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# “ANALOGUE MODELLING OF THE INFLUENCE OF ICE SHELF COLLAPSE ON THE FLOW OF ICE SHEETS GROUNDED BELOW SEA-LEVEL”

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## ABSTRACT

In this work we use analogue modelling to analyse the effect of sudden ice shelf breakup on the flow of ice draining an ice sheet grounded below sea level. Experimental results confirm that the removal of the buttressing effect exerted by the ice shelf results in significant acceleration of inland glaciers: the models show indeed a pronounced increase in ice velocity close to the grounding line. However, this effect does not significantly propagate upstream towards the internal portions of the ice sheet and rapidly decays with time. Therefore, the ice sheet is almost unaffected by flow perturbations induced by the disintegration of the ice shelf.

## 1. INTRODUCTION

Recent events of ice shelf collapse, such as the breakup of Antarctic Peninsula’s Larsen-A and Larsen-B ice shelves between 1995 and 2002, showed that these processes may strongly perturb the ice flow by inducing a sudden, significant increase in flow velocities. After these major events, indeed, glaciers accelerated up to eightfold [e.g., Rignot et al., 2004], a process which is thought to be related to the removal of the buttressing effect exerted by the ice shelves [e.g., Weertman, 1974; Hughes, 1977; Thomas, 1979]. Thus, the sudden disintegration of an ice shelf can induce the surge of ice streams, potentially causing severe depletion of continental ice levels. Large ice sheets grounded below sea level, such as the West Antarctic Ice Sheet, are believed to be particularly sensitive to the process, with their potential rapid reduction bearing obvious significant implications for eustatic sea level rise [Joughin and Alley, 2011].

Recent analysis [e.g., Furst et al., 2016; Reese et al., 2018] have tried to quantify in more detail the ice-shelf impacts on Antarctic stability, showing that the ice flow response is complex and spatially highly variable. For instance, there are ’passive’ portions of ice shelves that can be can be removed without major dynamic implications (the Larsen C Ice Shelf in the Weddell Sea is one example), whereas ice loss from other areas (e.g., Filchner-Ronne and Ross Ice Shelves) may have significant effects on upstream flow [see summary in Gagliardini, 2018]. This variability is related to the influence of many different parameters [e.g., geometry, thickness and rheological properties of the ice shelf, ice flow properties, geometrical characteristics of the grounding lines, etc.; e.g., Reese et al., 2018] on the buttressing effects and the influence of its removal on ice flow perturbations. Therefore, given the multiple uncertainties and the non-linear feedbacks and processes, a quantification of the future impact of ice-shelf loss to glacial flow in Antarctica is an extremely challenging task.

Besides many numerical models, which have been used to investigate the process [e.g., Huybrechts, 1990; Hindmarsh and Le Meur, 2001; Dupont and Alley, 2005; Goldberg et al., 2009; Gudmundsson, 2013], ice shelf breakup has been tested in previous analogue models [Corti et al., 2014], which however applied to ice sheets grounded above sea level (e.g., East Antarctic Ice Sheet; Antarctic Peninsula and the Larsen Ice Shelf). In this work we expand these previous results by performing simple small-scale laboratory models that analyse the influence of ice shelf collapse on the flow of ice streams draining an ice sheet grounded below sea level (e.g., the West Antarctic Ice Sheet).

## 2. EXPERIMENTAL SET-UP

### 2.1 EXPERIMENTAL PROCEDURE, MATERIALS AND SCALING

The analogue models were performed at the Tectonic Modelling Laboratory of Consiglio Nazionale delle Ricerche-Istituto di Geoscienze e Gerisorse of Florence, Italy. The models were characterised by dimensions (width, length) of 120cm x 70cm; the flowing ice was simulated by using Polydimethilsyloxane (PDMS), a transparent Newtonian silicone with a density of 965 kg $m^{-3}$ and a viscosity of ~1.5 $10^4$ [see Weijermars, 1986]. Previous experimental works have shown that the rheology of PDMS well approximates that of natural ice [Corti et al., 2003, 2008, 2014].

