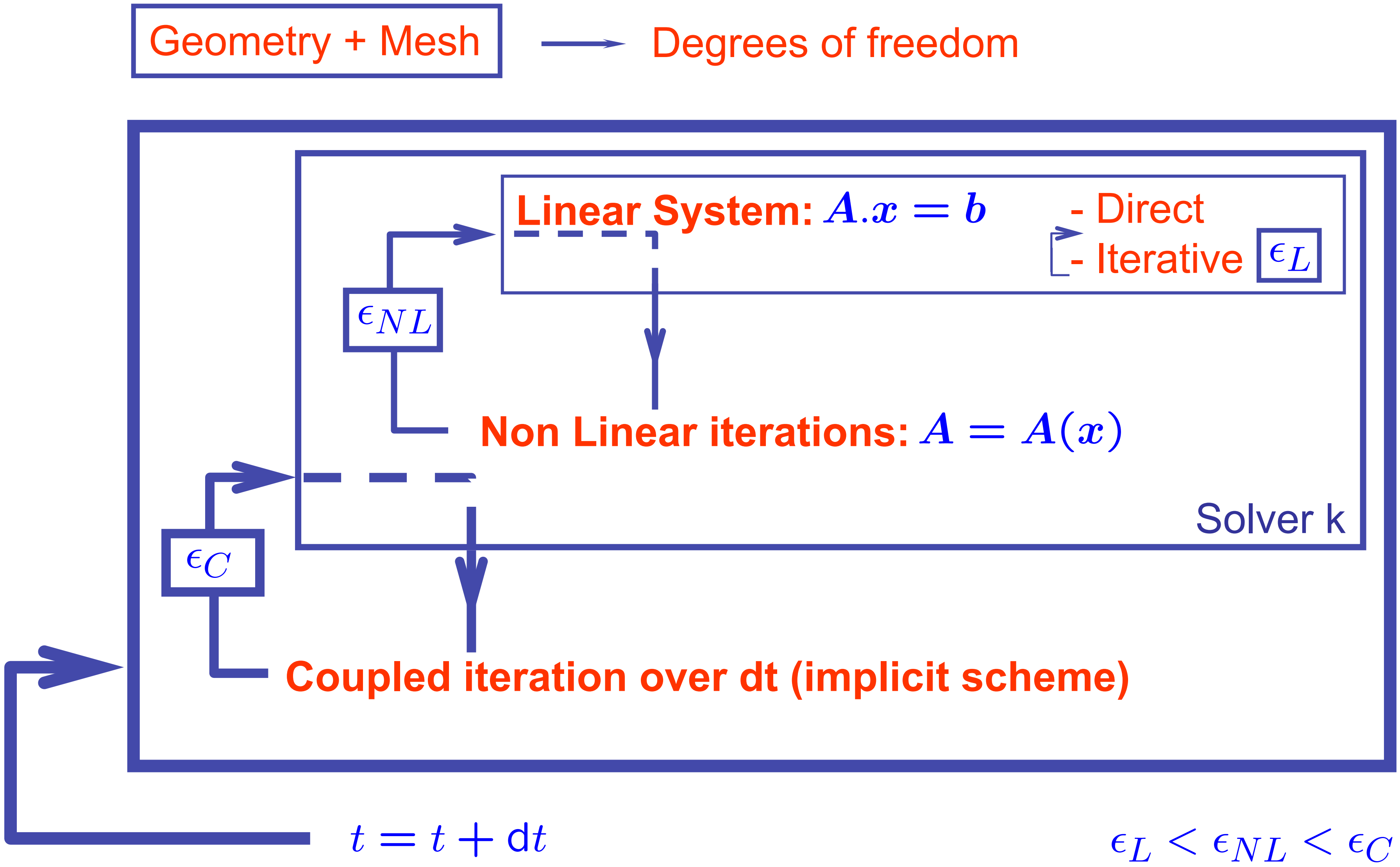
```
Simulation Type = Transient

Timestepping Method = "bdf"
BDF Order = 1
Output Intervals = 1
Timestep Intervals = 200
Timestep Sizes = 1.0

Steady State Min Iterations = 1
Steady State Max Iterations = 1
```

→ Timestepping Method: Backward Differences Formulae

→ Output Intervals: Save in .ep file

→ Steady State Max Iterations: To control the "implicity" of the solution over one time step (here 1 means explicite)

Step 3a – Sketch of a transient simulation



Step 3a – Free surface Solver

The free surface solver only apply to the boundary 3 (upper surface)

➡ Define a 2nd body which is the boundary 3.

```
Body 2
  Equation = 2
  Body Force = 2
  Material = 1
  Initial Condition = 2
End
```

where `Equation 2, Body Force 2 and Initial Condition 2` are defined for the free surface equation of the upper surface.

