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► To cite this version:

Julien Brondex, Olivier Gagliardini, Fabien Gillet-Chaulet, Mondher Chekki. Comparing the long-term fate of a snow cave and a rigid container buried at Dome C, Antarctica. *Cold Regions Science and Technology*, 2020, 180, pp.103164 -. 10.1016/j.coldregions.2020.103164 . hal-03493481

HAL Id: hal-03493481

<https://hal.science/hal-03493481>

Submitted on 17 Oct 2022

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

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Abstract

Ice Memory is an international project aiming at creating a global ice archive sanctuary in Antarctica. The design of a perennial subsurface storage space for the cores is a cornerstone of this project. Here, we use an ice/firn flow model to investigate possible storage solutions that would meet the specific requirements of the project. To this end, we consider two extreme cases in terms of rigidity of the facility: an ice cave ~~dug~~ excavated into the firn and a perfectly rigid container buried within it. We focus on the rate of sinking of the facility as well as on the rate of closure of the cave and the evolution of the normal stresses supported by the container. Our results show that the lifetime of a cave is highly affected by the initial density of snow in its surrounding. On the other hand, the presence of the rigid container within the domain perturbs the flow of snow, creating patches of high density in its surrounding and leading to significant normal stresses on its walls. In particular, strong stress concentrations are obtained at the container angles. These results prove that unreinforced shipping containers are unsuited for this task.

Keywords: Ice Memory, Polar subsurface constructions, Rigid container, Snow cave, Dome C

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1. Introduction

Ice Memory is an international project, which aims to create a global ice archive sanctuary in Antarctica gathering ice cores collected all over the world on glaciers that will likely have melted away in the coming decades due to climate change. The design of a perennial facility guaranteeing a safe storage of the ice cores over coming decades to centuries is the cornerstone of this project. Since it is the coldest place on Earth and because several scientific bases already stand at its surface, the interior of the Antarctic ice sheet appears to be the most suitable location for this undertaking. Moreover, burying the storage facility within the polar firn is a simple and efficient way to get a constant temperature that is not affected by seasonal variability, which is essential to preserve the quality of the cores.

After World War II, several subsurface structures aiming at providing year-round accommodation to militaries and/or scientists have been constructed on permanent snow fields (e.g. Mellor and Hendrickson, 1965; Clark, 1965; Kohlberg and Janneck, 2007). To this end, various construction techniques have been developed and experimented. They range from the direct burying of hard buildings into the firn to the excavation of unreinforced snow caves and tunnels, including a combination of both with hard buildings placed inside a network of snow tunnels that can be lined or roofed with some hard materials or left unrestrained (e.g. Abele, 1964; Mellor, 1968; Steffensen, 2012). However, snow behaves as a viscous fluid flowing under the influence of gravity and the natural fate of any cavity ~~dig~~excavated into the firn is to close-off. In addition, in regions where the annual surface mass balance is positive, any rigid structure buried into the firn has to withstand an ever-increasing pressure. As a result, although highly variable, the lifespan of the subsurface structures mentioned in the available literature seldom reaches the decade. Beyond this time window, severe distresses are usually reported, including failure of roof trusses, crushing of lined tunnels and severe closure of unrestrained tunnels (Mellor, 1968; Kovacs, 1970).

31 Beside the construction technique used, the lifespan of a subsurface structure
32 depends on the snow accumulation rate, the initial depth of the construction, the
33 initial size of the excavations, the vertical profiles of temperature and density, the
34 potential occurrence of melting event, the flow regime at the considered location,
35 and possibly other parameters not identified yet. In this context, Dome C
36 is probably one of the most favourable locations for this type of construction
37 because of the ~~very~~ combination of specific conditions prevailing there: very
38 low snow accumulation, very dry atmosphere, very low temperature making the
39 occurrence of melting events unlikely in the coming decades, and almost purely
40 vertical motion of snow making shear stresses negligible. In addition, since the
41 facility aims at storing ice cores only, it will not contain any internal heat source,
42 which has been shown to strongly increase the closure rate of snow cavities
43 (Clark, 1965). On the other hand, regular maintenance of the installation should
44 not be considered as a possible mean to increase its lifetime. Indeed, we must
45 consider the possibility that a continuous deployment of staff at Dome C could
46 be hampered in the future. All these particularities strengthen the need for an
47 ad hoc numerical study aiming at investigating optimal solutions to meet the
48 specific needs of this project. This numerical study is the subject of the present
49 paper.

50 Snow is a complex material and mathematical laws implemented in numeri-
51 cal models to account for its mechanical behaviour cannot claim to capture the
52 full complexity of underlying physical processes (Arthern et al., 2010). In addi-
53 tion, these laws involve many parameters, some of which are poorly constrained
54 or affected by significant spatial or temporal variability. As a consequence, the
55 first step of the present study consists in constructing an initial steady state of
56 the considered domain, which is then compared to available field measurements.
57 Starting from this initial state, we investigate the mechanical interactions be-
58 tween the storage structure and the surrounding flowing firn, considering two
59 end-member cases in terms of rigidity of the structure: an unreinforced snow
60 cave ~~dig~~ burrowed into the firn and a perfectly rigid container buried within it.
61 We put a particular focus on the rate of sinking of the storage facility as well

62 as on the rate of closure of the cave and the temporal evolution of the normal
63 stresses supported by the container. In Sect. 2, we introduce the model used
64 to conduct this study and present the experimental setup. The results obtained
65 for each experiment are presented in Sect. 3 and discussed in the last section.

66 2. Methods

67 2.1. Model description

68 The mechanical interactions between the storage solution and the surround-
69 ing compressible firn are modelled using the code Elmer/Ice (Gagliardini et al.,
70 2013). Elmer/Ice is an open-source finite-element software for ice sheets, glaciers
71 and ice flow modelling, which also includes a module for the rheology of com-
72 pressible firn (Gagliardini and Meyssonier, 1997) that has already been applied
73 in several studies (Zwinger et al., 2007; Gilbert et al., 2014; Licciulli et al., 2019).
74 All variables and parameters used in this study are summarized in Table 1.

75 2.1.1. Flow law

76 We adopt the flow law first proposed by Gagliardini and Meyssonier (1997)
77 and later corrected by Zwinger et al. (2007) to model the flow of firn, which
78 behaves as a non-linear viscous compressible fluid. ~~It-This law is intended to~~
79 ~~represent the secondary creep of firn. As such, processes related to primary~~
80 ~~creep and snow metamorphism are not accounted for. In addition, it~~ must be
81 stressed that this approach does not capture brittle fracture of snow, which
82 involves other mechanical processes. In particular, the present model is limited
83 to the description of the continuous deformation of a snow cave related to the
84 flow of firn and cannot provide any information on a potential collapse of the
85 latter. Nevertheless, none of the reports regarding subsurface constructions on
86 permanent snow fields available in the literature mention such an event (e.g.
87 Mellor, 1968; Kohlberg and Janneck, 2007; Steffensen, 2012).

88 The Cauchy stress tensor $\boldsymbol{\sigma}$ can be decomposed into an isotropic part $-p\mathbf{I}$,
89 where $p = -(\text{tr } \boldsymbol{\sigma})/3$ is the isotropic pressure (tr denotes the trace operator)

90 positive for compression and \mathbf{I} the unit tensor, and a traceless, deviatoric stress
 91 tensor, i.e.

$$\boldsymbol{\tau} = \boldsymbol{\sigma} - \frac{\text{tr } \boldsymbol{\sigma}}{3} \mathbf{I} = \boldsymbol{\sigma} + p \mathbf{I}. \quad (1)$$

92 Similarly, the deviatoric part $\dot{\boldsymbol{\epsilon}}$ of the strain-rate tensor $\dot{\boldsymbol{\epsilon}} = 1/2[\text{grad } \mathbf{u} +$
 93 $(\text{grad } \mathbf{u})^T]$, where \mathbf{u} is the velocity vector, is obtained by

$$\dot{\boldsymbol{\epsilon}} = \dot{\boldsymbol{\epsilon}} - \frac{\text{tr } \dot{\boldsymbol{\epsilon}}}{3} \mathbf{I} = \dot{\boldsymbol{\epsilon}} - \frac{\text{div } \mathbf{u}}{3} \mathbf{I}. \quad (2)$$

94 Invariants for the strain-rate can then be defined as

$$\gamma_e^2 = 2 \text{tr } (\dot{\boldsymbol{\epsilon}})^2 = 2 \dot{\epsilon}_{ij} \dot{\epsilon}_{ij}, \quad \dot{\epsilon}_D^2 = \frac{\gamma_e^2}{a} + \frac{(\text{div } \mathbf{u})^2}{b}, \quad (3)$$

95 and for the stress as

$$\tau^2 = \frac{1}{2} \text{tr } (\boldsymbol{\tau})^2 = \frac{1}{2} \tau_{ij} \tau_{ij}, \quad \dot{\sigma}_D^2 = a \tau^2 + b p^2. \quad (4)$$

96 The two functions $a = a(D)$ and $b = b(D)$ depend only on the relative density
 97 $D = \rho/\rho_i$, where ρ is the snow density and ρ_i is the ice density. Following
 98 Gagliardini and Meyssonier (1997), the relationships between the deviatoric
 99 and isotropic parts of the stress and strain-rate tensors write, respectively,

$$\boldsymbol{\tau} = \frac{2}{a} B^{-1/n} \dot{\epsilon}_D^{(1-n)/n} \dot{\boldsymbol{\epsilon}}, \quad (5)$$

100 and

$$p = -\frac{1}{b} B^{-1/n} \dot{\epsilon}_D^{(1-n)/n} \text{div } \mathbf{u}. \quad (6)$$

101 The parameter n used in Eqs. (5) and (6) is the flow law exponent, usu-
 102 ally set to $n = 3$, while B is a fluidity parameter which depends mostly on
 103 the temperature of the snow/ice. The firn temperature at Dome C is affected
 104 by the seasonal variability of surface temperatures only within a 10 m-thick
 105 layer. Below this surface layer, the firn has a constant temperature equal to the

106 annual mean surface air temperature, which is estimated at -55 °C (Leduc-
 107 Leballeur et al., 2015). For this reason, following recommendations of Cuffey
 108 and Paterson (2010), the fluidity parameter B is set to a uniform value of
 109 $B = 0.078 \text{ MPa}^{-3} \text{ a}^{-1}$. Regarding the functions a and b , we use the ana-
 110 lytical solution proposed by Duva and Crow (1994) for high relative densities
 111 ($0.81 < D < 1.0$):

$$a_0(D) = \frac{1 + 2(1 - D)/3}{D^{2n/(n+1)}}, \quad b_0(D) = \frac{3}{4} \left(\frac{(1 - D)^{1/n}}{n [1 - (1 - D)^{1/n}]} \right)^{2n/(n+1)} \quad (7)$$

