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Striped icebergs. Preliminary discussion on the
respective roles and positionings of sea ice, marine
ice, glacier ice and ice shelf

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Summary

We offer a few comments on the formation of striped icebergs. We discuss the different types of ice as distinguished by the authors: glacier ice, ice shelf, marine ice, sea ice. We rely on the hypothesis exposed in Guy (<hal-03559083>, 2022): the planar and columnar structures characterizing such icebergs result from the fingered solidification of sea water under the iceshelf ice (instability of the planar freezing front due to constitutional supercooling). We propose to separate marine ice into two types: - *type 1 - marine ice*, restricted to ice formation by nucleation within the water beneath the ice shelf; - *type 2 - marine ice*, for the fingered ice formed at the ice-water front below the ice shelf. The complete succession of zones may thus comprise, from top to bottom: glacier ice / type 2 - marine ice / type 1 - marine ice / seawater. Some results from the article by Warren et al. (JGR Oceans, 124, 2019) are discussed.

Keywords: icebergs; ice; sea ice; glacier ice; ice shelf; seawater; freezing; constitutional supercooling; columns; parallel planes; NaCl; solidification; self-organization; basalt columns

Introduction

The present text supplements the HAL notice submitted two years ago (Guy, 2022), which contained preliminary proposals on the formation of striped icebergs. In this addition, we have endeavored to distinguish between the different types of ice discussed by the authors, which we had not done. The whole is of a "preliminary" nature, outside any rigorous quantitative approach.

1. Reminder of Guy (2022)

During an exhibition on Antarctica, our attention was drawn to some spectacular structures visible in certain icebergs (views of such structures in icebergs of various origins can be found on the Internet). These consist of sets of vertical ice columns, or parallel planes (also vertical), forming colonnades. The latter are separated by horizontal surfaces from the rest of the iceberg above (the tilting of which modifies these directions); the diameters of the columns and the thicknesses of the planes appear decimetric to multi-decimetric.

The structures are inscribed in the mass of ice, with marine erosion and melting highlighting them (under overhangs of the massive iceberg). To the best of our knowledge, there does not seem to be any reasoned description or proposed explanation. We are content here to sketch out a potential interpretative framework. We do not go into detail about the reasons that guide us; they are inspired by our knowledge of the solidification of geological magmas giving comparable structures: columns and planes (Guy & Lecoze, 1990; Guy, 2010; Guy *et al.*, 2020). We thus imagine that, when it enters the sea, a piece of glacier (or, on a larger scale, an ice shelf such as those surrounding the Antarctic continent), constituting a significant reservoir of coldness, can, under certain conditions, cause the sea to freeze on contact with it in its submerged parts (new ice is thus formed; we will call this ice: *type 2 - marine ice*, see section 2). As the sea is rich in NaCl, the solidification (freezing) point of the water depends on the salt content in the vicinity of the ice/seawater contact. Depending on the temperature gradients involved, the phenomenon of *supercooling* may come into play, and the ice/water interface show instability; this is responsible for the *formation of digitations*, i.e. fingers, or parallel planes of ice, protruding into the water during freezing. Materials scientists discuss the three-dimensional temperature gradients that enable a bifurcation between the columnar and planar

regimes. As a result of their growth, the fingers/planes will weld together, leaving joints between them that correspond to more fragile zones, highlighted by later erosion / melting processes, when the iceberg rises or tilts. If water ice cannot contain salt, it can neither contain a whole range of chemical elements, including gases, which will be "expelled" to the outside. Could this explain the gaseous releases observed along the joints by some people (Raphaël Sané, pers. com., 2022) and sometimes considered to be responsible for the structures (when in fact they are a consequence of them)?

Preliminary semi-quantitative estimates (...) involving the main parameters of the problem (temperatures, enthalpy of fusion, heat capacities, thermal and molecular diffusivities, thermal gradients, slope of the liquidus in the phase diagram, involvement of solutal convection) are encouraging.

2. The different types of ice

We extend the previous lines after reading an article on "green icebergs" (Warren *et al.*, 2019)¹.

Vocabulary, nucleation process and competition between two "marine ices".

We need to link up with existing words, which the previous article mentions: glacier ice, marine ice, sea ice, ice shelf, iceberg. What we proposed in section 1 is *marine ice*, but we are now saying that we need to make a distinction between two type of marine ice: *type 1 - marine ice* and *type 2 - marine ice*.

