Comparing the long-term fate of a snow cave and a rigid container buried at Dome C, Antarctica

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Ice Memory Project

"Our goal is to create a global ice archive sanctuary in Antarctica, a continent devoted to science and peace, in an effort to preserve ice cores from the world's key endangered glaciers."

→ Organisation of drilling missions on several glaciers of interest around the world

- 2016: Col du Dôme, Mont-Blanc (France)
- 2017: Illimani, Andes (Bolivia)
- 2018: Belukha, Altaï (Russia)
- 2018: Elbrus, Caucasus (Russia)

→ Drilling missions involve extracting two or three full ice cores from each glacier

- One for immediate analysis based on currently available techniques
- One or two for storage in the archive

→ Bring archive cores to Antarctica for long-term storage

- Storage facilities burried into the polar firn

Need for a perennial storage solution !!

Questions raised by the ice cores storage at Dome C

General goal: **Design of a storage solution for the ice cores, which will be buried in the firn at Dome C with the aim of lasting over a hundred year period.**

→ What is the typical lifetime of a cave dug into the firn ?

→ What are the mechanical interactions between the compressible firn and a rigid container ?

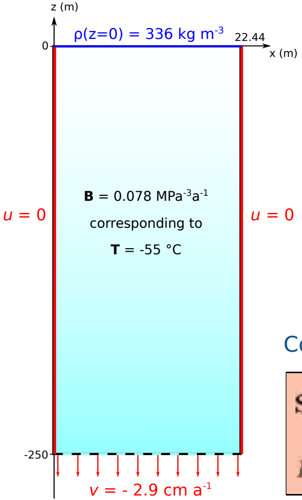
- How does the density evolve around the container ?
- What are the loads supported by the container ?
- How does these loads evolve over time ?
- What is the relative motion between the container and the top surface ?

→ Does a usual shipping container could bear these loads ?

→ If not, what kind of reinforcements would be required given the numerous constraints (budget, climate conditions, transport, limited technical means on site, ...)

Production of an initial steady state

Model Presentation



Stokes Equations:

$$\mathrm{div}(\boldsymbol{\sigma}) + \rho \mathbf{g} = 0$$ **Momentum conservation**

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \mathbf{v}) = 0$$ **Mass conservation**

Firn is compressible ! → ρ depends on depth and time

$$\mathbf{S} = \boldsymbol{\sigma} + p\mathbf{I}$$ Deviatoric stress tensor

$$\dot{\mathbf{e}} = \dot{\boldsymbol{\epsilon}} - \frac{\mathrm{div}(\mathbf{v})}{3}\mathbf{I}$$ Deviatoric deformation rate tensor

Constitutive law of firn/ice:

$$\mathbf{S} = \frac{2}{a} B^{-1/n} \delta^{(1-n)/n} \dot{\mathbf{e}}$$

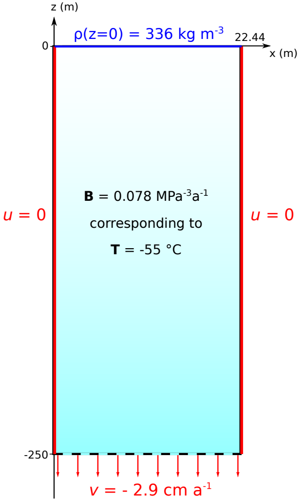
$$p = -\frac{1}{b} B^{-1/n} \delta^{(1-n)/n} \mathrm{div}(\mathbf{v})$$

where a and b functions of $D = \rho/\rho_{ice}$

(Gagliardini and Meyssonnier, 1997)

Production of an initial steady state

STEP 1: Get an initial density field



Solve...

$$\mathrm{div}(\boldsymbol{\sigma}) + \rho \mathbf{g} = 0$$

New velocity field

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \mathbf{v}) = 0$$

New density field

... until a steady state is reached → after ~10 ka

Requires:

- Initial conditions

  $\rho(t=0) = \rho_{ice} - 586 \exp(0.017\, z)$

  with $\rho_{ice} = 922$ kg m^{-3} *(Leduc-Leballeur et al., 2015)*

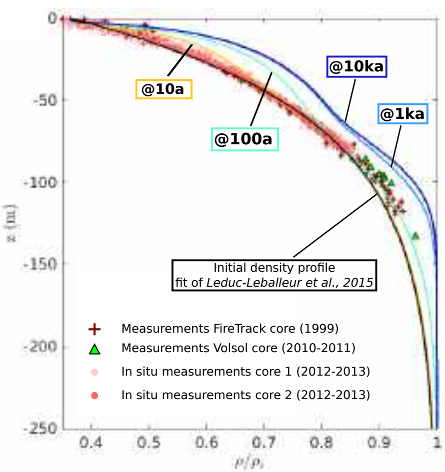
- Boundary conditions

  Hypothesis: $\frac{\partial H}{\partial t} = 0 \longrightarrow \Phi(z=0) = \Phi(z=-250)$

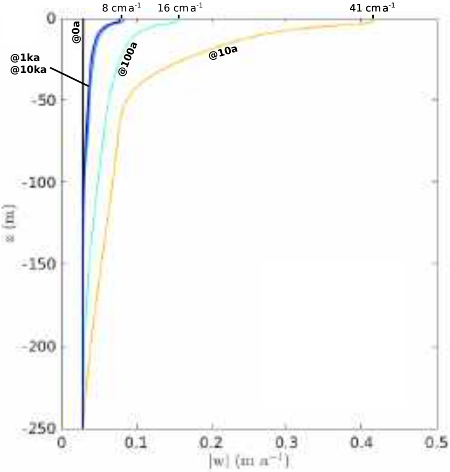
  with $v(z=0) = -7.79 \text{ cm a}^{-1}$ *(Parrenin et al., 2007)*

