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)

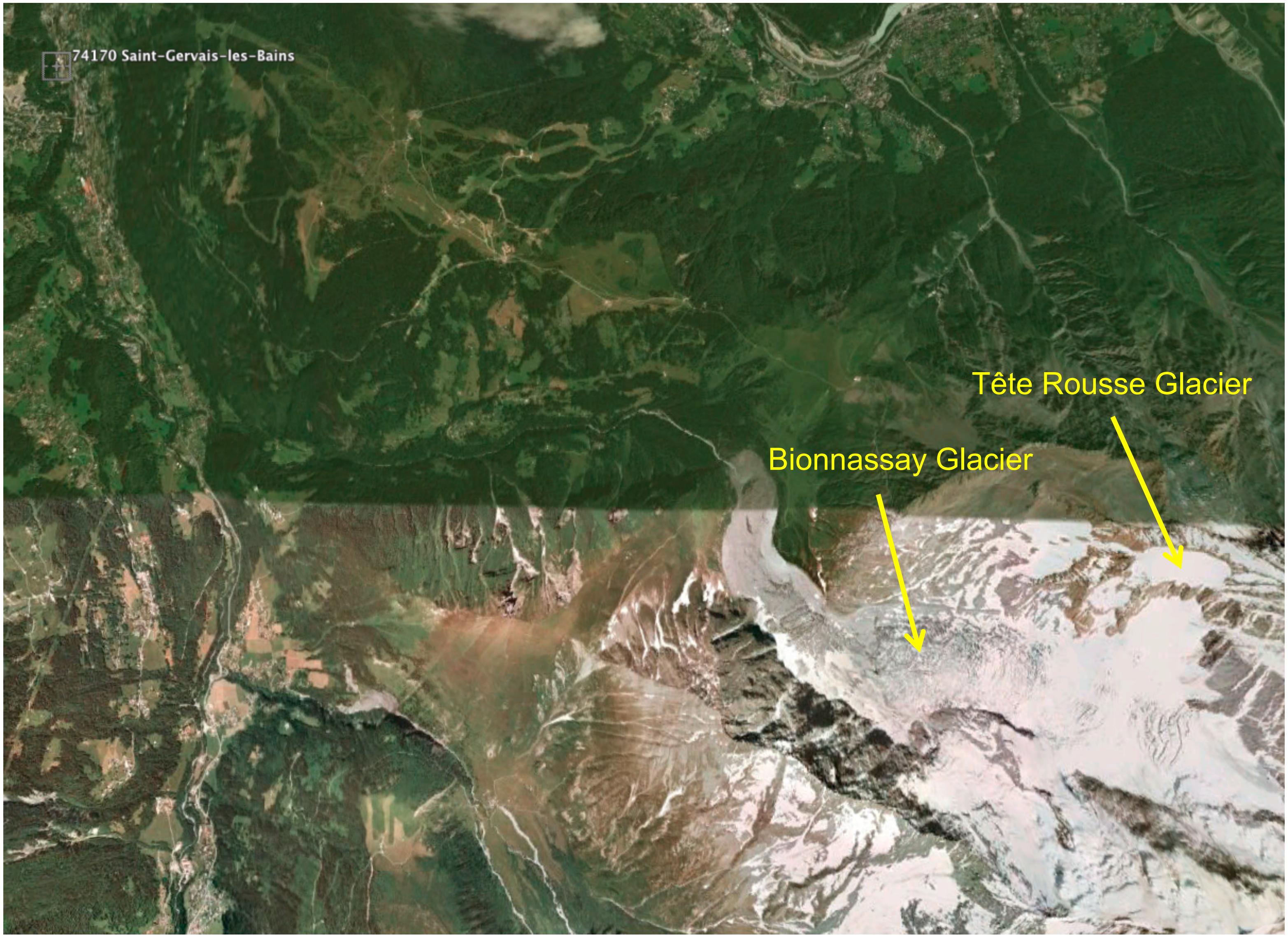
✓ **Step 2**

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

✓ **Step 3**

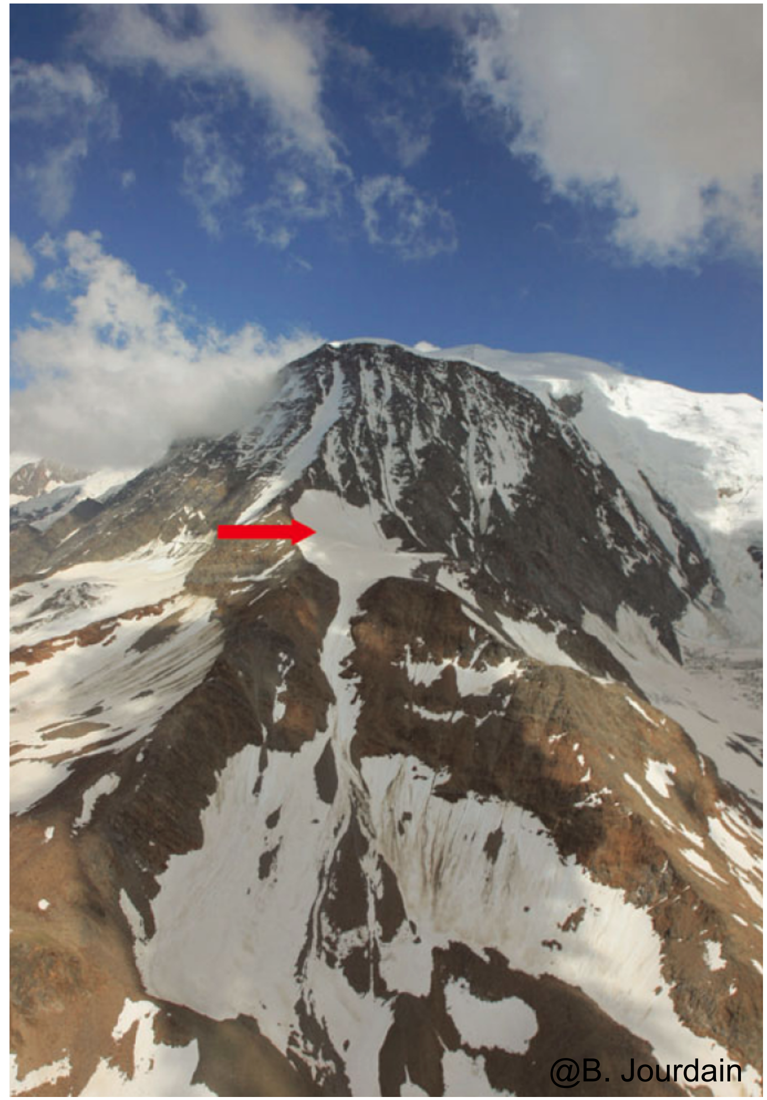
- Rate of closure of the cavity for a given drainage scenario (prognostic)

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 to 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

2016 - Still under survey – build of an artificial spillway

The 1892 catastrophe

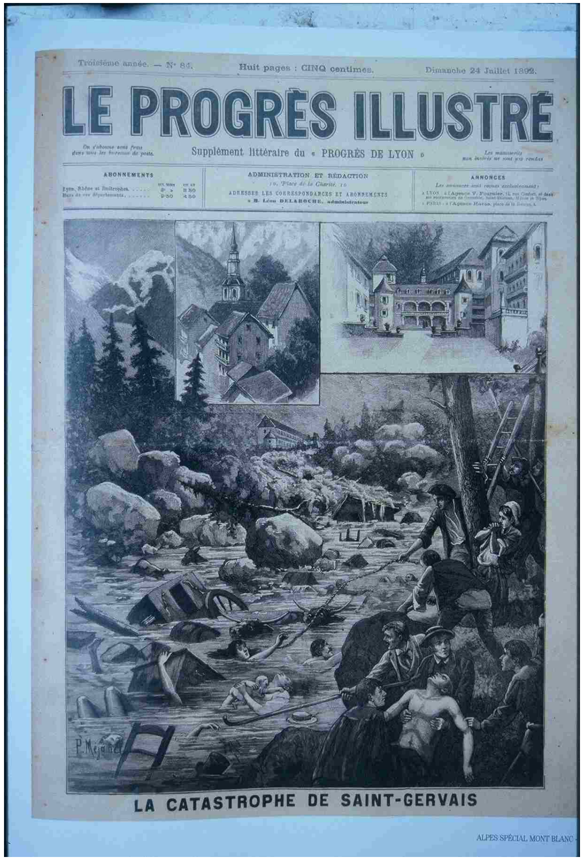
11 July 1892

175 fatalities

100 000 m^3 of water

Flood produced

800 000 m^3 of sediment


Troisième année. — N° 84. Huit pages : CINQ centimes. Dimanche 24 Juillet 1892.