Type 2 - marine ice is the plane- or column-structured *marine ice*; it is similar to metallurgists' cells or to rock columns and planes we discussed in the texts quoted in section 1 (arising from the solidification of geological magmas). *Type 2 – marine ice* forms directly from the ice shelf (or possibly iceberg) ice in its lower part (see Figures 1 and 2). There is no need to nucleate new ice; new ice grows from old ice (glacier ice); if thermal gradients allow, this ice can be structured into planes or columns (cf. supercooling).

*Type 1 - marine ice*² forms in mid-water ahead of the formation front of *type 2 marine ice* (or simply ahead of the base of the ice shelf or iceberg if *type 2 marine ice* does not form, see

¹ When we refer to the "authors" below, they are first those of this article.

² We have kept number 1 for what is already described in the literature, and encompasses types 1 and 2 in this article. We now restrict the designation 1 s.s. (*type 1 - marine ice sensu stricto*) to that which is not structured in

figures). A nucleation threshold corresponding to a certain degree of supercooling must be exceeded (this is known as homogeneous nucleation). This ice will rise and stick to the ice of the ice shelf (whether primary glacier ice or type 2 - marine ice).

When the two marine ice types (type 1, type 2) develop simultaneously, we have two different layers (see Fig. 2). This raises the question of contact between the two types of marine ice. It is likely that type 2 - marine ice pushes back type 1 - marine ice and that there is no "mixing", resulting in an overall clear contact at the macroscopic level. There may be cases where the contact is more irregular, but this remains to be seen (depending on possible observations).

Sea ice is similar to type 1 - marine ice in its formation (homogeneous nucleation in the water), but it would take more observation and reflection to understand the differences with type 1 - marine ice: according to the authors, sea ice retains more salt and gas. If we compare it to type 2 - marine ice, we can understand why there is less salt and bubbles in type 2 - marine ice than in sea ice (efficient expulsion of everything that does not fit into the ice network, during cell growth). As the authors did not distinguish between the two types of marine ice (they would not always have done so anyway, given the observation conditions), it is possible that, when they say that the solid phase is less rich in salt in marine ice than in sea ice, they mean type 2 - marine ice.

Note that the previous figures, showing the succession:

- Exterior solid or cold wall (in this case glacier ice) / Solid consisting of ice structured into cells (in the sense of metallurgists), i.e. type 2 - marine ice / Solid consisting of type 1 - marine ice ("equiaxed" in the sense of metallurgists) / Liquid (sea water)

is strictly what is observed in metallurgical ingots (before complete solidification, the liquid eventually disappearing inside the equiaxed zone). The equiaxed zone (or type 1 - marine ice) corresponds to the *entablature* of volcanic flows; the colonnade corresponds to type 2 - marine ice. What is new here is that the system is not completely symmetrical. In the case of metallurgical ingots, as in the case of volcanic flows, solidification takes place from two "cold" surfaces: the edges of the ingot on both sides, the outside of the magmatic flow (cold air) and its base (cold ground); in both cases, zones are repeated, giving:

wall / cell zone / equiaxed zone / cell zone / wall

columns nor planes (for which the designation is 2); but depending on the conditions of observation, the authors cannot distinguish between the two types of marine ice.

for ingots

or

compact zone (+/- scoria) / (upper) colonnade / entablature / (lower) colonnade / compact zone (+/- scoria)

with frozen zones at the top and bottom (outer surfaces) in the case of volcanic flows. Depending on the overall size of the ingot or the magma flow, the succession may be not complete. In the case of ice, if there were also cooling from below and not just from above, we could have (purely "theoretical") :

glacier ice / type 2 - marine ice / type 1 - marine ice / then back to type 2 - marine ice / glacier ice

3. Other observations reported by the authors

When the authors talk about *marine ice* (they obviously do not specify whether it is type 1 or 2), we think it could be type 1 - marine ice, or type 2 - marine ice, or both. It depends on the case and/or the observation conditions.

Indeed, if the observation is made by drilling into the ice shelf down to its base (or by geophysics), the structures of the possible type 2 - marine ice cannot be easily seen. We "simply" see ice that is different from the glacier ice of the mass. When we see the green color³, it is more likely to be type 1 - marine ice.

Type 2 - marine ice has indeed been seen, as the article just quoted devotes a paragraph to it: "striped icebergs". But the authors cannot hide their embarrassment at the explanation of its formation, writing "*probably result from tension...*". This story of basal crevasses filling with seawater that immediately freezes seems highly improbable to us; how can we account for the regularity of alternating glacier ice and type 1 -marine ice? As far as we are concerned, striped icebergs typically show type 2 - marine ice, structured in the course of its development.