Modelled vs observed density profiles

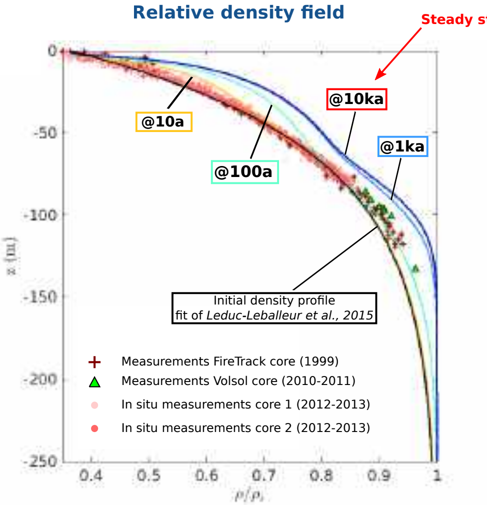
Relative density field

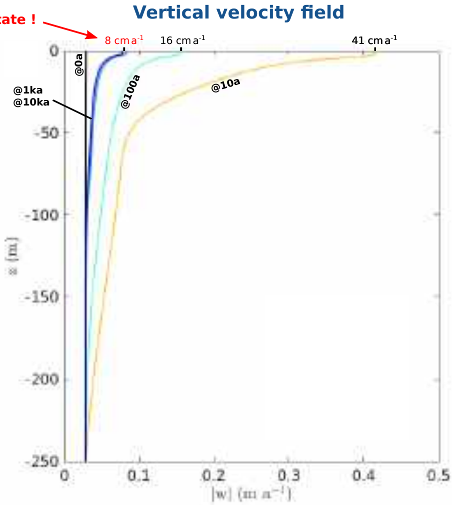


Vertical velocity field



Modelled vs observed density profiles





A polar snow cave in practise: a construction recipe

Photo Credit: J.P. Steffensen, NEEM 2012 report

A polar snow cave in practise: a construction recipe

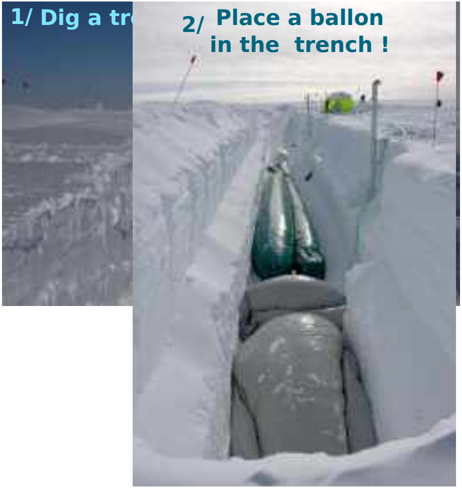


Photo Credit: J.P. Steffensen, NEEM 2012 report

A polar snow cave in practise: a construction recipe

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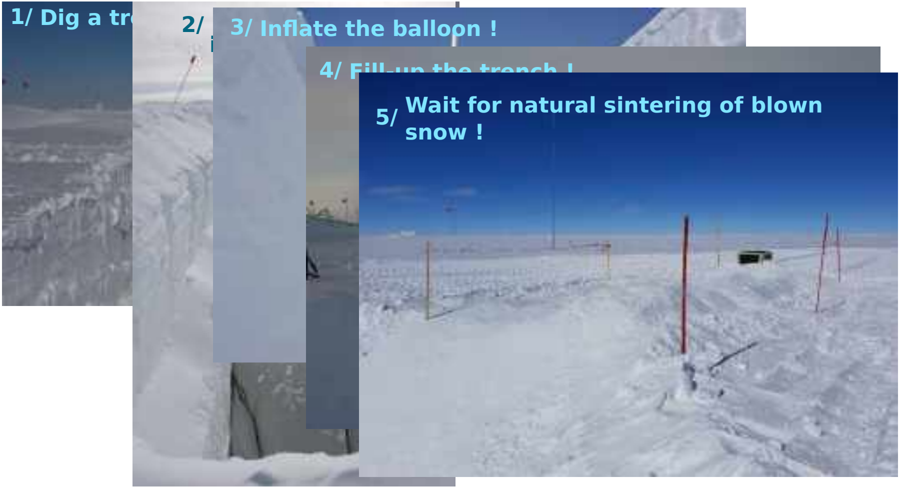

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A polar snow cave in practise: a construction recipe

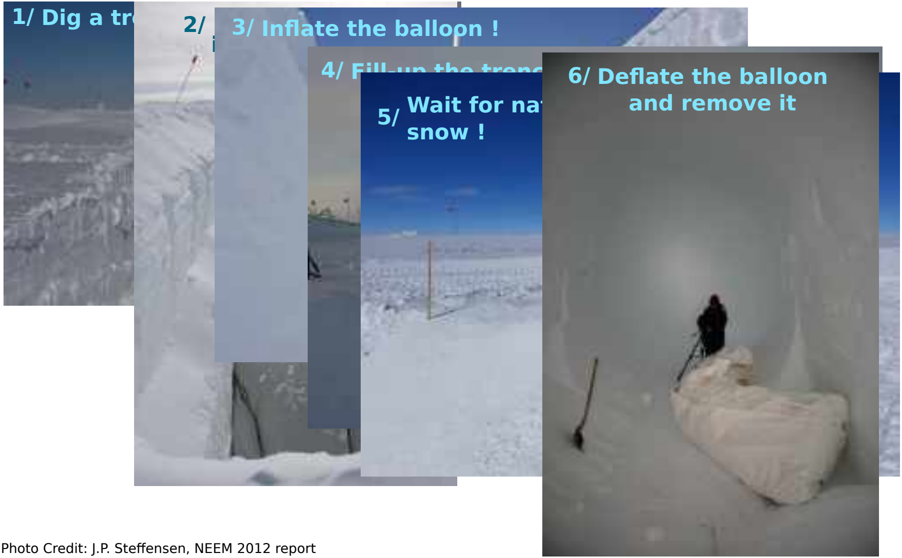
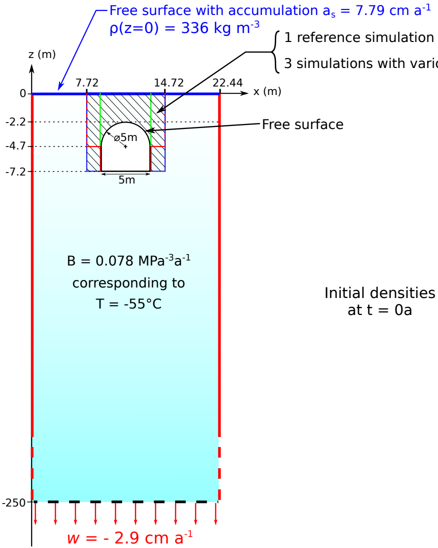