LE PROGRÈS ILLUSTRÉ

Supplément littéraire du « PROGRÈS DE LYON »

ABONNEMENTS

ADMINISTRATION ET RÉDACTION

ADRESSER LES CORRESPONDANCES ET ABONNEMENTS

ANNONCES

LA CATASTROPHE DE SAINT-GERVAIS

ALPES SPÉCIAL MONT BLANC

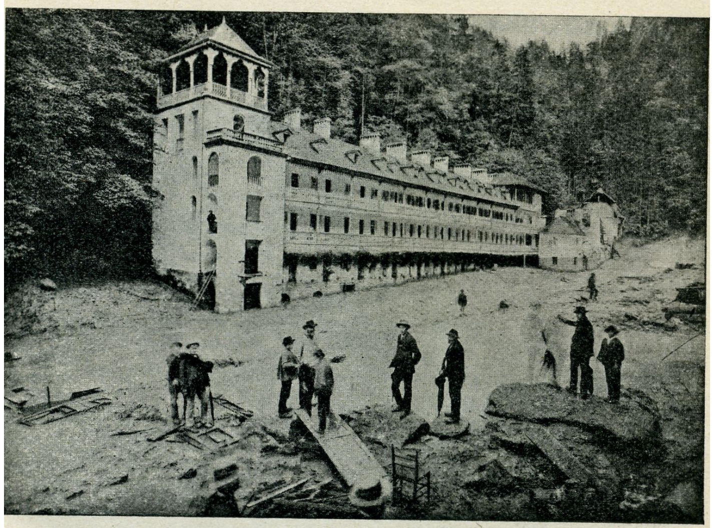
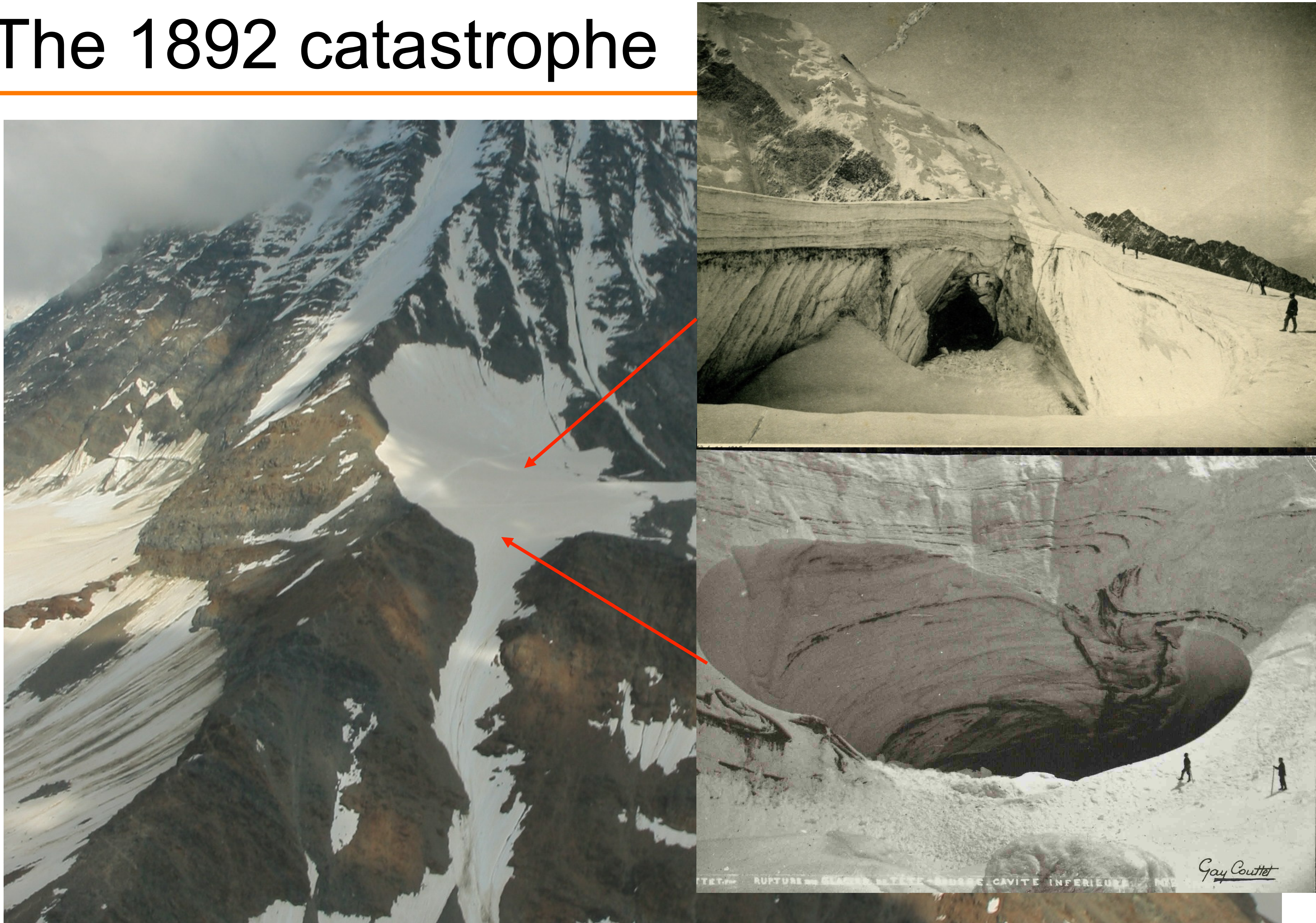



Fig. 22. — Le pont de la route départementale n° 4 tourné et submergé par la lave. 13 juillet 1892. — Cliché Kuss.

