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

Local collaborations: LGGE, IsTerre, CEMAGREF, LTHE

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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)

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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

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

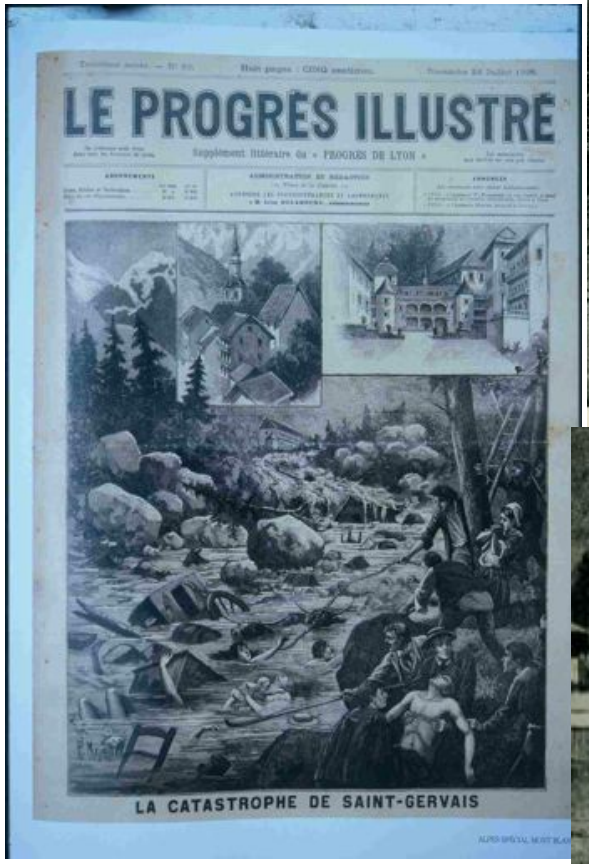
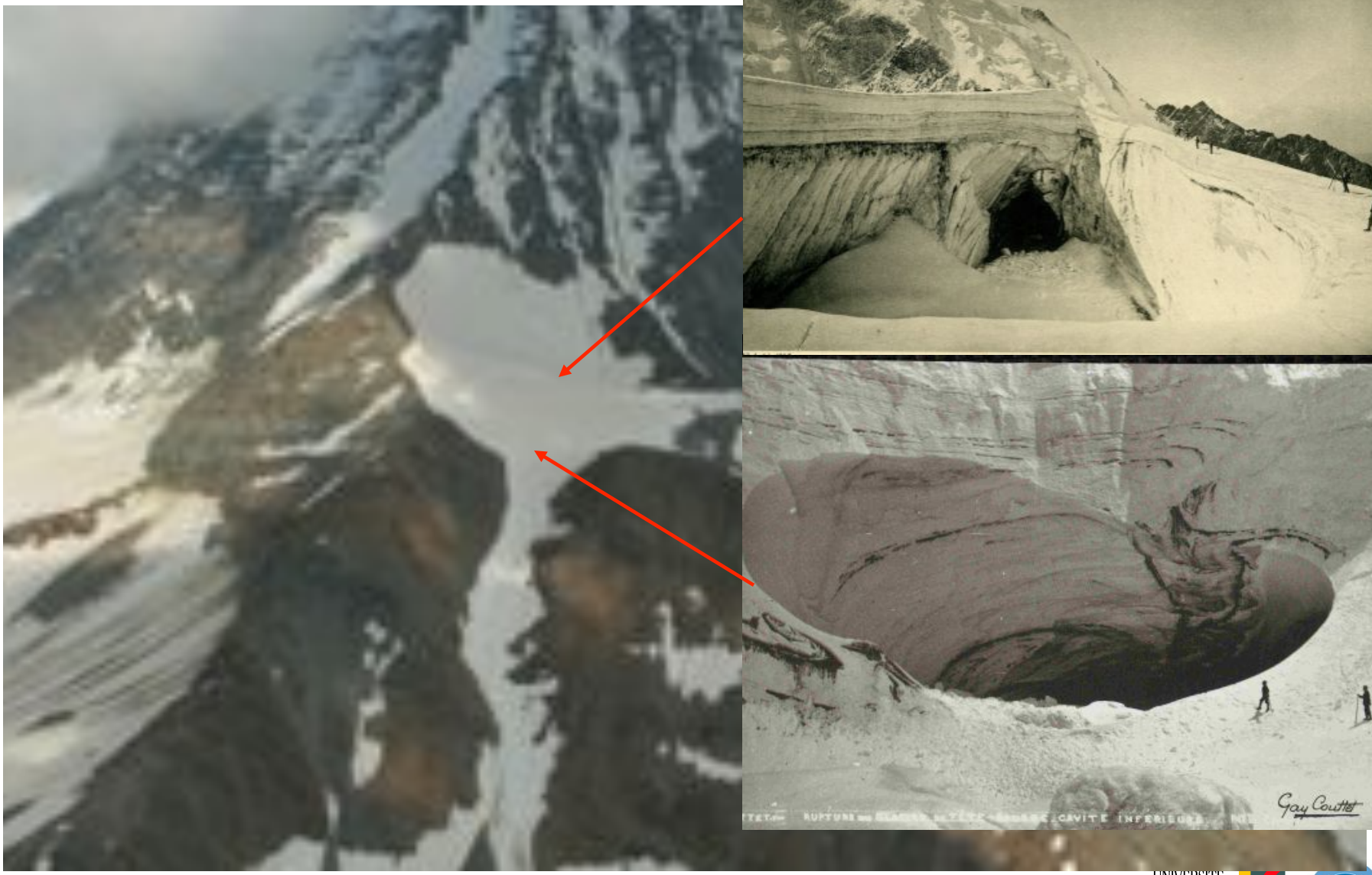



Fig. 22. — Le pont de la route départementale n° 4 tourné et submergé par la lave.
13 juillet 1892. — Cliché Kilian.

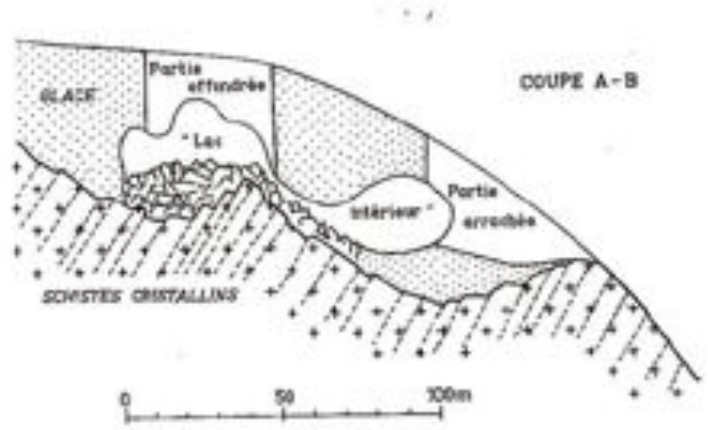
The 1892 catastrophe



The 1892 catastrophe

a

[Vallot et al., 1892]

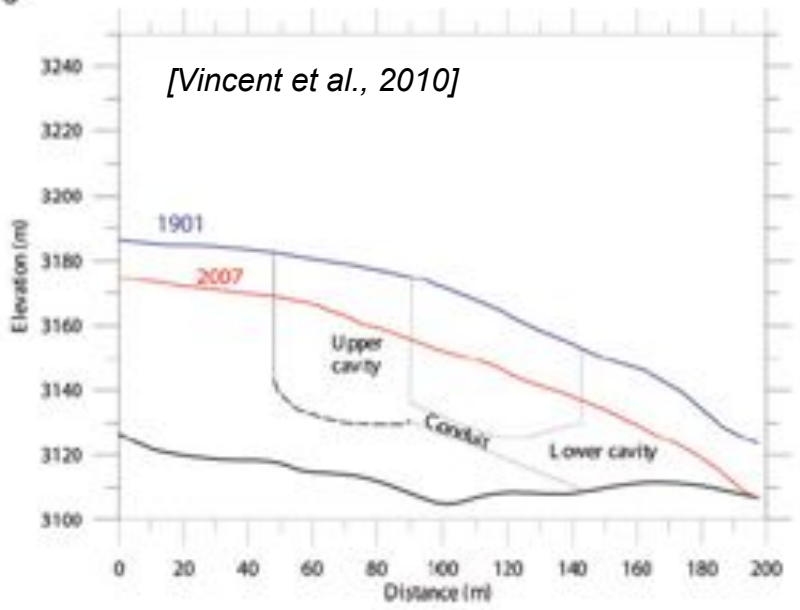


1892
cavities are the result of crevasses that became filled with meltwater

[Vallot et al., 1892]

b

[Vincent et al., 2010]

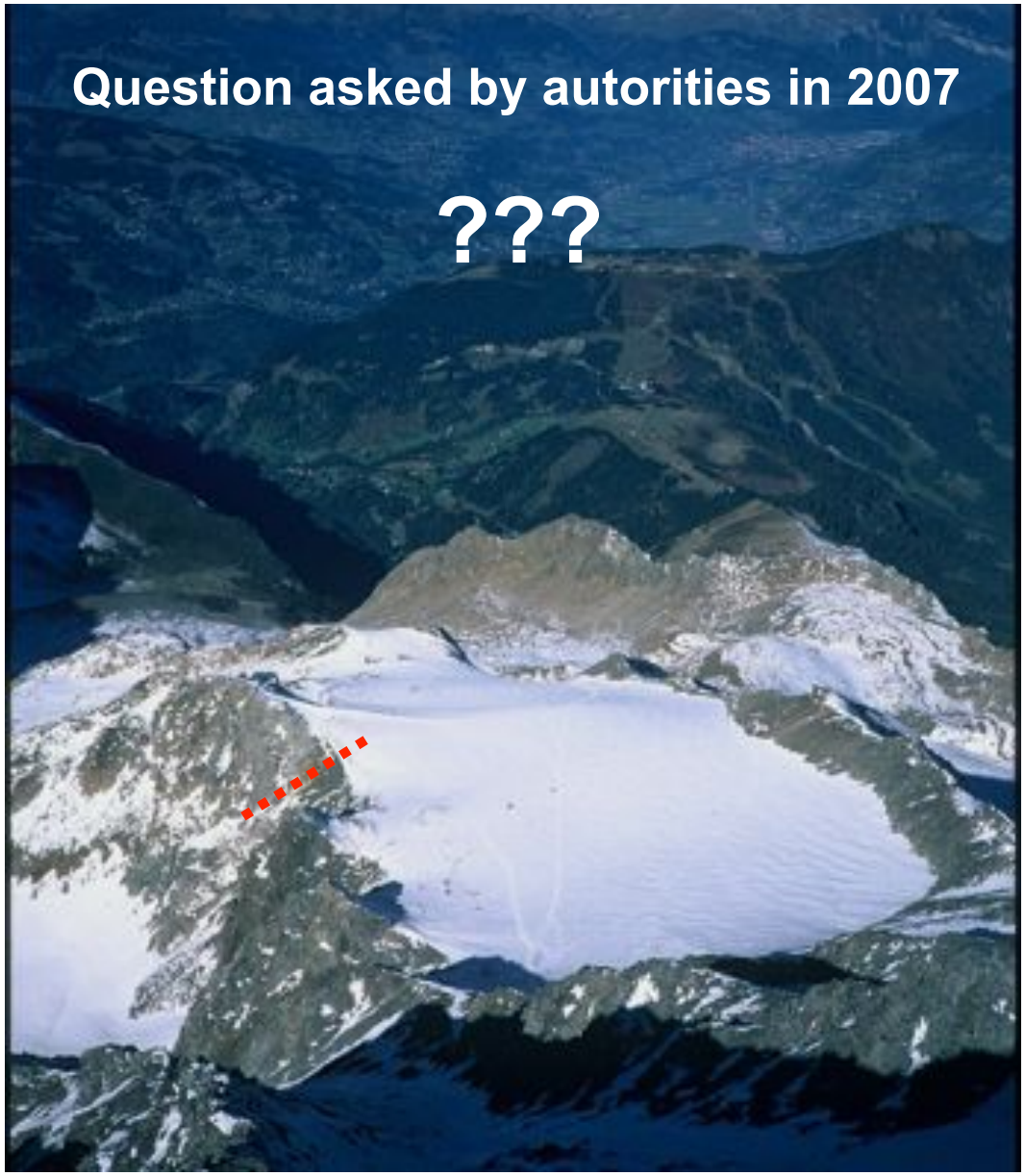


2010
"…the origin of the water reservoir was very likely a supraglacial lake formed before 1878, during the period of negative mass balance."

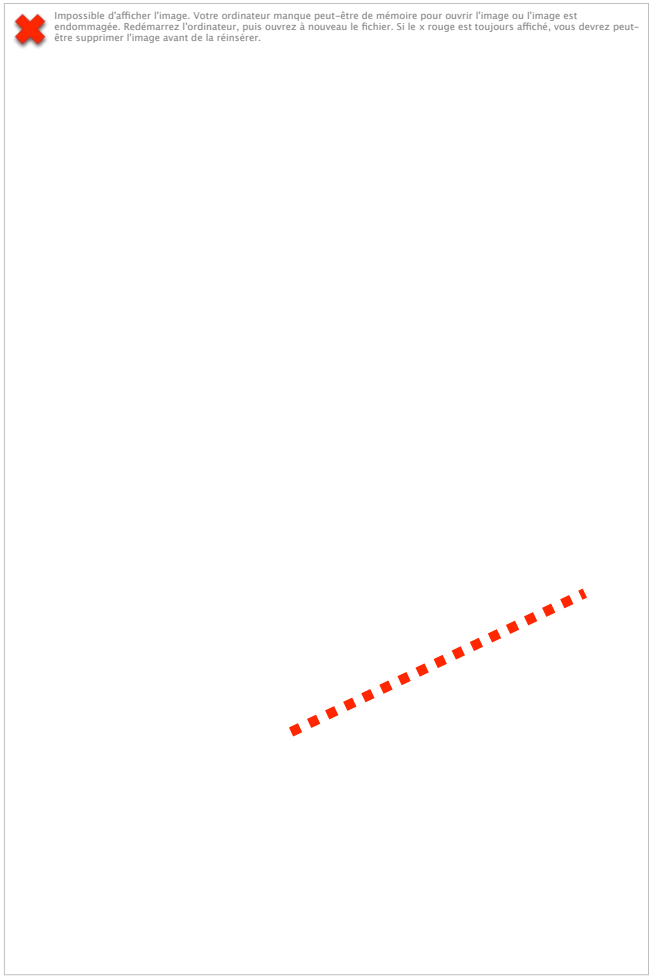
"Given that the mean surface mass balance was positive between 1878 and 1892, the lake was hidden from the surface until the outburst flood of 1892"

[Vincent et al., 2010]

Is there still a risk at Tête Rousse ?



Is it still necessary to maintain the 1904 tunnel?