We also wonder why the isotopic profiles ($\delta^{18}\text{O}$ ratio across a strip of marine ice from a striped iceberg), seem incomplete, without documenting all the ice zones that contain them (i.e. also including strips of primitive glacier ice whose supposed crevasses would be filled with marine

³ According to the authors of the article cited, the green color is caused by a combination of effects due to the interaction of light with ice (giving a blue color) and effects due to the incorporation by the ice of fine organic or mineral particles (iron oxides in particular). In the case of type 2 -marine ice, all kinds of impurities are expelled from the growing ice cell.

ice). Put another way, we cannot see how the analyzed strip relates to any adjacent strips (which should be glacier ice according to the model?). On the contrary, in our view, the isotopic profile, showing an increase in the ratio $\delta^{18}\text{O}$ inside the band of marine ice compared with its edges, can be explained by a distillation phenomenon; this is well known in other contexts: the ice that forms preferentially incorporates ^{18}O , and the remaining water, which will then freeze, is depressed in heavy isotope at the edges of the advancing digitation. It would have been interesting to carry out the isotopic profiles overlapping several strips including the supposed glacier ice strips.

Conclusion

For the moment, we are not looking at the various papers on the subject that should be consulted. The preceding lines are simply a progress report. We are therefore maintaining our initial proposal (the strips in striped icebergs are due to fingering during water freezing at their base because of constitutional supercooling), while adjusting it to associate it with other facts of which we were unaware (type 1- marine ice). We will see in the future whether this framework should be kept as it is, amended, or abandoned. It invites us to make new observations, to take measurements of various kinds (chemical, petrofabric), to read about related subjects, and to debate with experts.

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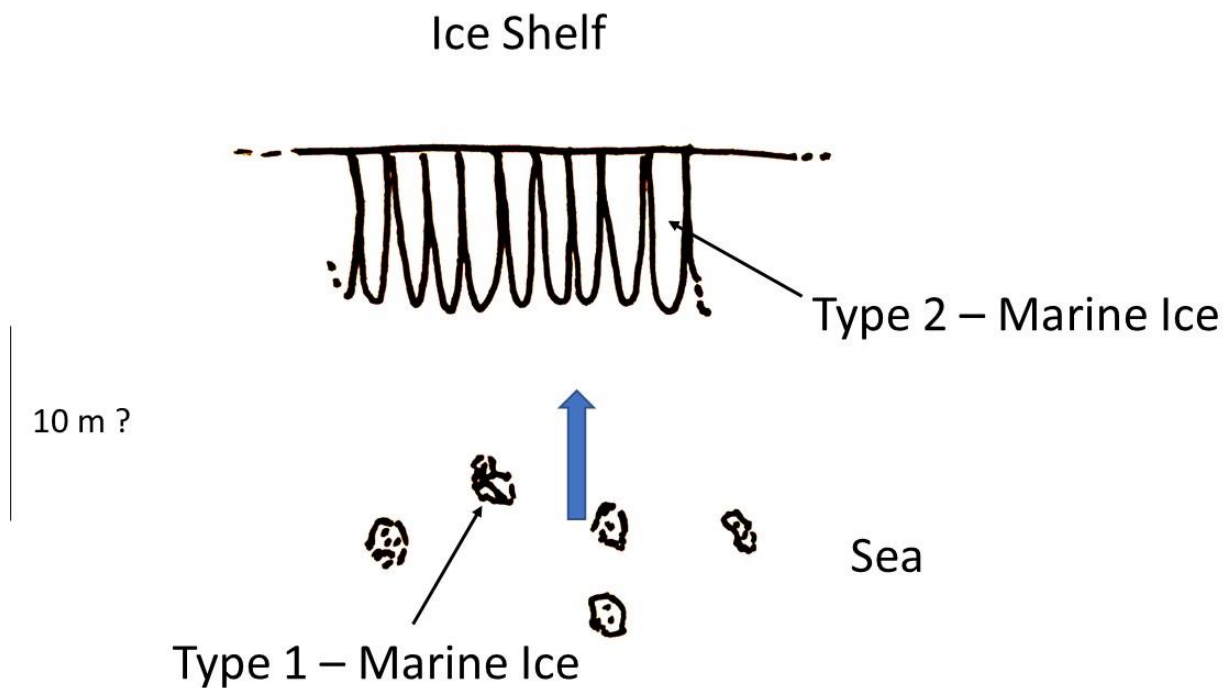


Figure 1

Formation of two types of marine ice, added from below to the glacier ice of the ice shelf. If thermal gradient conditions allow, type 2 - marine ice, structured in prismatic or planar cells, forms directly at the contact with the lower part of the ice shelf. If supersaturation conditions allow, type 1 - marine ice forms within the sea water, by homogeneous nucleation. Because of its lower density than water, this type 1 - marine ice will rise and stick to the lower surface of the platform, or to the lower boundary of the growing type 2 - marine ice; it will form a layer by agglomeration (as shown in the following figure; we will assume that the two types 1 and 2 of marine ice do not mix, with type 2 ice pushing back type 1, which is debatable).