The models consisted of a large PDMS reservoir with dimensions of 120cm x 50 cm (simulating an ice sheet) flowing into a water tank with dimensions of 120cm x 20cm (simulating the ocean; Figure 1). Both the silicone reservoir and water rested over a flat metal table. Each experiment consisted of an initial stage in which the silicone (analogue ice) was allowed to escape from the front end of the reservoir and to flow into the water tank to form a floating platform (simulating the ice shelf). This stage lasted at least one week, after which a steady state flow of silicone was reached and monitored (pre-collapse stage). These steady conditions were altered by cutting the silicone at the valley outlet and manually removing the basal silicone platform (and thus the backstresses it imposes on the flowing analogue glacier) to simulate -although simplified- the natural process of ice shelf collapse (post-collapse stage). After removal of the floating platform about two thirds of the flowing silicone were under water, the remaining one third was above the water level; the base of the PDMS was stuck to the table below the water level, thus simulating conditions of ice sheets grounded below sea level (Figure 1).

During each stage of the experiments, the base of the PDMS layer was stuck to the analogue bedrock, such that no basal sliding was involved and glacier flow was only related to internal ductile deformation, well reproducing the mechanics of motion of polar glaciers [e.g., Benn and Evans, 1998].

With the adopted set-up, the removal of the buttressing effect exerted by the lower platform was the only major parameter inducing the perturbation on the silicone flow. During all the different phases of the experiments, the velocity of the silicone surface was monitored by analyzing (through top view pictures taken at regular time intervals) the progressive displacement of a passive grid of particles on the model surface.

The geometric scaling ratio was $10^{-5}$, such that 1 cm in the models simulated 1 km in nature; a velocity of PDMS of 1 mm/hour simulated natural velocities of ~100 m/year for a natural viscosity of ~$10^{13}$ Pa s. and one hour of the experiments corresponded to ~1 year in nature.

### 2.2 LIMITATIONS AND SEMPLIFICATIONS

Our experimental setup induces an artificial lateral stability to the ice sheet flow, which may influence the model results. However, the dimensions of the model (with width>>thickness) prevents flow in the central part of the experiment to be significantly controlled by the lateral boundary conditions. As a confirmation of this, the difference in flow velocity at the edges and in the central parts of the model are very limited (see below). Therefore, the dynamics of the model is influenced by the interplay among ice-shelf buttress, ice flow and basal boundary conditions, which is what we wanted to isolate in our experiments.

As in previous similar experiments [Corti et al., 2014], no seasonal processes were reproduced in the modelling, such that the time progression of flow perturbations must be taken as a proxy only. Also, no ice supply on the ice sheet was modelled, since according to scaling analysis negligible amount of silicone would be added to the evolving models; this allows better isolating the effect of ice sheet collapse on the flow perturbations [Corti et al., 2014]. Similarly, other complex processes (such as basal ice melting induced by upwelling and infiltration of warm water) were not reproduced in this modeling.

Finally, our models simplified the physical properties of ice as being homogeneous: in nature, instead, the rheology of the ice (especially at the grounding line and close to it) is far from being homogeneous and its density is not vertically and horizontally homogeneous [e.g., Tsai et al., 2015].

## 3. EXPERIMENTAL RESULTS

Figure 2 illustrates the result of a standard experiment, in which the thickness of PDMS was about 0.8cm at the experimental grounding line and about 1.5 cm in the internal parts of the analogue ice sheet (Figure 1); the cut removing the floating platform has been per-