[Vincent et al., 2010]

Glaciological studies (2007 to 2010)

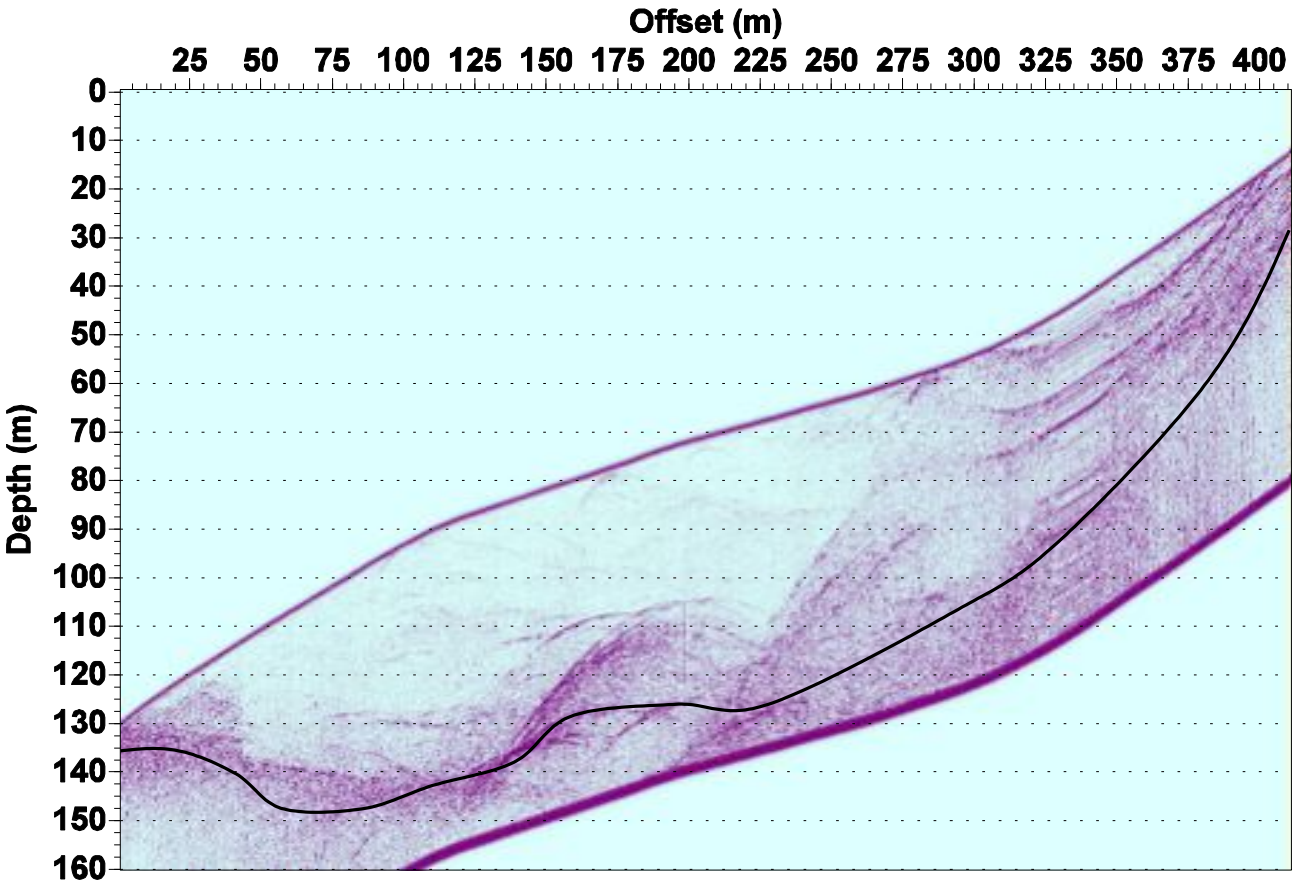
. Topographic measurements

. Radar measurements

. Temperature measurements

. Mass balance measurements

Radar measurements



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

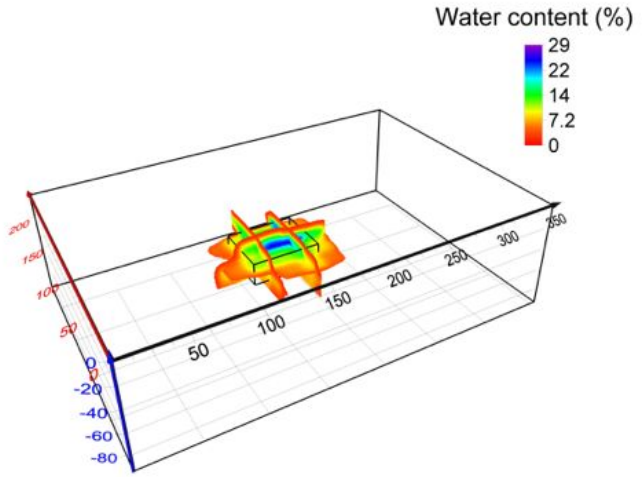
[Garambois, ISTerre]

3D-SNMR

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

(LTHE, Grenoble)

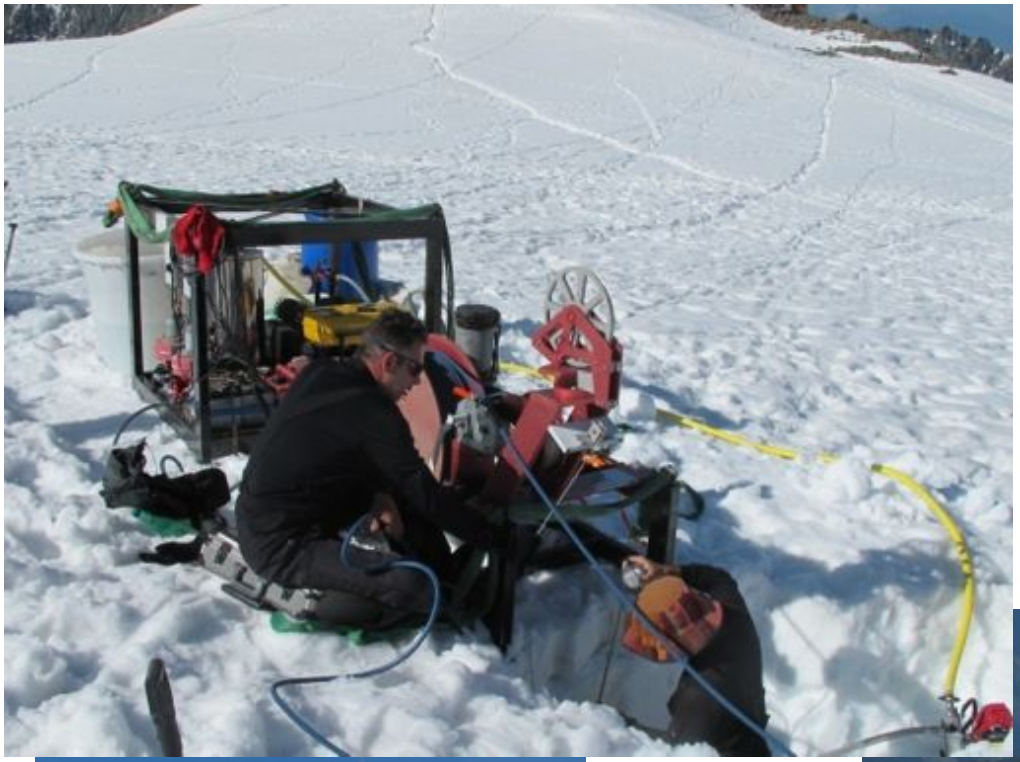
3D-SNMR



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.

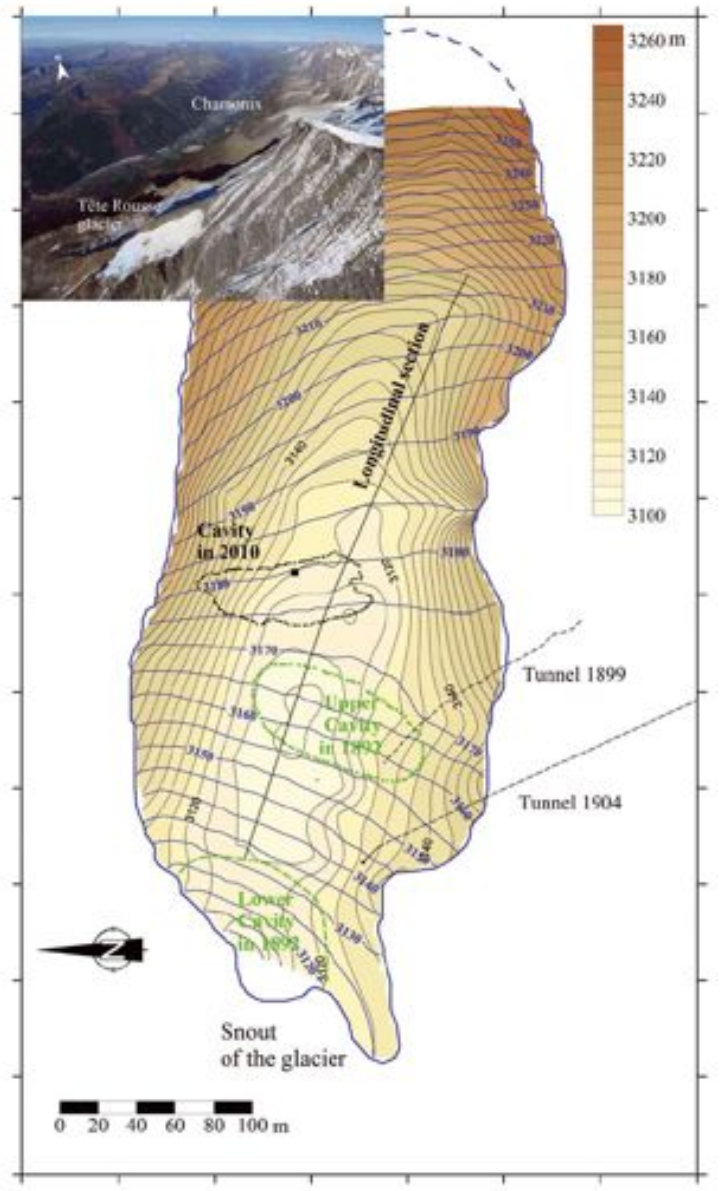
A difficult field work

Drainage of the cavity

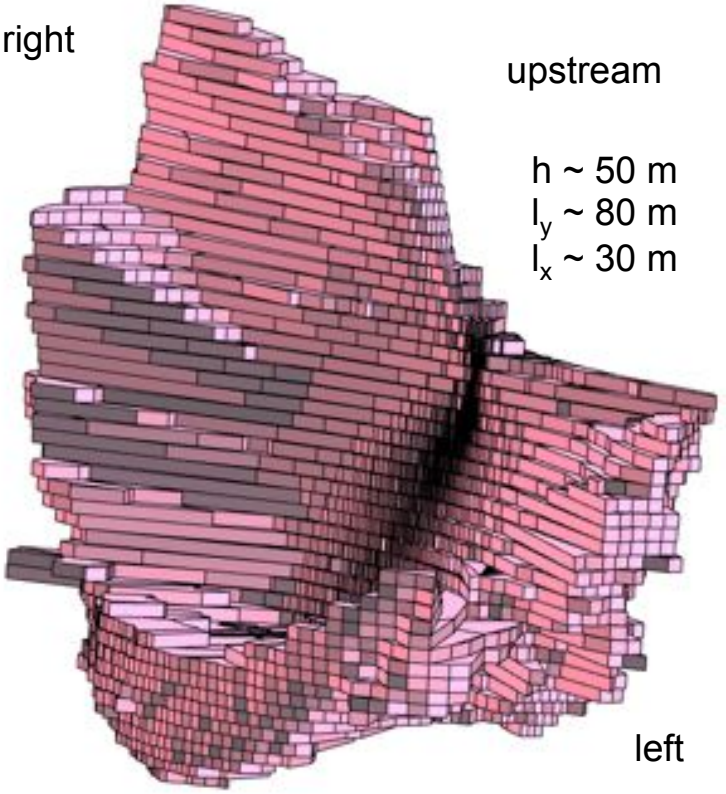
A new risk ?


But was stopped the 1st September :
What was the risk of breakout of the cavity roof induced by the artificial drainage?

Geometry of the 2010 cavity



from sonar measurements



Timing for answering

Sonar data (cavity geometry)