Photo Credit: J.P. Steffensen, NEEM 2012 report

Simulations of an ice cave

STEP 2: Snow cave

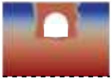


Initial densities at t = 0a

Reference simulation

Simulation narrow trench

Width of trench = balloon diameter

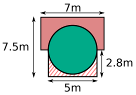


Simulation large trench

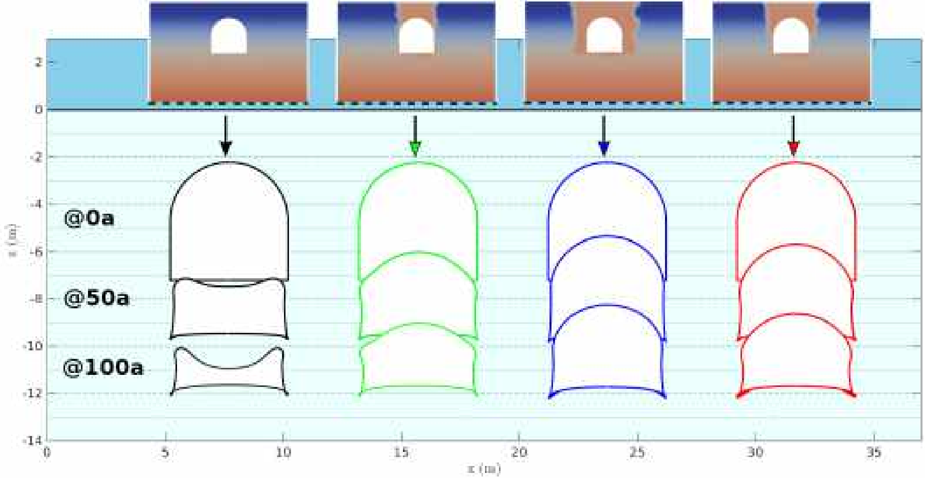
Trench 2m larger than balloon on both side

Simulation trench Dôme C 2018/2019

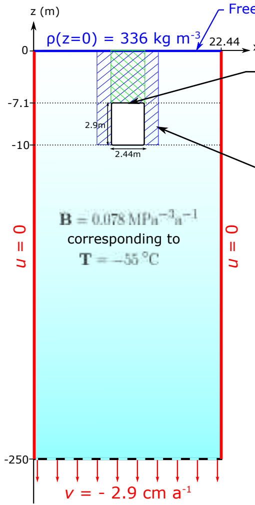
T-shape trench based on field test:



Cave shape over time

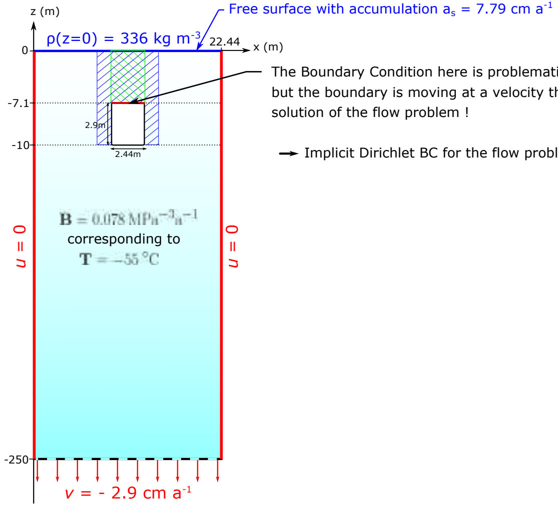


Simulations of a rigid container



- 3 simulations without accounting for weight of container:
  - 1 **reference simulation** with steady density field @10ka
  - 1 with **narrow trench** with initial density ρ = 550 kg m^{-3}
  - 1 with **large trench** with initial density ρ = 550 kg m^{-3}
- Same 3 simulations with weight of container + payload (26 tons)
- What is the rate of sinking of the container ? Does this sinking rate increase significantly with weight ?
- What are the stresses that the container walls willl have to support over time ?

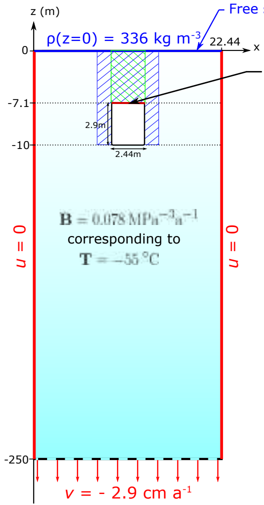
Simulations of a rigid container



The Boundary Condition here is problematic : No flux condition but the boundary is moving at a velocity that is part of the solution of the flow problem !

→ Implicit Dirichlet BC for the flow problem

Simulations of a rigid container



The Boundary Condition here is problematic : No flux condition but the boundary is moving at a velocity that is part of the solution of the flow problem !

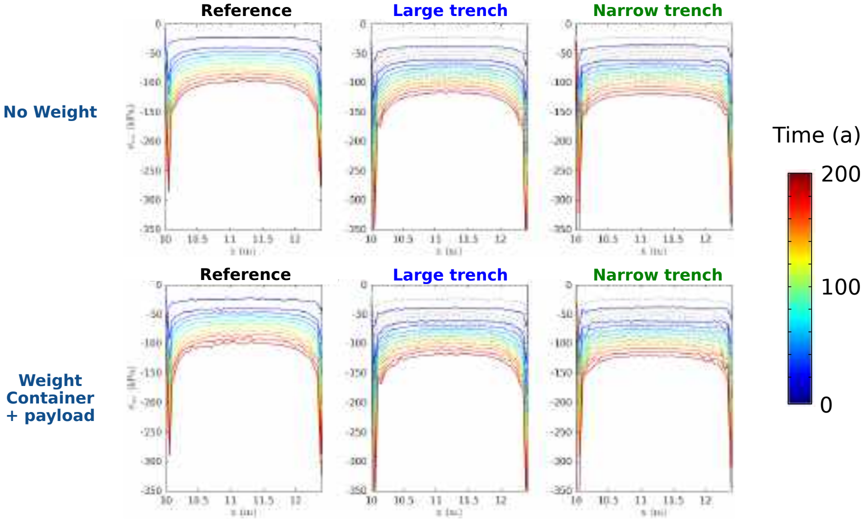
→ Implicit Dirichlet BC for the flow problem

We use **Lagrange multipliers** to force the vertical velocities of all nodes belonging to container roof to be equals to each others