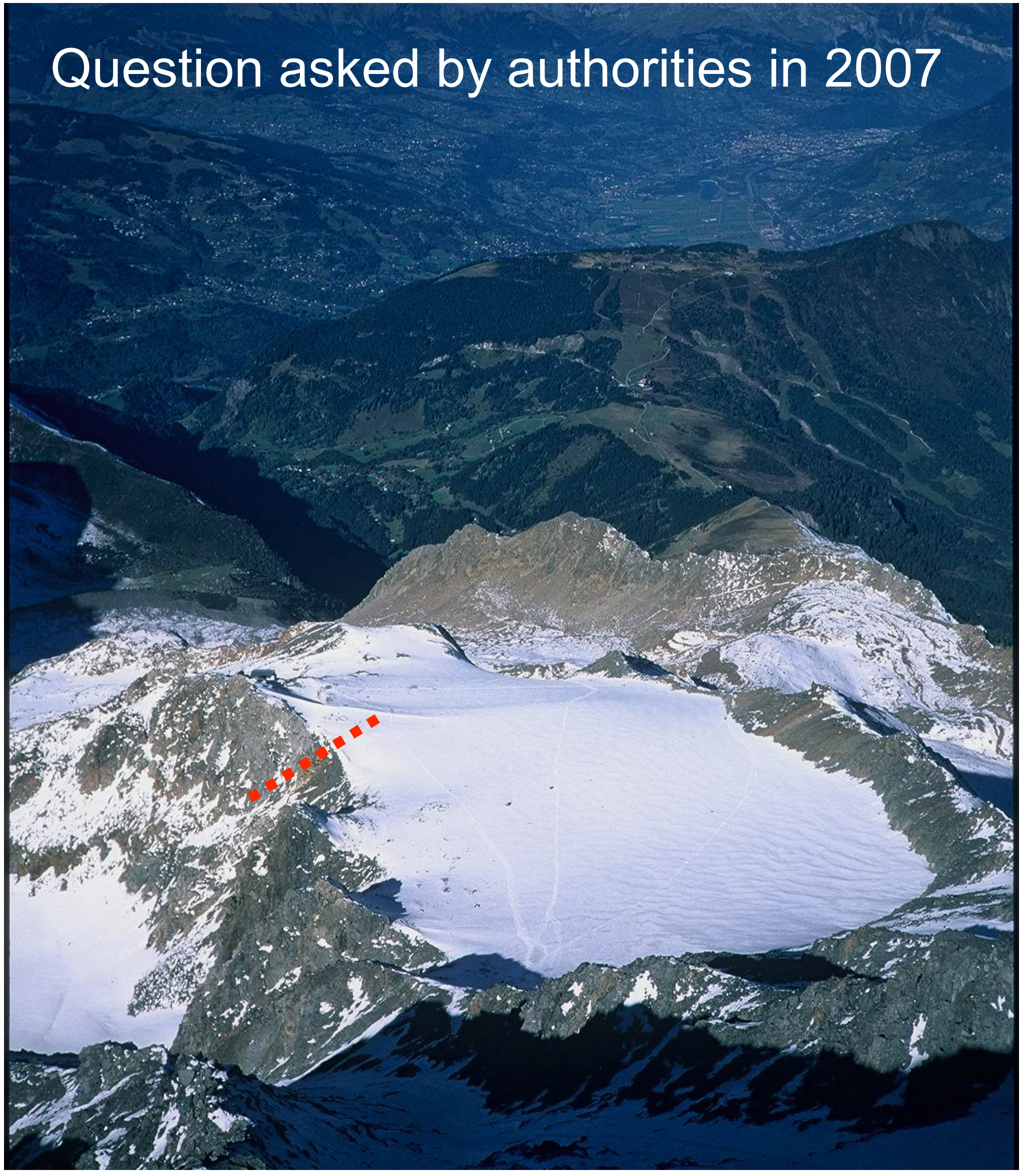
@Vincent, LGGE

The 1892 catastrophe



@Vincent, LGGE

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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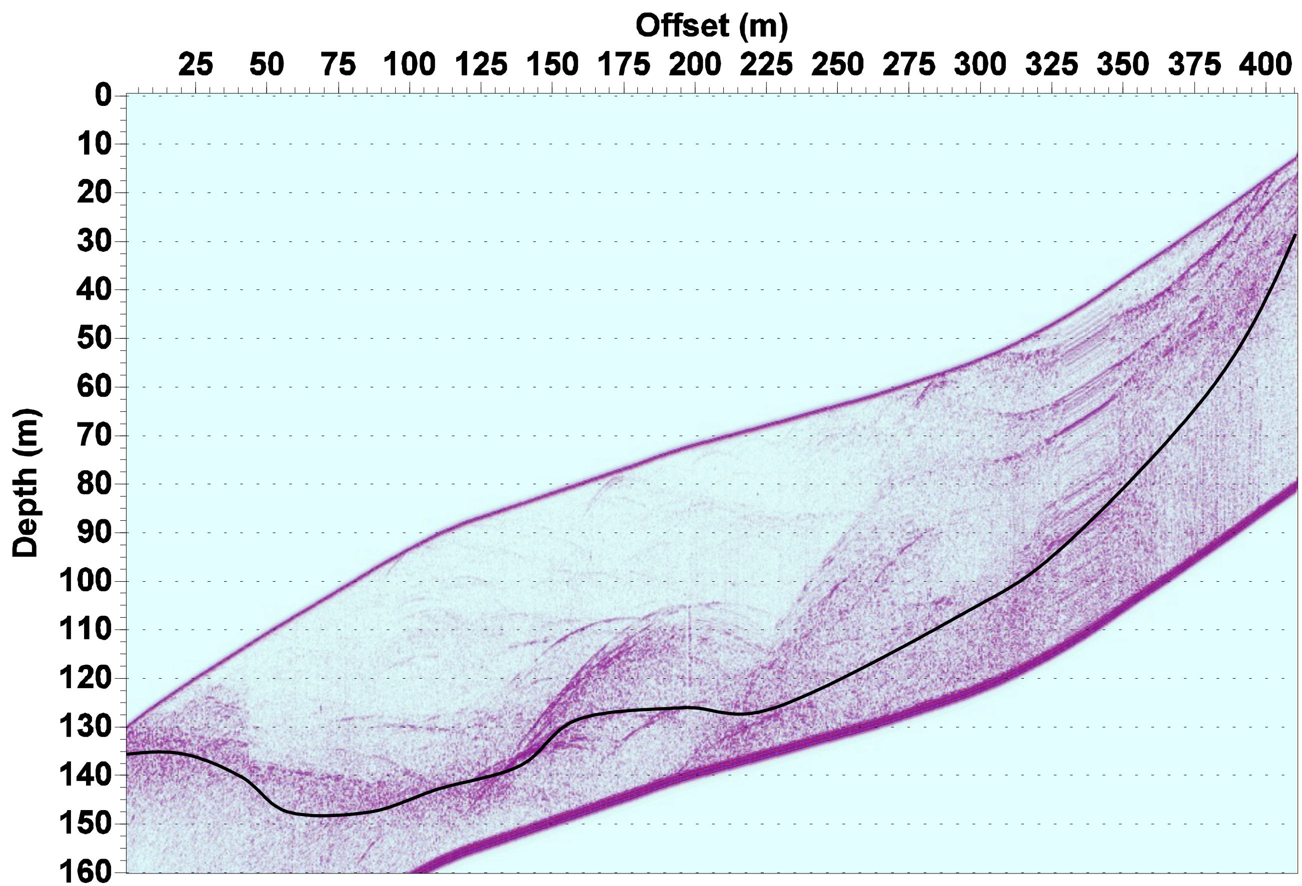
Glaciological studies



@Vincent, LGGE

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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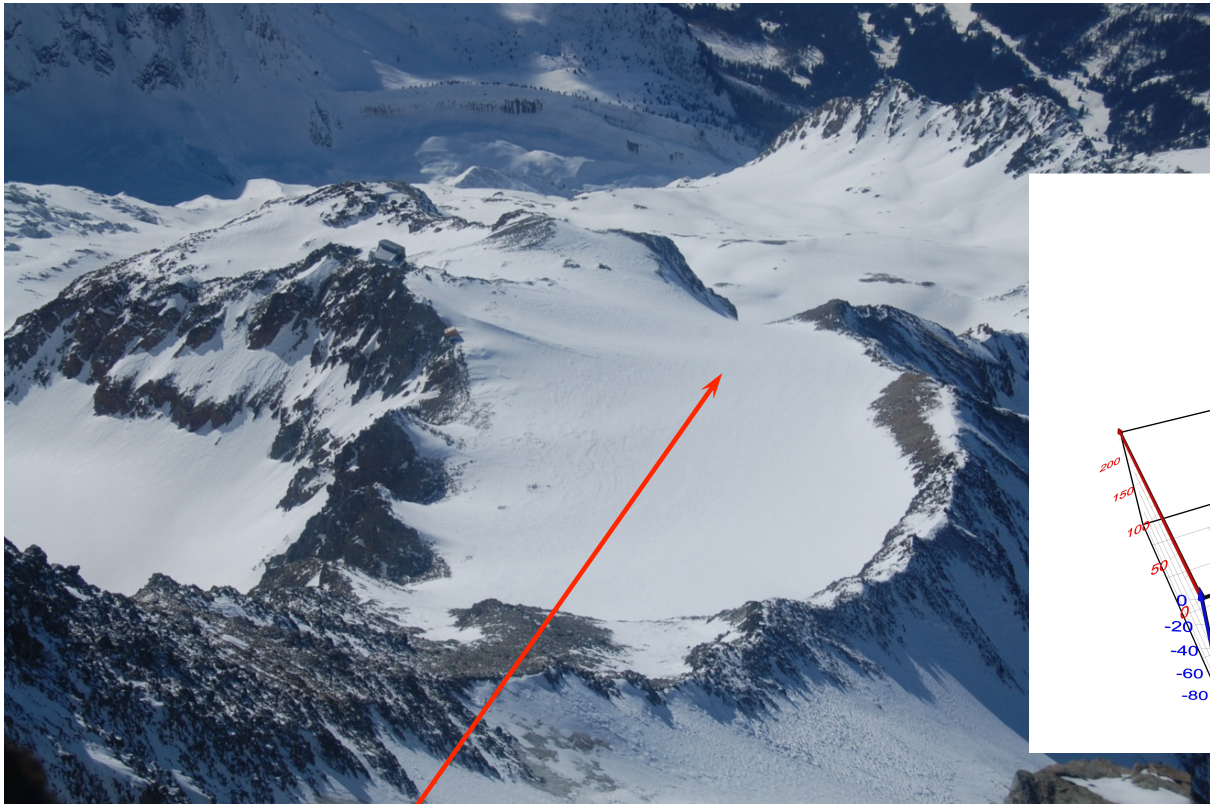
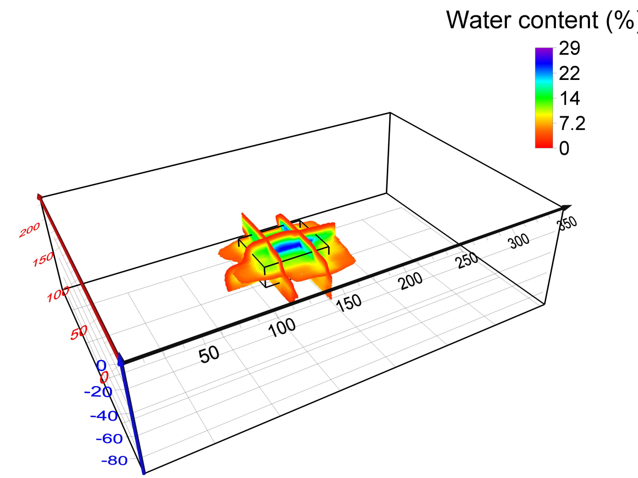
Glaciological studies