Tell in BC2 that this is the body 2:

```
Boundary Condition 3
   Body Id = 2
         …
End
```

Step 3a – Add the Free surface Solver

```
Solver 4
  Equation = "Free Surface Top"
  Variable = String "Zs Top"
  Variable DOFs =  1
  Exported Variable 1 = String "Zs Top Residual"
  Exported Variable 1 DOFs = 1

  Procedure = "FreeSurfaceSolver" "FreeSurfaceSolver"
  Before Linsolve = "EliminateDirichlet" "EliminateDirichlet"

  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-9
  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 = 1.00

  Steady State Convergence Tolerance = 1.0e-03

  Stabilization Method = Bubbles
  Apply Dirichlet = Logical False

! How much the free surface is relaxed
  Relaxation Factor = Real 1.00

! Is there a maximum step-size for the displacement
! use/or not accumulation
  Use Accumulation = Logical True

! take accumulation to be given normal to surface/as vector
  Normal Flux = Logical False
End
```

Step 3a – Upper Surface

Body Force 2:

```
Body Force 2
  Zs Top Accumulation Flux 1 = Real 0.0e0
  Zs Top Accumulation Flux 2 = Real 0.0e0
  Zs Top Accumulation Flux 3 = Real 0.0e0
End
```

Equation 2:

```
Equation 2
  Active Solvers(1) = 2
  Flow Solution Name = String “Flow Solution”
  Convection = String Computed
End
```

Initial Condition 2: (tell that $z_s(x,0)$ is given by the surface DEM)

```
Initial Condition 2
  Zs Top = Variable Coordinate 1
    Real Procedure ”./USF_TR" “TopSurface"
End
```

Step 3a - StructuredMeshMapper

We know say in StructuredMeshMapper that the top (and bottom) surface is defined by the variable zs top:

```
Solver 1
  Equation = "MapCoordinate"
  Procedure = "StructuredMeshMapper" "StructuredMeshMapper"

  Active Coordinate = Integer 3
  Mesh Velocity Variable = String "dSdt"
  Mesh Update Variable = String "dS"
  Mesh Velocity First Zero = Logical True

  Top Surface Variable Name = String "Zs Top"
  Bottom Surface Variable Name = String "Zs Bottom"
End
```

And delete from the BC the initial definition of the top (and bottom) surface:

```
Boundary Condition 3
!!! this BC is equal to body no. 2 !!!
  Body Id = 2

  Top Surface = Variable Coordinate 1
    Real Procedure "./USF_TR" "TopSurface"
End
```

Step 3a – Same for the bedrock

Name of the variable: `Zs Bottom`
Add solver : `Solver 5`
Add equation: `Equation 3`

Modify the the Bottom surface BC (3):

```
Boundary Condition 2
  Body Id = 3
  ~~Bottom Surface = Variable Coordinate 1~~
  ~~    Real Procedure "./USF_TR" "BottomSurface »~~
End
```

Add a limiter to ensure that $z_b \geq b$
In the material section

```
Min Zs Bottom = Variable Coordinate 1
    Real Procedure "./USF_TR" ”Bedrock"
Max Zs Bottom = Real +1.0e10
```

+ in the Free Surface solver : `Apply Dirichlet = Logical True`

Step 3a – Newton linearization

If you want to use Newton linearization for the non-linear iterations, don't forget to reset the conditions used to move from Picard to Newton at each time step, by adding:

```
Solver 1

  Nonlinear System Reset Newton = Logical True

End
```

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Step 3b – Add a drainage scenario

Add an evolution of the water load of the form:

$$h_w = 3170.0 - t * \Delta h_w / \Delta t$$

Work to do:
write a MATC function hw to prescribe the water load evolution

Step 3b – Add a drainage scenario

MATC function `hw` to prescribe the water load evolution:

```
! Water load function of time (in year)
! Decrease by DH in DT
$ function hw(t) {\
   DH = 70.0;\
   DT = 20.0;\
   _hw = 3170.0 - t*365.25*DH/DT ;\
}
```

Call in the bedrock BC

```
External Pressure = Variable time, Coordinate 3
   Real MATC "rhow*gravity*(hw(tx(0))-tx(1))
```

More Steps ???

Some idea:

- go to parallel

- add the Savedata solver to get upper and lower surfaces output

- add the StructuredProjectToPlane solver

```
Solver 2
  Equation = "HeightDepth"
  Procedure = "StructuredProjectToPlane” "StructuredProjectToPlane"
  Active Coordinate = Integer 3

  Operator 1 = depth
  Operator 2 = height
End
```

References

Gagliardini O., F. Gillet-Chaulet, G. Durand, C. Vincent and P. Duval, 2011. Estimating the risk of glacier cavity collapse during artificial drainage: the case of Tête Rousse Glacier. Geophys. Res. Lett., 38, L10505, doi:10.1029/2011GL047536.