112 Thus, in the limiting case for which $D = 1$ (pure ice), $a = 1$ and $b = 0$, and
 113 the snow/firn law reduces to the classical incompressible Glen’s flow law tra-
 114 ditionally used to model glacier flow. For smaller relative densities, we use
 115 parameterized forms of functions a and b that were first proposed by Gagliar-
 116 dini and Meyssonier (1997) by fitting cold room experiments and densification
 117 measured at Site 2 (Greenland), before being slightly corrected by Zwinger et al.
 118 (2007) for a study of the Gorshkov crater glacier (Kamchatka, Russia) as:

$$a(D) = \begin{cases} \exp(13.22240 - 15.78652D), & D \leq 0.81 \\ a_0(D), & 0.81 < D \leq 1.0 \end{cases} \quad (8)$$

$$b(D) = \begin{cases} \exp(15.09371 - 20.46489D), & D \leq 0.81 \\ b_0(D), & 0.81 < D \leq 1.0 \end{cases} \quad (9)$$

119 Relations (8) and (9) have been shown to produce acceptable results for simu-
 120 lated density profiles and surface velocities at Col du Dôme, Mont-Blanc, France
 121 (Gilbert et al., 2014). It is important to note that the parametrizations adopted
 122 for these two functions is a source of uncertainty on the simulated density profiles
 123 as well as on flow velocities and, therefore, on the computed stresses. Ideally,
 124 these functions should be re-calibrated on a case-by-case basis for each particu-
 125 lar applications. However, this would be a time-consuming task requiring a lot
 126 of in-situ measurements for a limited benefit since it would anyway not allow to
 127 capture the high spatio-temporal variability of the density as measured over the

128 first few tens of meters of the polar firn (e.g Leduc-Leballeur et al., 2015). For
 129 this reason, we have used for the present work the relations (8) and (9) without
 130 further modifications.

131 2.1.2. Field equations

132 To keep the computational cost affordable, we solve the full Stokes equa-
 133 tions, with the constitutive law of firn described above, on a two-dimensional
 134 rectangular domain in a (x, z) vertical plan, the z axis being the vertical pointing
 135 upwards. The momentum balance, in which acceleration terms are neglected,
 136 reads

$$\operatorname{div} \boldsymbol{\sigma} + \rho \mathbf{g} = 0, \quad (10)$$

137 where $\mathbf{g} = (0, -g)$ is the gravity vector. The spatio-temporal evolution of density
 138 is governed by the mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \operatorname{div} \rho \mathbf{u} = 0. \quad (11)$$

Equations (10) and (11) are coupled to an advection equation governing the
 evolution of the domain top surface, which is a free surface. This equation
 reads:

$$\partial_t z_s + u \partial_x z_s = w + a_s, \quad (12)$$

139 where $\partial_i z_s$ denotes the partial derivative of the function z_s relative to the vari-
 140 able i , z_s is the top surface altitude, w the vertical component of the velocity
 141 vector and a_s the annual surface mass balance. Although snow precipitations in
 142 Antarctica are expected to increase slightly in the future (Palerme et al., 2017),
 143 uncertainties regarding the local evolution of surface mass balance are high and
 144 the value of a_s is kept constant in all simulations of the present study.

145 *2.1.3. Boundary conditions*

146 The top surface being a stress-free surface, the following Neumann condition
 147 applies:

$$(\boldsymbol{\sigma} \cdot \mathbf{n})|_{z_s} = \mathbf{0}, \quad (13)$$

148 where \mathbf{n} is the normal unit vector to the considered boundary. The domain is
 149 assumed to be a perfect dome, which implies purely vertical flow in the absence
 150 of any obstacle and yields the following Dirichlet condition on both sides:

$$(\mathbf{u} \cdot \mathbf{n})|_{x_l} = (\mathbf{u} \cdot \mathbf{n})|_{x_r} = 0, \quad (14)$$

151 where x_l and x_r are, respectively, the left and right horizontal boundaries of
 152 the domain. The bottom boundary condition is based on the assumption that,
 153 on the time scales at stake in our simulations, the altitude of the surface at
 154 Dome C is constant. As a consequence, all the snow accumulated at the top
 155 surface over an arbitrary period of time must be balanced by an equivalent mass
 156 of snow/ice flowing out of the domain through its bottom boundary over the
 157 same time period, which yields the condition:

$$(\mathbf{u} \cdot \mathbf{n})|_{z_b} = \frac{a_s \rho(z = z_s)}{\rho(z = z_b)}, \quad (15)$$

where z_b is the altitude of the bottom boundary, which is kept fixed in time.
 Finally, the resolution of Eq. (11) requires a Dirichlet condition on the top
 boundary, which is the only inflow boundary of the domain. This condition is
 simply given by:

$$\rho(z = z_s) = \rho_s, \quad (16)$$

158 where ρ_s is the density of fresh snow.

159 *2.2. Description of the experiments*

160 *2.2.1. Initialisation*

161 Using the model described above, we run a first transient experiment in
 162 order to produce an initial steady density field. The domain considered for this

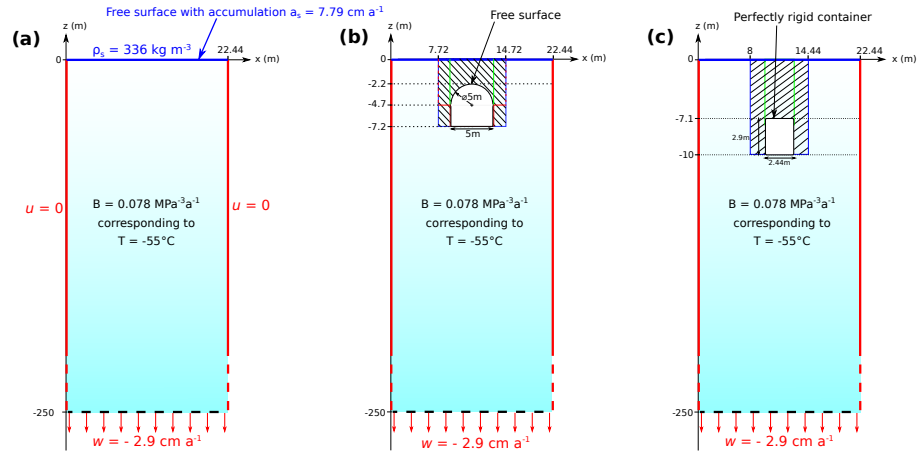
Parameter	Value	Units
g	9.81	m s^{-2}
B	0.078	$\text{MPa}^{-3} \text{a}^{-1}$
n	3	—
ρ_i	922	kg m^{-3}
ρ_s	336	kg m^{-3}
a_s	0.078	m a^{-1}

Table 1: List of parameter values used in this study.

163 initialisation step is shown in Fig. 1a. Its horizontal extension is arbitrarily set
164 from $x_l = 0$ m to $x_r = 22.44$ m. The sensitivity of the results to this choice
165 is discussed in the Supplement. Regarding the vertical dimension, it must be
166 stressed that the ice thickness at Dome C is ~~estimated at~~ of 3273 ± 5 m (Parrenin
167 et al., 2007), while, on the considered time scales, the storage facility is expected
168 to evolve within the first few tens of meters below the surface only. The choice
169 of the vertical extension is then a trade-off between a restricted domain size
170 limiting the computational cost of simulations and a domain deep enough so
171 that the sensitivity of the results to the bottom boundary condition (15), which
172 is poorly constrained, is limited. As a consequence, the vertical limits of the
173 initial domain are set to $z_b = -250$ m and $z_s = 0$ m.

174 The resolution of Eq. (11) requires the prescription of an initial density field.
175 We use the parametrized function derived by Leduc-Leballeur et al. (2015),
176 which corresponds to the best fit in the least squares sense to density measure-
177 ments performed on two 80-m-long ice cores drilled at Dome C in the austral
178 summer 2012-2013. This parametrization is also used to calculate the values
179 of densities at the top and bottom boundaries of the domain as required by
180 conditions (15) and (16).

181 For this simulation, we use an unstructured mesh made of 14656 three-
182 node triangular elements of uniform size. The typical spacing between two
183 neighbouring nodes is of ~ 1 m. To be sure that a steady solution is reached at



Modeled

Figure 1: Modelled domain and associated boundary conditions implemented for (a) the initialisation, (b) the snow cave experiment and (c) the rigid container experiment. Top and lateral boundary conditions represented on (a) are also valid for (b) and (c) but were not reported for the sake of readability. The hatched areas in (b) and (c) represent the various considered shapes for the trench of high initial density surrounding the cave/container as mentioned in the text: the narrow trench (green), the wide trench (blue), and the T-shape trench (red) for (b) only.

184 the end of the simulation, the prescribed total simulation time is of 10 ka and
 185 the timestep size of 1 a.

186 2.2.2. Snow cave experiment

187 A well-proven technique to build a snow cave into the polar firn relies on the
 188 use of an inflatable balloon. First, the balloon is placed in a trench excavated
 189 in the snow. Then, the balloon is inflated and snow is blown back on the top
 190 of it until the trench is filled up. After sufficient age hardening of snow has
 191 occurred (typically after a few days), the balloon is deflated and removed from
 192 the resulting snow cave. This technique is already mentioned in the report of
 193 Mellor (1968), but is not detailed very much. A recent implementation of this
 194 concept was performed in 2012 by members of the Center for Ice and Climate
 195 from the University of Copenhagen for the NEEM ice core drilling project in

196 North-West Greenland (Steffensen, 2012). Careful monitoring of the deforma-
 197 tions of this construction showed encouraging results, leading the Ice Memory
 198 steering committee to initiate its own field test at Dome C (Ascione and Scalet,
 199 2019).