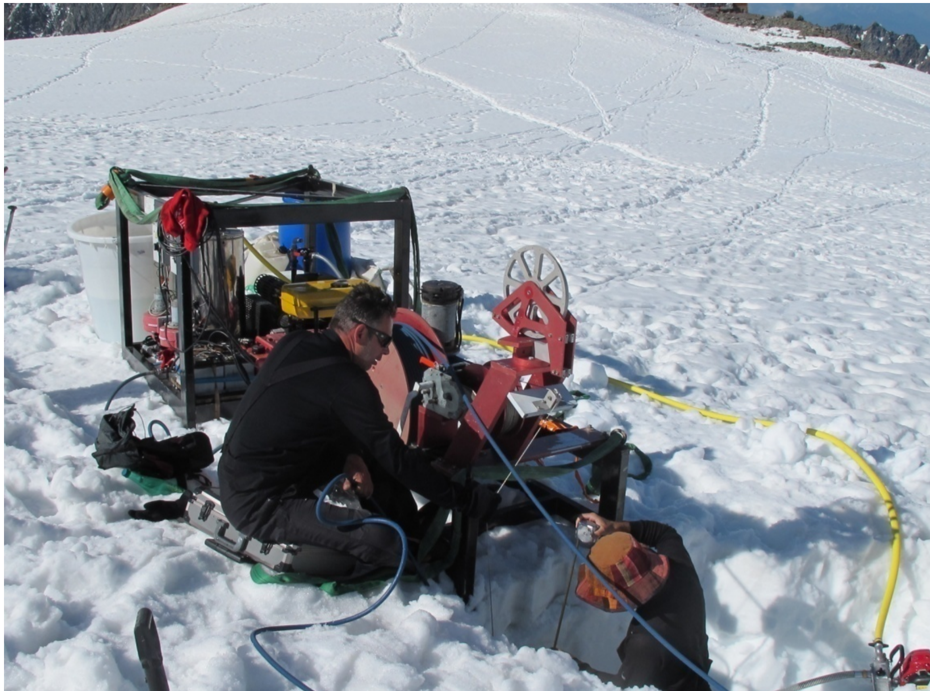


Water volume of 65 000 m^3

Report presented to public authorities in March 2010

@Vincent, LGGE

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

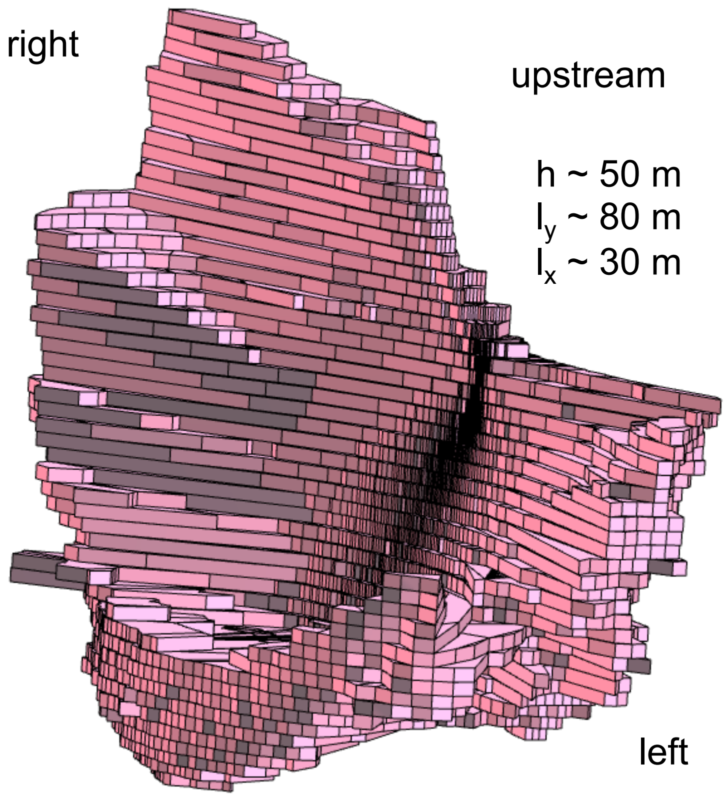
A new risk ?


But was stopped on the 1st of September :
What was the risk of collapse 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?



Time-line for investigations

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

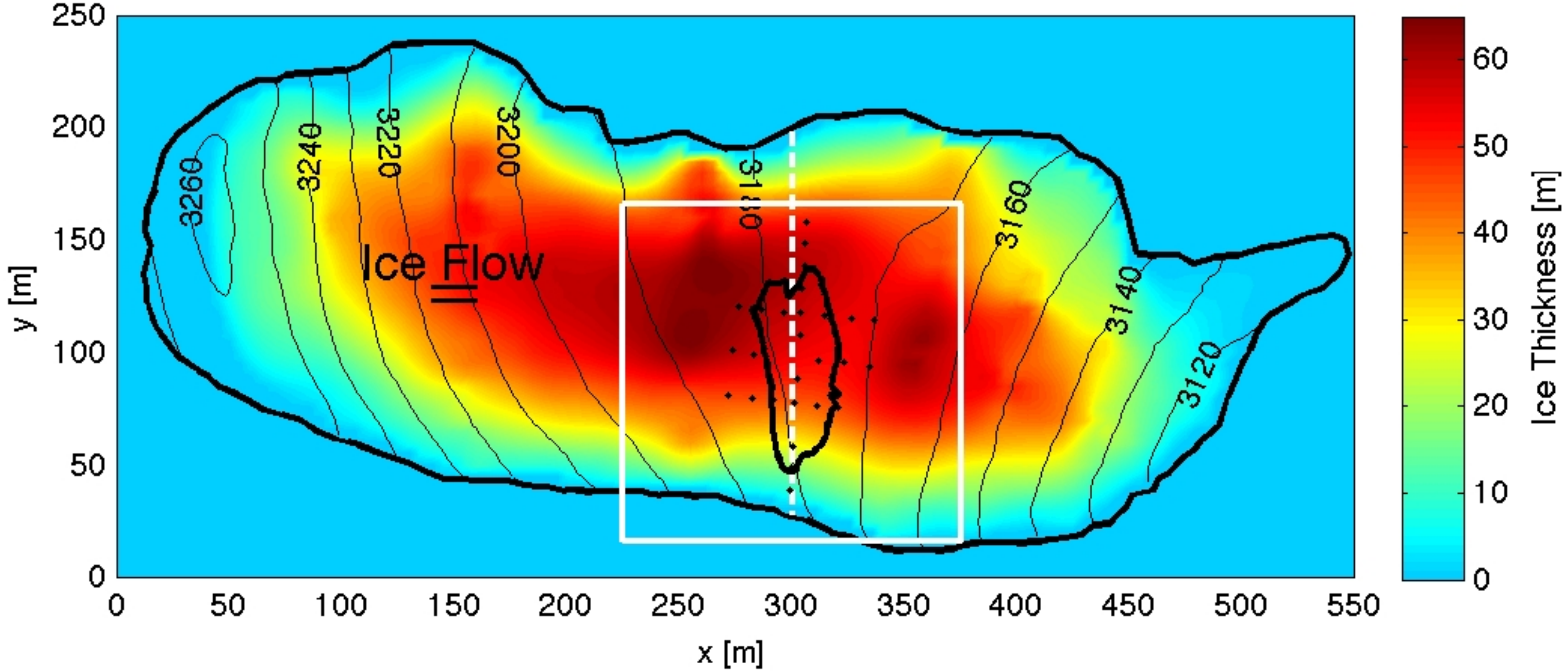
Proposed application

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 empty cavity (0.6 m/a at the centre of the glacier)
- 27 Stakes to measure surface displacement during drainage



Material:

README.txt

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

Step1: Makegeo.py, teterousse1.sif

Step2a: Makegeo_2.py, teterousse2a.sif

Step2b: teterousse2b.sif

Step3a: teterousse3a.sif

Step3b: teterousse3b.sif

Modelling Tête Rousse Glacier

✓ **Step 1** - Tête Rousse Glacier flow without a water filled-cavity (diagnostic)

✓ **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 1: 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

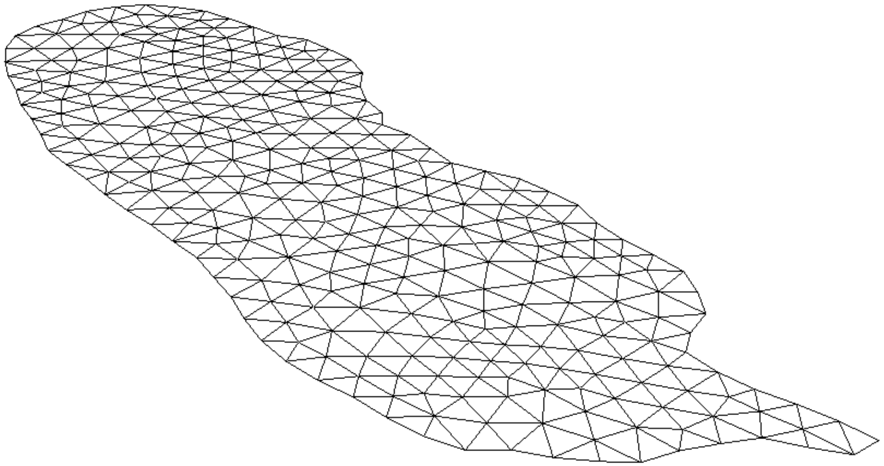
Step 1: steps to make the mesh

1/ build the **`teterousse0.geo`** file (input file of GMSH, footprint of the glacier)

2/ **`gmsh`** to get **`teterousse0.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 (see the sif file)



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

The python script Makegeo.py :

- read the point coordinates in the contour file
- create the teterousse0.geo file (input file for GMSH)

Options :

- the contour can be made of one spline or many lines in between points

- one can choose the size of the elements around the contour

Step 1: **GMSH** (create a .msh file)

```
> gmsh teterousse0.geo -1 -2
```

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

line commands:

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

```
> ElmerGrid 14 2 teterousse0.msh -autoclean
```

transform a GMSH mesh (14) into an Elmer mesh (2)

```
> ElmerGrid 14 5 teterousse0.msh -autoclean
```

transform a GMSH mesh (14) into a vtu file (5)
use Paraview to visualize the mesh

Step 1: 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 second solver to be executed is the StructuredMeshMapper