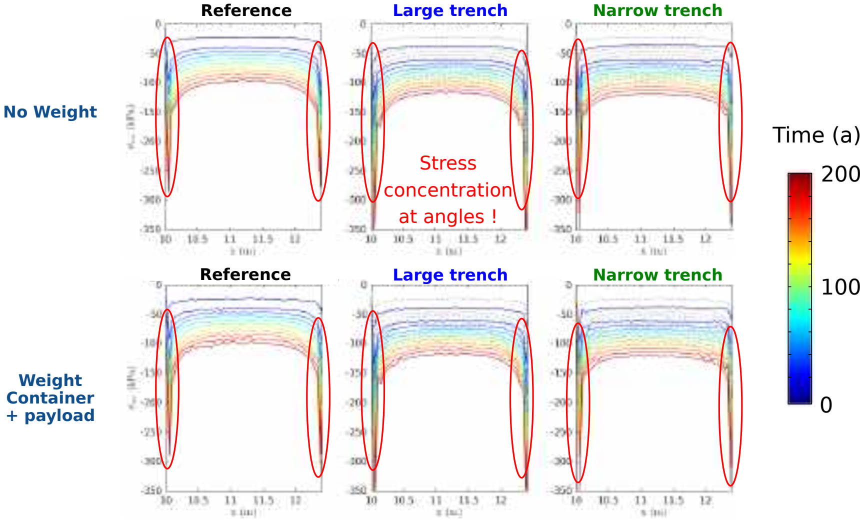
Periodic BC are imposed for normal and tangential velocities between container roof and floor

On container sides, we force the normal (i.e horizontal) velocity to zero and we do not impose any condition on the tangential(i.e vertical) velocity (free slip)

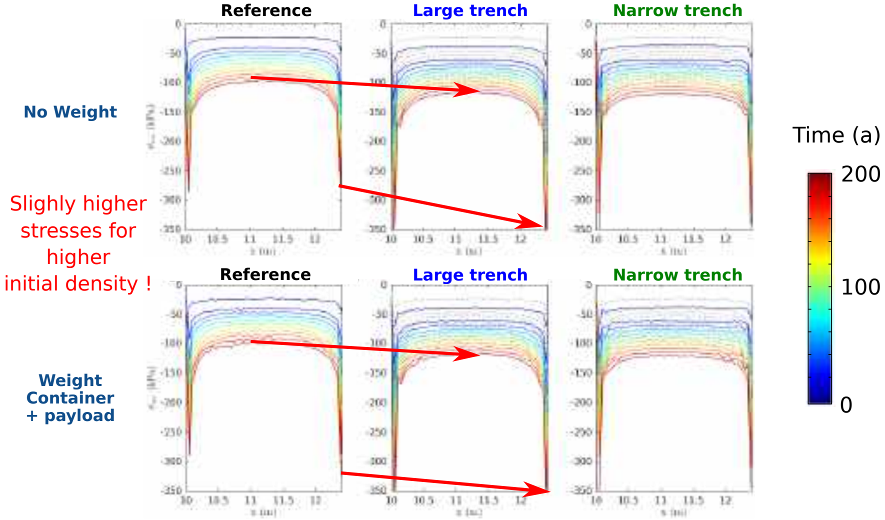
Normal stress on container roof



Normal stress on container roof



Normal stress on container roof



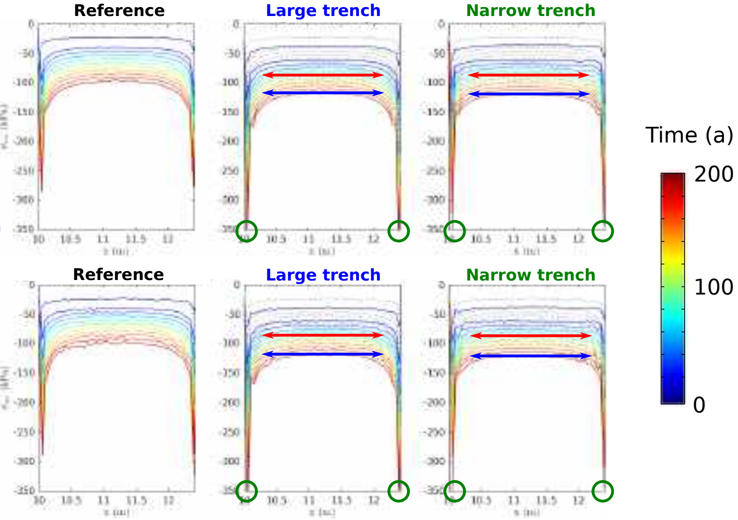
Normal stress on container roof

No Weight

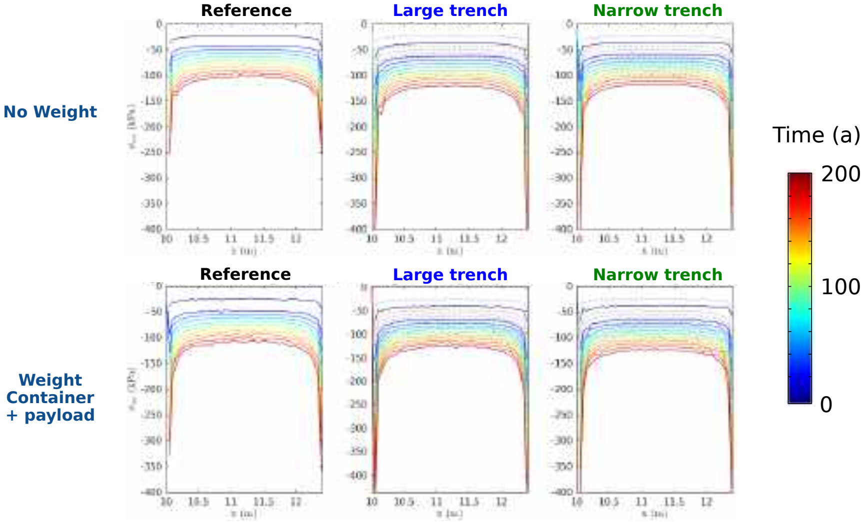
Normal stress on middle roof:
@100a: ~90 kPa
@200a: ~120 kPa