200 The numerical setup that we are presenting here, and in particular the initial
 201 depth of the modelled cave, is based on this field test (Fig. 1b). The transverse
 202 section of the cave corresponds to the combination of a square that is 5 m on
 203 each side and of the incircle of this square: the top half of the section is thus
 204 a half circle of diameter 5 m while the bottom half is a rectangle. The highest
 205 point of the cave is located 2.2 m below the firn surface, which is perfectly flat
 206 at the beginning of the simulations. As for the initialisation, the mesh is made
 207 of three-node triangular elements. However, for this experiment, the mesh is
 208 not uniform. High refinement is prescribed within a rectangle surrounding the
 209 cave where the typical spacing between two neighbouring nodes is of ~ 5 cm.
 210 Outside of this highly refined rectangle, the elements size increases following
 211 a geometric progression towards the boundaries of the domain, such that the
 212 typical spacing between two neighbouring nodes at the bottom boundary of the
 213 domain is of ~ 1.2 m.

214 The cave/firn interface is treated as a stress-free surface, which will close-
 215 off over time due to the flow of firn. From a mechanical point of view, this is
 216 equivalent to state that the cave/firn interface has no rigidity at all. At each
 217 time step, the displacement $\delta \mathbf{x}_k$ of a node k belonging to this interface is given
 218 by:

$$\delta \mathbf{x}_k = u_k \delta t \mathbf{x} + w_k \delta t \mathbf{z}, \quad (17)$$

219 where u_k and w_k are, respectively, the horizontal and vertical components of
 220 the flow velocity computed at node k , and δt is the timestep size. To deal with
 221 these displacements, we use a module available in Elmer/Ice which displaces the
 222 nodes through a deformation of the whole mesh, with the constrain of keeping
 223 the nodes located on the lateral and bottom boundaries of the domain at fixed

224 positions. However, a problem arises after a few tens of years of simulation,
225 when the mesh is too deformed with elements overlapping each others. For this
226 reason, an automatic remeshing procedure was developed. Every 20 a, the run
227 is stopped and a new mesh of the geometry in its current state is created. For
228 this new mesh, the elements size is a function of the distance relative to the
229 firn/cave interface, which has moved and deformed over the course of the run.
230 This function is parametrized in order to get small elements of uniform size, with
231 a distance between two neighbouring nodes of about 5 cm, within the first 10 cm
232 surrounding the firn/cave interface. As going further away, the size of elements
233 increases linearly. All the physical fields computed at the end of the 20 a run
234 preceding the remeshing step, in particular the velocity and density fields, are
235 then linearly interpolated on the new mesh, which constitutes the initial state
236 for a new 20 a transient run. This procedure is repeated until the end of the
237 simulation. The total simulation time is set to 150 a as the deformation of the
238 cave becomes too high beyond this time window. The consecutive remeshing
239 steps necessarily induce a loss of information through interpolation diffusion
240 between two consecutive runs, especially in places where the considered fields
241 are strongly non-linear. However, since the mesh is always highly refined in the
242 area of interest, it turns out that the final results are not significantly affected
243 by this procedure.

244 The snow cave experiment includes four simulations which only differ by
245 the initial density prescribed in the close vicinity of the cave. For the reference
246 simulation, the initial density field corresponds to the steady density field ob-
247 tained at the end of the initialisation run. For the three other simulations, this
248 initial density field is slightly modified to account for the trench involved in the
249 construction process of the cave, which is backfilled with snow of higher density
250 by a snow blower. In order to assess the importance of the trench size and shape
251 on the lifetime of the cave, we investigate three cases: (1) a single trench with
252 a width corresponding exactly to the balloon diameter (narrow trench case),
253 (2) a single trench which is two meters larger than the balloon on both sides
254 (wide trench case), and (3) a T-shape trench with 1 m wide ledges on both sides

255 of the cave mimicking the on-going Dome C field test mentioned above. The
256 exact dimensions and shapes of the trenches involved in these three cases are
257 reported in Fig. 1b. The sensitivity to the width of the top horizontal branch of
258 the T-shape is investigated by running two additional simulations for which this
259 branch is, respectively, 2 and 3 m wider than the cave on both sides. Inside the
260 trench, the initial density of blown snow is forced to $\rho(x, z, t = 0) = 550 \text{ kg m}^{-3}$,
261 which corresponds to the density measured after backfilling at Dome C. Outside
262 the trench, the initial density is again the steady density field obtained at the
263 end of the initialisation. Note that the sensitivity of the lifetime expectancy of
264 the cave to its initial geometry has also been evaluated by running four similar
265 simulations as the ones presented here, but considering a perfect circle for the
266 initial shape of the cave (Supplement).

267 *2.2.3. Rigid container experiment*

268 In this experiment, we consider the opposite end-member in terms of rigidity
269 of the storage solution: a perfectly rigid container buried within the firn. The
270 chosen dimensions for the container width and height, i.e. $w_c = 2.44 \text{ m}$ and $h_c =$
271 2.9 m respectively, are based on the dimensions of the 20ft shipping containers
272 commonly operated in Antarctica by the French Polar Institute (Institut Paul-
273 Emile Victor, IPEV). The container floor is initially located at $z = -10 \text{ m}$. This
274 initial depth is motivated by the fact that below 10 m, the firn temperature is
275 constant, which is preferable for the long-term quality of the cores.

276 Imposing a perfect rigidity of the container is equivalent to impose a no
277 flux condition at the firn/container interface. However, because the container
278 is advected with the flowing firn, the velocity of firn at this interface is part
279 of the solution to the flow problem. In other words, the resistance opposed by
280 the container to the flow of firn translates into an implicit Dirichlet boundary
281 condition for the flow problem, defined on a moving boundary which corresponds
282 to the firn/container interface. As commonly done when dealing with flows
283 around moving rigid bodies (e.g. Glowinski et al., 1999), the vertical velocities
284 of all nodes belonging to the container roof (i.e. normal velocity to the roof)

285 are forced to be equal to each other through the use of Lagrangian multipliers.
286 In addition, we impose periodic boundary conditions for the firm normal and
287 tangential velocities between the container roof and floor, while the horizontal
288 velocity (i.e. normal velocity) is forced to zero on the two container sides.
289 There are no imposed conditions regarding the tangential velocity of firm on the
290 container sides, which means that a relative motion between the snow and the
291 container is allowed over these two interfaces. However, another possibility is
292 that the snow sticks to the container sides. In that case, the boundary condition
293 which needs to be applied to the container sides is a no slip condition. In between
294 these two end-members, it could also be assumed that there is some kind of
295 friction between the container sides and the snow flowing around. In that case
296 a friction law should be implemented as the boundary condition. Since such a
297 law is difficult to constrain, we have made the choice to run all the simulations
298 of this experiment with a free slip boundary condition on the container sides.
299 The sensitivity of the results to this choice turns out to be low, as discussed in
300 the Supplement.

301 As for the snow cave experiment, the initial mesh of the domain is made
302 of three-node triangular elements, and is characterized by a high refinement
303 around the container which decreases linearly as going further away. The con-
304 tainer being perfectly rigid, the container/firm interface undergoes a rigid body
305 displacement. Concretely, this is achieved by extracting the vertical flow velocity
306 of firm at the nodes belonging to the roof of the container. The vertical displace-
307 ment of all nodes belonging to the container/firm interface over one timestep is
308 given by the product between the vertical flow velocity computed at this par-
309 ticular node and the size of the timestep, while the horizontal displacement of
310 these nodes is forced to zero. As in the snow cave case, the whole mesh deforms
311 as the container sinks, and needs to be re-designed every 20 a of simulation
312 through the same procedure as the one described previously.

313 The rigid container experiment gathers a total of six simulations, corre-
314 sponding to a combination of three different initial densities and two different
315 container weights. Because the container is perfectly rigid, the total simulation

316 time is not limited by its deformation and is set to 200 a for all the simulations.
317 A reference simulation is run for which the initial density field is the steady
318 density field obtained at the end of the initialisation run. The second and the
319 third simulations include a trench of initial density $\rho(x, z, t = 0) = 550 \text{ kg m}^{-3}$,
320 which has the same width as the container for the former and which is two
321 meters larger than the container on both sides for the latter. These first three
322 simulations do not consider the weight of the container itself or of the payload
323 it contains. Therefore, we run three similar experiments which differ only by
324 the fact that the weight of the container and its payload is accounted for. To
325 this end, we consider a total weight of 26 tons, which corresponds to a container
326 tare weight of about 2 tons and a payload weight of about 24 tons. This total
327 weight is divided by the total length of the container, i.e. $l_c = 6 \text{ m}$, since only a
328 vertical section of the container is considered. Finally, the weight is applied as
329 a uniform pressure spread on the container floor.

330 **3. Results**

331 *3.1. Initialisation*

332 Figure 2 shows the evolution of the computed relative density and vertical
333 velocity profiles over the course of the initialisation run. Although the vertical
334 density profile used to initialize the model is derived from measurements, the
335 model is initially out of equilibrium. This is first the consequence of the poor
336 constrain prevailing on several model parameters, and most notably, on the pa-
337 rameters at stake in the two functions a and b used in the constitutive laws (5)
338 and (6). Second, the prescribed initial density profile is itself poorly constrained.
339 Indeed, the density measurements performed on cores drilled at Dome C show
340 very high variability over the first 20 to 30 meters below the firn surface. As a
341 consequence, the prescribed initial density profile is poorly representative over
342 this surface layer. Moreover, this profile is derived from measurements per-
343 formed on two 80-m-long ice cores and it turns out that, beyond this depth, it

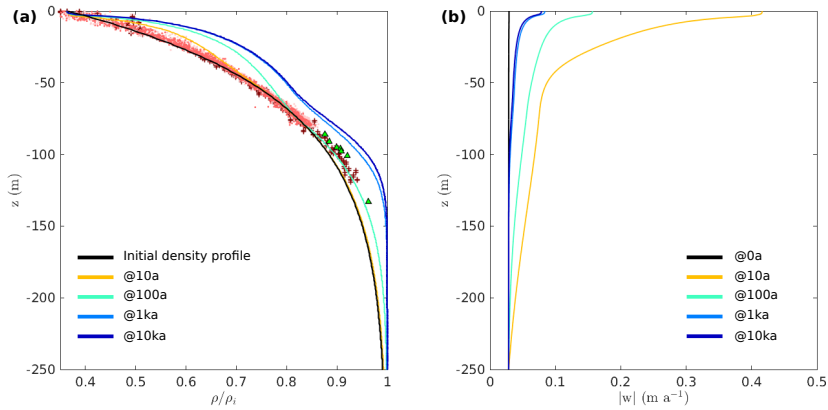


Figure 2: Evolution of (a) the vertical relative density profile and of (b) the vertical velocity profile over the course of the initialisation run. In (a), red crosses correspond to measurements of densities on the 1999 FireTrack firn core (Augustin et al., 2004), green triangles are density measurements on the 2010-2011 Volsol core (Burr et al., 2018), light and dark red points correspond to measurements carried out on the two 80-m-long 2012/2013 ice cores by Leduc-Leballeur et al. (2015) and used to derive the initial density profile (black).