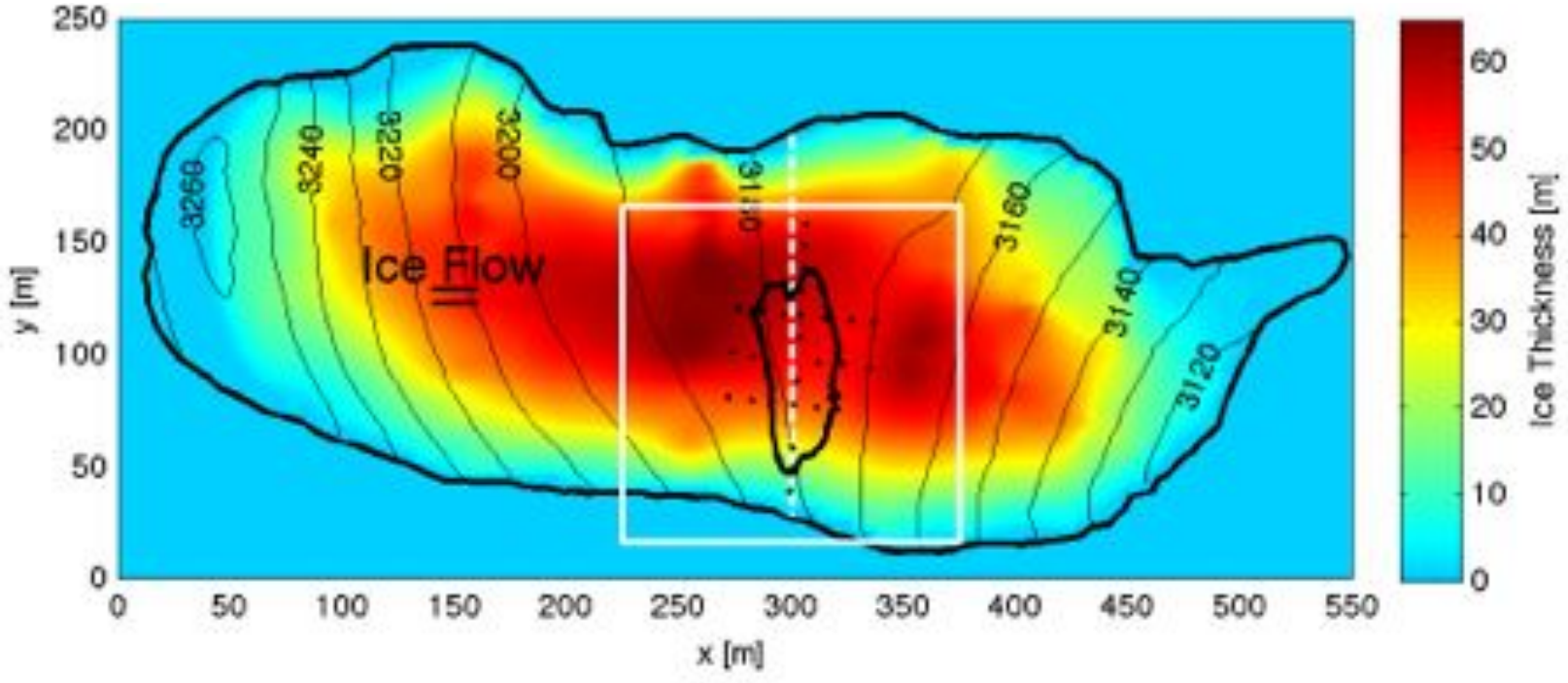
Septembre

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		

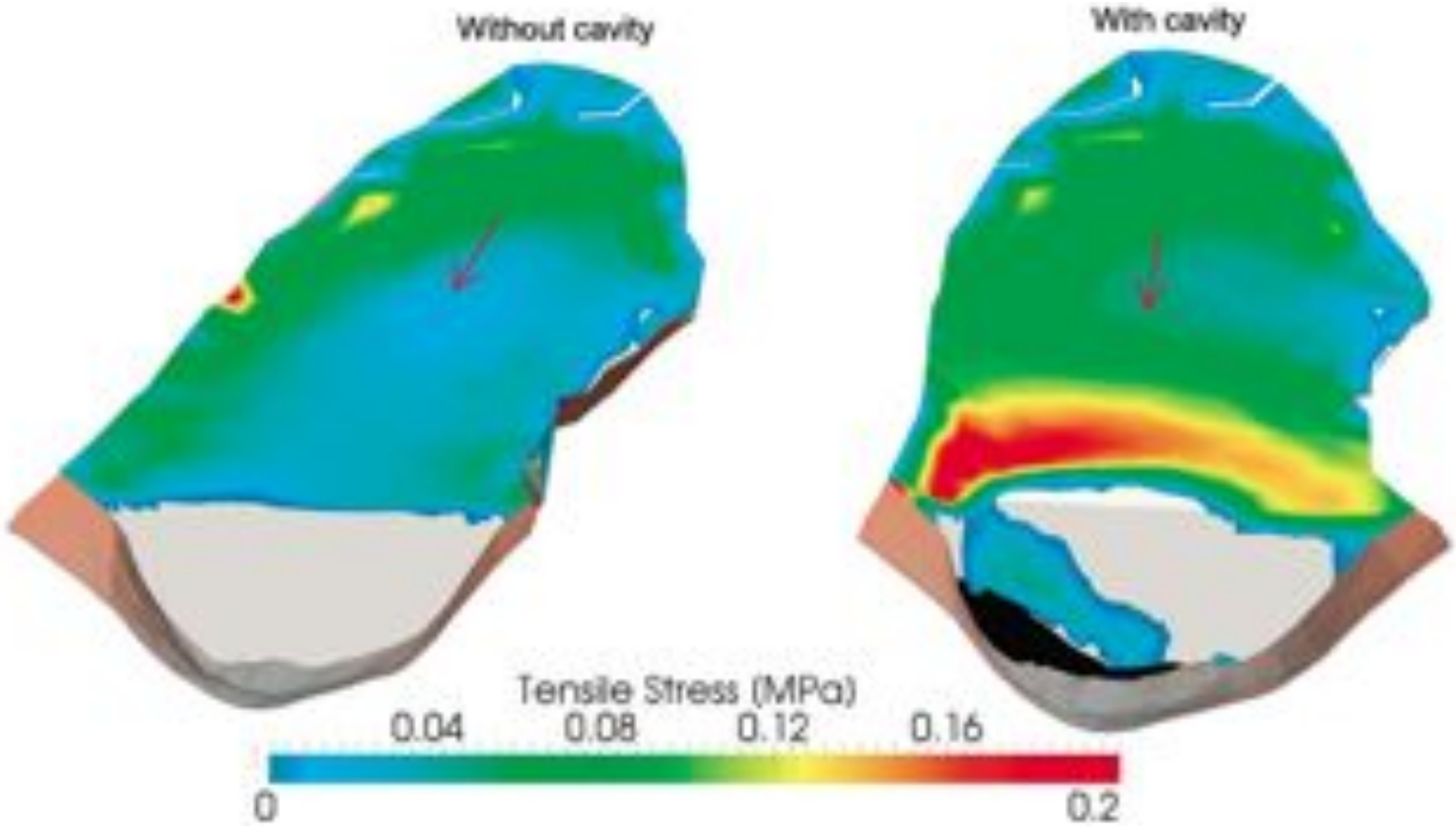
Meeting with the mayor of St Gervais

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



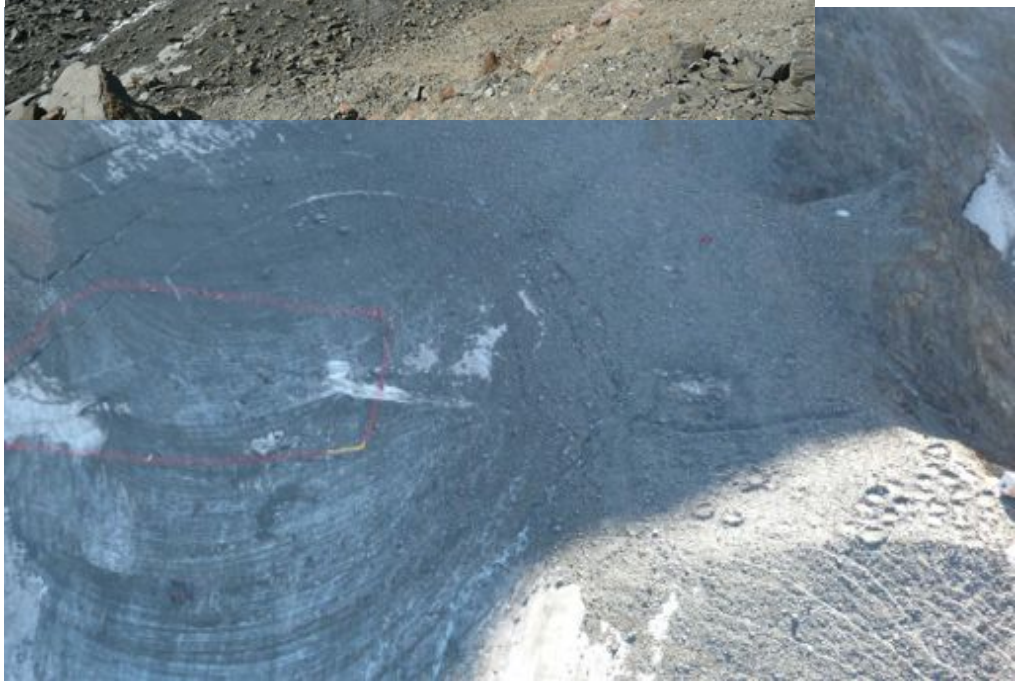
Finite element model Elmer/Ice : glacier + cavity

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

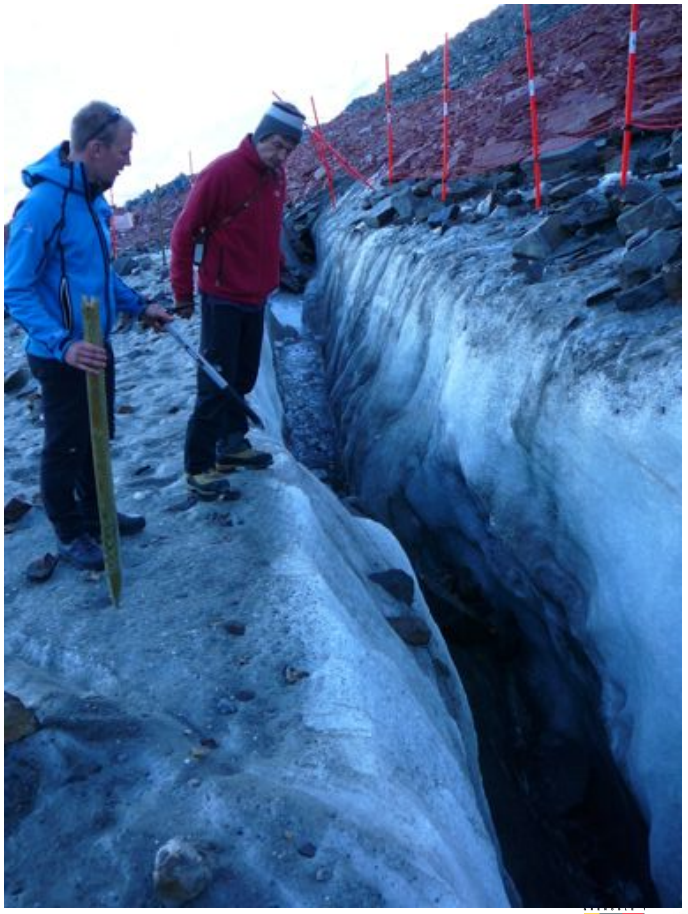
➔ survey of the surface displacement during the pumping

[Gagliardini et al, 2011]

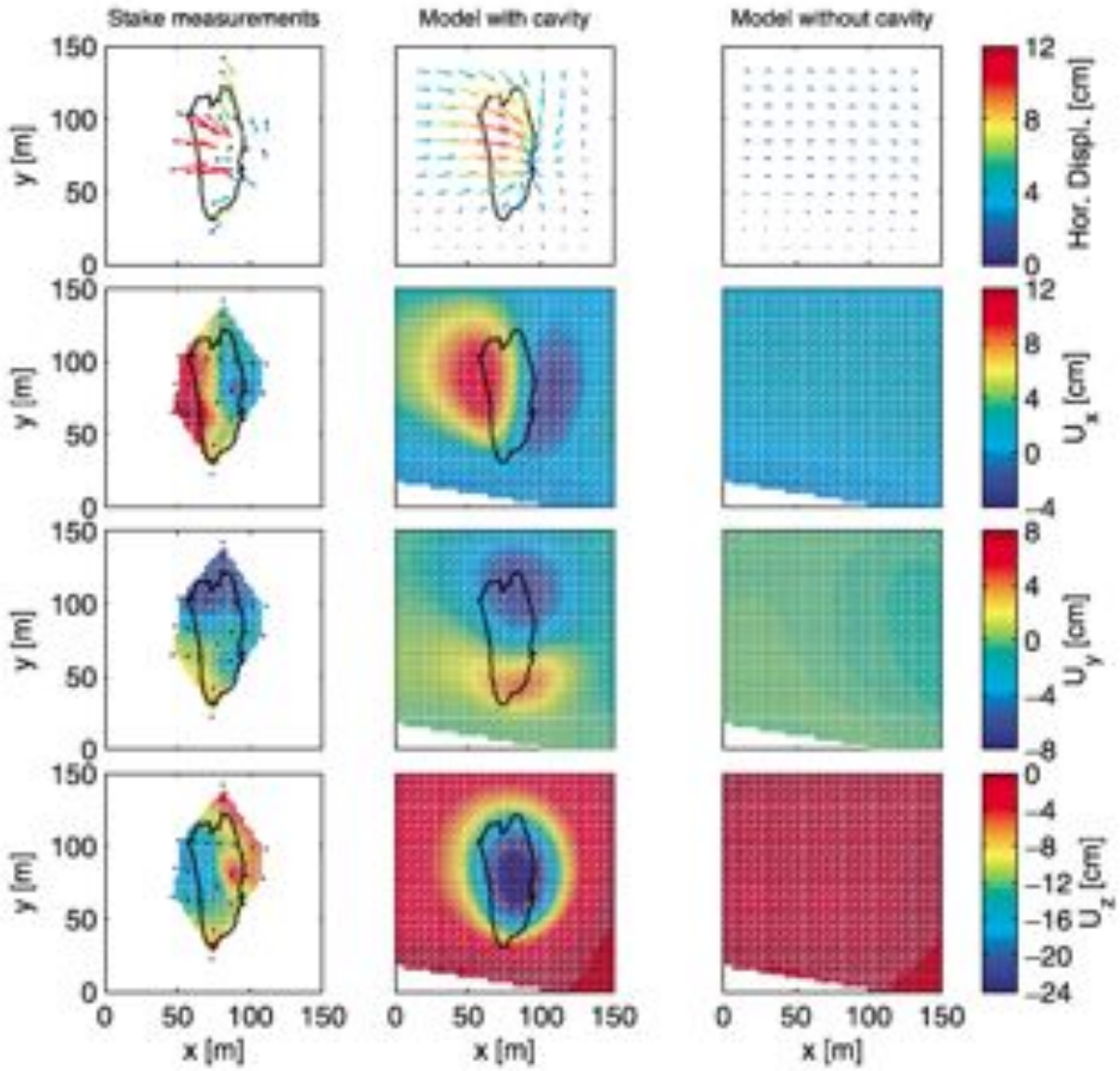
A posteriori validation of the flow model

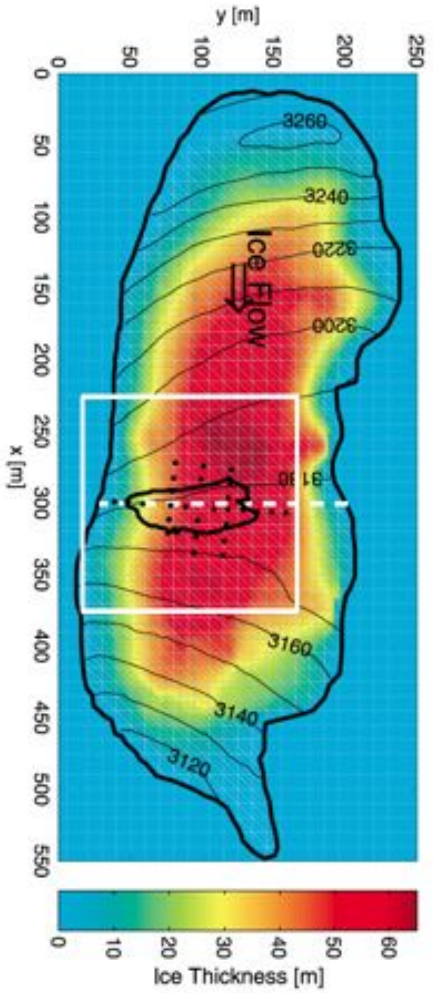


circular crevasses observed in August 2011



From surface displacements





[Gagliardini et al, 2011]

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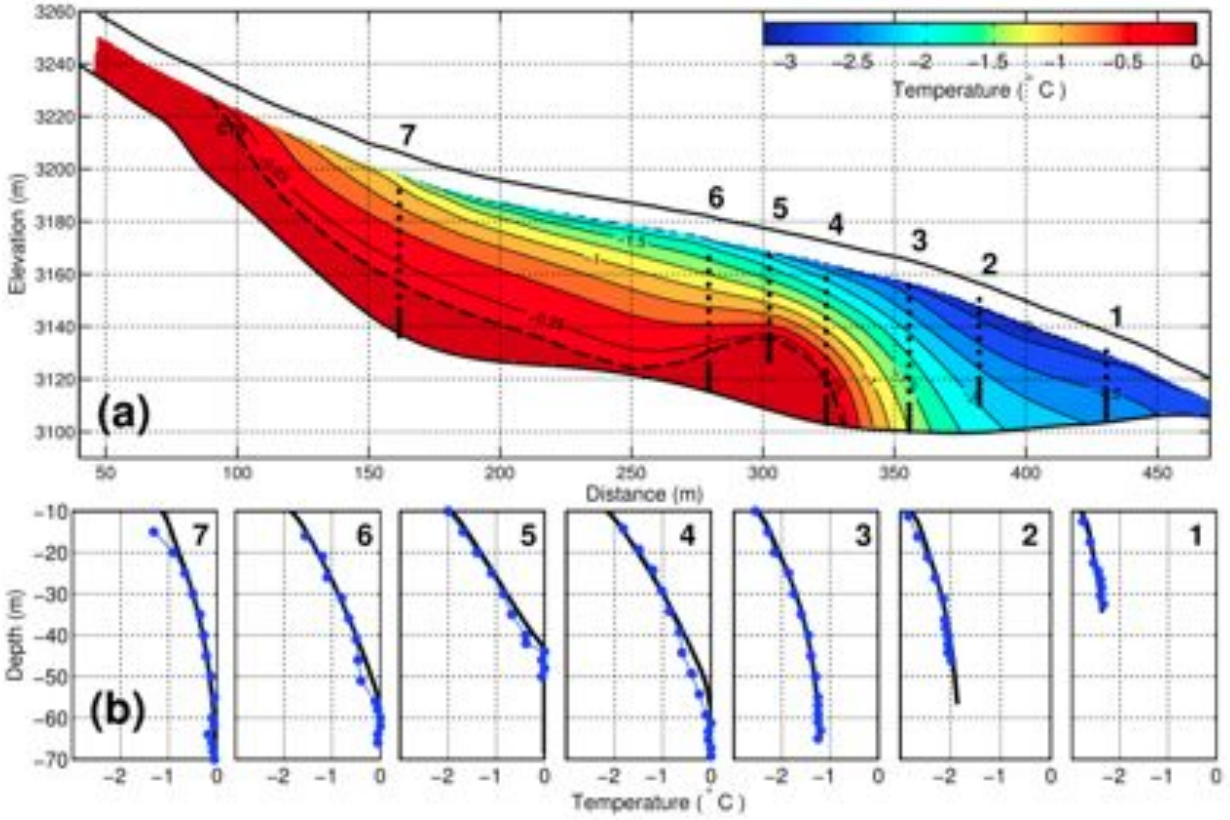
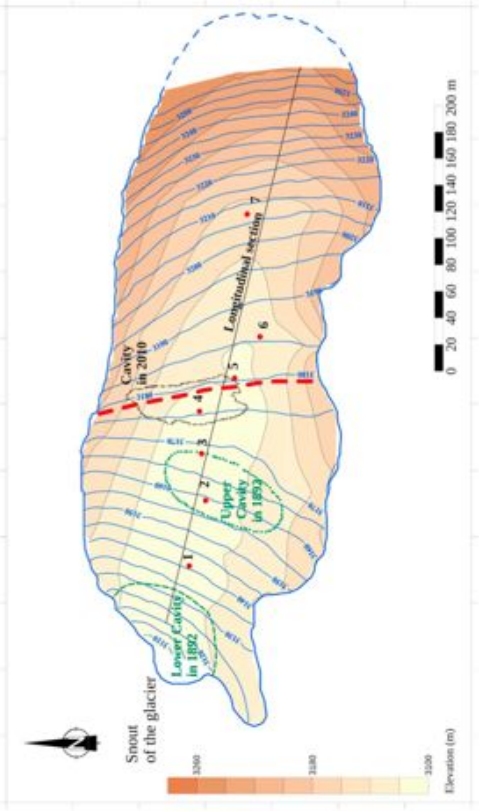
Thermal regime of Tête Rousse glacier

Measured / Modelled temperature in 2010





[Gilbert et al, 2012]