Stress concentration at angles:
~350 to 400 kPa

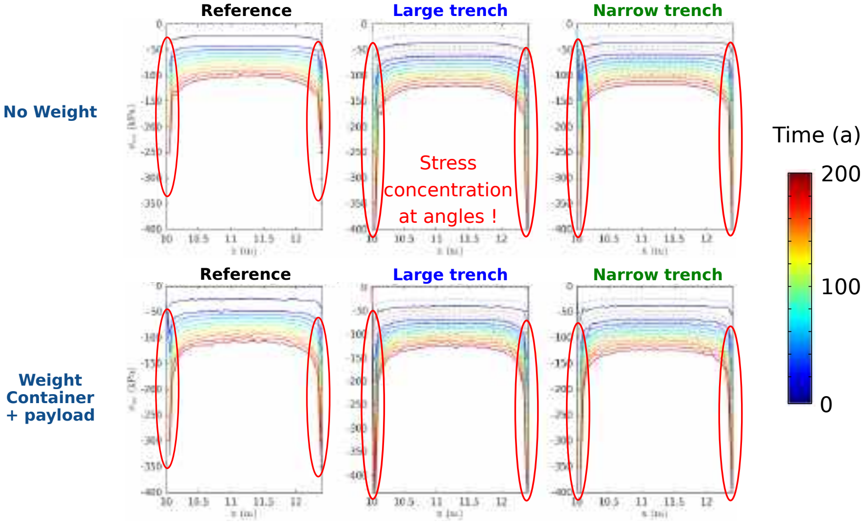
Weight Container + payload



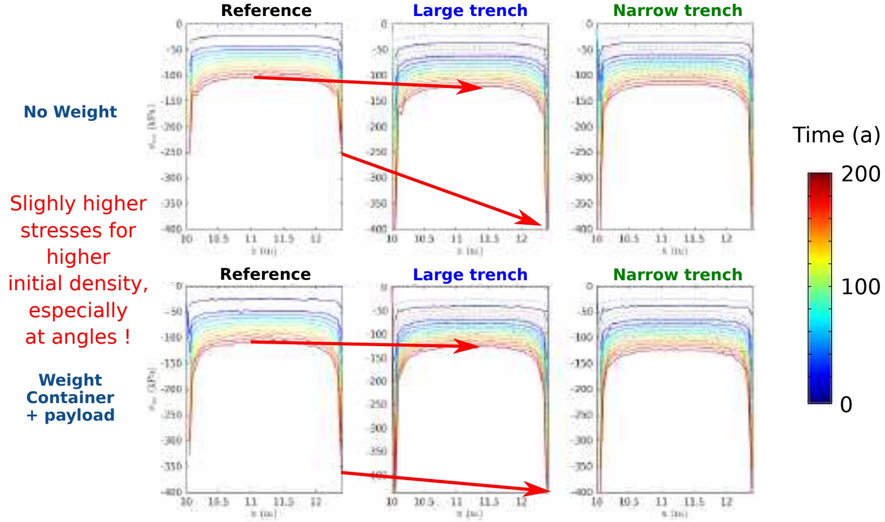
Normal stress on container floor



Normal stress on container floor



Normal stress on container floor



Normal stress on container floor

No Weight

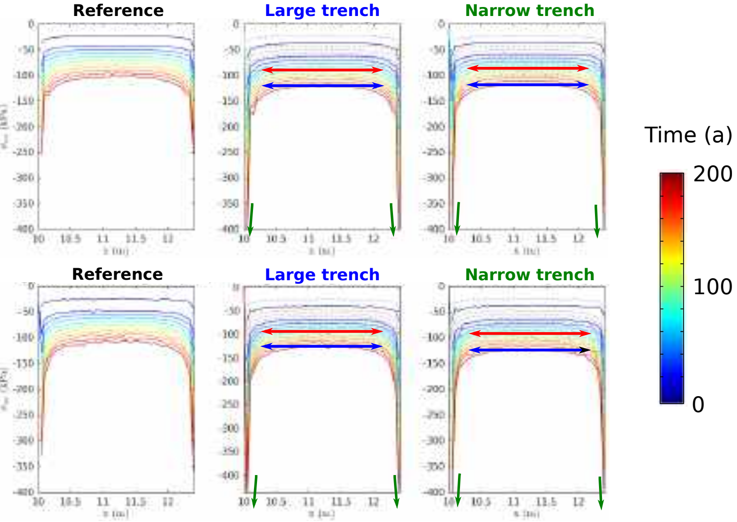
Normal stress on middle roof:
@100a: ~90 kPa
@200a: ~120 kPa

Stress concentration at angles:
up to 430 kPa

Weight Container + payload

Normal stress on middle roof:
@100a: ~90 kPa
@200a: ~125 kPa

Stress concentration at angles:
up to 450 kPa



Conclusion and perspectives

- Results regarding the ice cave must be confirmed by in situ tests, but it appears that:
  - → The **size of the trench** in which the ballon is placed is **very important**
  - → Particular conditions prevailing at Dome C seems to induce **low closure rates**

- The sinking of the container is slow and not very sensitive to initial density and weight (the roof is below **7.1m of snow initially, ~11.8m after 100yr** and **~16.2m after 200yr** of simulation)

- Normal stresses after **200yr** of simulation are of ~**120 kPa on the middle of roof and floor** and of **up to 450 kPa at angles** due to strong stress concentrations

- Maximum normal stresses after **200yr** of simulation are of **~60 kPa on container sides**

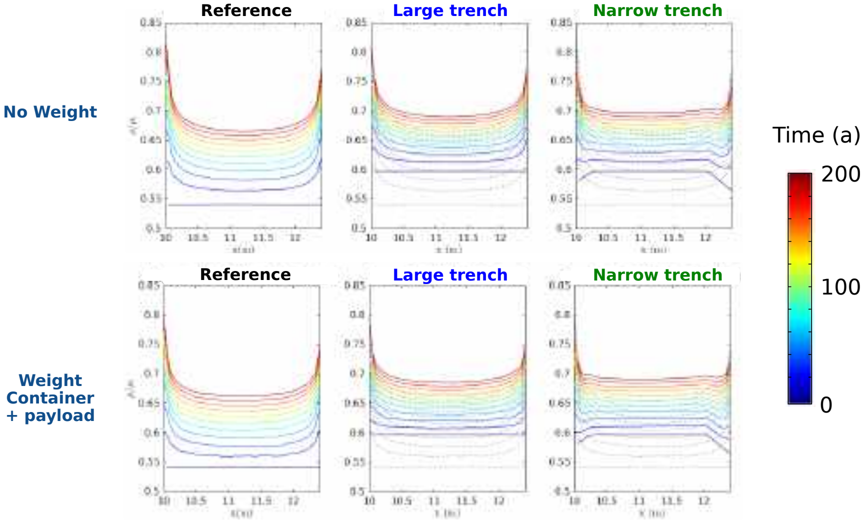
- These results **depart significantly** from the ones obtained when considering **hydrostatic pressure** only

Conclusion and perspectives

Thank you !