344 underestimates densities compared to deeper measurements performed on other
 345 cores drilled at Dome C (Fig. 2a).

346 After 10 a of simulation, the vertical velocity profile shows an inflection point
 347 at a depth of about 50 m below the firn surface. Above this depth, vertical ve-
 348 locities increase rapidly towards the firn surface to reach about 41 cm a^{-1} at
 349 the surface. Below this depth, the vertical velocities are of a few cm a^{-1} only
 350 and decrease slowly as going deeper to reach the value imposed by boundary
 351 condition (15), i.e. 2.87 cm a^{-1} , at the bottom of the domain. This flow regime
 352 induces significant compressive stresses which ease the densification of the low
 353 density surface layers as they are advected downward. Thus, while the mod-
 354 elled densities are still very close to the initial profile at depth (as well as at
 355 the surface because of boundary condition (16)), in a depth range comprised
 356 between 5 m and 45 m below the firn surface they are getting slightly higher
 357 than measured densities. After 100 a of simulation, the vertical velocity has
 358 considerably decreased over the whole firn column, and particularly within the

359 top 50 m below the firn surface. The vertical velocity at the surface is of about
360 16 cm a^{-1} at 100 a. The firn density at a given depth keeps increasing. In par-
361 ticular, by that time, the modelled density of the deepest layers of the domain is
362 getting higher than that of the initial profile. Beyond 1000 a of simulation, the
363 modelled density at a given depth is systematically in the higher range or higher
364 than the measured ones. Between the penultimate and the last timestep of the
365 initialisation run, the density field has evolved by less than 0.001%, and we con-
366 sider that the density profile obtained at 10 ka corresponds to a steady state.
367 Given the high spatial variability of measured densities over the top 20 to 30
368 meters, the initial density profile is hardly more consistent with measurements
369 over this surface layer than this steady density profile. In addition, the first
370 computed surface vertical velocity is of about 41 cm a^{-1} , which is largely above
371 the observations. In contrast, as expected from the implemented boundary con-
372 dition (15), the computed vertical velocity at the surface for the steady state
373 corresponds to the observed mean annual surface accumulation, i.e. slightly less
374 than 8 cm a^{-1} (Parrenin et al., 2007).

375 *3.2. Snow cave experiment*

376 Figure 3 shows the evolution of the shape and the position relative to the
377 surface of the cave over the course of the experiment for each of the considered
378 initial density fields. Although not represented in Fig. 3, a few centimeter-high
379 bump tends to form at the firn surface in all cases, except for the reference run for
380 which a few centimeter-deep cavity appears from the first years of the simulation.
381 These surface deformations can be seen on the animation of the full simulations
382 included in the Supplement. The deformation of the cave is strongly sensitive to
383 the initial density in its immediate surrounding. First, the deformation patterns
384 of the roof are different when the trench is included than when it is not. Indeed,
385 for the reference simulation, the shape of the roof evolves progressively from
386 concave to convex, inducing a close-off of the cave that is much faster than for
387 the three other cases. In contrast, for all the considered cases, the lateral walls
388 and floor show similar deformation patterns with progressive curvature toward

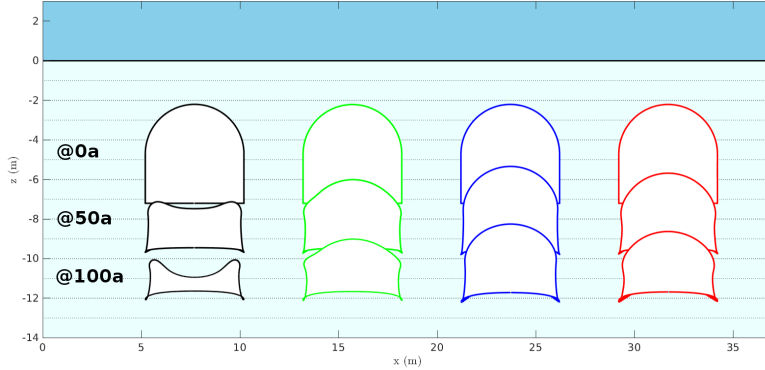


Figure 3: Shape and position of the cave at $t = 0$ a, $t = 50$ a and $t = 100$ a for the various prescribed initial density field: reference simulation (black), narrow trench case (green), large trench case (blue) and T-shape trench case (red). Note that the four considered cases have been positioned arbitrarily on the horizontal axis and that, for the sake of readability, the slight deformations of the firm surface occurring over time are not represented.

389 the interior of the cave. Furthermore, the magnitude of the deformation also
 390 depends on the initial density field: the wider the high density trench, the less
 391 readily the cave closes-off. These different magnitudes of deformation can be
 392 explained by the fact that a patch of high density snow surrounding the cave
 393 enables stress transfer around the cave to the underlying firn layers. Thus, apart
 394 from the reference simulation for which the cave rapidly becomes unusable, the
 395 close-off is slow, with a height reduction of the order of ~ 1 m after 50 a of
 396 simulation for the T-shape trench case and even slightly less for the large trench
 397 case.

398 The evolution over time of the position of the cave pseudo-center, which is
 399 defined as the middle of the segment joining the highest and lowest points of
 400 the cave belonging to its central axis, is represented in Fig. 4a. After 139 a of
 401 simulation for the reference run, the cave is too deformed and the pseudo-center
 402 of the cave is no longer defined. Note also that the fact that the rate of sinking
 403 seems much higher for the reference simulation than for the other runs is actually
 404 due to the strong asymmetrical deformation of the cave which tends to shift the

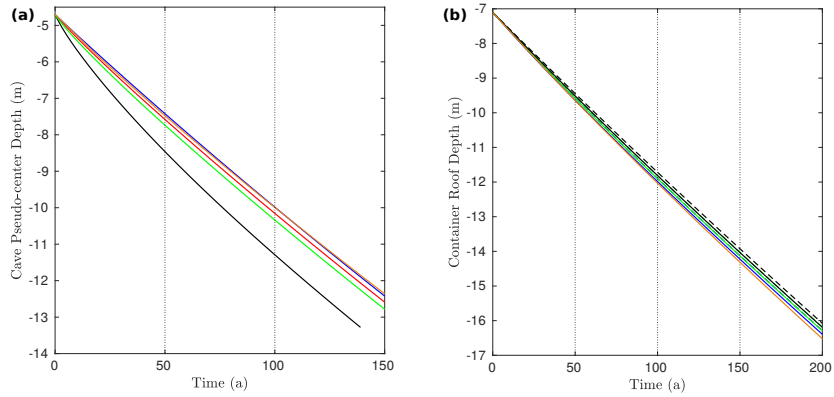


Figure 4: Evolution over time of the position of (a) the pseudo-center of the cave and (b) the roof of the container for the various considered cases: reference simulation (black), narrow trench case (green), large trench case (blue), and T-shape trench case (red) for (a) only. The position over time of a snow particle in the unperturbed initial steady density field is represented in orange (superimposed with or very close to blue line in both cases). In (b), results obtained without considering the weight of the container (dashed lines) and accounting for the weight of the container and its payload (continuous lines) are both represented.

405 pseudo-center of the cave downward. Similarly, although deformations are much
 406 smaller for all the other considered cases, the magnitude of the roof deformation
 407 is systematically a bit more important than that of the cave floor, which again
 408 tends to shift slightly the position of the cave pseudo-center downward. With
 409 this in mind, Fig. 4a shows that, unsurprisingly, the initial density field has little
 410 influence on the rate of sinking of the cave, which is of the order of $\sim 5 \text{ cm a}^{-1}$
 411 for all the considered cases. This rate of sinking is similar to the rate of sinking
 412 of a snow particle in the unperturbed initial steady density field (orange line in
 413 Fig. 4a which is almost superimposed on the blue line).

414 From results reported here, it appears that a perfectly rectangular trench
 415 larger than the cave is the best option to maximize the lifetime of the latter.
 416 However, for practical reasons related to the construction process, the T-shape
 417 is the most convenient shape for the trench as it enables to keep the balloon in
 418 place while snow is blown back on it. For this reason, two additional simulations

419 considering a T-shape trench with a horizontal branch, respectively, 2 and 3 m
420 wider than the cave on each sides have been run. It turns out that the wider the
421 horizontal branch of the T-shape, the longer the lifetime of the cave. However,
422 the gain in terms of lifetime between a branch that is 1 m larger than the balloon
423 diameter on each side and one that is 2 m larger is more important than the
424 gain obtained when the branch is 3 m larger instead of 2 m larger. In other
425 words, beyond a certain width of the horizontal branch of the T-shape, the gain
426 in terms of lifetime of the cave is not sufficient to justify the amount of work
427 required to make the branch larger. Our results suggest that a branch being
428 2 m larger than the balloon diameter on each side is a good compromise for a
429 balloon with a 5 m diameter.