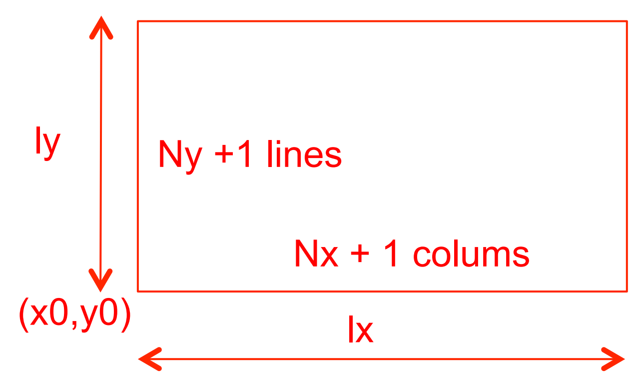
```
Solver 2
  Equation = "MapCoordinate"
  Procedure = "StructuredMeshMapper" "StructuredMeshMapper"
  Active Coordinate = Integer 3        (3d problem - mesh moves in z direction)
  Mesh Velocity Variable = String "dSdt"
  Mesh Update Variable = String "dS"
  Mesh Velocity First Zero = Logical True
  Displacement Mode = Logical False
  Correct Surface = Logical True
  Minimum Height = Real 1.0
End
```

zs = min(zs, bed+1.0)

Step 1: In the sif file

Read, interpolate and store in 2 variables the bed and surface DEM

```
Solver 1
  Exec Solver = "Before Simulation"
  Equation = "Read DEMs"
  Procedure = "ElmerIceSolvers" "Grid2DInterpolator"
  ! Bedrock DEM
  Variable 1 = String "bedDEM"
  Variable 1 data file = File "../Data/DEM_TR_bed.dat"   name of the DEM file
  Variable 1 x0 = Real 947700.0d0
  Variable 1 y0 = Real 2104850.0d0
  Variable 1 lx = Real 600.0                              define the DEM file structure
  Variable 1 ly = Real 350.0
  Variable 1 Nx = Integer 301
  Variable 1 Ny = Integer 176
  Variable 1 Invert = Logical False
  Variable 1 Fill = Logical False
  Variable 1 Position Tol = Real 1.0e-1
  Variable 1 No Data = Real -9999.0
  Variable 1 No Data Tol = Real 1.0

  ! Surface DEM ...
End
```



Step 1: In the sif

BedDEM and ZsDEM (variable) must be declared in one solver (Stokes for example)

```
Exported Variable 3 = -dofs 1 "BedDEM"
Exported Variable 4 = -dofs 1 "ZsDEM"
```

Keywords Bottom Surface and Top Surface (needed by the solver StructuredMeshMapper) are assigned the value of these two variables

```
!Bed rock BC
Boundary Condition 2
  Bottom Surface = Equals BedDEM

  ...

End

! Upper Surface BC
Boundary Condition 3
  Top Surface = Equals ZsDEM
End
```

Step 1: 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)

assume a constant temperature of -1°C

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

Step 1: use Glen's law

```
#yearinsec = 365.25*24*60*60
#rhoi = 900.0/(1.0e6*yearinsec^2)
#rhow = 1000.0/(1.0e6*yearinsec^2)
#gravity = -9.81*yearinsec^2
! Prefactor from Cuffey&Paterson (2010) in MPa^{-3} a^{-1}
#A1 = 2.89165e-13*yearinsec*1.0e18
#A2 = 2.42736e-2*yearinsec*1.0e18
#Q1 = 60.0e3
#Q2 = 115.0e3

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 #Q1
  Activation Energy 2 = Real #Q2
  Glen Enhancement Factor = Real 1.0
  Critical Shear Rate = Real 1.0e-10

  Constant Temperature = Real -1.0
End
```

s^{-1} Pa^{-3} to a^{-1} MPa^{-3}

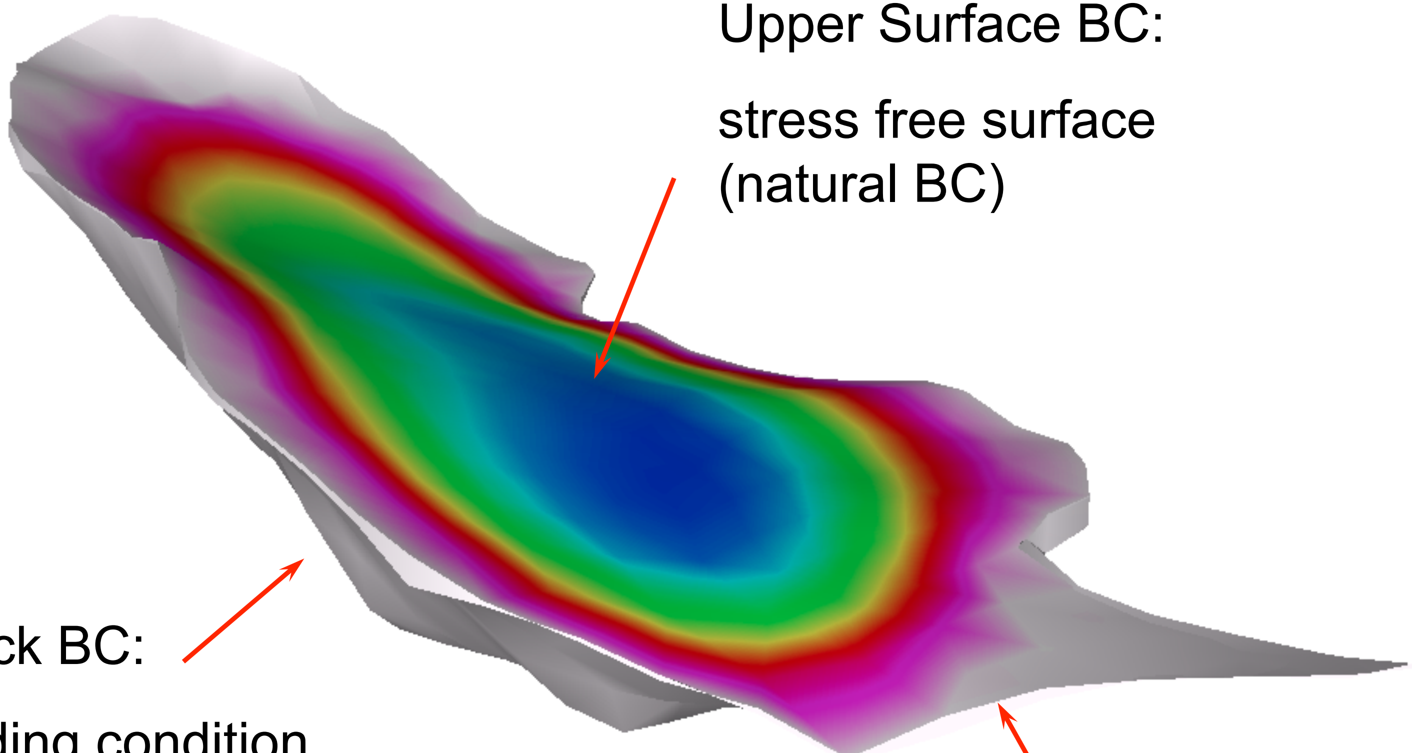
Step 1: Hypothesis of the modelling

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 1: 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 = Equals BedDEM
  Velocity 1 = Real 0.0
  Velocity 2 = Real 0.0
  Velocity 3 = Real 0.0
End

! Upper Surface
Boundary Condition 3
  Top Surface = Equals ZsDEM
End
```

Null horizontal velocities

No sliding

Natural BC, nothing to do!

Step 1: 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

```
Solver 4
  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 1: Stress Solver

- Tell you want the Cauchy stress to be computed (Material Section) (else you will get the deviatoric stress)

```
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 1: Eigenvalues Solver

Objective: compute the eigenvalues of the Cauchy stress tensor

```
Solver 5
   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: Eigenvalues Solver

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

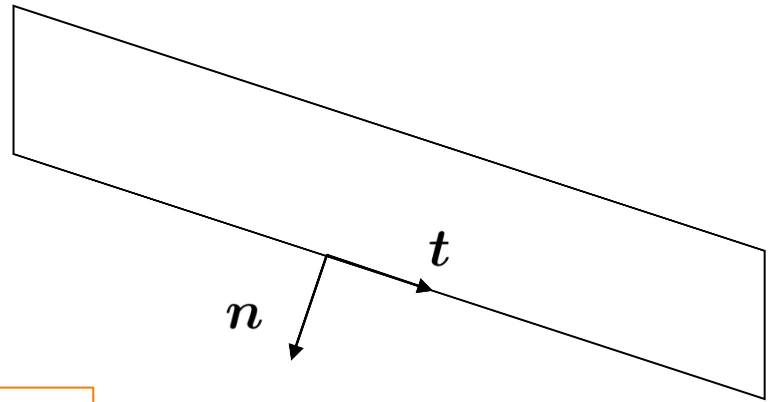
`Eigenstress.1` → S_1
`Eigenstress.2` → S_2
`Eigenstress.3` → S_3

Step 1: Add sliding on the bedrock

Friction law in Elmer (2d case illustrated):

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

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



where n is the surface normal vector

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

Step 1: 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 ?