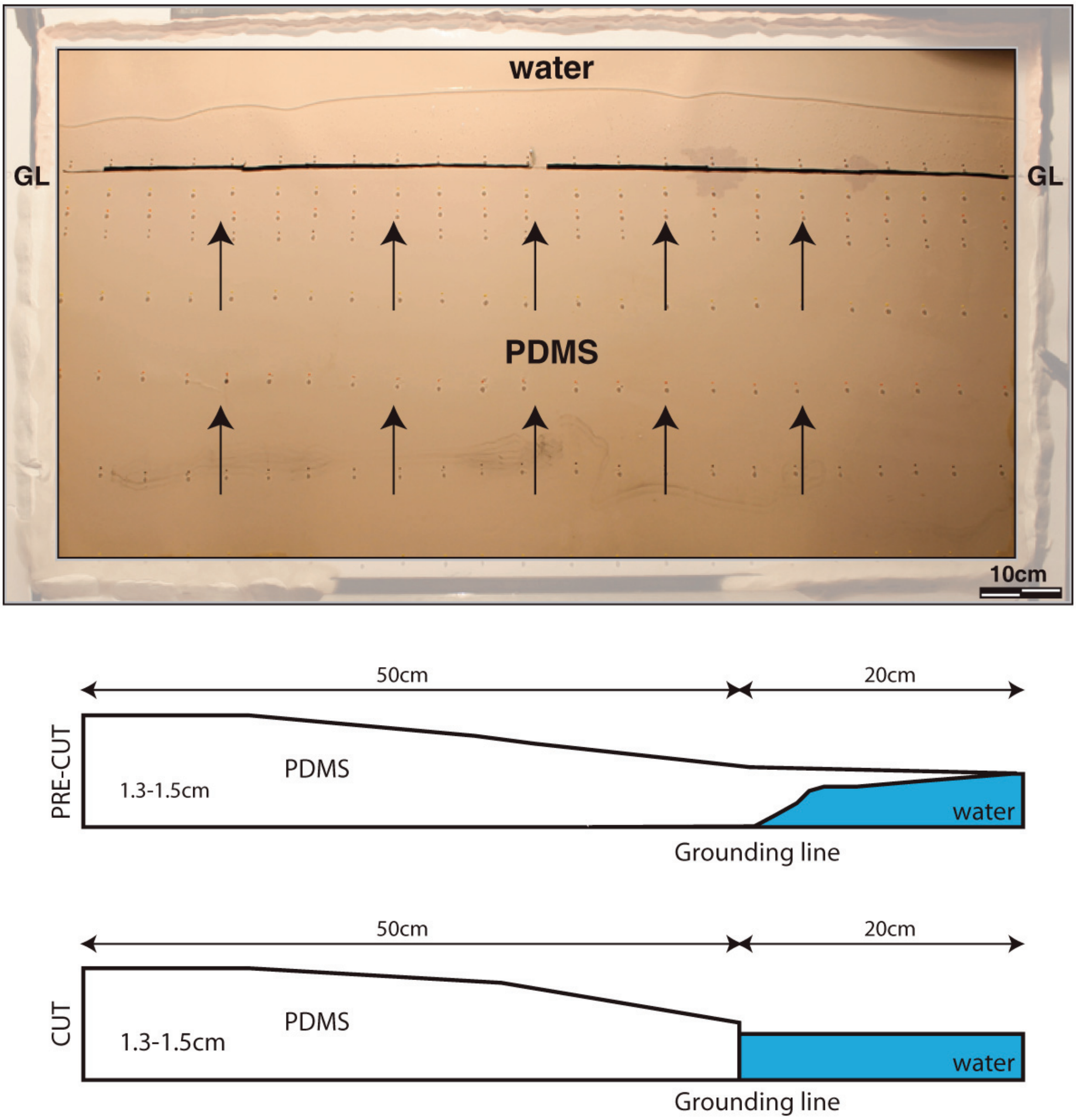

**FIGURE 1.** Sketch of the experimental apparatus. Upper panel: top-view photo of a typical experiment; bottom panels: schematic cross-sections. GL: grounding line; PDMS: Polydimethilsyloxane. See text for details.

formed exactly at the grounding line.

Steady flow of silicone in the pre-collapse stage was characterized by a mean velocity close to 1 mm/hr (corresponding to ~100 m/yr in nature) (Figures 2,3). Sudden removal of the lower silicone platform and of the backpressure it exerted on the flowing ice resulted in an almost instantaneous increase in velocity close to the grounding line: measured in the first hour after collapse, the velocity increased up to about 10 times the pre-collapse conditions (Figures 2,4). This acceleration was accommodated by stretching and thinning of the silicone in the proximity of the grounding line. After this initial phase of strong increase in velocity at the grounding line, the effect tended to propagate upstream, although with more limited effects. More specifically, in the second hour after the cut the velocity experienced a relative increase in a region 10 cm (~10 km) upstream of the grounding line, whereas close to this line the analogue ice was characterised by parallel relative decrease in flow rate (Figures 3,4). Although in places still observable 3 hours after the cut, the increase in velocity regularly decreased with time. Irrespective of the time span from the collapse, the effects in flow perturbations induced by the ice shelf removal were no more detectable at about 150 mm (~15 km) from the grounding line.

