From scientific research to risk management: the case of the water-filled cavity within the Tête Rousse Glacier (French Alps)

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Outline

- History, from 1892 to today
- Why is there a cavity? Since when?
- How to measure the cavity volume / geometry?
- Where is the water coming from?
- Evolution of the cavity geometry?
Location (Mont Blanc Area, French Alps)

City of Saint Gervais

Bionnassay Glacier

Tête Rousse Glacier
Location (Mont Blanc Area, French Alps)

Tête Rousse Glacier
3100 to 3300 m
0.08 km² (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

Today - Observation of the glacier and volume of water in the cavity
The 1892 catastrophe

11 July 1892

175 fatalities

200 000 m$^3$ of water + ice

Flood produced

800 000 m$^3$ of sediment
The 1892 catastrophe
The 1892 catastrophe

1892 cavities are the result of crevasses that became filled with meltwater

[Vallot et al., 1892]

2010 “…the origin of the water reservoir was very likely a supraglacial lake formed before 1878, during the period of negative mass balance.”

“Given that the mean surface mass balance was positive between 1878 and 1892, the lake was hidden from the surface until the outburst flood of 1892”

[Vincent et al., 2010]
Is there still a risk at Tête Rousse?

Is it still necessary to maintain the 1904 tunnel?

Question asked by authorities in 2007

Is there still a risk at Tête Rousse?

[Is it still necessary to maintain the 1904 tunnel?]

[Vincent et al., 2010]
Glaciological studies (2007 to 2010)

. Topographic measurements
. Radar measurements
. Temperature measurements
. Mass balance measurements
The radar measurements showed a zone (volume) with an anomaly.

[Garambois, ISTerre]
3D-SNMR

In Sept 2009, geophysical survey using the Surface Nuclear Magnetic Resonance imaging

(LTHT, Grenoble)
3D-SNMR

Water volume of 65 000 m³

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!
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

The artificial drainage started the 26 of August
A new risk?

But was stopped the 1st September:

What was the risk of breakout of the cavity roof induced by the artificial drainage?
Geometry of the 2010 cavity

from sonar measurements

right

upstream

h ~ 50 m

l_y ~ 80 m

l_x ~ 30 m

left
Timing for answering

Sonar data (cavity geometry)

Meeting with the mayor of St Gervais

Olivier GAGLIARDINI - 22 Oct 2014 - Tête Rousse
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 center of the glacier)
- 27 Stakes to measure surface displacement during drainage
Stress analysis from ice flow modelling

Finite element model Elmer/Ice: glacier + cavity

**Conclusion:** «the chance of the cavity roof to collapse is low, but cannot be excluded »

Survey of the surface displacement during the pumping

[Gagliardini et al, 2011]
A posteriori validation of the flow model

circular crevasses observed in August 2011
From surface displacements

[Gagliardini et al, 2011]
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✓ History, from 1892 to 2012

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Thermal regime of Tête Rousse glacier

Measured / Modelled temperature in 2010

[Gilbert et al, 2012]
The cavity clearly influence the temperature field

Measures

Model with cavity

Model without cavity

[Gilbert et al., 2011]
Importance of the firn thickness

- release of latent heat by refreezing of meltwater in the firn

“Paradoxically, periods with negative mass balances, associated with warmer air temperature, tend to cool the glacier, whereas years with colder temperatures, associated with positive mass balances, tend to increase the glacier temperature by increasing the firnpack depth and extent.”

[Gilbert et al, 2012]
Evolution of the snow and firn thickness

Rapid and large changes of snow thickness over the last 200 years

1878-1892: period of positive mass balance, increased the snow pack thickness

Since 1980: decrease of the snow pack

[Gilbert et al, 2012]
Temperature told us about the age of the cavity (~30 years)

[Gilbert et al, 2012]
Influence of the bedrock topography

[@Garambois, ISTerre]
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How to measure the cavity shape

✓ Sonar
  - give the geometry
  - cannot see the whole cavity (shaded parts)

✓ Ground-Penetrating Radar (GDR)
  - give the geometry
  - difficult to analysis reflexions in the cavity

✓ Surface Nuclear Magnetic Resonance imaging (3D-SNMR)
  - Good estimate of the total volume of liquid water
  - Don’t give the geometry

✓ From volume pumped
  - Can reconstruct dV as a function of the altitude
  - Cannot get the bottom of the cavity (water not pumped)
Water level since 2010 (from piezometers)

- Glacier surface elevation above the cavity

Pumping 2010: 47,728 m³
Pumping 2011: 16,162 m³
Pumping 2012: 8,682 m³
Water level since 2010

Measurement problems or real pressure variation?
Water level since 2010

Daily variation of the pressure (outflow from old drillings)
Water level and meltwater
from the 24 August to the 10 October 2012

[Vincent et al, in prep]

from the 25 July to 2 August 2014

[Vincent et al, in prep]
Volume – level evolution

From the volume pumped, one can reconstruct the cumulative volume of the cavity as a function of the altitude.
Evolution of the cavity geometry

[Vincent et al, in prep]
Reconstruction of the volume evolution

2009
53 500 m³

from 3D-SNMR

Pumping 2010
47 728 m³

27 Sept 2010
19 500 m³

Sept 2011
18 500 m³

Pumping 2011
16 162 m³

August 2012
11 200 m³

June 2012
8 500 m³

June 2011
7 000 m³

2009
53 500 m³
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Weather measurements

8 June 2011  3 July 2011  11 August 2011  16 September 2011
Link with surface runoff

[Vincent et al, in prep]
Phase shift between melt and filling

[Vincent et al, in prep]
Where is the water coming from?

water from melt of snow/firn upstream the rimaye.
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Stakes networks

27 Stakes in 2010

30 Stakes in 2011

44 Stakes in 2012
Vertical surface velocity [mm/d]

Max winter displacement 2.52 m

Max winter displacement 0.6 m

Pumping 2010

Pumping 2011

Pumping 2012
Evolution of the cavity geometry

Growing phase
Before 2010
Cavity under pressure

Artificial Drainage phase
Autumn 2010, 2011 and 2012
Cavity shrinking

Refilling phase
Winter-> Summer 2010, 2011 and since Autumn 2012
Cavity growing, pressure limited by the numerous drilled holes
Evolution of the volume of the cavity

**2010 to 2011**
- Stakes
- MNT Lidar
- MNT GPS

**2011 to 2012**
- Stakes

Volume from the surface deflexion
= volume lost by the cavity

<table>
<thead>
<tr>
<th>Year</th>
<th>Pumped</th>
<th>lost</th>
<th>surface deflexion</th>
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<tbody>
<tr>
<td>2010</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>16</td>
<td>28</td>
<td>15 +/-5</td>
</tr>
<tr>
<td>2012</td>
<td>9</td>
<td>7</td>
<td>4 +/-2</td>
</tr>
</tbody>
</table>
Evolution of the cavity geometry

[Vincent et al, in prep]
Evolution of the cavity geometry

2010
2011

----- sonar
- - - GPR

[Vincent et al, in prep]
Evolution of the cavity geometry

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

✓ a collaborative work in an operational context

✓ a program research to better understand this phenomena

✓ a real mechanical experiment for ice creep

✓ are there other cavities in other glaciers? Where? Which conditions?

✓ not the end of the story of Tête Rousse glacier...