Modelling Tête Rousse Glacier

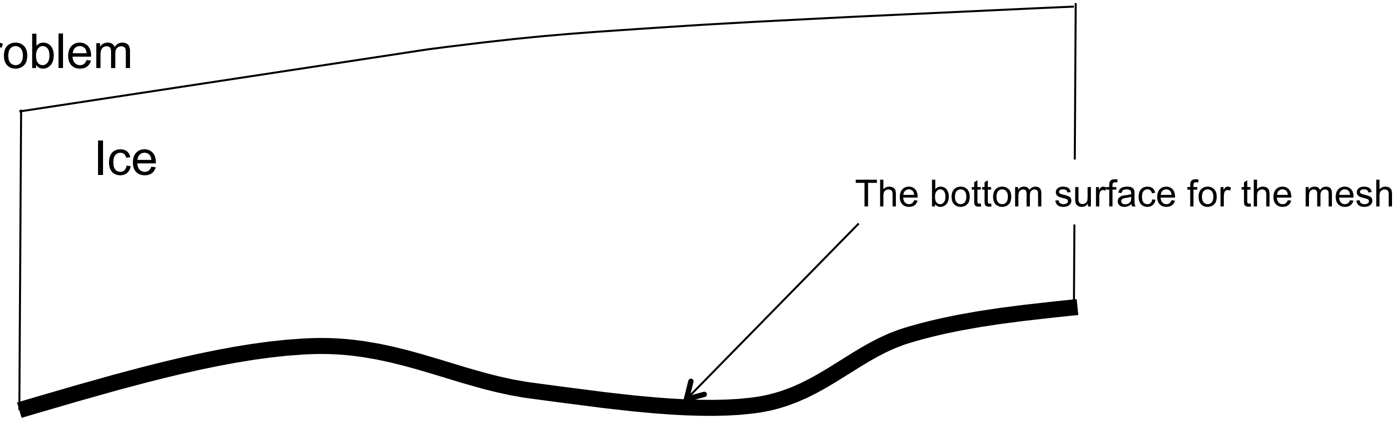
- ✓ **Step 1** - Tête Rousse Glacier flow without a water filled-cavity (diagnostic)

- ✓ **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

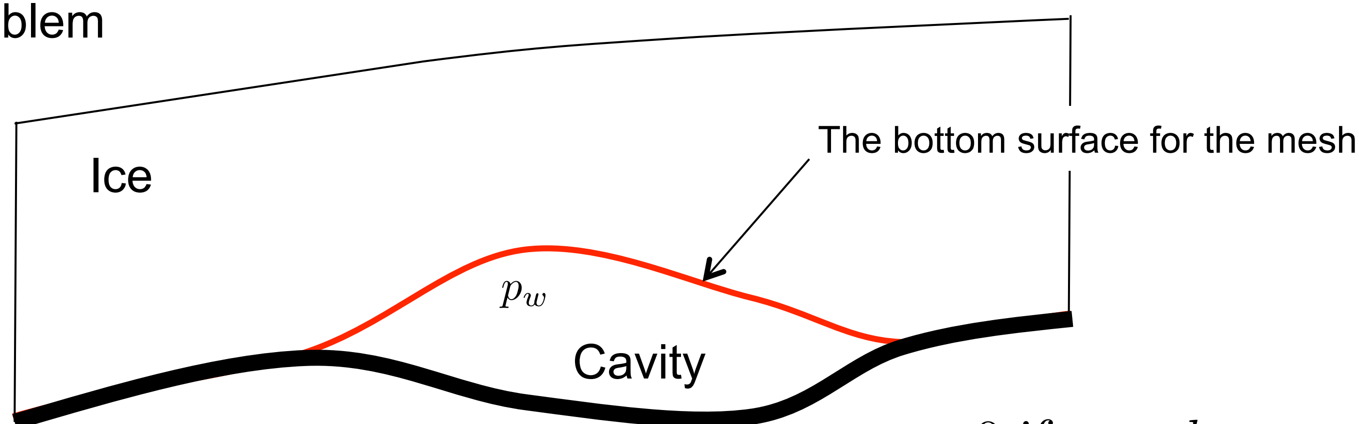
Step 2a: Add the cavity (empty of water)

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 of the ice is now given by the DEM_TR_cavity.dat DEM file.

Change the StructuredMeshMapper to read this DEM and store it in the ZbDEM variable

Declare this new variable (in Stokes solver section):

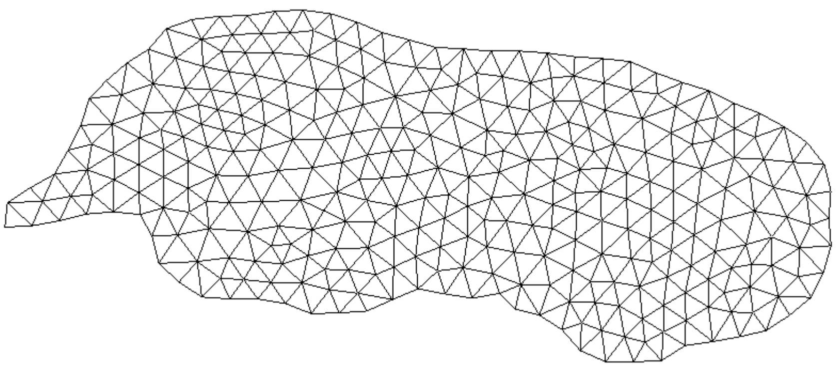
```
Exported Variable 5 = -dofs 1 "ZbDEM"
```

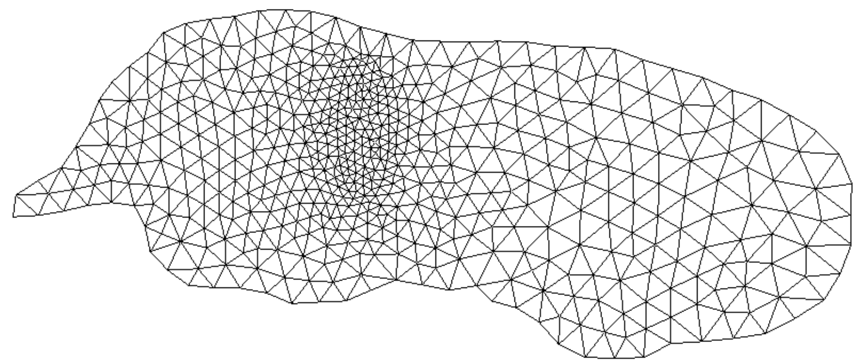
Change the boundary condition 2:

```
Boundary Condition 2
  Bottom Surface = Equals ZbDEM
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.py` file to create this new mesh

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

The python script Makegeo_2.py :

- read the point coordinates in two contour files (cavity and glacier)
- create the teterousse.geo file (input file for GMSH)

Options :

- the contour can be made of one spline or many lines in between points
- one can choose the size of the elements around the two contours

Make the mesh :

```
> gmsh teterousse.geo -1 -2
> ElmerGrid 14 2 teterousse.msh -autoclean
```

See the difference between the two python script:

```
> diff Makegeo_2.py ../Step1/Makegeo.py
```

Step 2a: Change in the basal BC

The basal BC will be of the form:

```
  Velocity 1 = Real 0.0
  Velocity 1 Condition = Variable ZbDEM, BedDEM
    Real LUA "(function() if tx[0] > (tx[1] + 0.01) then
return -1.0 else return 1.0 end end)()"
```

See alternatives 2 and 3 in LUA in the sif file

Velocity 1 Condition = -1 if zbDEM > BedDEM => Don't apply "Velocity 1 = 0"
= +1 if zbDEM <= BedDEM => Apply "Velocity 1 = 0"

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

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

Step 2a: Change in the basal BC

2nd Solution – use a f90 user function instead of LUA language

The basal BC will be of the form:

```
  Velocity 1 = Real 0.0
  Velocity 1 Condition = Variable ZbDEM, BedDEM
    Real Procedure "../PROG/USF_TR" "MaskCavity"
```

Compile the user function USF_TR.f90 in PROG/