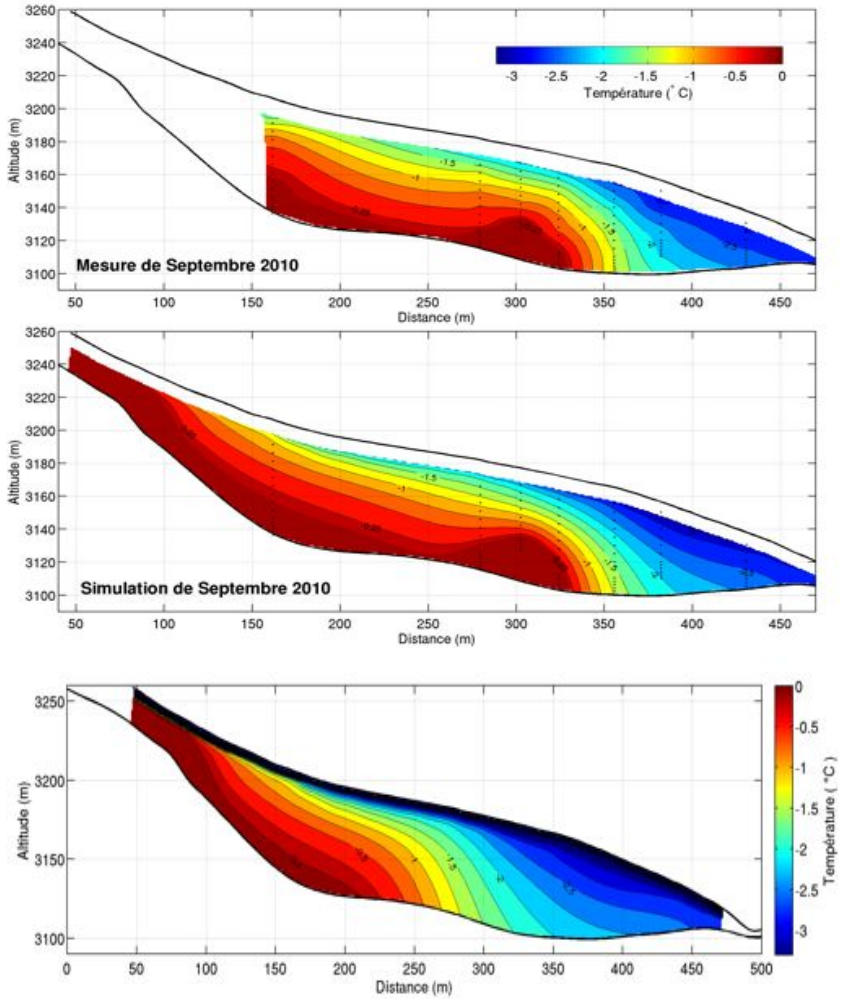
Thermal regime of Tête Rousse glacier

The cavity clearly influence the temperature field

Measures

Model
with cavity

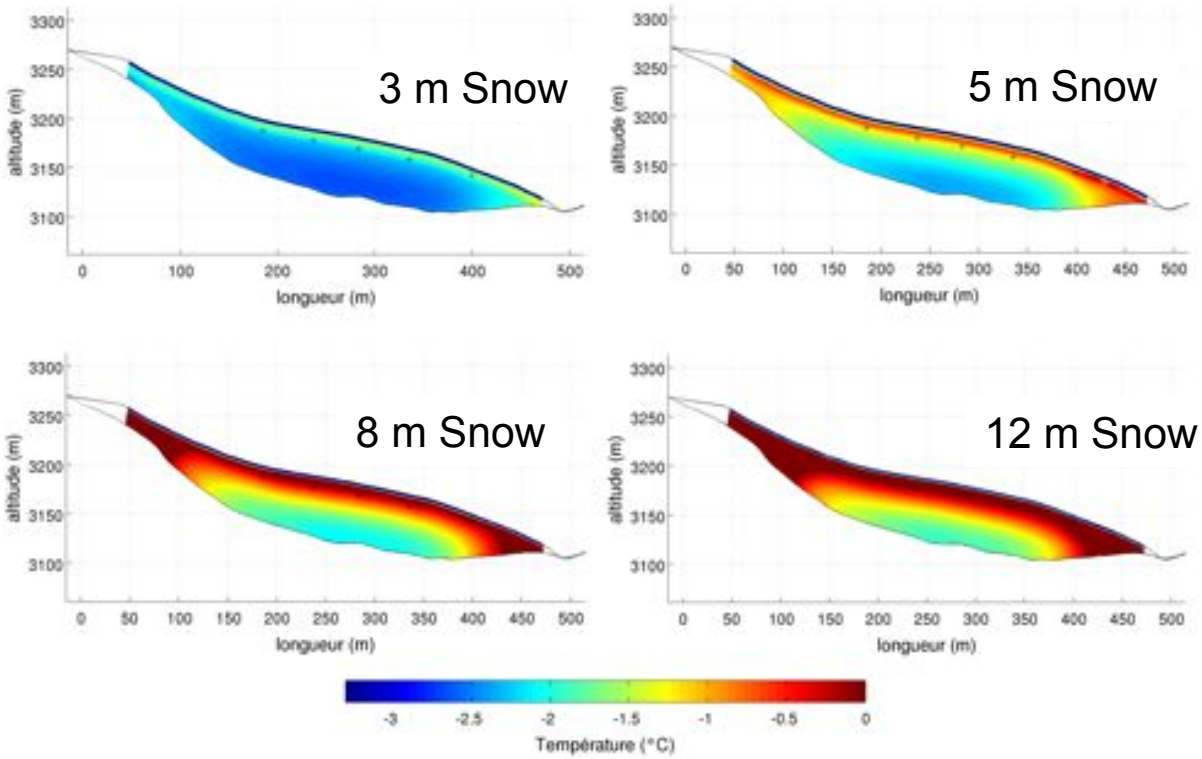
Model
without cavity



[Gilbert et al., 2011]

Importance of the firn thickness

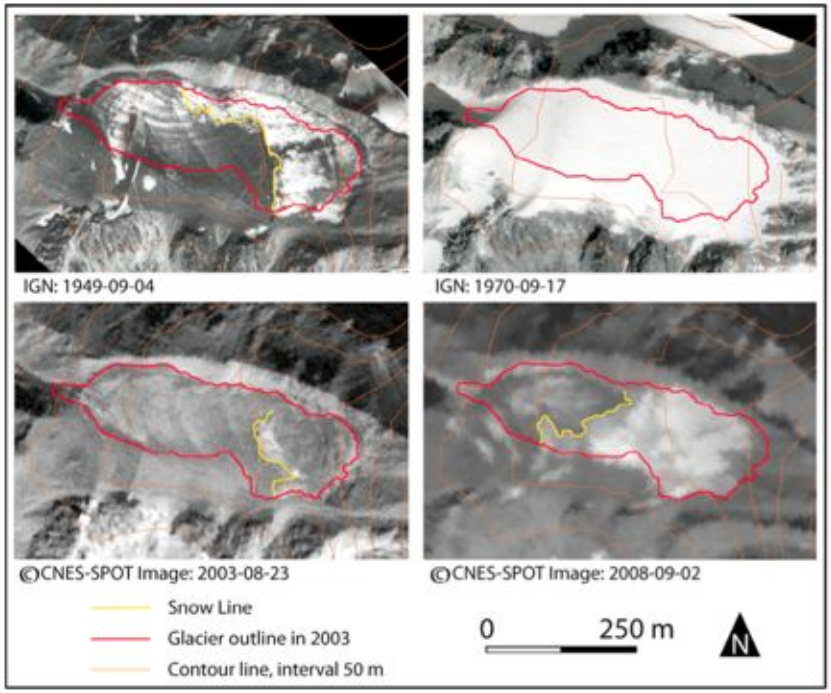
➔ release of latent heat by refreezing of meltwater in the firn



"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]

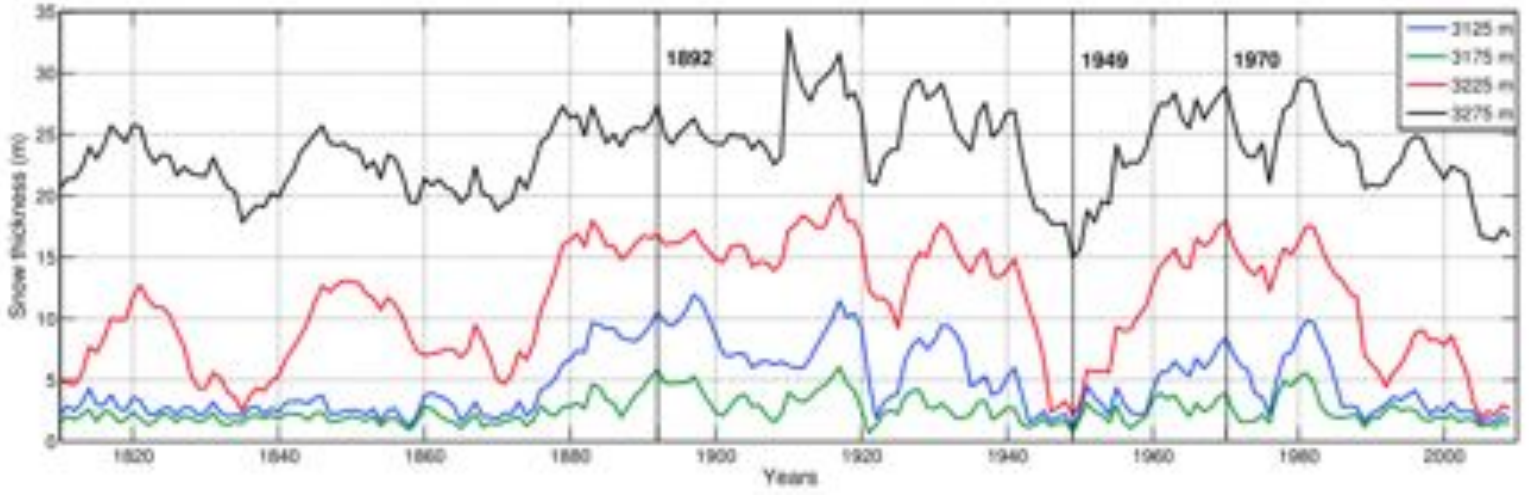
Evolution of the snow and firn thickness



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

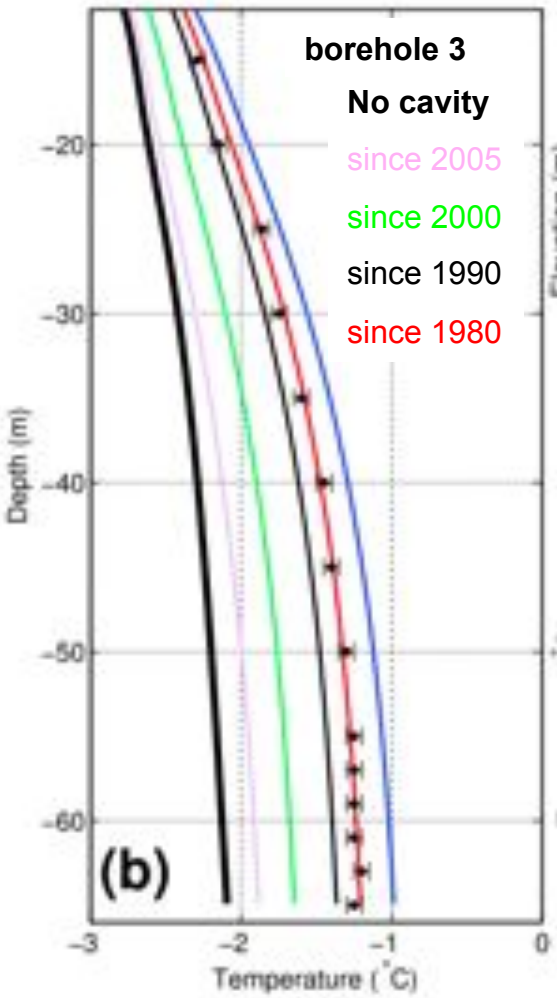
1878-1892: period of positive mass balance, increased the snow pack thickness

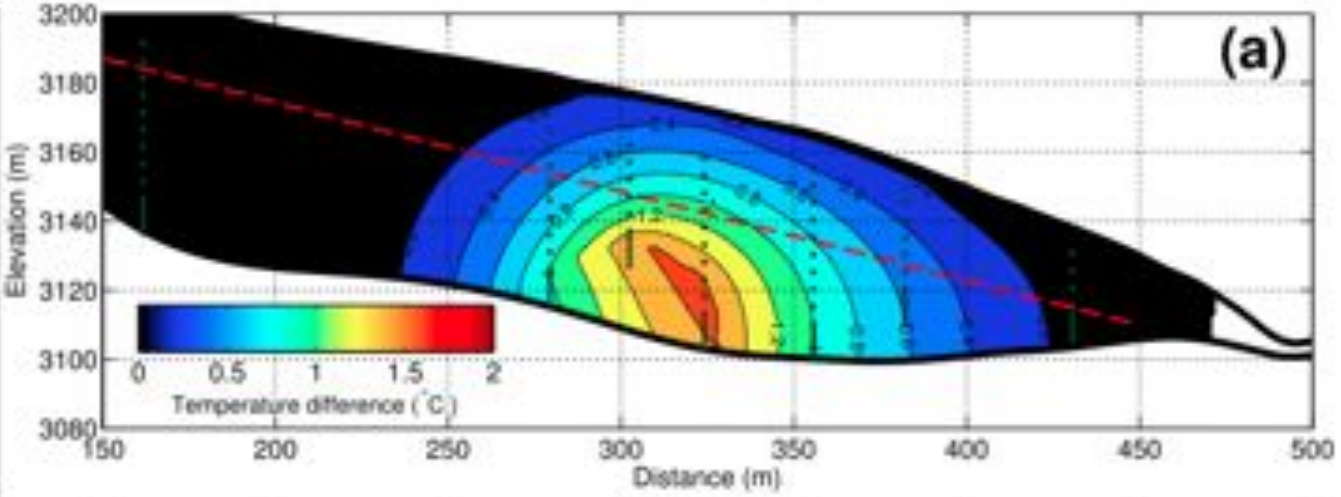
Since 1980: decrease of the snow pack

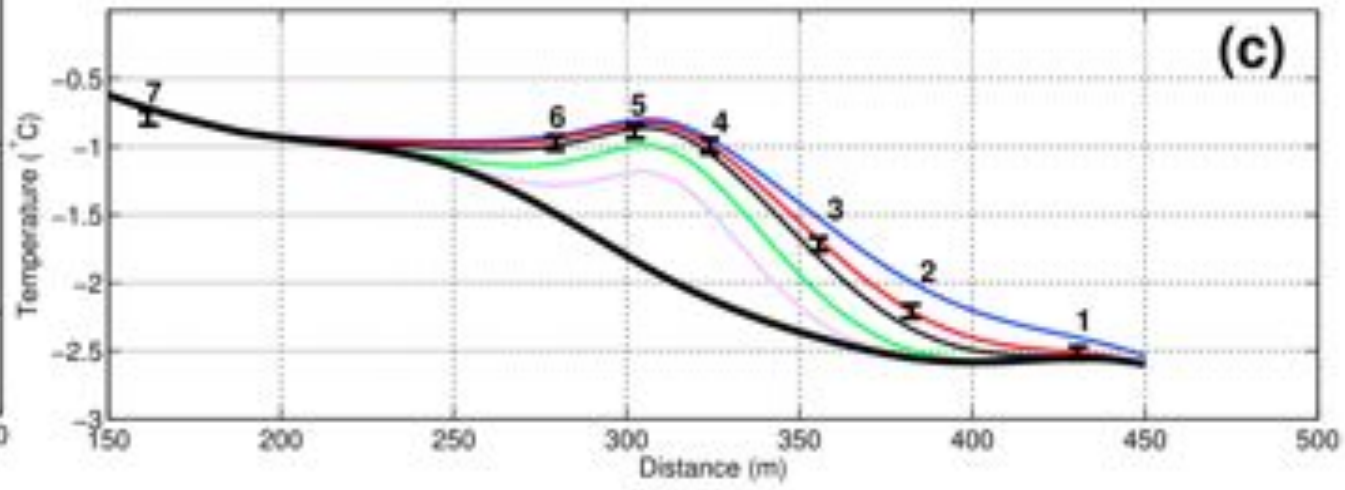


[Gilbert et al, 2012]