430 *3.3. Rigid container experiment*

431 Figure 4b shows the evolution of the position of the roof of the container
432 over time for the six main simulations. As for the snow cave experiment, the
433 rate of sinking of the container is not very sensitive to the initial density field
434 in its surrounding. It also shows little sensitivity to weight consideration: for
435 each case of initial density, the version of the container for which the weight
436 is accounted for sinks hardly faster than the unloaded version. Overall, the
437 rate of sinking of the container is similar to that of the snow cave, i.e. of
438 the order of $\sim 5 \text{ cm a}^{-1}$. As the container sinks, the density of snow in its
439 immediate surrounding increases. Figure 5 shows the evolution over the course
440 of the simulation (one plot every 20 years) of the snow relative density along the
441 container roof for the six considered cases. The same figure for the container
442 floor is included in the Supplement (Fig. S1). The progressive densification of
443 snow observed on the container roof is obviously partly due to the fact that snow
444 is denser at higher depths, but also to the apparition of a patch of higher density
445 on the container roof as snow encounters the container while flowing downward.
446 Within this patch of higher density, firm velocities are slightly lower than at
447 the same depth further away from the container, in places where the density
448 field is not perturbed by the presence of the latter. This explains why, when

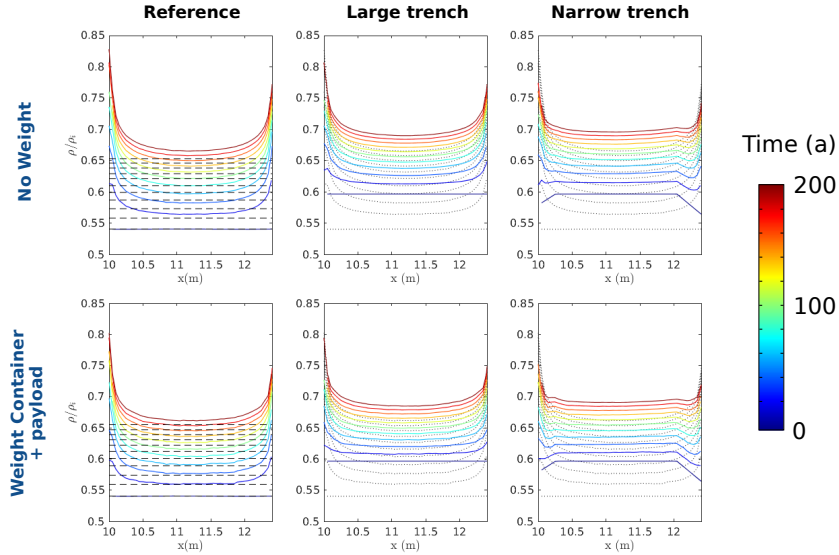


Figure 5: Evolution over time of the snow relative density along container roof for the six considered cases. For the two reference simulations (i.e. with and without weight), we report the value of the unperturbed initial relative density at the depth at which the container roof finds at the considered time of the simulation (black dashed lines). For the no weight (resp. with weight) large and narrow trenches simulations, we report the results obtained for the no weight (resp. with weight) reference simulation to ease comparison (black dotted lines).

449 compared to the sinking of a snow particle flowing in the unperturbed initial
 450 steady density field (orange line in Fig. 4b), the sinking of the container is
 451 systematically very slightly slower than the latter. This patch of higher density
 452 is not very sensitive to the weight of the container and is very similar for the
 453 narrow and large trench cases. In contrast, the reference simulation (for both
 454 the unloaded and loaded cases) shows lower snow density on the container roof
 455 over the whole simulation, which is not surprising since, by construction, it
 456 starts with a much lower density at the firn/container interface than when a
 457 high density trench is included. The patch of higher density also appears in
 458 the vicinity of the container floor (Fig. S1). At this location, the sensitivity to
 459 the initial density field around the container as well as to whether the weight
 460 is considered or not is stronger. The relative density along the container floor

461 in the case of the unloaded reference run does not depart very much from the
 462 unperturbed relative density. In contrast, when the weight of the container and
 463 its payload is accounted for and/or when the high density trench is included,
 464 the modelled relative density along the container floor turns out to be higher
 465 than the corresponding unperturbed relative density at the same depth. This
 466 is because the weight of the container and/or the weight of the dense snow of
 467 the trench above the container is transferred to the underlying snow layers (the
 468 container being perfectly rigid) and tends to compress them, enhancing their
 469 densification. A remarkable feature concerning every considered cases - although
 470 less marked on the container floor for the unloaded reference simulation - is the
 471 occurrence of very localised peaks of high relative density at each corner of the
 472 container roof and floor. At these places, the relative density is significantly
 473 higher than that at the middle of the container roof/floor.

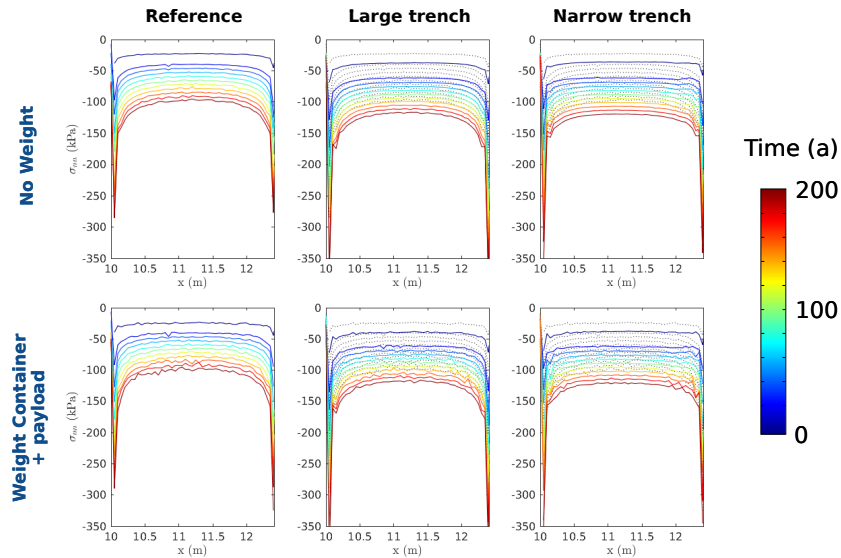


Figure 6: Evolution over time of the normal stresses along container roof for the six considered cases. For the no weight (resp. with weight) large and narrow trenches simulations, we report the results obtained for the no weight (resp. with weight) reference simulation to ease comparison (black dotted lines).

474 Figure 6 shows the evolution over time (one plot every 20 years) of the normal

475 stresses exerted by snow along the container roof for the six considered cases.
 476 The same figure for the container floor is included in the Supplement (Fig. S2).
 477 Note that all these stresses are negative because they are compressive stresses.
 478 The patterns of these normal stresses are correlated to the previously described
 479 patterns of relative density. In particular, the peaks of high density obtained
 480 at corners at both container floor and roof are correlated to strong stresses
 481 concentrations in these same areas. Further away from the corners, normal
 482 stresses are up to four times lower. Apart from the two reference simulations
 483 which systematically produce lower normal stresses, the order of magnitude of
 484 the normal stresses supported by the middle parts of the container roof/floor
 485 are mostly independent of the initial density around the container and whether
 486 or not the weight is considered. The stress concentrations at corners are more
 487 sensitive to these two parameters, but these values must be considered with
 488 caution since they are much more sensitive to the numerics, including mesh
 489 refinement and linear interpolation following remeshing steps. At the end of the
 490 simulation, the order of magnitude of the normal stresses experienced by the
 491 middle parts of the container roof/floor is of ~ 120 kPa, whereas it reaches up
 492 to ~ 450 kPa at floor corners where the stress concentrates, and slightly less,
 493 i.e. up to ~ 400 kPa, at roof corners.

In order to ~~quantify the gap between these normal stresses and evaluate~~
~~the importance of using a complex flow model to estimate the loads supported~~
~~by the container instead of simply assuming that these loads are limited to~~
 the hydrostatic pressure ~~prevailing at the considered depths, calculated at any~~
~~considered depth from available density profiles, we make a further analysis~~
~~which consists in quantifying the gap between these two quantities. Figure 7~~
~~shows~~ the temporal evolution (one plot every 20 years) of the ratio between
~~these two quantities is represented in Figure 7 modelled normal stresses and~~
~~hydrostatic pressure~~ for the six considered cases. The hydrostatic pressure is
 calculated as:

$$P_{static} = -\rho_{mean}gH, \quad (18)$$

494 where g is the gravity, H is the height of snow above the container roof at the
 495 considered time of the simulation, and ρ_{mean} is the mean density integrated ~~from~~
 496 ~~the firn surface to~~ along a vertical line centered on the container ($x = 11.22$ m)
 497 from the depth at which the container roof is located at the considered time to
 498 the firn surface using the undisturbed density field as obtained at the end of
 499 the initialisation run. ~~In particular, this undisturbed~~ This density field does not
 500 include any trench of high density ~~and does not~~ neither does it account for the
 501 gradual increase in density observed on the roof of the container, as this latter
 502 phenomenon could not be quantified without the use of a proper flow model. As
 503 a consequence, hydrostatic pressure calculated for the narrow and large trench
 504 cases are underestimated due to the initial 7.1 m high column of denser snow
 505 on the top of the roof which is not taken into account. The same figure for
 the container floor is included in the Supplement (Fig. S3). It turns out that

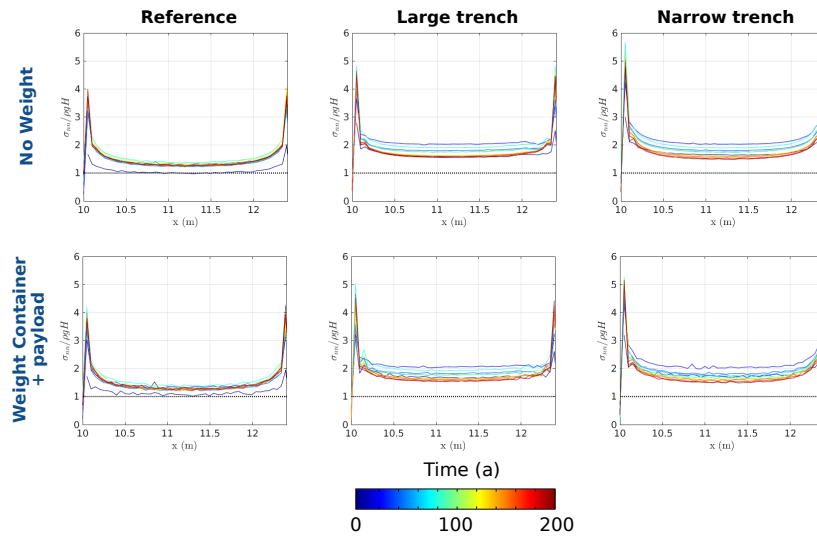


Figure 7: Evolution over time of the ratio between ~~calculated-modelled~~ normal stresses and hydrostatic pressure along container roof for the six considered cases.