```
elmerf90 USF_TR.f90 -o USF_TR
```

Best solution for large problem:

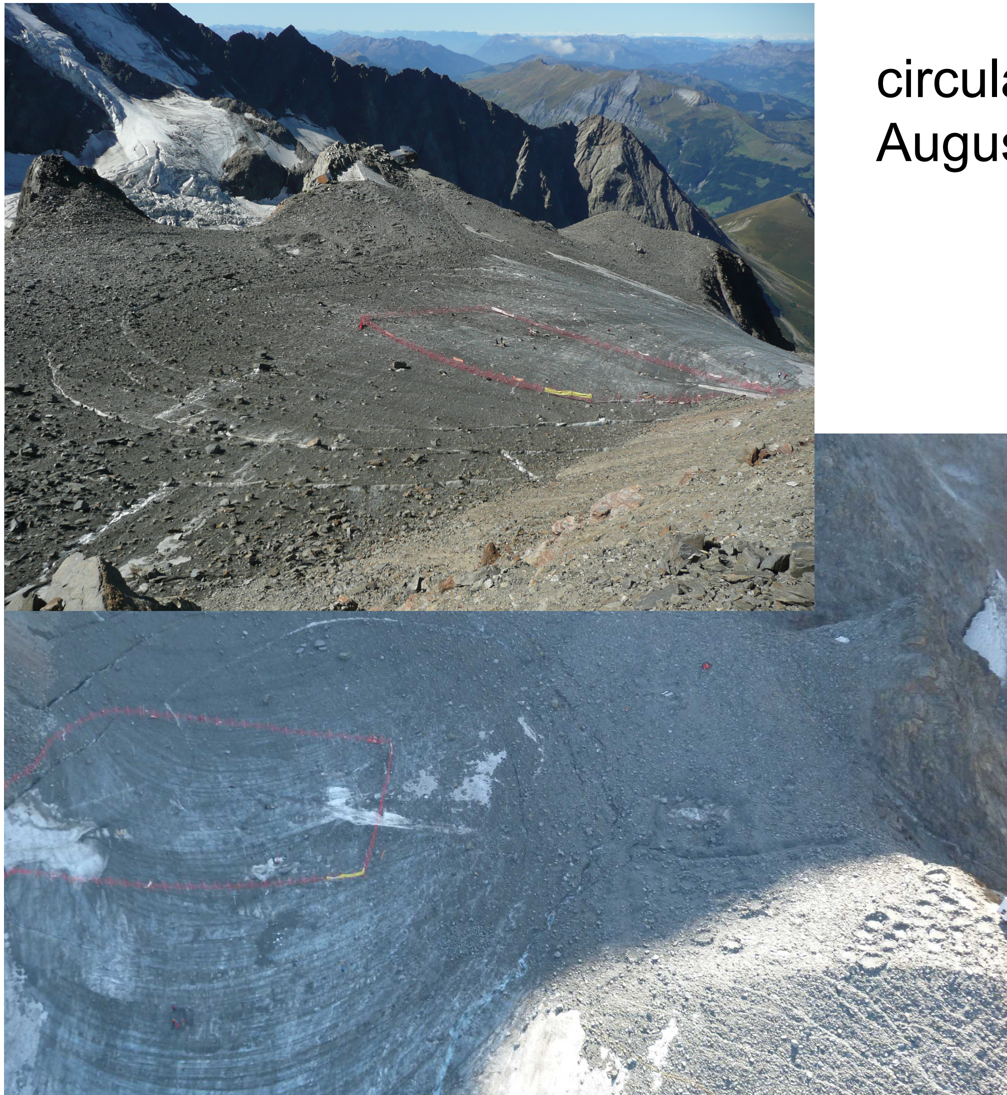
a f90 user function is much faster than MATC coding in the sif!

To be tested against LUA!

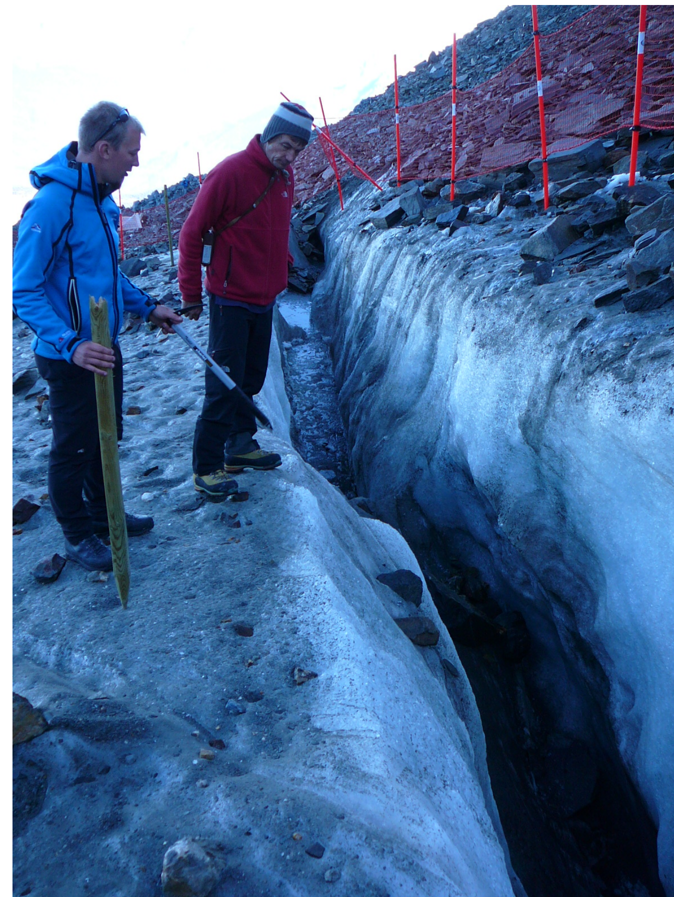
Step 2a: MaskCavity user function

```
FUNCTION MaskCavity ( Model, nodenumber, Input) RESULT(Mask)
   USE types
   USE CoordinateSystems
   USE SolverUtils
   USE ElementDescription
   USE DefUtils
   IMPLICIT NONE
   TYPE(Model_t) :: Model
   TYPE(Solver_t), TARGET :: Solver
   INTEGER :: nodenumber
   REAL(KIND=dp) :: Input(2), Mask
   REAL(KIND=dp) :: znode, zbed

   znode = Input(1)
   zbed = Input(2)

   IF (znode > zbed+0.1) THEN
      Mask = -1.0
   ELSE
      Mask = 1.0
   END IF
END FUNCTION MaskCavity
```

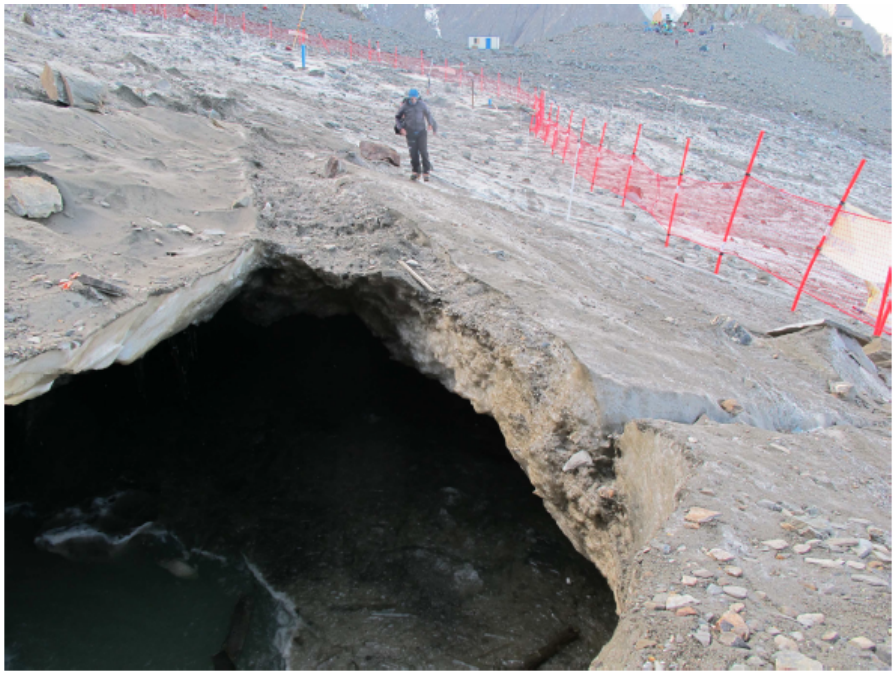
Observed crevasses one year after 1st drainage



circular crevasses observed in August 2011



Evolution of the cavity geometry



Break off of part of the cavity roof after the 2012 artificial drainage.

Modelling Tête Rousse Glacier

✓ **Step 1** - Tête Rousse Glacier flow without a water filled-cavity (diagnostic)

✓ **Step 2**

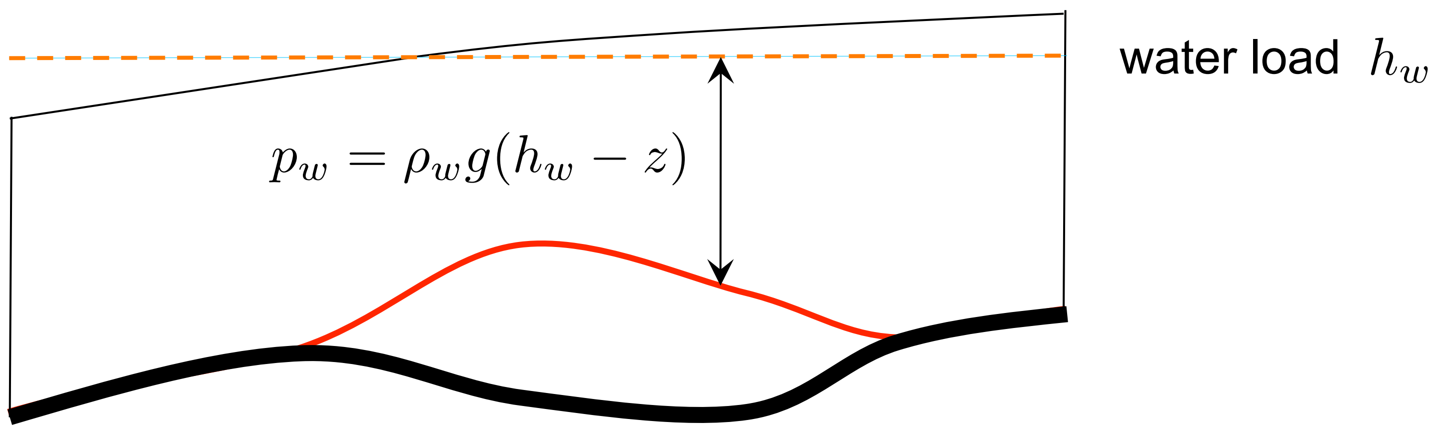
- 2a Influence of an empty cavity below Tête Rousse Glacier (diagnostic)
- 2b Apply a water pressure in the cavity

✓ **Step 3**

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

Step 2b: Add a water pressure

Modify the SIF to add a water pressure