Thermal regime of Tête Rousse glacier



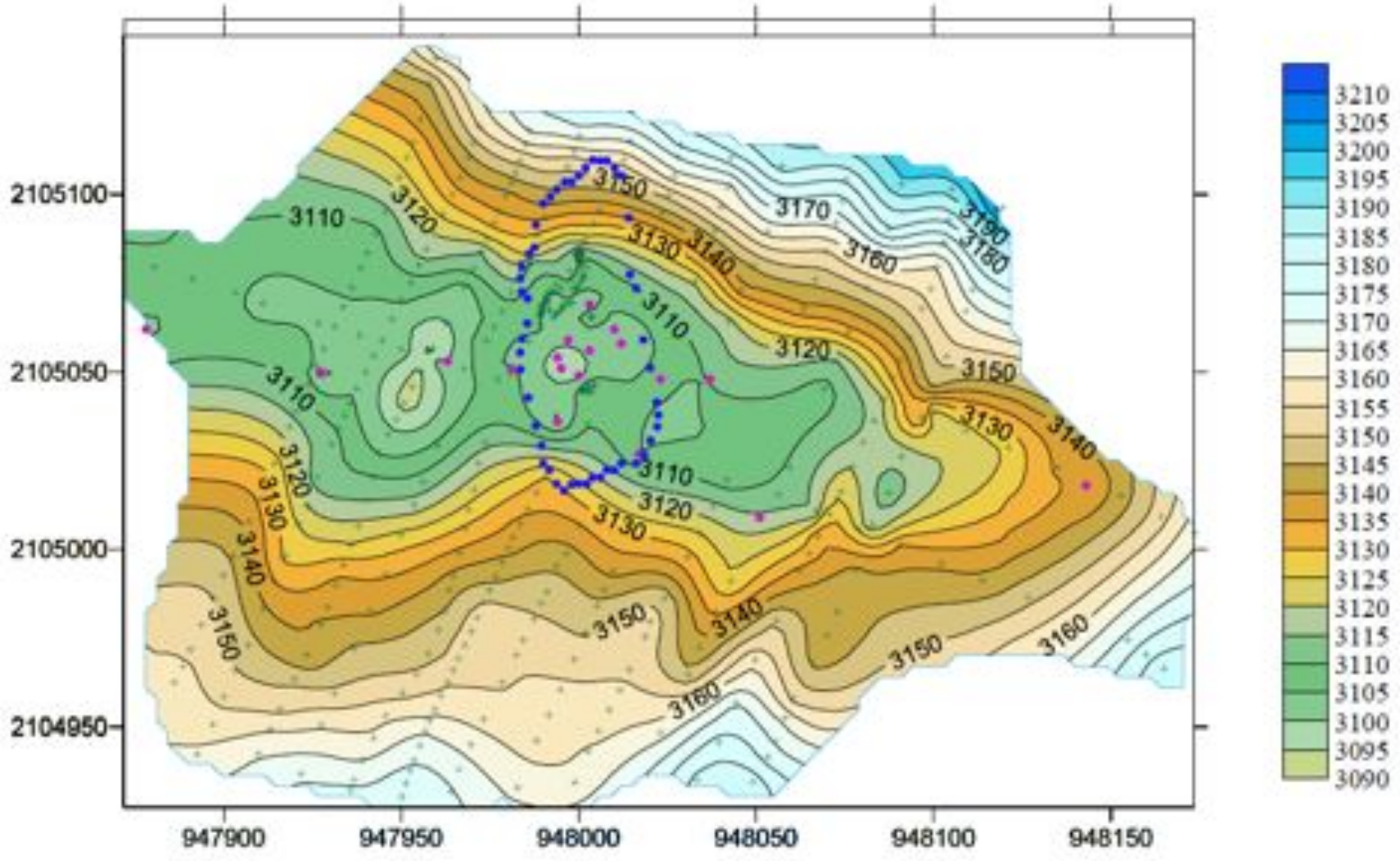




Temperature told us about the age of the cavity (~30 years)

[Gilbert et al, 2012]

Influence of the bedrock topography



[@Garambois, ISTerre]

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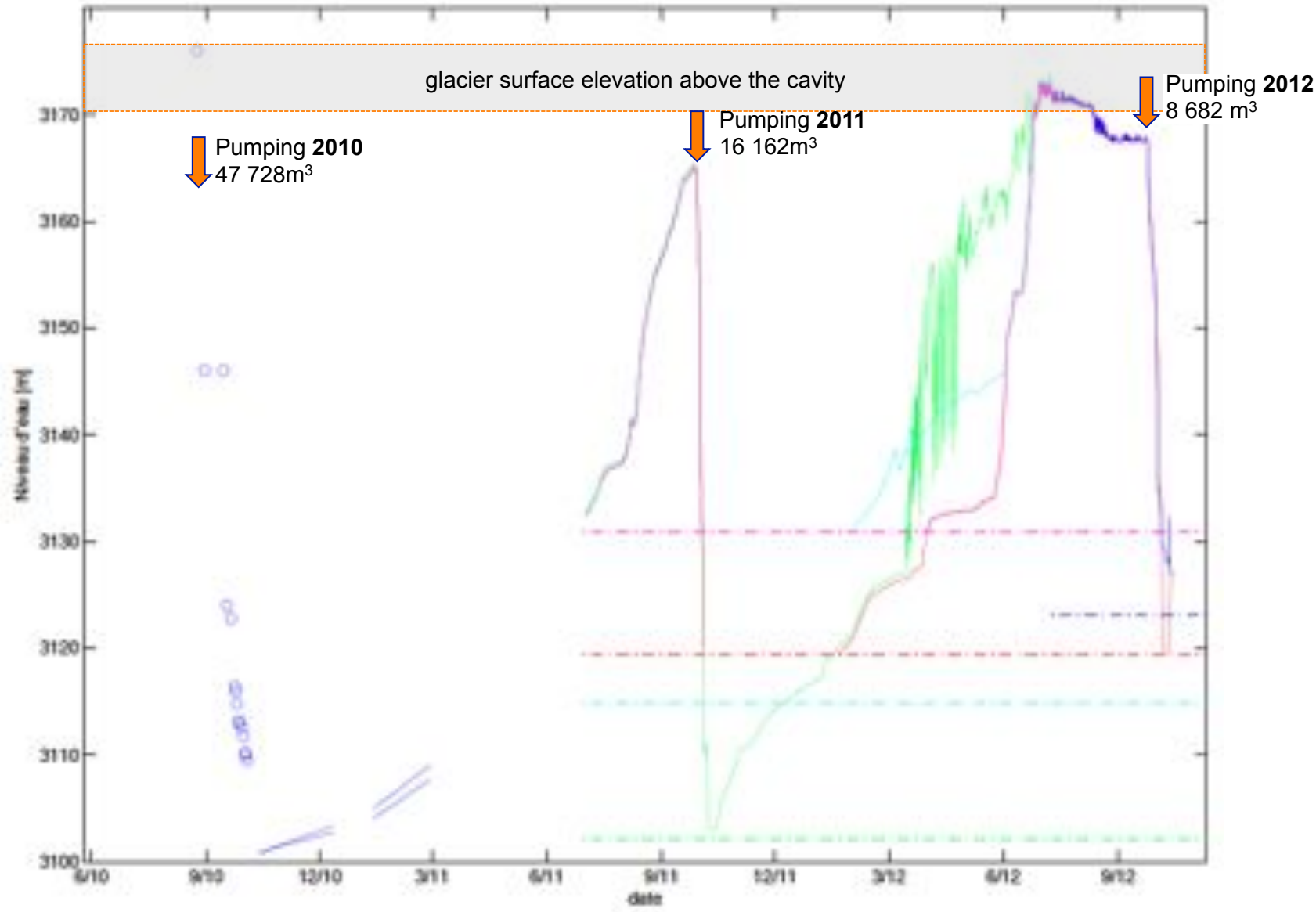
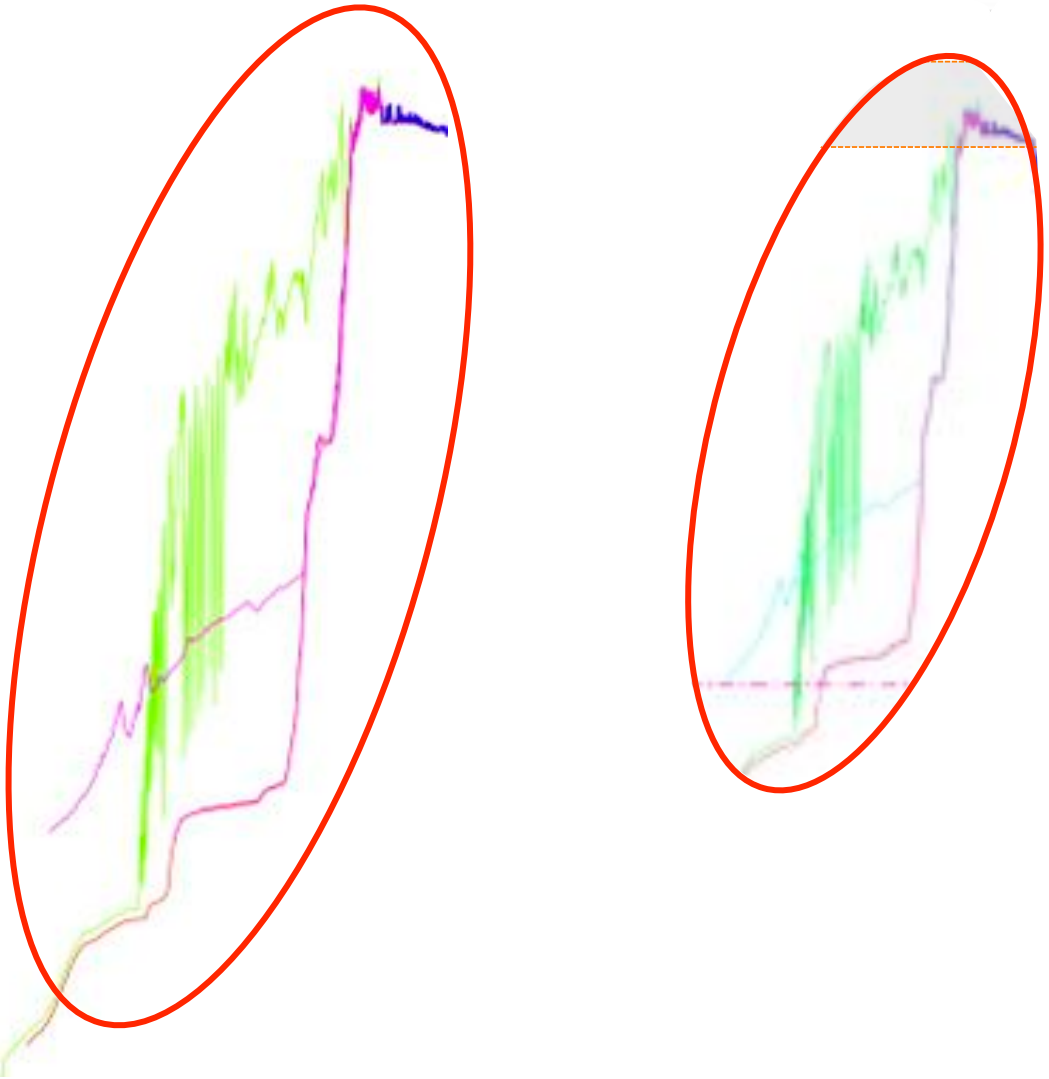
How to measure the cavity shape

- ✓ 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)

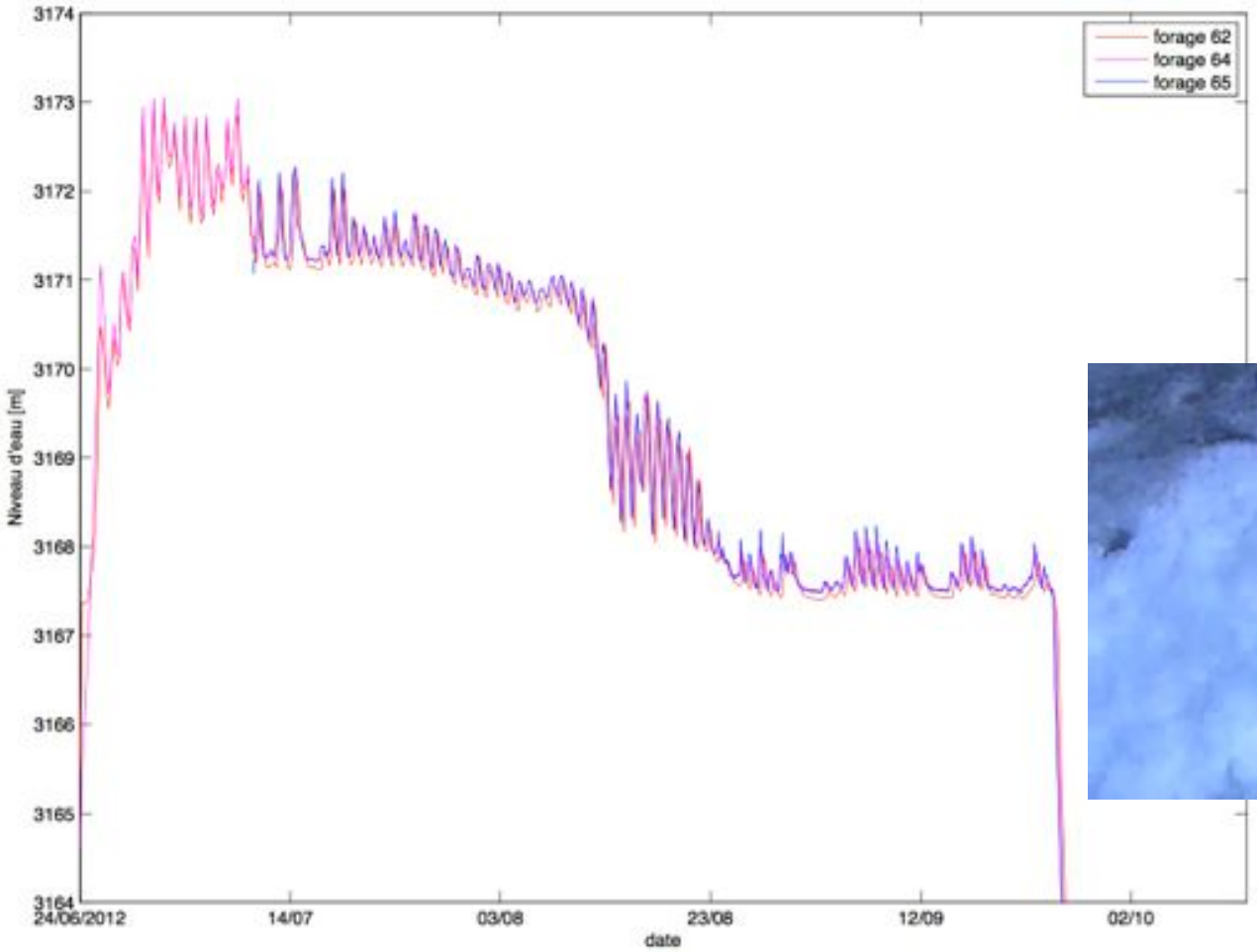


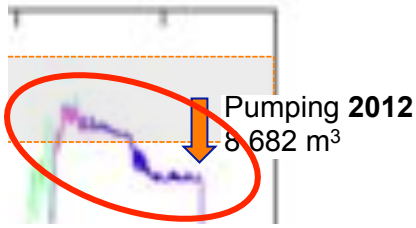
Water level since 2010



Measurement problems or real pressure variation ?