.... Questions ?

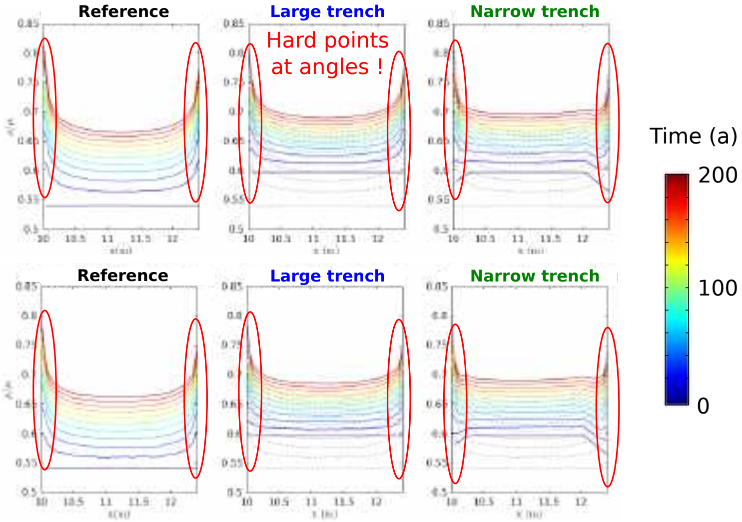
Snow Densification over container roof



Snow Densification over container roof

No Weight

Weight Container + payload

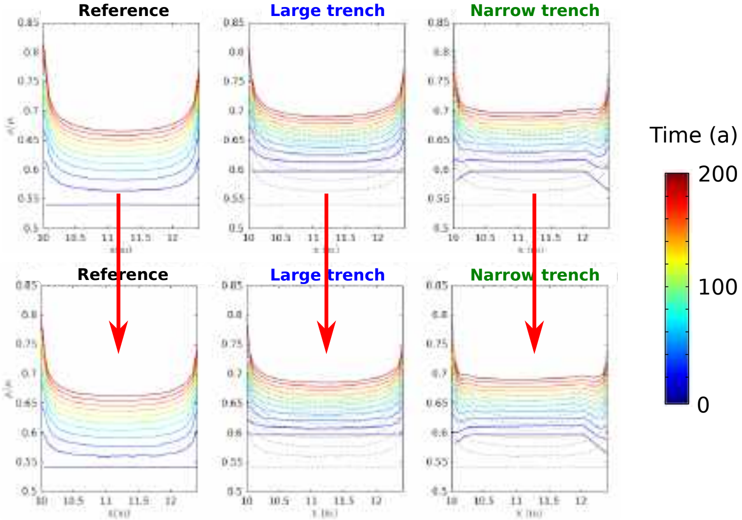


Snow Densification over container roof

No Weight

Not much influence of weight for densification **on roof** !

Weight Container + payload



Snow Densification over container roof

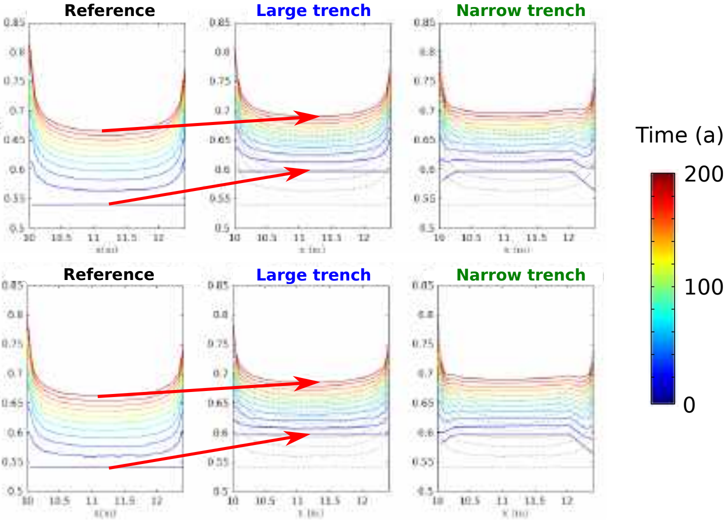
No Weight

Sensitivity to initial density !

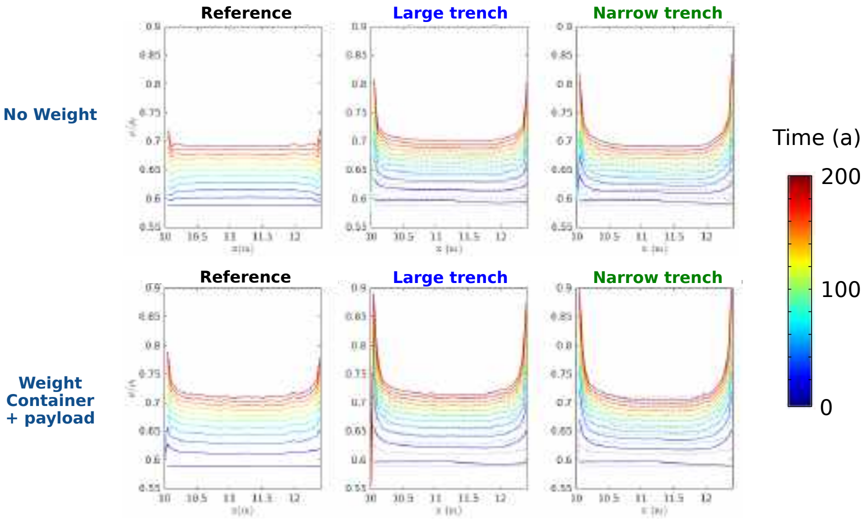
↓

decreases over time...