```
#hw = 3176.0
```

the water load

In the bedrock BC

```
External Pressure = Variable Coordinate 3
   Real LUA "rhow*gravity*(hw-tx[0])
```

will only apply where a Dirichlet BC is not applied i.e. in the cavity

Modelling Tête Rousse Glacier

✓ **Step 1** - Tête Rousse Glacier flow without a water filled-cavity (diagnostic)

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- 2a Influence of an empty cavity below Tête Rousse Glacier (diagnostic)
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✓ **Step 3**

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

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, needs 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 = 50
Timestep Sizes = #10.0/365.25

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

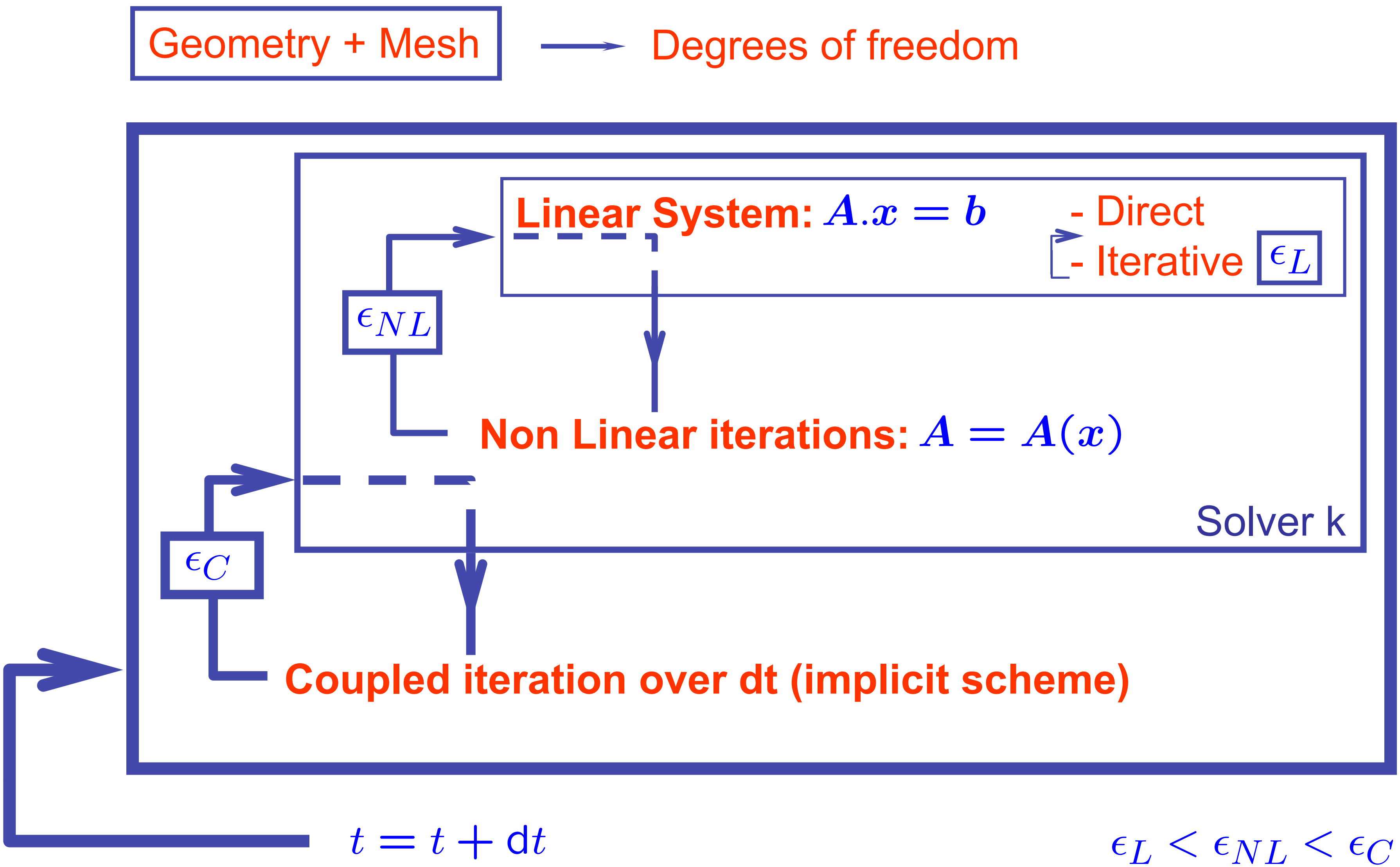
→ Backward Differences Formulae

→ To control the “implicity” of the solution over one time step (here 1 means explicit)

```
Restart File = "../../Step2a/teterousse/teterousse_Step2a_.result”
Restart Position = 0
Restart Time = Real 0.0
Restart Before Initial Conditions = Logical True
```

→ We need a restart to have the ZsDEM and ZbDEM variables for the initial condition of Zs and Zb

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 on 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 BC3 that this is the body 2:

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

Step 3a – Add the Free surface Solver

```
Solver 6
  Equation = "Free Surface Top"
  Variable = String "Zs"
  Variable DOFs =  1
  Exported Variable 1 = String "Zs 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
End
```

Step 3a – Upper Surface

Body Force 2:

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

Equation 2:

```
Equation 2
  Active Solvers(1) = 6
  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 = Equals ZsDEM
End
```

Step 3a - StructuredMeshMapper

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

```
Solver 2
  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"
  Bottom Surface Variable Name = String "Zb"

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 = Equals ZsDEM
End
```

Step 3a – Same for the bedrock

Name of the variable: `Zb`
Add solver : `Solver 7`
Add equation: `Equation 3`

Modify the the Bottom surface BC (3):

```
Boundary Condition 2
  Body Id = 3
  ~~Bottom Surface = Equals ZbDEM~~
End
```

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

```
Min Zb = Equals BedDEM
Max Zb = 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 3
  Equation = "Navier-Stokes"
  Nonlinear System Reset Newton = Logical True

End
```

Step 3a – Cavity volume

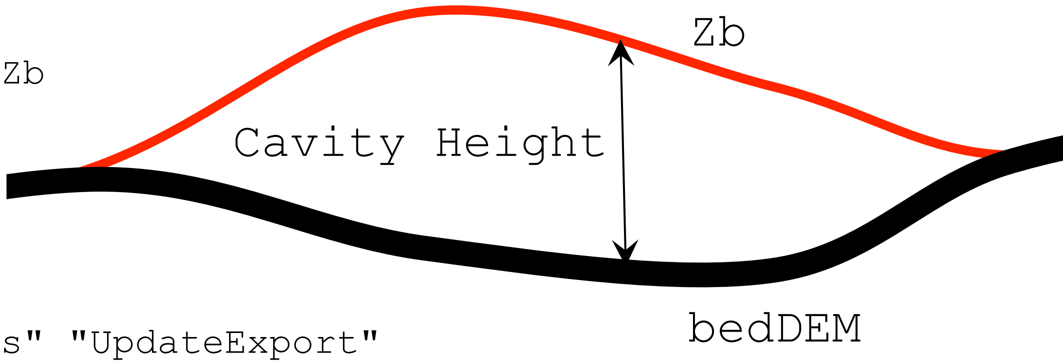
Add the SaveScalars (Elmer) and UpdateExport (Elmer/Ice) solvers to save the cavity volume at each time step in an ASCII file.

```
Body Force 3
  Cavity Height = Variable bedDEM, Zb
      Real LUA "tx[1]-tx[0]"
End

Solver 8
   Equation = "UpdateExport"
   Procedure = File "ELmerIceSolvers" "UpdateExport"
   Variable = -nooutput "dumy"

   Exported Variable 1 = -dofs 1 "Cavity Height"
End

Solver 9
  Procedure = File "SaveData" "SaveScalars"
  Filename =  "teterousse_$Step".dat"
  File Append = Logical True
  Variable 1 = String "Time”
  Variable 2 = String "Cavity Height"
  Operator 2 = String "int"
End
```



create a variable containing the cavity height

Step 3a – Two subtleties...

1/ Need of the restart...

Initial conditions are set before the first solver is executed
Impossible then to initialize with an other variable
This is then done by using a restart and specifying:

```
Restart Before Initial Conditions = Logical True
```

2/ Problem when a solver is called two time in the same sif...

Need to make a copy of the object file to avoid mixing of the saved variables in the solver from two different calls:

```
cp $ELMER_HOME/share/elmersolver/lib/FreeSurfaceSolver.so
MyFreeSurfaceSolver
```

Use a different call in the sif file for Zb:

```
Procedure = "./MyFreeSurfaceSolver" "FreeSurfaceSolver"
```

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Step 3b – Add a drainage scenario

Add an evolution of the water load of the linear 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

- write a User Function to do the same (see USF_TR.f90)

Step 3b – Add a drainage scenario

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

```
! Water load function of time (in year)
! Decrease by DH in DT and h > 3100.0
---LUA BEGIN
 function hw(t)
   DH = 70.0
   DT = 20.0
   h = 3170.0 - t*365.25*DH/DT
   if (h > 3100.0) then return h else return 3100.0 end
 end
---LUA END
```

Call in the bedrock BC

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

Go parallel

This test should work in parallel as it is.

What is needed is just a partitioned mesh (here 2 partitions):

```
> ElmerGrid 14 2 teterousse0.msh -autoclean -metis 2 4
```

create a file `ELMERSOLVER_STARTINFO` which contains the name of the sif file on its first line,

and then

```
> mpirun -np 2 ElmerSolver
```

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.