Water level since 2010

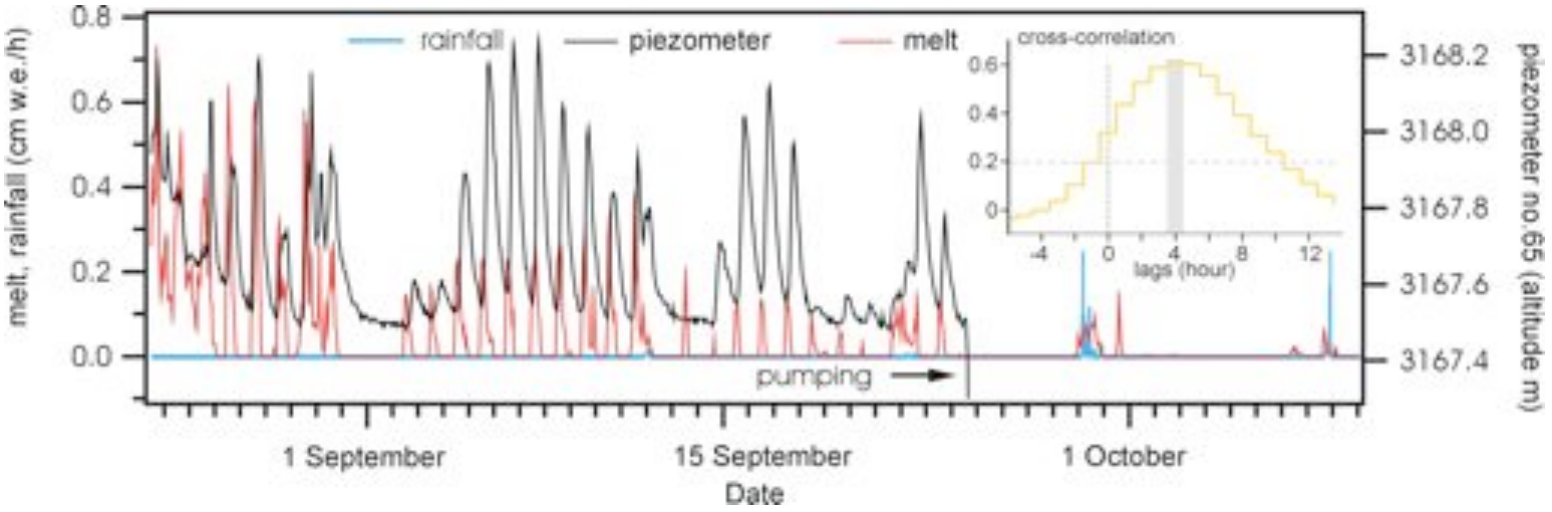




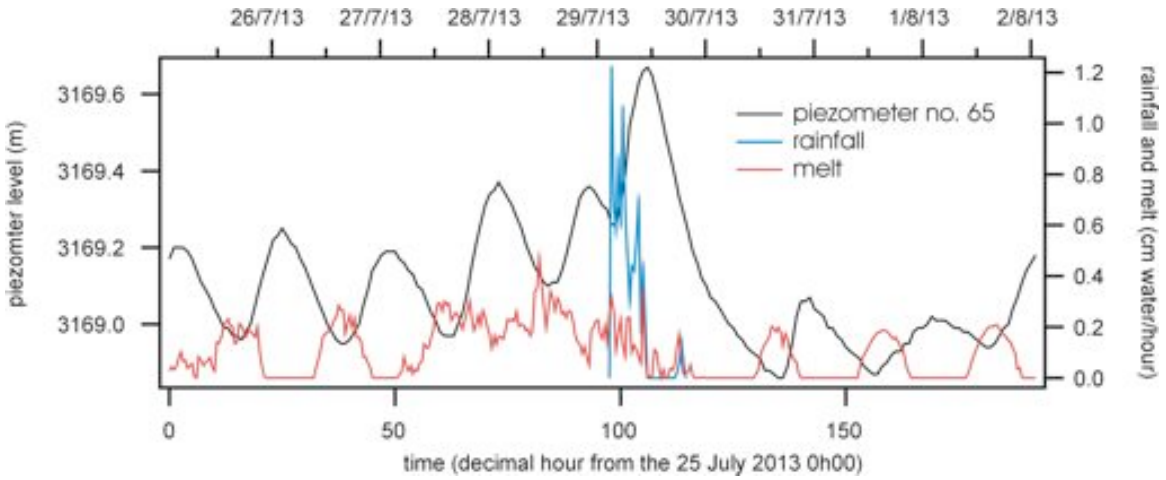
Daily variation of the pressure (outflow from old drillings)

Water level and meltwater

from the 24 August to the 10 October 2012



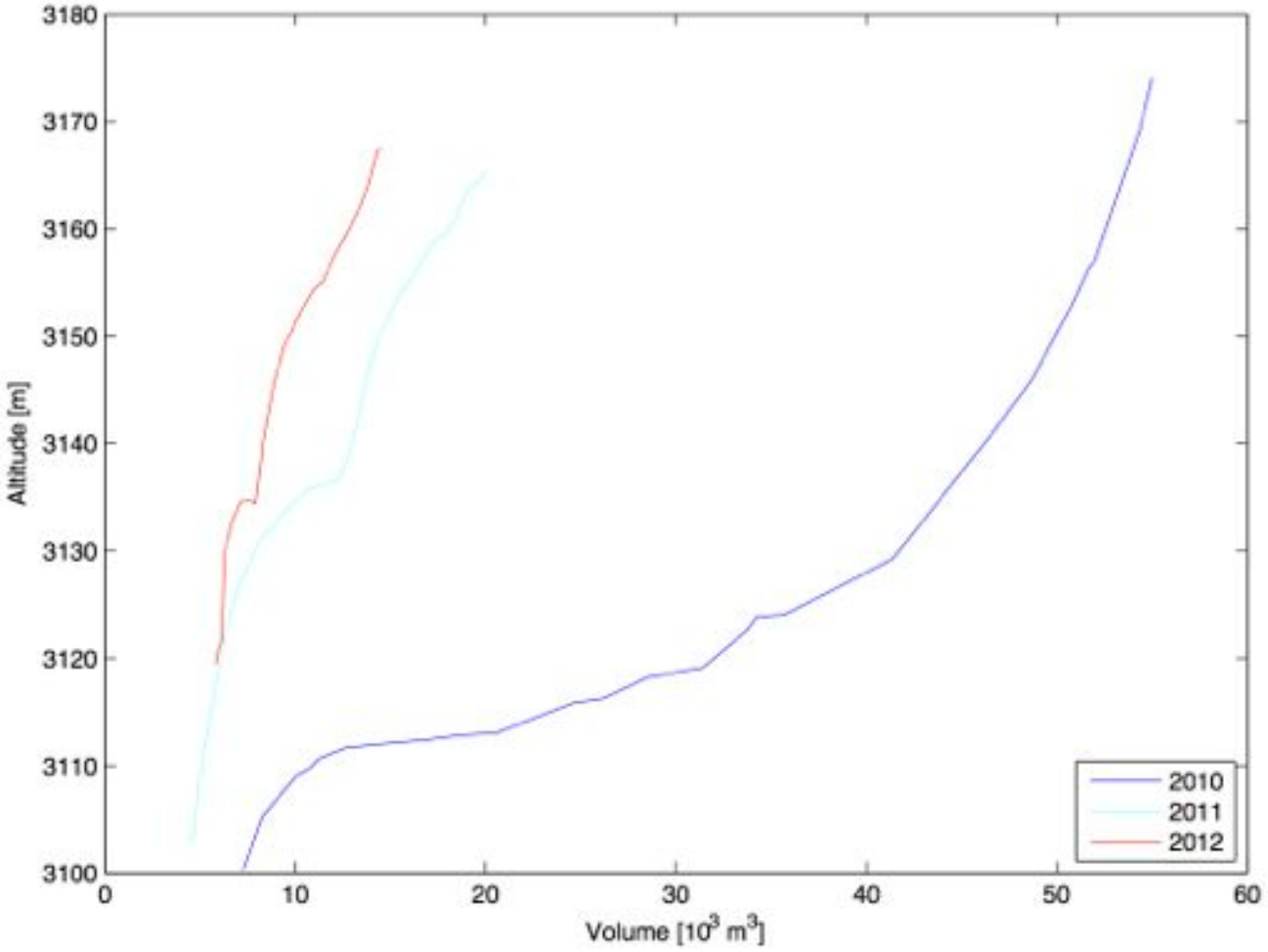
from the 25 July to 2 August 2014



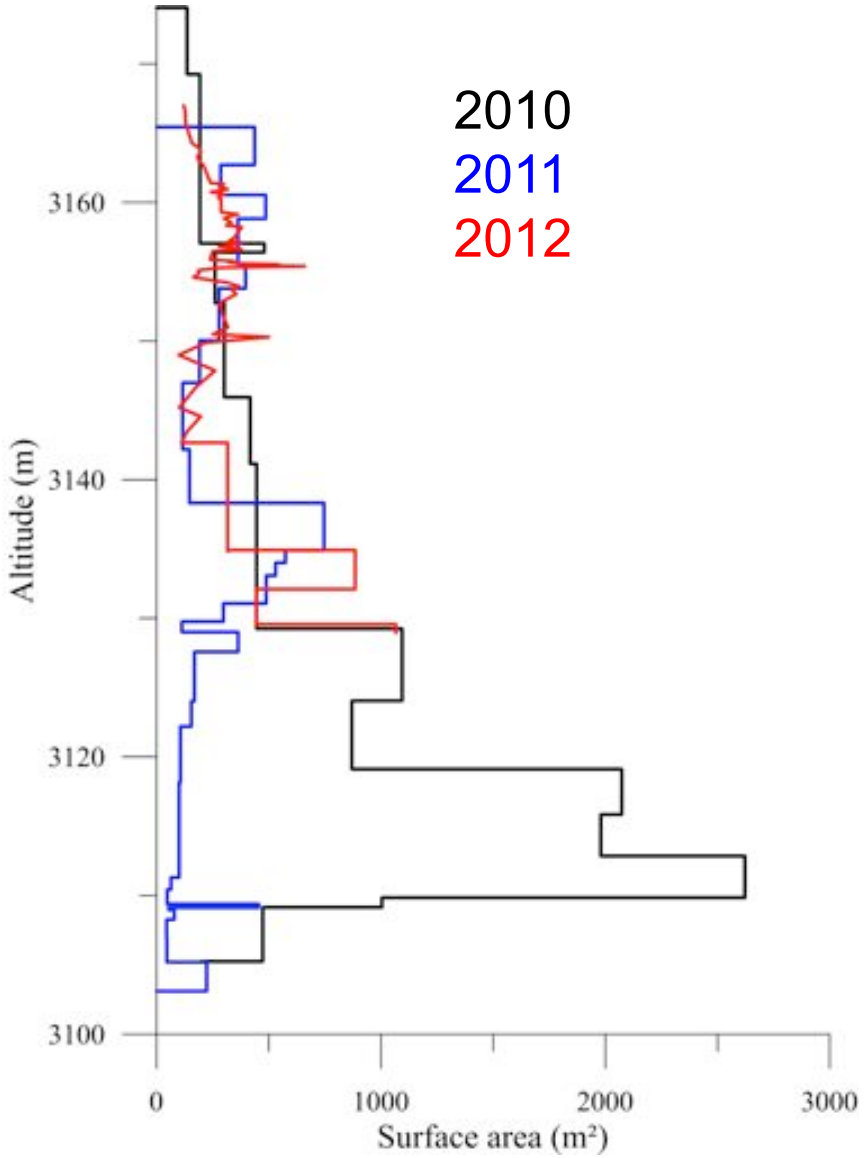
[Vincent et al, in prep]

Volume – level evolution

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

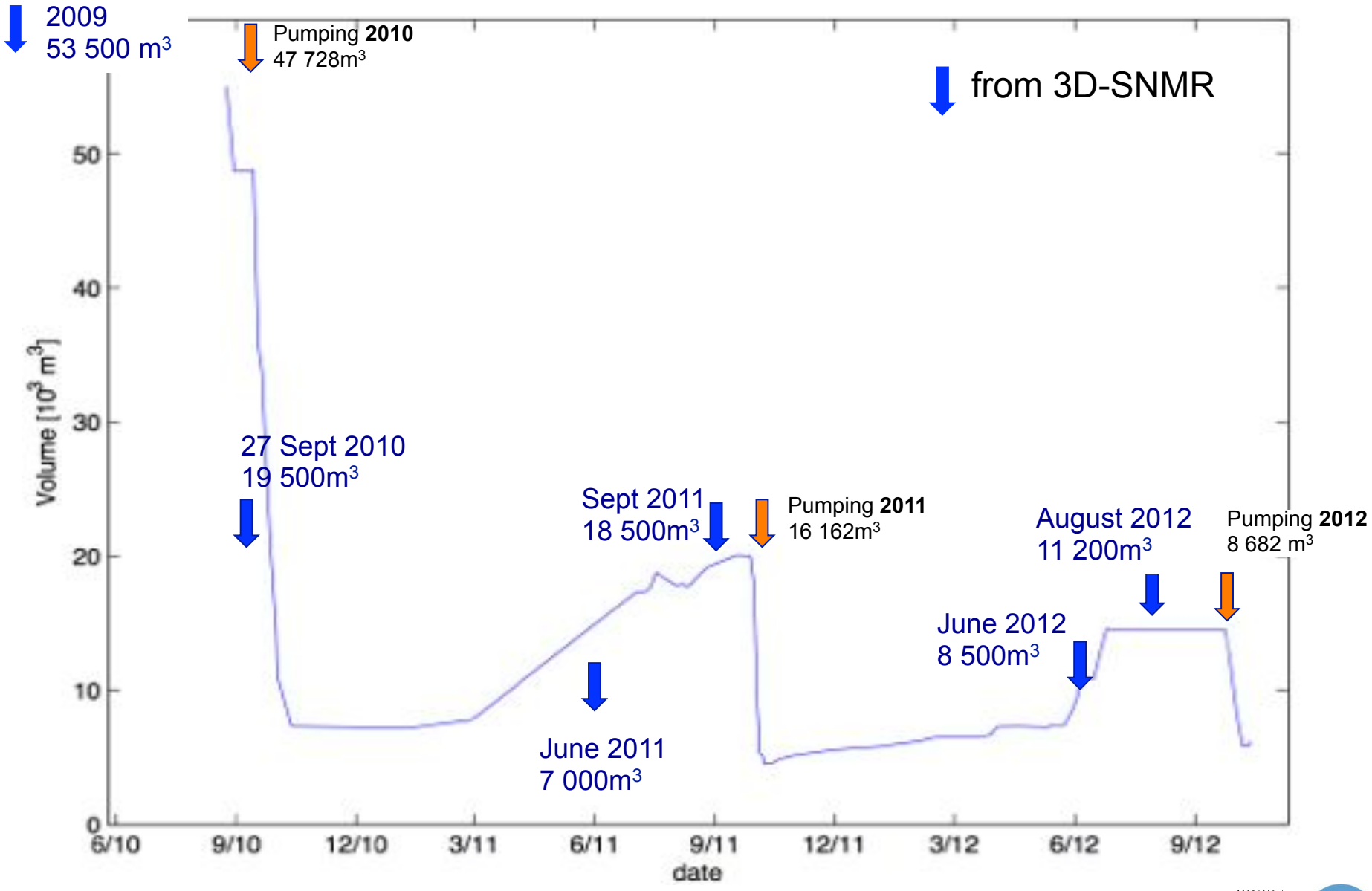


Evolution of the cavity geometry



[Vincent et al, in prep]

Reconstruction of the volume evolution



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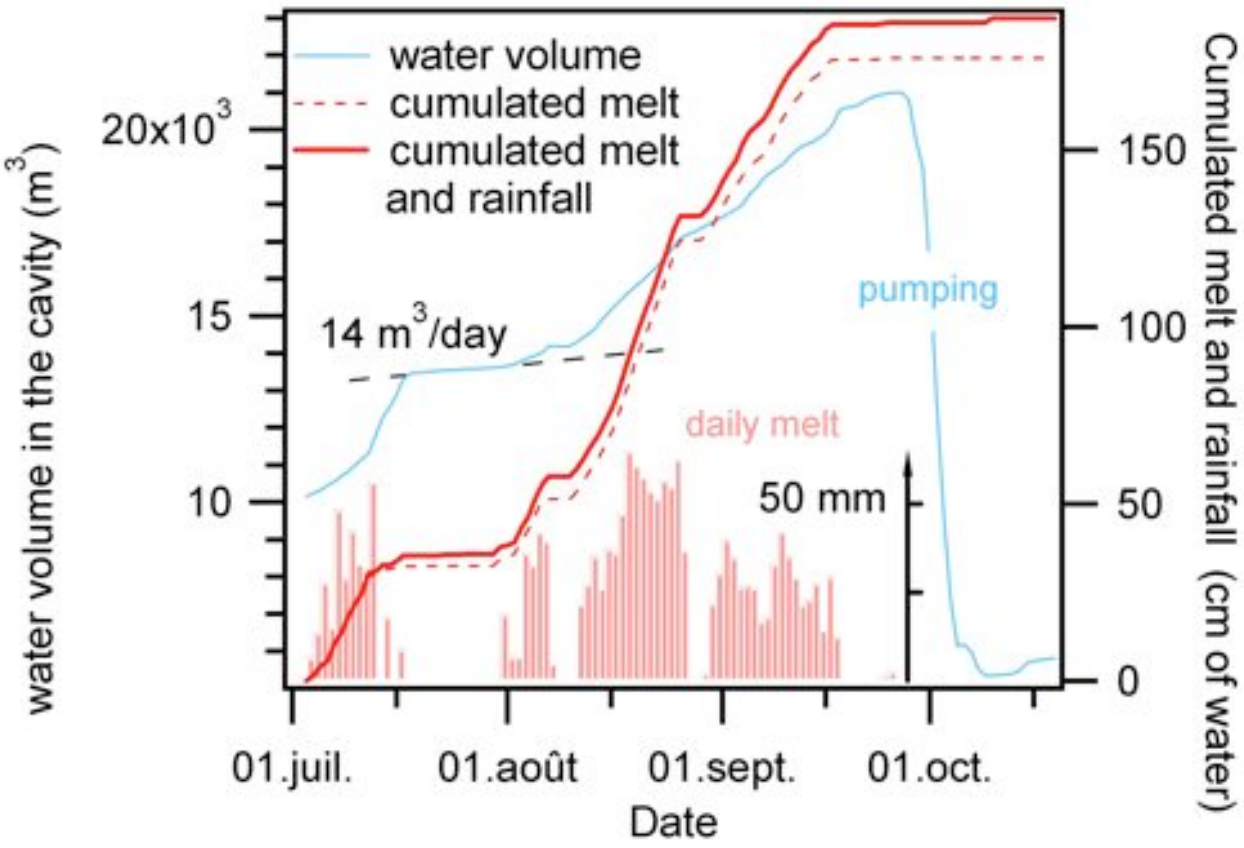
Weather measurements