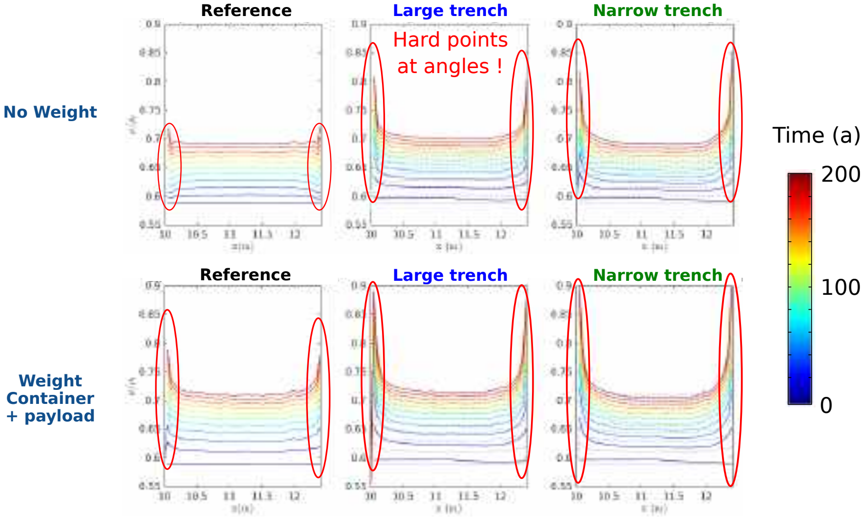
Weight Container + payload



Snow Densification over container floor



Snow Densification over container floor

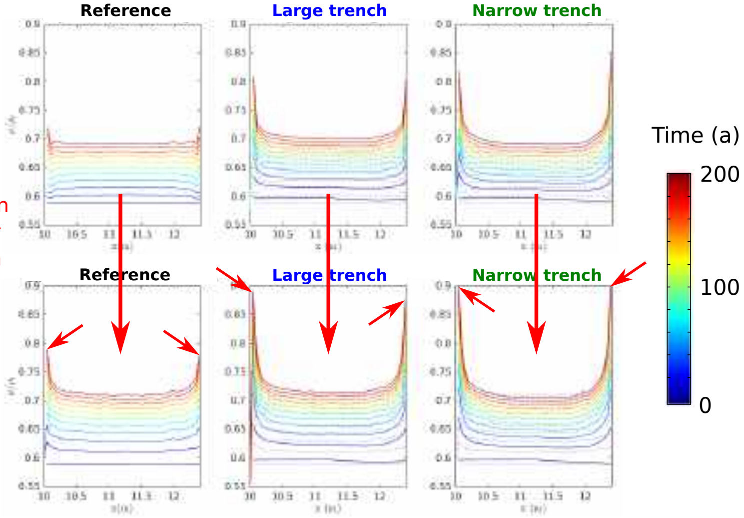


Snow Densification over container floor

No Weight

Weight has an influence for densification **on floor** !

Weight Container + payload

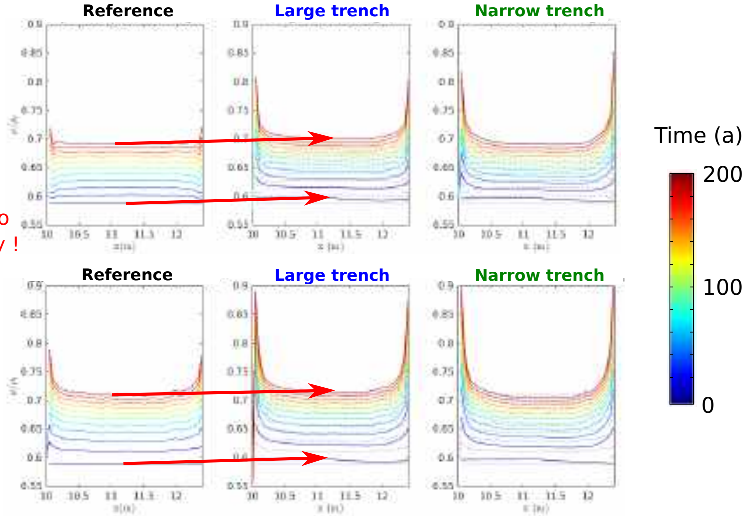


Snow Densification over container floor

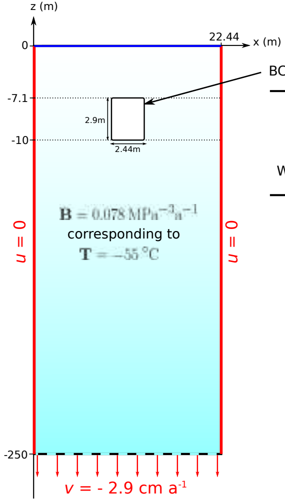
No Weight

Lower sensitivity to initial density !

Weight Container + payload



Firn/container interface: Free slip or no slip ?



BC used for previous simulations: **Free slip**

→ Relative motion between container sides and snow is allowed

What if we change this BC for: **No slip ?**

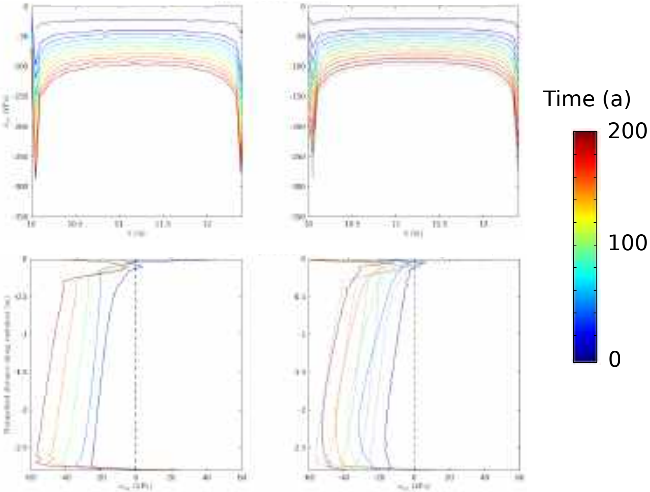
→ Snow is sticked to container walls, i.e. the velocity of snow at the container/firn interface equals the container velocity (no relative motion between snow and container walls)