506
 507 accounting for the particular rheology of firn ~~leads to much~~ and the effect of its
 508 flow around the container leads to significantly higher normal stresses on the
 509 container than assuming purely hydrostatic loads ~~and an~~ calculated from the

510 unperturbed density field. ~~This state of fact is likely due, for a large part, to~~
511 ~~the gradual densification of snow in the container vicinity. If the ratio between~~
512 ~~σ_{nn} and~~ Indeed, although the ratio between σ_{nn} and P_{static} stays of around 2
513 obtained over most of the container roof for all the cases which include a trench
514 of high initial density can partly be explained by the non-consideration of this
515 trench in the calculation of the hydrostatic loads, this explanation does not hold
516 for the stress concentration at corners and neither does it for the ratio of around
517 1.3 obtained over most of the container roof during the whole simulation for the
518 two reference simulations, it reaches values around 2 for all the cases including
519 . More than the gradual densification of snow at the container/firn interface
520 which remains localised in the close vicinity of the container, the gap between
521 modelled normal stresses and hydrostatic pressure, and in particular the stress
522 concentrations at corners, are attributable to dynamic stresses related to the flow
523 of firn around the container. In particular, the peaks of high density occurring at
524 corners reflect locally increased compressive stresses which induce higher snow
525 compaction. Further calculations made for the high density trench reference
526 simulation without weight show that $\sim 65\%$ of the difference between the total
527 normal stress on the middle of the roof and the hydrostatic load calculated
528 from the unperturbed density field results from dynamic stresses whereas the
529 remaining $\sim 35\%$ is due to the gradual densification of snow in the close vicinity
530 of the roof. For the two cases including a trench, dynamical stresses explain
531 only $\sim 30\%$ of this difference, the remaining $\sim 70\%$ being mostly due to the
532 presence of the trench of high initial density but also partly to the gradual
533 snow densification. It is interesting to note that significant deviation from
534 lithostatic pressure at the interface between two bodies with a viscosity ratio of
535 10 or more has also been reported in the context of geodynamic reconstruction
536 (Moulas et al., 2014; Luisier et al., 2019). Regarding the floor center part, the
537 ratio between σ_{nn} and P_{static} is slightly lower, with values around 1 when the
538 trench is not included and around 1.3 otherwise (Fig. S3), this latter value
539 being again partly due to the non-consideration of the high density trench in the
540 hydrostatic pressure calculation. In other words, the normal stresses along the

541 container floor are less affected by the flow than those along the container roof.
542 Note that this ratio does not evolve very much over the course of the simulation,
543 especially beyond the first 20 years. As stated above, values obtained at corners
544 must be handle with care as they are more sensitive to the numerics. Yet, results
545 presented here tend to show that normal stresses concentrated at roof and floor
546 corners are of the order of 4 to 6 times higher than corresponding hydrostatic
547 pressures in an unperturbed density field, emphasizing the imperative need for
548 a flow model in order to get realistic estimates of snow loads, which are a
549 prerequisite to the design of a reliable storage solution.

550 Figure 8 shows the evolution over time (one plot every 50 years) of normal
551 stresses exerted by snow along one container side for the six considered cases.
552 Note that the experimental setup being perfectly symmetric by construction, the
553 results obtained on the right and left sides of the container are almost identical
554 (slight differences occur over time, especially in the narrow trench case, because
555 of the remeshing procedure and induced linear interpolation but are negligible).
556 The normal stresses on container sides turns out to have very low sensitivity
557 to the consideration of weight. Indeed, if tiny differences obtained between the
558 loaded and unloaded versions for each of the three initial density cases exist,
559 they are mostly attributable to the small differences in the sinking rate, with the
560 loaded cases inducing slightly deeper containers than the unloaded cases at each
561 of the considered times. Another remarkable feature is the low, or even null,
562 normal stress localised on the top corners of the container sides. This is because
563 the snow tends to detach from the wall of the container in this area. However,
564 the contact between snow and the container wall is firmly restored just a few
565 centimetres lower. The maximal normal stress supported by the container wall
566 occurs just a few centimetres above the bottom corners of the container sides.
567 It is interesting to note that even for the reference simulation these maximal
568 stresses are lower than the ones supported by the container roof which confirms
569 that normal stresses depart from purely hydrostatic loads, in which case deeper
570 snow layers would necessarily induce higher pressure on the container.

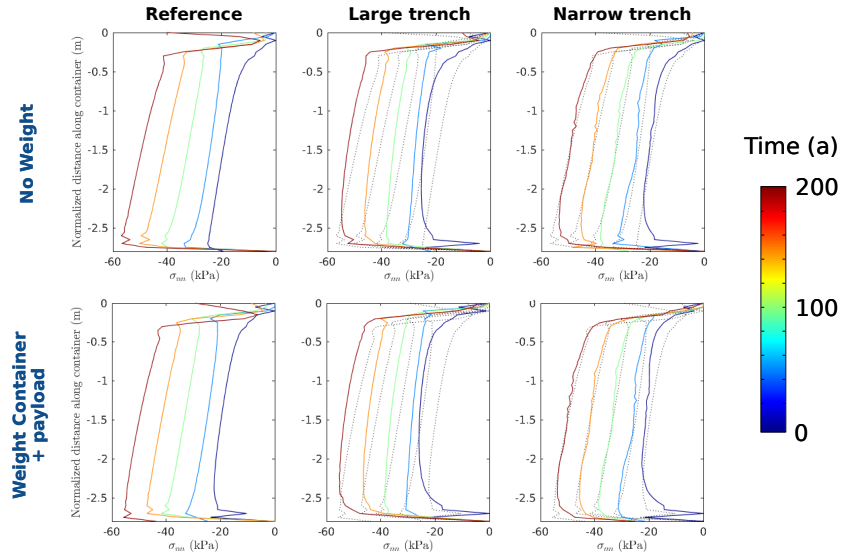


Figure 8: Evolution over time of the normal stresses along container side for the six considered cases. The vertical axis is the normalized distance along container side, with $z = 0$ m corresponding to the roof position and $z = -2.9$ m corresponding to the floor position. For the no weight (resp. with weight) large and narrow trenches simulations, we report the results obtained for the no weight (resp. with weight) reference simulation to ease comparison (black dotted lines).

571 4. Discussion

572 Among the few polar subsurface constructions reported in available literature,
 573 the Old South Pole Station is probably the one for which surrounding conditions
 574 are the closest to those prevailing at Dome C (very low accumulation, very cold
 575 snow, almost purely vertical firn motion, ...). The Old South Pole Station
 576 was built during the 1956-57 austral summer and, despite relatively low annual
 577 accumulation ($\sim 20 \text{ cm a}^{-1}$, mostly due to wind transport), the roofs were
 578 entirely buried by ~ 180 cm of snow by 1960 due to snow drift (Mellor, 1968).
 579 However, the station kept being operated until the 1970s. In 1997, i.e. 40 years
 580 after its construction, pictures were taken inside the station (Barna et al., 2015).
 581 These pictures show some localised distresses of the structure, such as the
 582 failure of some timbers in a corridor and the crushing of a corrugated steel arch

583 (which must have been enhanced by asymmetrical loads related to drifted snow
584 accumulation in the main wind direction as the construction was initially raised
585 on the surface). However, these failures seem quite limited when compared
586 to a similar photo report performed at Camp Century (northwest corner of
587 the Greenland Ice Sheet) in 1969, only ten years after the construction of the
588 station (Kovacs, 1970). This tends to support that (1) locations with very low
589 accumulation rates and almost purely vertical flow, such as Dome C, are ideal
590 for undertaking of long-term subsurface constructions and (2) it is preferable to
591 have the storage facility buried below the surface from the beginning to avoid
592 problems related to snow drift, such as fast accumulation and asymmetrical
593 loads.

594 Although the initial position of the snow cave, which has been fixed to match
595 the conditions of the current field test on-going at Dome C, is a few meters
596 shallower than that of the container, it turns out that both solutions show similar
597 sinking rates, of the order of $\sim 5 \text{ cm a}^{-1}$, independently of the initial density in
598 their immediate vicinity. Such slow sinking rates are valuable from a logistical
599 point of view as they imply that the cores should remain easily accessible in the
600 future: accessing the storage facility after several decades should not require
601 much more work than that needed for its initial implementation. However,
602 one must keep in mind that this result relies strongly on the assumption that
603 the annual surface mass balance will not evolve significantly over the targeted
604 lifespan of the storage facility.

605 Provided that a sufficiently large trench of high initial density is ~~dig~~ excavated
606 to welcome the balloon during the construction process, the rate of closure of a
607 snow cave is relatively slow. Without in situ measurements, it is difficult to say
608 whether such slow closure rates are ~~related to the uncommon~~ fully attributable
609 to the favorable conditions prevailing at Dome C (~~very low accumulation, very~~
610 ~~cold snow, ...~~), or if they are reflecting model biases, such as an overestimated
611 initial density profile leading to underestimated flow velocities. First measure-
612 ments of the test cave currently monitored at Dome C should be available soon
613 and will shed light on this issue. In any case, despite these slow deformation

614 rates, the cave should not be considered as perennial for timescales beyond
615 ~ 100 a. As a consequence, if the snow cave is the adopted solution for the
616 Ice Memory project and if targeted lifetime goes beyond the century, a strategy
617 regarding the long-term maintenance of the storage solution should be planned.
618 The choice of the time interval at which maintenance of the cave should be
619 performed is a trade-off between the amount of work required to reach the cave
620 (which increases as the height of snow above the cave increases), and the cost
621 and logistic required to perform this work, which tends to prohibit a too short
622 return time.

623 At the other end of the rigidity spectrum, we have considered the case of a
624 perfectly rigid container. In fact, traditional shipping containers such as those
625 used for logistics in Antarctica are designed in such a way that it is possible to
626 stack up several of them on top of each other, the loads being fully supported
627 by the four corner posts. The floor is composed of a reinforced base structure
628 usually made of two bottom side rails and a number of crossmembers which
629 are welded together as a sub-assembly on which plywood boards are longitudi-
630 nally laid and fixed to support and transfer the load of the freight. In contrast,
631 the roof and sides are usually constituted of several die-stamp corrugated steel
632 sheets that are butt jointed together to form large panels by automatic welding.
633 In the traditional use of freight containers, these steel panels are not supposed
634 to bear any significant load and their thicknesses are usually of a few millimetres
635 only. As a consequence, given its overall dimensions, an unreinforced shipping
636 container is obviously not able to bear the normal stresses that have been high-
637 lighted in the present study.

638 An option is then to strengthen the shipping containers operated at Dome C
639 through ad hoc structures, which could either be set up inside the containers
640 or mounted outside. Such structures must be designed in order to tackle both
641 the mechanical and functional issues, i.e. to take over the snow loads while
642 preserving sufficient space for core storage. This state of fact underlines the
643 importance of the present study: a good knowledge of the magnitude, spatial
644 repartition and temporal evolution of the normal stresses supported by the

645 container is a prerequisite for the design of an optimal reinforcement structure.