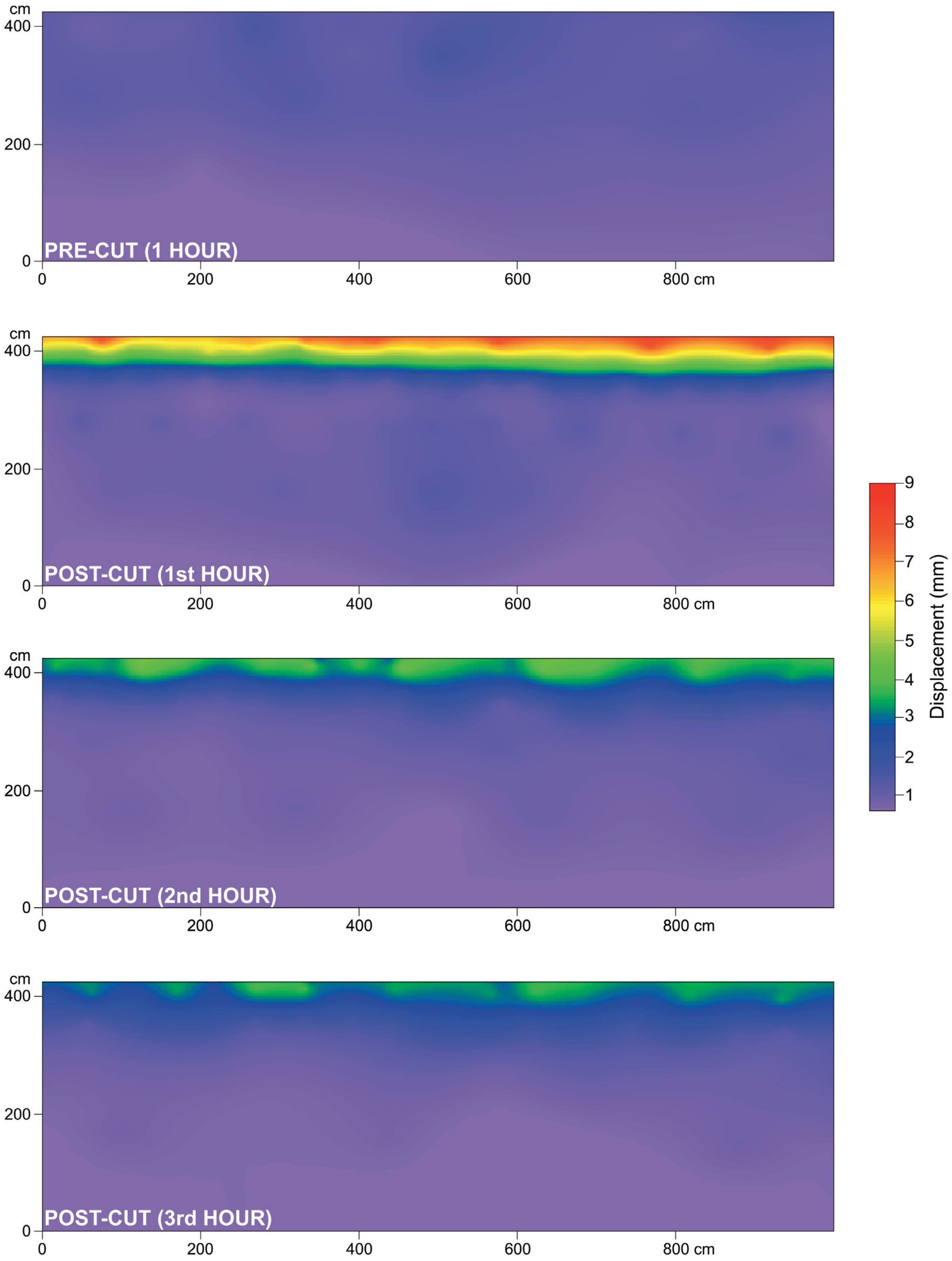

**FIGURE 2.** Velocity field at different stages of the evolution of the standard model. In this experiment the thickness of PDMS was about 0.8 cm at the experimental grounding line (GL) and about 1.5cm in the internal parts of the analogue ice sheet; the cut removing the floating platform has been performed exactly at the grounding line. Note the significant increase in velocity after the buttressing effect of the floating platform has been removed (post-cut conditions). Also note the limited difference in flow velocity at the edges and in the central parts of the model, indicating the absence of significant boundary effects related to the lateral stability of the analogue ice sheet.