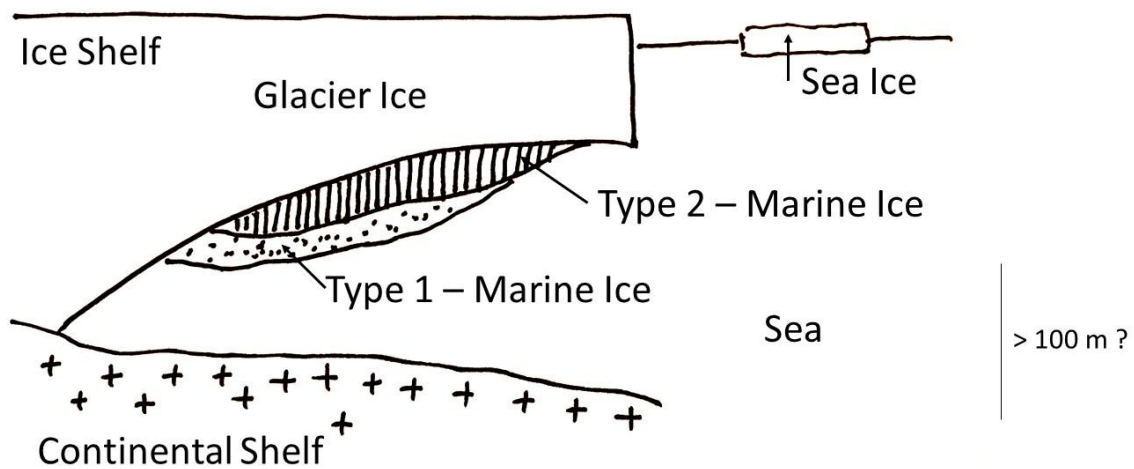
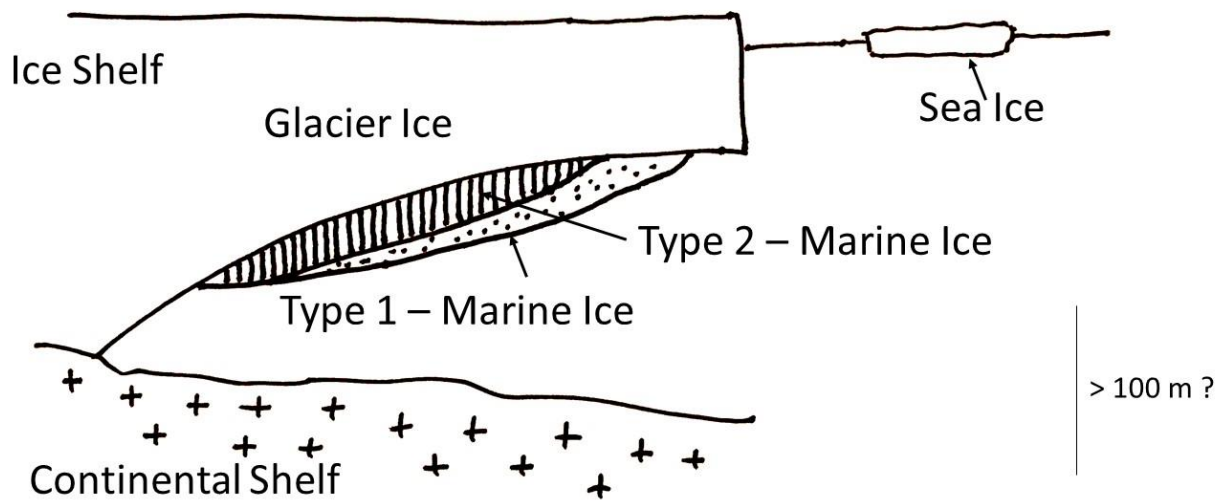


Figure 2

Overall chart showing the different types of ice that can be observed (under the hypotheses discussed in the text and according to the mode of formation shown in Figure 1). In a) (top) and b) (bottom), two slightly different scenarios are presented for the lateral arrest (in the shallower part and in the deeper part) of the two superimposed layers of type 1 and type 2 marine ice. Additional knowledge (temperature values, pressures, salinities, temperature gradients, water movements, etc.) will be needed to choose among the two scenarios (or propose another one).