646 5. Conclusion

647 One of the major challenges raised in the frame of the Ice Memory project is
648 the design of a permanent storage facility, which would ensure safe subsurface
649 storage over coming decades to centuries at affordable cost. To tackle this
650 challenge, we have used a numerical model describing the viscous flow of firn to
651 assess the temporal evolution of the two opposite end-member cases in terms
652 of rigidity of the structure, i.e. an unreinforced snow cave and a perfectly rigid
653 container. The use of such a model proved necessary not only to assess the cave
654 deformation over time but also to get realistic estimates of the loads supported
655 by the container.

656 The particular conditions prevailing at Dome C leads to slow rate of sinking
657 of the storage facility and tend to increase its lifetime expectancy in comparison
658 to what has been reported in available literature regarding subsurface construc-
659 tions tried in the past. In particular, provided that the trench of high initial
660 density surrounding the inflatable balloon involved in its construction process
661 is sufficiently large, the closure rate of a snow cave ~~dug~~-burrowed into the firn
662 turns out to be relatively slow. Yet, if targeted lifespan of the storage solution
663 exceeds the century, the use of rigid structure buried within the firn will have
664 to be considered.

665 As the annual mass balance at Dome C is expected to remain positive in the
666 long term, such a construction will be submitted to ever-increasing snow loads.
667 For a structure buried at an initial depth of 10 m, these loads are significant
668 from the beginning of the simulations. In particular, strong stress concentrations
669 occur at the container angles. Because their roof and sides are not designed to
670 provide any significant mechanical resistance, traditional shipping containers
671 such as those operated in Antarctica are not suited for this purpose, unless
672 specifically reinforced. A possibility is then to take advantage of the results
673 presented here in order to design optimal ad hoc reinforcement structures.

674 **Code and data availability**

675 Elmer/Ice code is publicly available through GitHub (<https://github.com/ElmerCSC/elmerfem>).
676 All the simulations were performed with the version 8.4 (Rev: 6b6e592f) of
677 Elmer/Ice. All scripts used for simulations and post-treatment as well as model
678 output are available upon request from authors.

679 **Author contribution**

680 Olivier Gagliardini and Julien Brondex designed the study. Julien Brondex
681 conducted the simulations with support of all co-authors. Julien Brondex wrote
682 the paper with contributions of all co-authors.

683 **Declaration of Competing Interest**

684 All authors declare that they do not have any conflict of interest

685 **Acknowledgements**

686 This work was funded by Fondation Université Grenoble Alpes. This study
687 was performed as a part of the Ice Memory project, which is led by the french In-
688 stitut Paul-Emile Victor (IPEV) and the italian Agenzia Nazionale per le Nuove
689 Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA). All the com-
690 putations presented in this paper were performed using the GRICAD infrastruc-
691 ture (<https://gricad.univ-grenoble-alpes.fr>), which is supported by Grenoble re-
692 search communities. We thank ENEA-UTA for the coordination of the snow
693 cave experiment at Concordia Station, and Rocco Ascione, Rémi Foletto and
694 Philippe Possenti for the snow drilling and density measurements conducted
695 on the roof of the first artificial snow cave. The snow cave excavation and
696 monitoring have been performed using the Concordia Station system and was
697 supported by IPEV and PNRA. We warmly thank Jérôme Chappellaz and Gre-
698 gory Teste for multiple fruitful discussions.

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1 Supplement 1: Additional figures

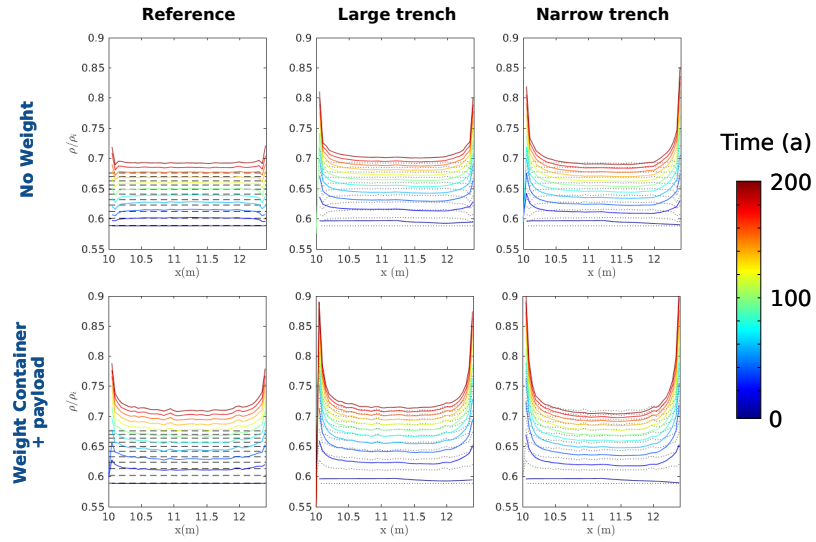


Figure S1: Evolution over time of the snow relative density along container floor for the six considered cases. For the two reference simulations (i.e. with and without weight), we report the value of the unperturbed initial relative density at the depth at which the container roof finds at the considered time of the simulation (black dashed lines). For the no weight (resp. with weight) large and narrow trenches simulations, we report the results obtained for the no weight (resp. with weight) reference simulation to ease comparison (black dotted lines).

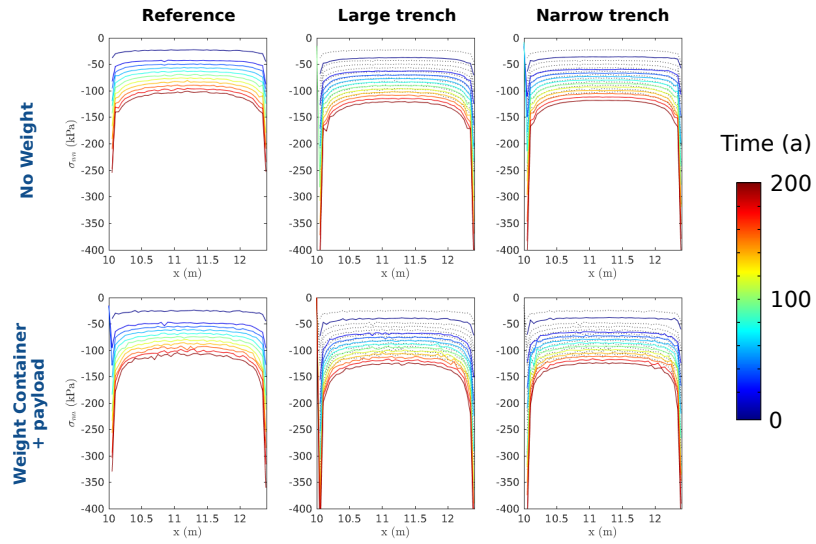


Figure S2: Evolution over time of the normal stresses along container floor for the six considered cases. For the no weight (resp. with weight) large and narrow trenches simulations, we report the results obtained for the no weight (resp. with weight) reference simulation to ease comparison (black dotted lines).

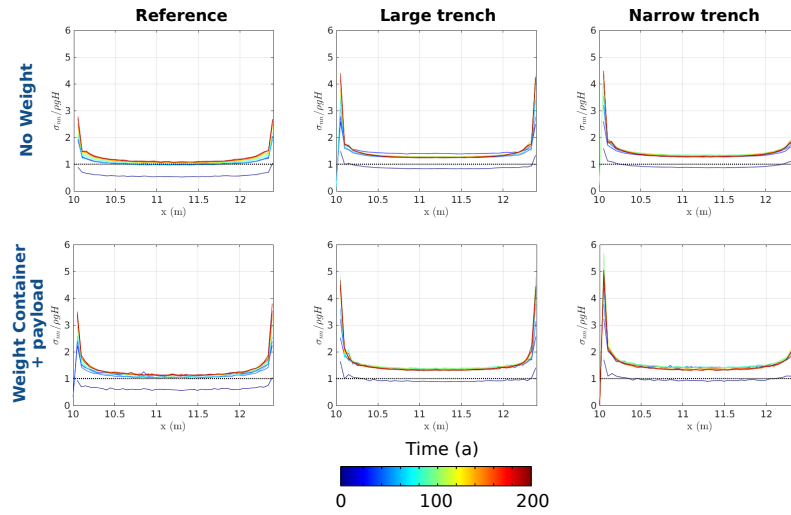


Figure S3: Evolution over time of the ratio between calculated normal stresses and hydrostatic pressure along container floor for the six considered cases.

2 Supplement 2: Sensitivity to the domain width

3 Here, we assess the sensitivity of the results to the total width of the domain.
4 In results presented in the main paper, the total width of the domain is of
5 22.44 m, which corresponds to a domain that is 10 m wider than the obstacle
6 (i.e. the container or the cave) on both sides. Given the experimental set up,
7 for which none of the model parameters have any dependency on the horizontal
8 coordinate x , the flow of firm should not be perturbed by the presence of the
9 obstacle beyond a certain distance to the latter. The question is whether 10 m
10 is a sufficient distance so that the flow regime at the right and left boundaries
11 of the domain is not affected by the presence of the obstacle. Otherwise, it can
12 be expected that the results obtained in the immediate vicinity of the obstacle
13 will be affected by the total width of the domain. This sensitivity analysis
14 was performed for the container case only. Indeed, the container being a rigid
15 obstacle that the firm has to bypass in its flow, we expect that the latter will
16 be perturbed over a larger distance than in the case of the cave, which is a free
17 surface. In other words, should the modelled domain be sufficiently wide for the
18 case of the container, it will also be for the case of the cave.