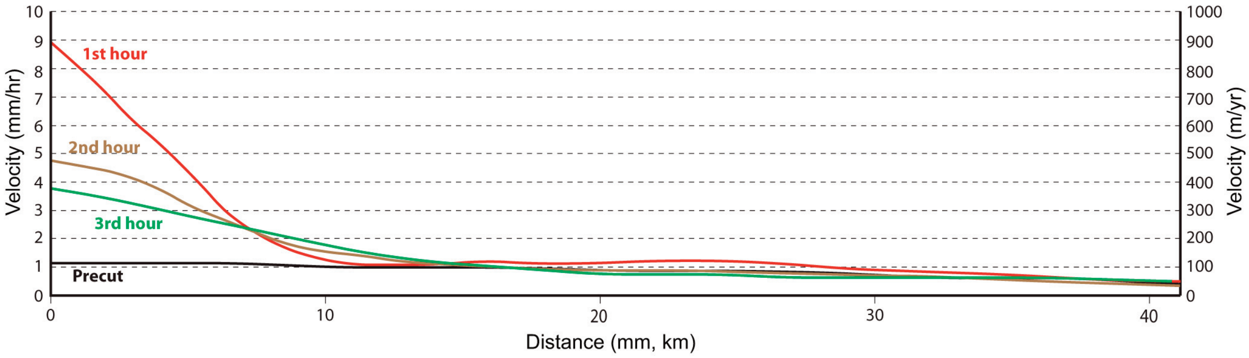

**FIGURE 3.** Velocity profiles in the central part of the model at different stages of evolution.

We tested different models with variable initial boundary conditions (e.g., variable thickness of the silicone, variable dimensions of the models) but we found no significant differences in the main model outcomes. The effect was indeed always prominent at the grounding line, but rapidly decreasing moving away from this area and with time.

## 4. DISCUSSION AND CONCLUSIONS

The current small-scale modelling was designed to reproduce and analyse the influence of ice shelf collapse on the flow of ice streams draining an ice sheet grounded below sea level (e.g., the West Antarctic Ice Sheet). The simple model set-up allows isolating the effect of the removal of the backstresses that the floating platform exerts on the flowing glaciers, thus offering insights into the influence of this parameter on the flow perturbations resulting from a collapse event. In line with previous modelling [e.g., Corti et al., 2014], the experimental results support a significant increase in glacier velocity close to the grounding line, with post-breakup velocities increasing up to tenfold with respect to the steady, pre-breakup conditions.

The process is accompanied by significant ice thinning at the grounding line and a regular decrease of the velocity variations both upstream and with time. This behaviour matches -at a first order- the typical response of ice flow to major ice shelf collapses in nature, as for instance deduced from monitoring of the behaviour Antarctic Peninsula's glaciers after the collapse of Larsen-A and Larsen-B ice shelves [e.g., Rignot et al., 2004]. However, the decay of the velocity perturbation (scaled values of within 3 years) may not match some observations in the Antarctic Peninsula, where some glaciers are observed to still flow considerable faster 15-20 years after the collapse [e.g., Wuite et al., 2015; Gagliardini, 2018]. As explained in Corti et al. [2014], this difference is likely related to the simplification of the modelling approach, which did not consider the slowdown of glaciers during the winter that is expected to prolong the flow perturbation and delay the establishment of a new equilibrium.

As observed in previous experiments [Corti et al., 2014], for values of ice thickness in the range of 800-1000 m at the grounding line, the increase in velocity following ice shelf breakup does not significantly propagate upstream towards the internal portions of the ice sheet: the effect is indeed almost undetectable at about 15 km from the grounding line.

Moreover, the velocity perturbation induced by ice shelf breakup rapidly decays with time, such that the ice sheet is almost unaffected by flow perturbations. These results may indicate that the removal of buttressing alone do not represent the major factor inducing depletion of ice sheets and threatening their stability; other parameters (e.g., basal sliding, steepness of the back slope, ice supply) have been shown to be unable to significantly affect the experimental outcomes.

However, we stress again that the this modeling is very simple and cannot take into account all the processes at play in nature. For instance, ice melting induced by upwelling of warm water is believed to represent a major process able to force the retreat of the grounding line and thus destabilize ice sheets grounded below the sea level [e.g., Gramling, 2014].