Sensitivity to firn/container BC

Free slip | **No slip**

Normal Stress on container roof

Normal Stress on container side



Sensitivity to firn/container BC

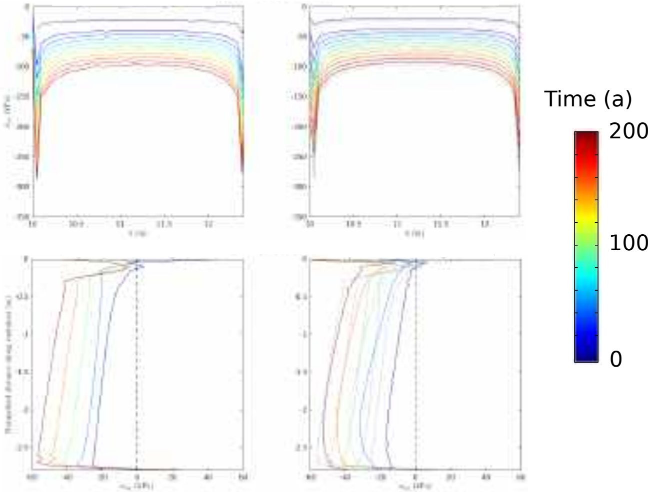
Free slip **No slip**

Normal Stress on container roof

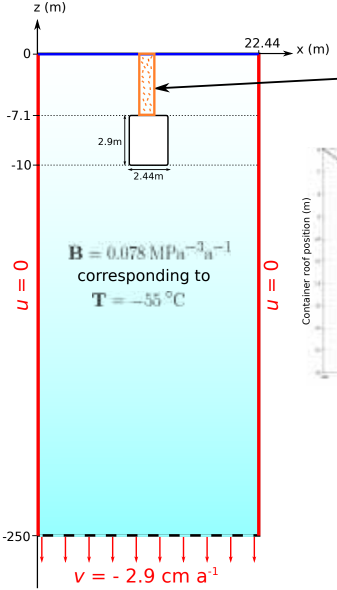
Low sensitivity of stresses to BC at firn/container interface

Free slip condition is the safe side !

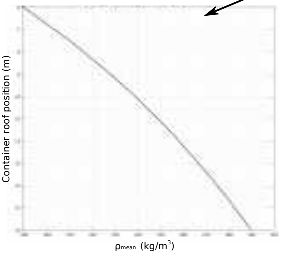
Normal Stress on container side

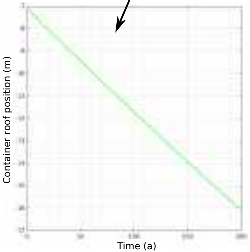


Is using Elmer really necessary ?



Hydrostatic pressure: $p_{static}(z) = -\ \rho_{mean}\ g\ z$

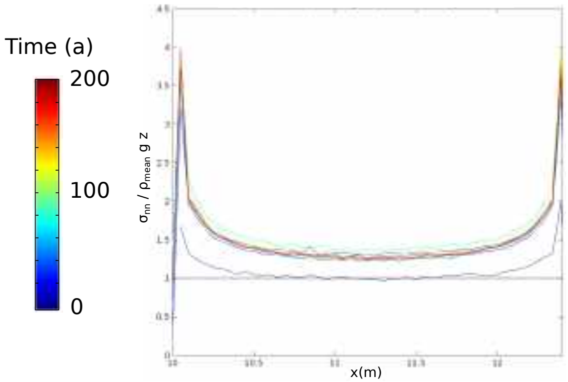




How much calculated normal stresses depart from hydrostatic pressure ?

Using Elmer is really necessary !

Ratio between normal stress on roof and hydrostatic pressure for reference simulation (no weight)

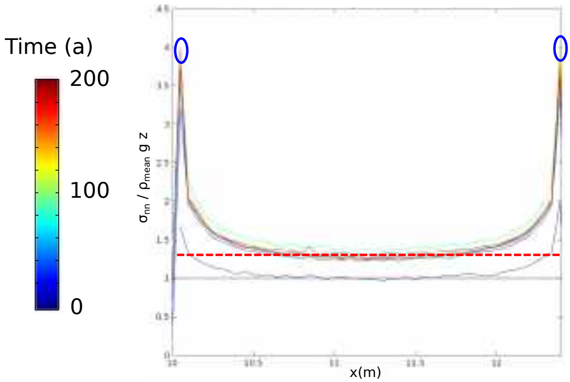


From @20a, the ratio does not evolve in time

Modelled normal stresses always higher than hydrostatic stresses

Using Elmer is really necessary !

Ratio between normal stress on roof and hydrostatic pressure for reference simulation (no weight)



From @20a, the ratio does not evolve in time

Modelled normal stresses always higher than hydrostatic stresses

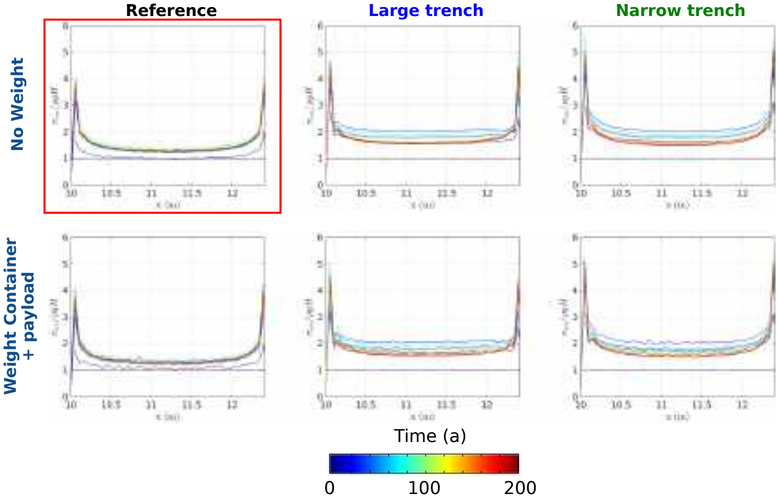
↓

By a factor ~1.4 in the middle

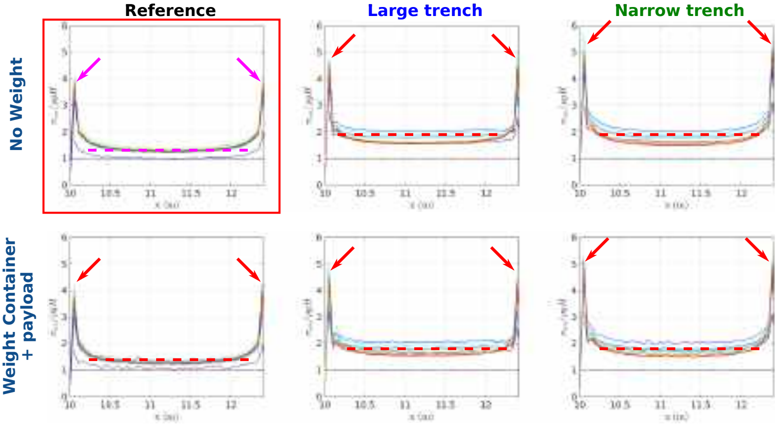
By a factor ~4 at angles

Firn rheology must be taken into account when calculating stresses

Using Elmer is really necessary !



Using Elmer is really necessary !



The gap between modelled normal stresses and hydrostatic loads is **even higher for other considered cases**