19 To confirm that a horizontal dimension of 22.44 m is sufficient, we run an
20 additional simulation, which corresponds to the reference simulation of the con-
21 tainer case without weight as presented in Section 2.2.3, except that the domain
22 total width is extended to be comprised between $x_l = 0$ m and $x_r = 102.44$ m.
23 The container is then placed in the middle of the domain, i.e. between $x = 50$ m
24 and $x = 52.44$ m, so that the domain is 50 m wider than the container on both
25 sides. Figure S4 shows a comparison of the normal stresses obtained along the
26 container roof, the container floor and the container sides for the two considered
27 domain width. As shown by this figure, results turn out to be almost insensi-
28 tive to the domain width. This means that a total width of 22.44 m is sufficient
29 so that the flow regime at the left and right boundaries of the domain is not
30 affected by the presence of the container, and it is then useless to make the
31 domain wider. Indeed, the computation time is close to 3 times larger for the

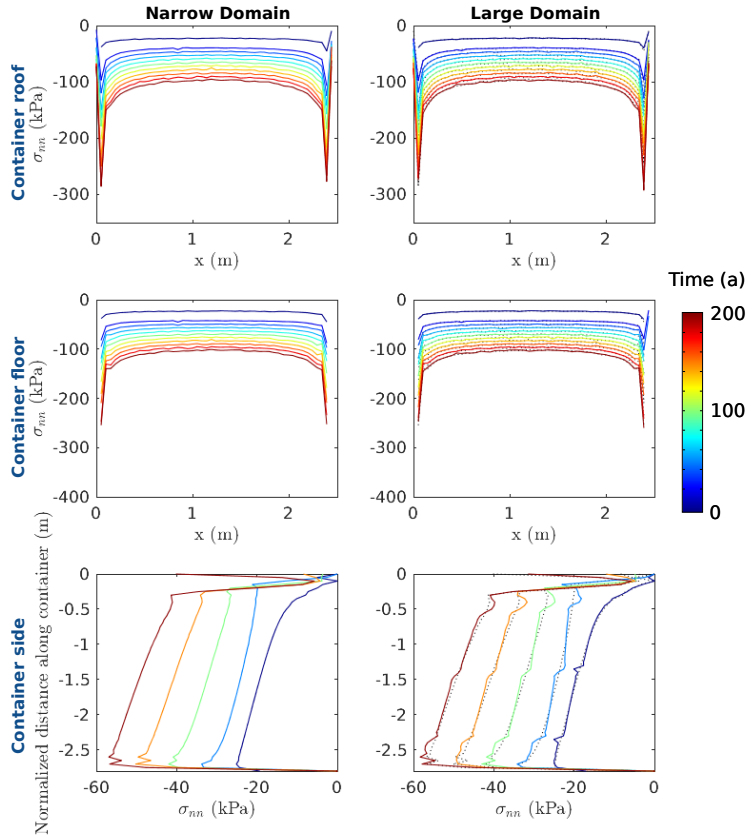


Figure S4: Normal stresses along the container roof (top row), the container floor (middle row) and the container sides (bottom row) for the reference simulation without weight for the narrow domain (left column) and the large domain (right column).

32 simulation with the 102.44 m-wide domain than the corresponding one with the
 33 22.44 m-wide one.

34 Supplement 3: Sensitivity to the initial shape of the cave

35 Here, we want to assess the sensitivity of the results obtained regarding the
 36 snow cave to its initial shape. To this end, we performed similar simulations
 37 as the ones presented in section 2.2.2, the only difference being that the initial
 38 shape of the cave is a perfect circle. Figure S5 shows the evolution of the

39 shape and the position relative to the surface of the cave over the course of the
 simulation for each of the considered initial density fields.

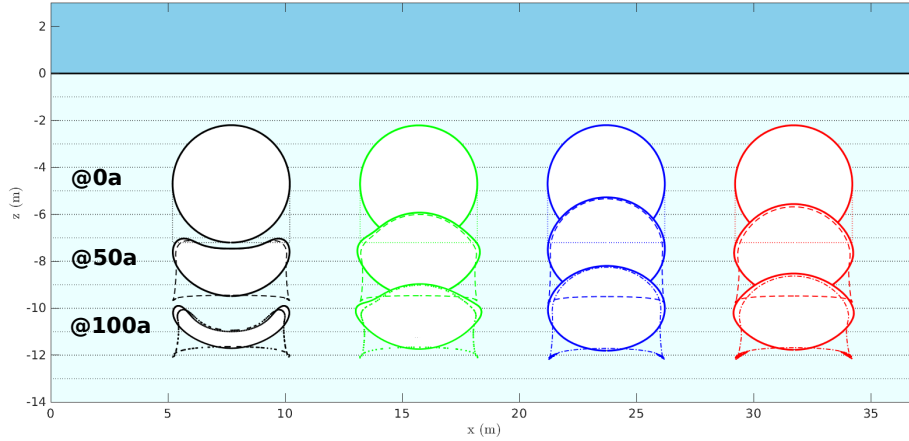


Figure S5: Shape and position of an initially perfectly circular cave at $t = 0$ a, $t = 50$ a and $t = 100$ a for the various prescribed initial density field: reference simulation (black), narrow trench case (green), large trench case (blue) and T-shape trench case (red). The results regarding the half circle/square combination cave presented in the main paper are also reported for ease of comparison. Note that the four considered cases have been positioned arbitrarily on the horizontal axis and that, for the sake of readability, the slight deformations of the firn surface occurring over time are not represented.

40

41 For the two cases for which the trench is larger than the balloon, the cave
 42 is sort of pinched and similar pattern of deformations occur on the roof and
 43 on the floor of the cave, so that the points corresponding to the right and
 44 left extremities of the firn/cave interface almost define a horizontal symmetry
 45 axis. In contrast, the initial horizontal symmetry of the cave rapidly vanishes
 46 for the case of the narrow trench and even more so for the reference run. For
 47 each one of the four considered cases, the deformation of the upper half of the
 48 circle is very similar to the deformation of the roof of the cave when the latter
 49 is the combination of a square and half circle over the first 40 to 50 years of
 50 simulation. In the same time, the lower half of the circular cave deforms much

51 slower than that of the half circle/square combination cave, for which the sides
52 of the square tend to curve inward. These differences in the deformations of
53 the lower halves of the two shapes end up affecting the upper halves, and after
54 the first 40 to 50 years of simulation the differences in terms of deformation
55 between the upper half of the circular cave and the upper half of the circle/square
56 combination cave become perceptible, with the upper half of the circle/square
57 combination cave shrinking faster than that of the circular cave. At the end
58 of the simulation, although the initial volume of the cave was higher for the
59 circle/square combination than for the circular cave, the relative volume loss of
60 the former is higher than that of the latter.

61 Despite the slight differences in terms of deformation patterns described
62 above, the initial shape of the cave turns out to have minor influence on the
63 lifetime expectancy of the cave, at least for the two tested shapes. In particular,
64 this initial shape is much less critical than the initial shape of the trench in which
65 the balloon is placed during the construction phase. Therefore, we suggest to
66 opt for the circle/square combination as the initial shape of the cave, which is
67 obviously more convenient for storage due to its flat floor, and to concentrate
68 the efforts on having a large trench of high initial density surrounding it. Ideally
69 this trench should have a rectangular shape or, if not possible, a T-shape with
70 a sufficiently large top branch.

71 **Supplement 4: Sensitivity to the firm/container boundary condition**

72 Here, we assess the sensitivity of the results obtained for the rigid container
73 case to the implemented boundary condition at the firm/container interface.
74 As stated in Section 2.2.3, all simulations regarding the rigid container case
75 presented in the main text rely on a free slip condition at the firm/container
76 interface. However, it is also possible that, instead of flowing freely around the
77 container, the snow sticks to its walls. In terms of modelling, this latter case
78 corresponds to a no slip boundary condition. Therefore, we run an additional
79 simulation, which corresponds to the reference simulation without weight as

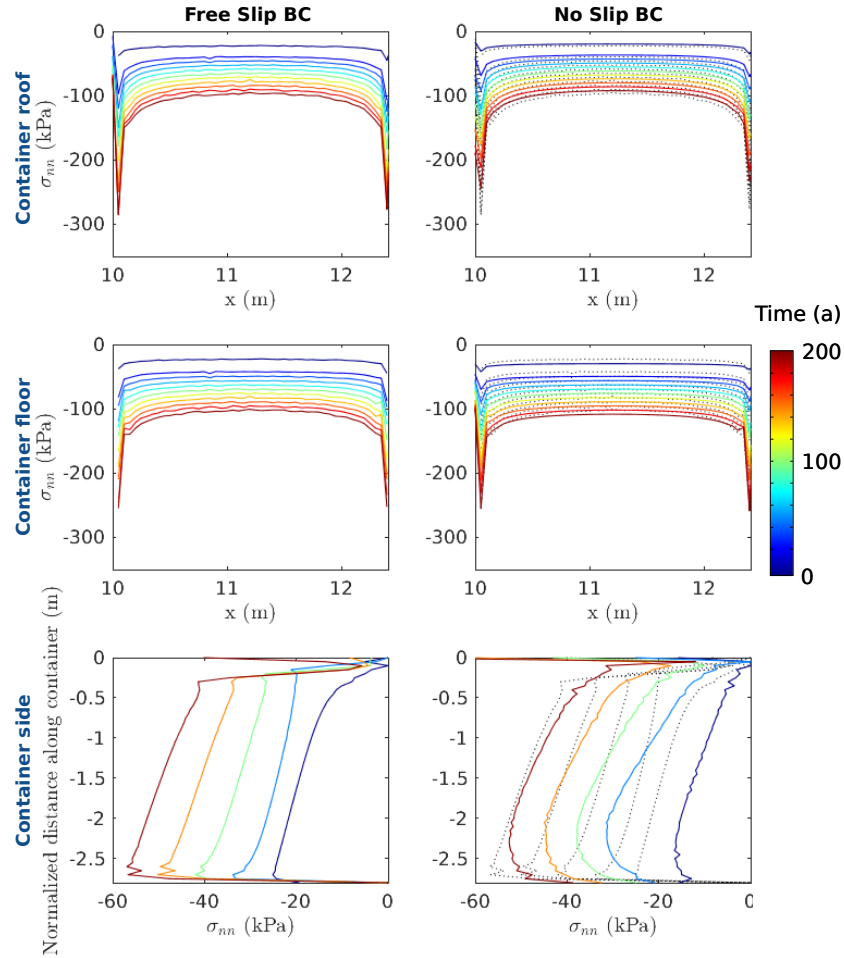


Figure S6: Normal stresses along the container roof (top row), the container floor (middle row) and the container sides (bottom row) for the reference simulation without weight with a free slip (left column) and a no slip (right column) boundary condition at the firn/container interface.

80 presented in Section 2.2.3, but with a no slip condition instead of the free slip
 81 condition at the firn/container interface. Figure S6 shows a comparison of the
 82 normal stresses obtained along the container roof, the container floor and the
 83 container sides for the two considered boundary conditions.

84 The sensitivity of these stresses to the implemented boundary condition at

85 the firm/container interface turns out to be low, with only 4% (resp. 5%) of
86 difference for the normal stress on the middle part of the container roof (resp.
87 container floor) at the end of the simulation. This difference is slightly higher
88 on the container sides, with a difference of 7% on the maximum normal stress
89 exerted on the lower part of the container sides at the end of the simulation. In
90 addition, the use of a free slip boundary condition at the firm/container interface
91 put us on the safe side since it produces the highest normal stresses, which
92 are the ones that need to be considered when dimensioning a reinforcement
93 structure.