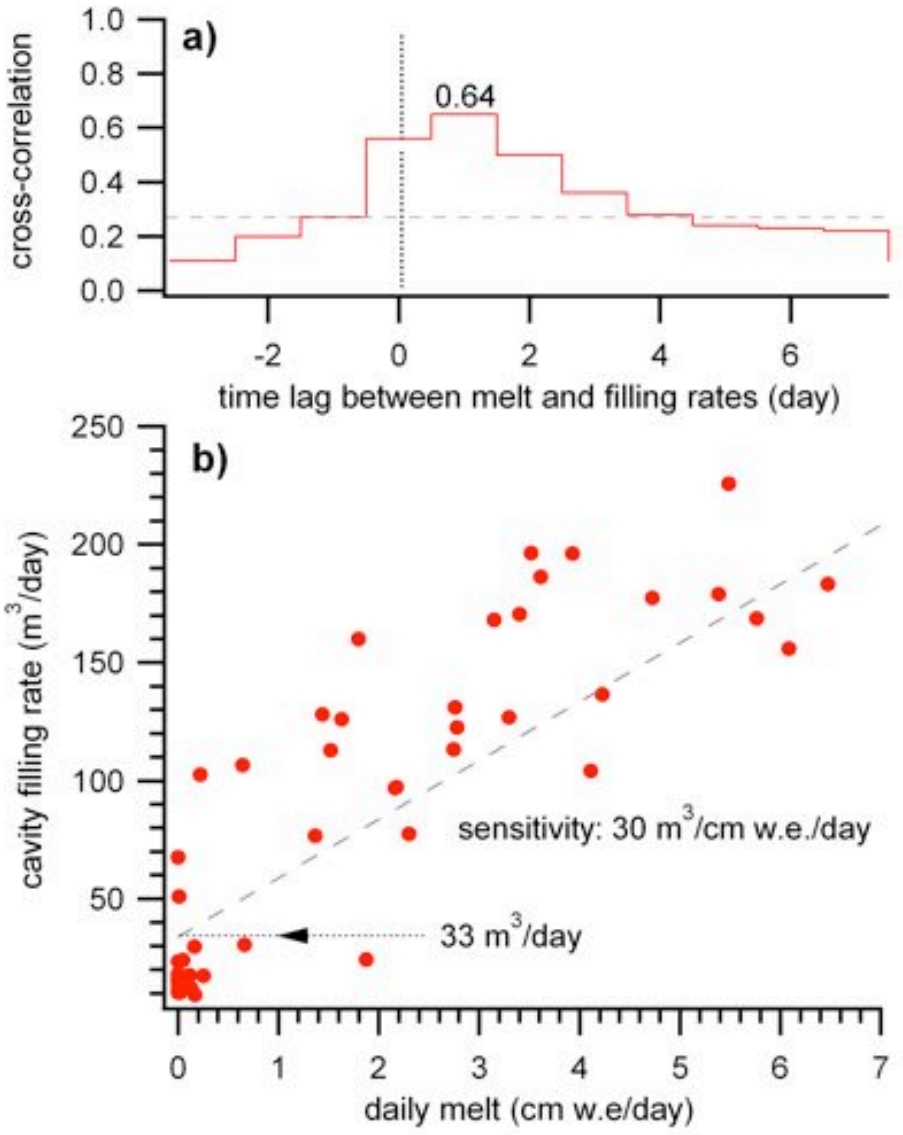
8 June 2011 | 3 Jully 2011 | 11 August 2011 | 16 September 2011

Link with surface runoff



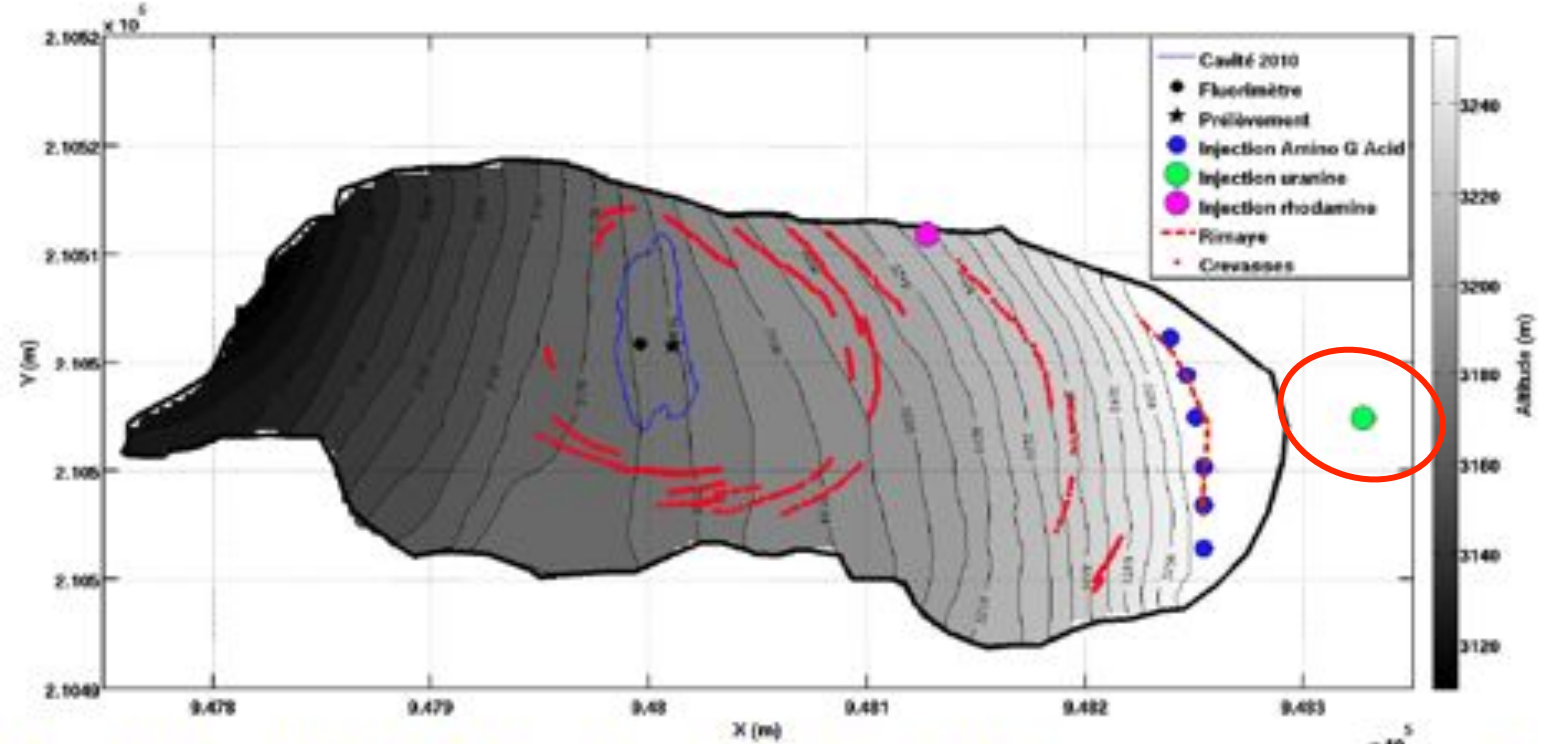
[Vincent et al, in prep]

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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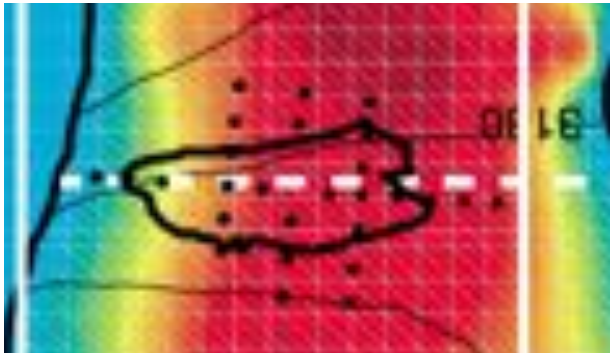
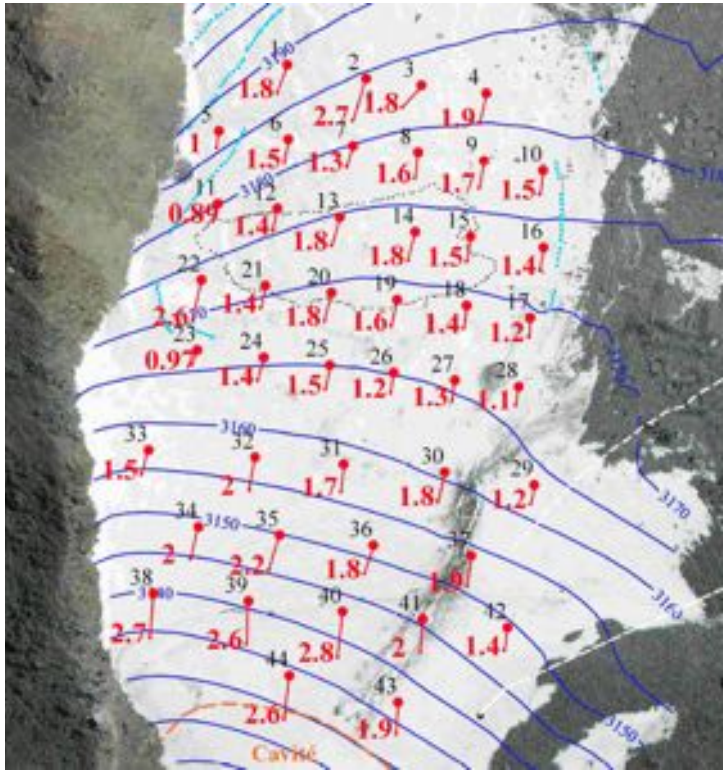
Stakes networks

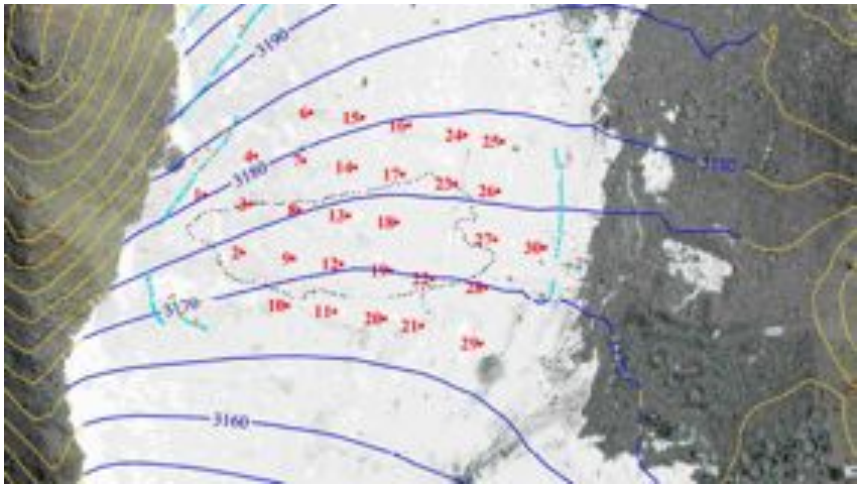
27 Stakes in **2010**



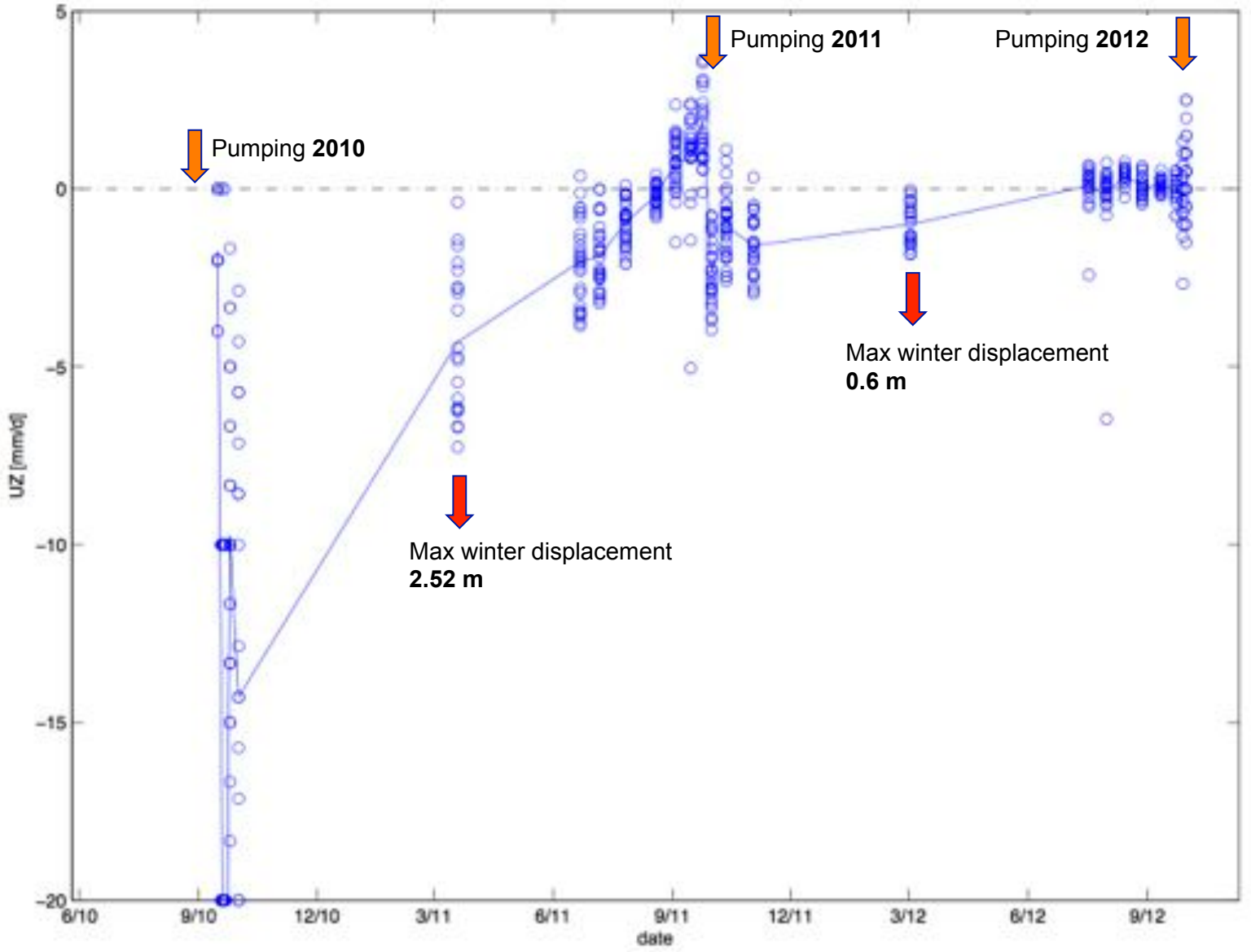
44 Stakes in **2012**



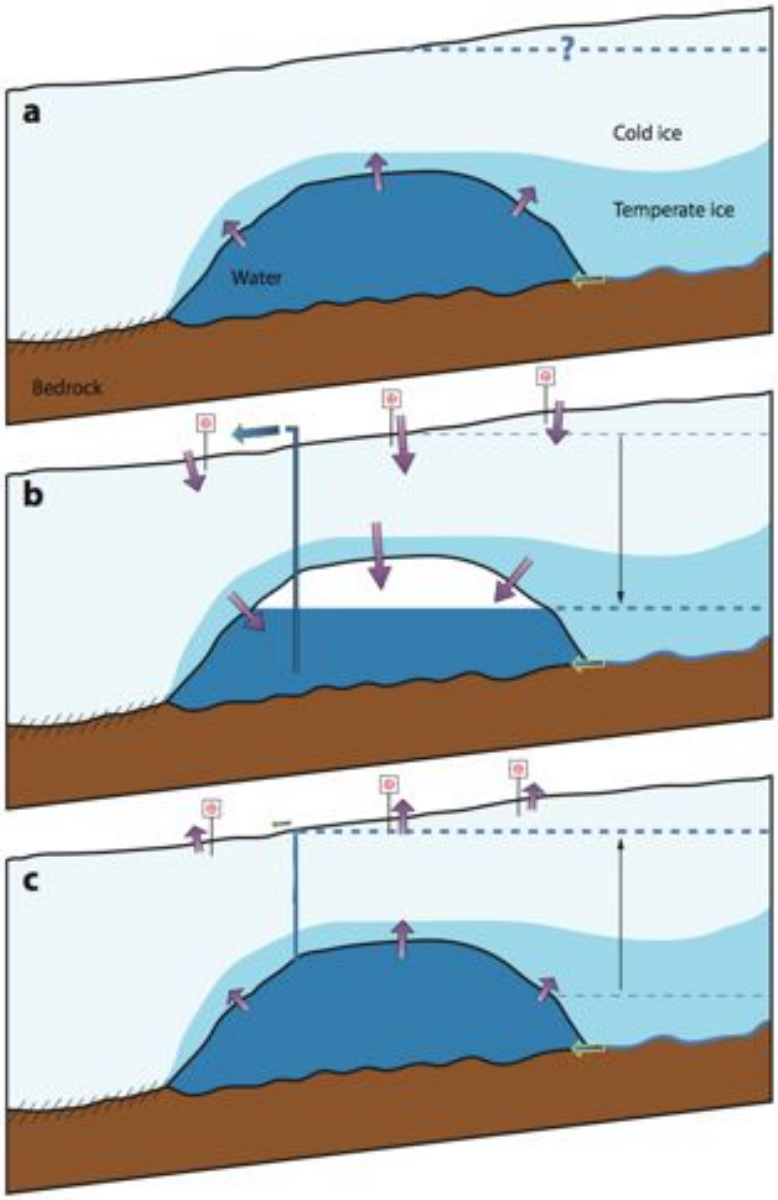
30 Stakes in **2011**



Vertical surface velocity [mm/d]