In addition, many other parameters (e.g., ice thickness and rheology, geometrical characteristics of the grounding lines, etc.; e.g., Reese et al., 2018] have a potential control on the effects related to the removal of the ice-shelf buttressing. Therefore, the experimental results have to be taken with caution, and may simply represent a simple starting point for more sophisticate modeling required to reproduce the complex conditions characterizing ice shelf/sheet instability.

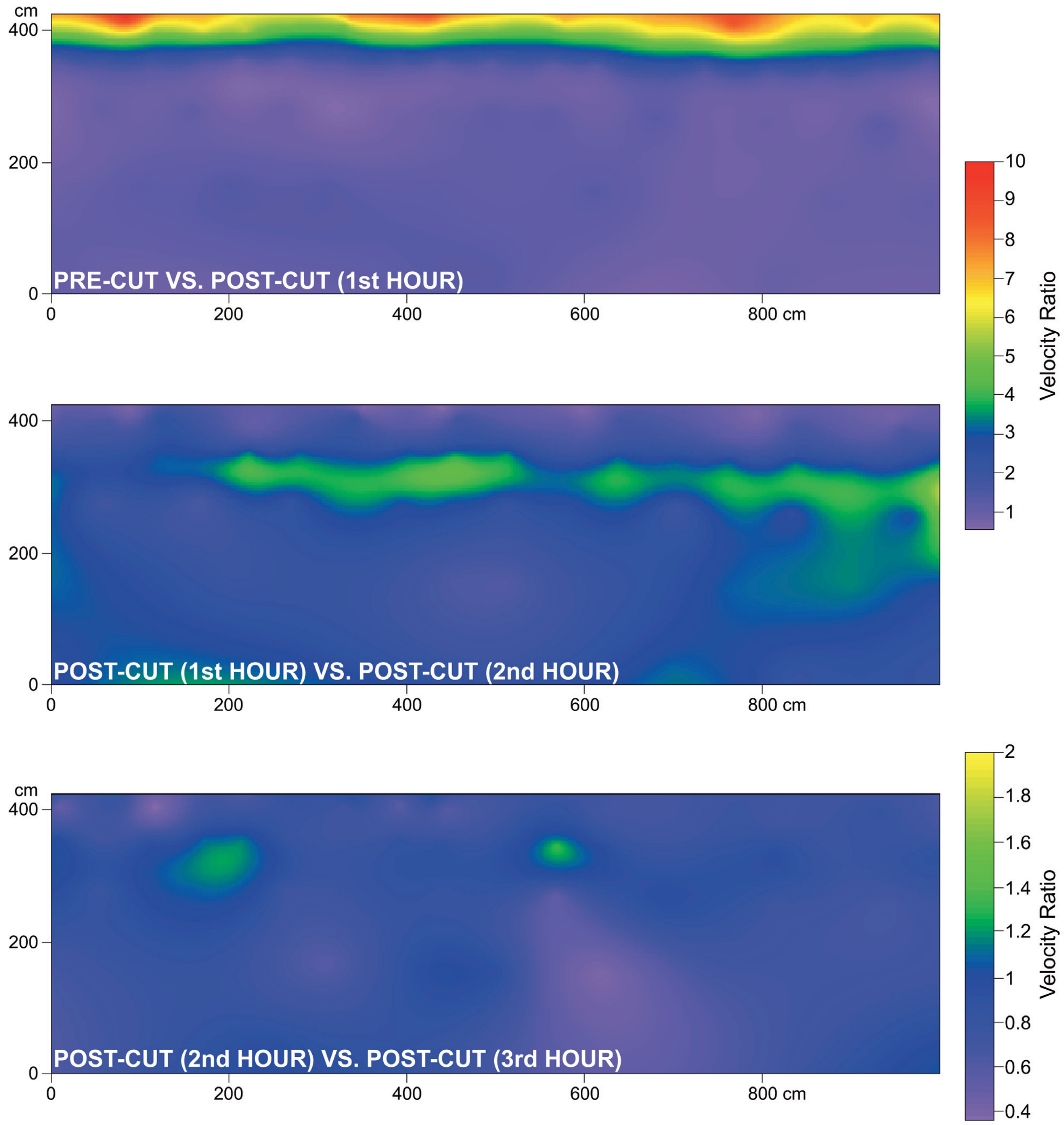

**FIGURE 4.** Velocity ratio among different stages of model evolution. Note the tenfold increase in velocity in the first hour after the floating platform has been removed.

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