Evolution of the cavity geometry



Growing phase
Before 2010
Cavity under pressure

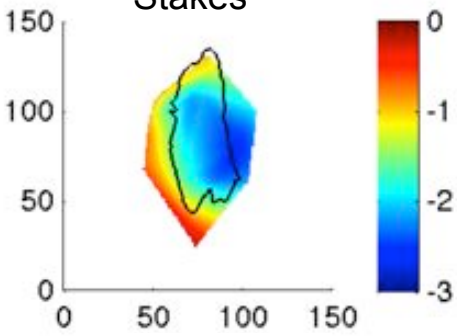
Artificial Drainage phase
Autumn 2010, 2011 and 2012
Cavity shrinking

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

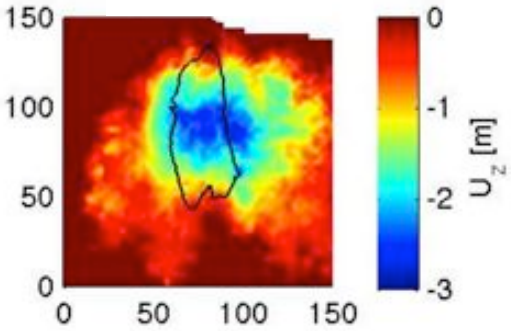
Evolution of the volume of the cavity

2010 to 2011

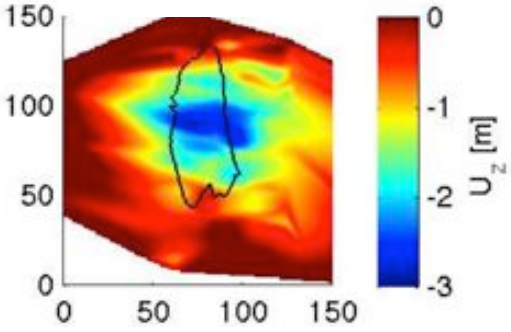
Stakes



MNT Lidar

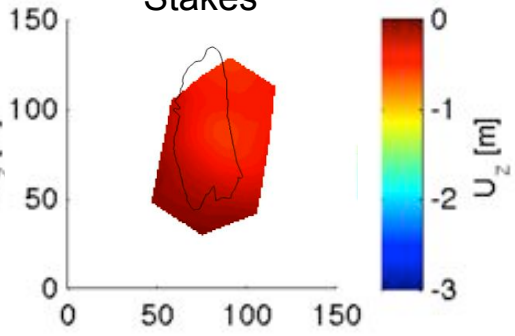


MNT GPS

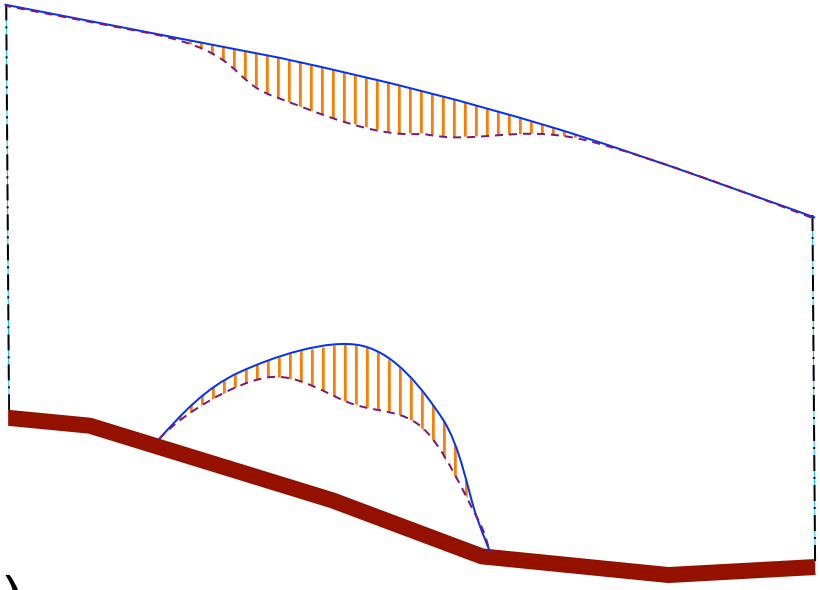


2011 to 2012

Stakes



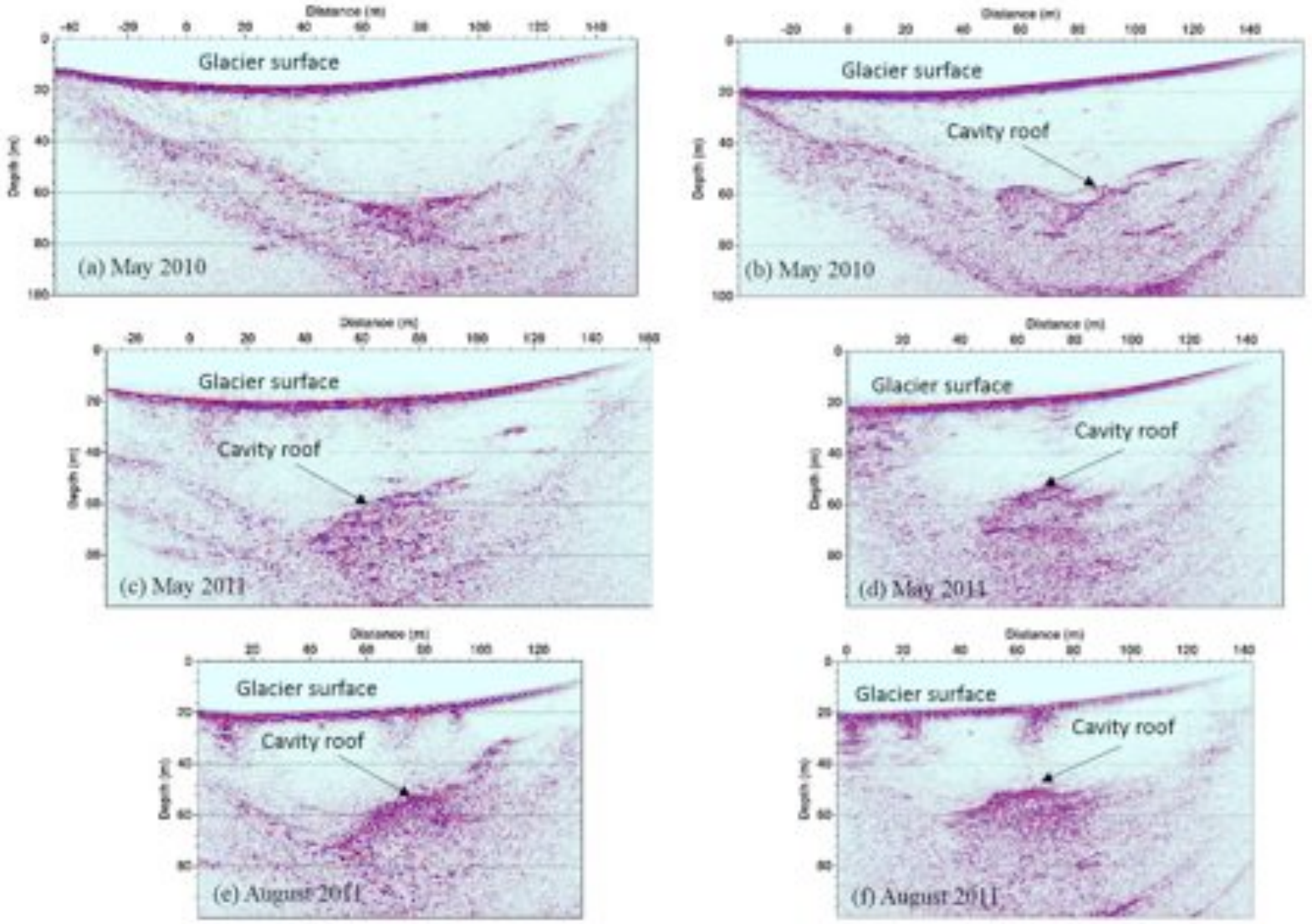
Volume from the surface deflexion
= volume lost by the cavity



Volume (10^3 m^3)

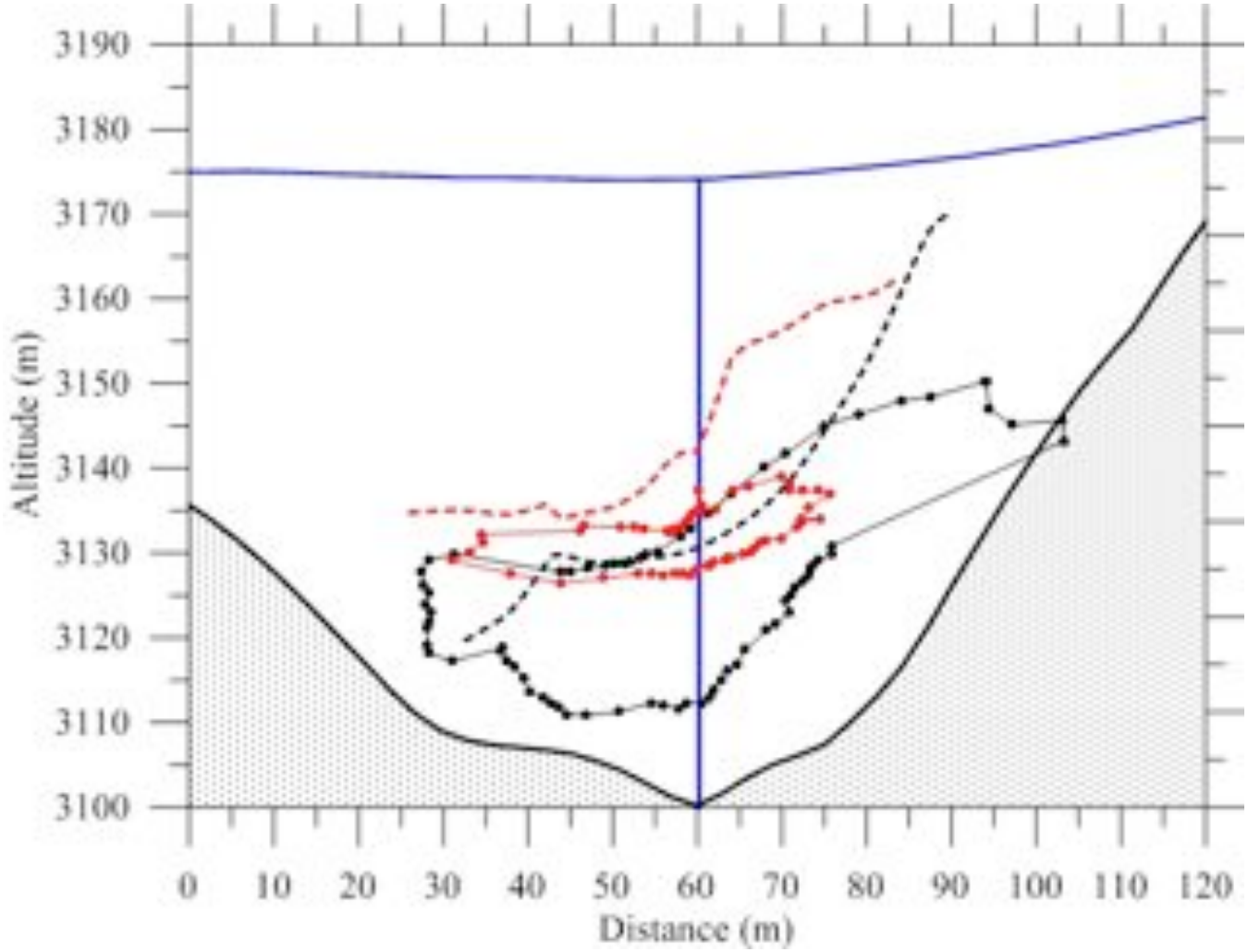
Year	Pumped	lost	surface deflexion
2010	48		
2011	16	28	15 +/-5
2012	9	7	4 +/- 2

Evolution of the cavity geometry



[Vincent et al, in prep]

Evolution of the cavity geometry

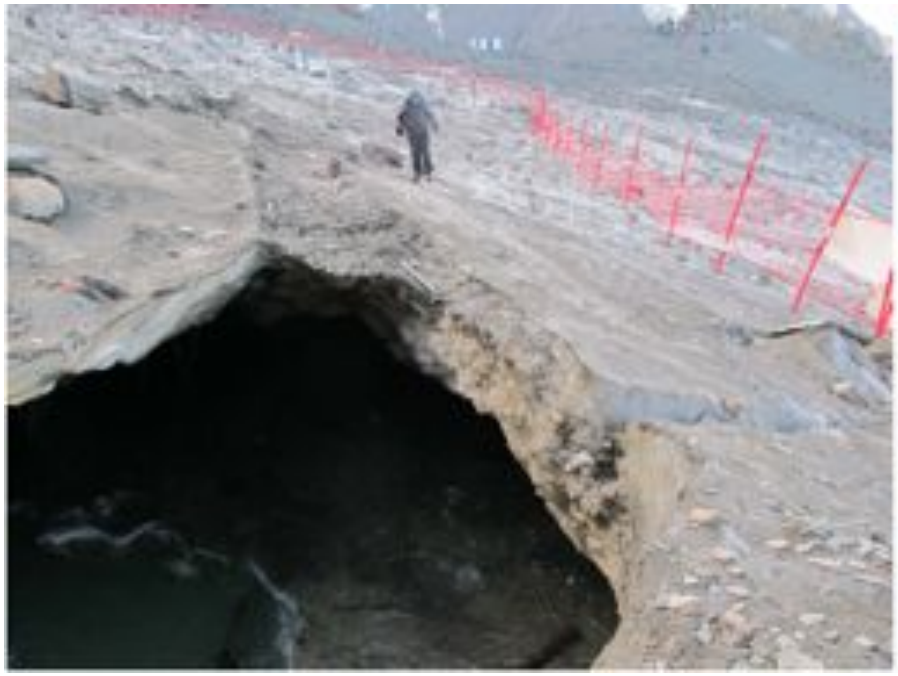


2010
2011

----- 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...