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Small-scale modeling of ice flow perturbations induced by sudden ice shelf breakup

Giacomo Corti [a,*], Antonio Zeoli [b], Irene Iandelli [b]

[a] Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse, Unità Operativa di Firenze, via G. La Pira, 4, 50121 Firenze, Italy
[b] Museo Nazionale Antartide, Università degli Studi di Siena, via del Laterino, 8, 53100 Siena, Italy

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ABSTRACT

The sudden breakup of ice shelves is expected to result in significant acceleration of inland glaciers, a process related to the removal of the buttressing effect exerted by the ice shelf on the tributary glaciers. In this paper, this process is analyzed by means of scaled analogue experiments reproducing the flow of a valley glacier draining an ice sheet grounded above sea level into an ice shelf, and analyzing the dynamic perturbations resulting from ice shelf disintegration and removal of buttressing effect. Models show a significant increase in glacier velocity close to its outlet following ice shelf breakup, a transient effect that does not significantly propagate upstream towards the ice sheet and rapidly decays with time. Basal lubrication and variations in ice thickness do not significantly influence the process that thus leaves the ice sheet almost unaffected by flow perturbations.

1. Introduction

Many glaciers in Greenland and Antarctica flow into the sea, terminating in extensive ice shelves which act as a buttress for their glaciers and slow their flow. A marine shelf breakup is expected to induce an increase in glacier speed, as flowing glaciers no longer encounter resistance on reaching the ocean, until a new equilibrium is established (e.g., Weertman, 1974; Hughes, 1977; Thomas, 1979). The collapses of Antarctic Peninsula's Larsen-A and Larsen-B ice shelves between 1995 and 2002 confirmed these inferences. Glaciers draining the Larsen A ice sheet accelerated up to threefold after its 1995 collapse (De Angelis and Skvarca, 2003; Rott et al., 2004). After disintegration of Larsen B ice shelf in 2002 some of the glaciers (Hektoria, Green and Evans glaciers) accelerated up to eightfold between 2000 and 2003 and decelerated moderately in 2003, while others (Jorum and Crane glaciers) accelerated up to threefold (Rignot et al., 2004). Increase in velocity up to fivefold close to the calving front was still observed some years after the collapse (Rott et al., 2011). Concomitant with the increase in velocity, glaciers significantly stretched and thinned close to their grounding line (Rignot et al., 2004). These abrupt variations in the evolution of the glaciers have been mainly attributed to the removal of the buttressing ice shelf, a finding supported by the observation that glaciers that remained well buttressed by the remnant Larsen B shelf (Flask and Leppard glaciers) did not accelerate (Rignot et al., 2004). Thus, the abrupt removal of an ice shelf can trigger the surge of ice streams, potentially causing severe depletion of continental ice levels with obvious implications for eustatic sea level rise (Joughin and Alley, 2011). Several numerical models have analyzed the process, but the complex boundary conditions adopted and the different modeling approaches make it difficult to isolate the role of ice-shelf buttressing on the large-scale dynamics of ice sheets, whose role thus remains controversial (Huybrechts, 1990; Hindmarsh and Le Meur, 2001; Dupont and Alley, 2005; Goldberg et al., 2009; Gudmundsson, 2013).

In this paper we use simple small-scale laboratory models to reproduce the flow of a valley glacier draining an ice sheet into an ice shelf and to investigate the flow perturbations induced by ice shelf collapse. Model results apply to ice sheets grounded above sea level (e.g., East Antarctic Ice Sheet; Antarctic Peninsula and the Larsen Ice Shelf); the analysis of more complex settings characterized by ice sheets largely grounded below sea level (e.g., West Antarctic Ice Sheet) is not investigated in the current experiments.

2. Experimental set-up

2.1. Experimental procedure

The analogue models were performed at the Tectonic Modelling Laboratory of Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Gerisorse of Florence, Italy and at the Museo Nazionale Antartide, University of Siena, Italy. The apparatus consisted of a 45 cm × 45 cm × 15 cm upper reservoir (simulating an ice sheet) made of a Plexiglas box connected to a lower water tank (simulating the ocean) with dimensions of 40 cm × 30 cm × 10 cm. A 40 cm-long channel (a glacier

* Corresponding author. Tel.: +39 055 2757528; fax: +39 055 290312.
E-mail address: giacomo.corti@igg.cnr.it (G. Corti).

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valley) with a U-shaped section (10 cm wide, 5 cm high) connected the reservoir to the tank; channel inclination was ~5° (Fig. 1). The experiments considered a geometrical scaling ratio of $2 \cdot 10^{-5}$, such that 1 cm in the model corresponded to about 500 m in nature and the U-shaped channel was representative of a 20 km long, 5 km wide glacial valley. Ice thickness in the models varied between 1.5 and 3 cm (i.e., 750–1500 m in nature). The flowing ice was simulated by using polydimethylsiloxane (PDMS), a transparent Newtonian silicone with a density of 965 kg m^{-3} and a viscosity of $\sim 1.5 \cdot 10^4$ (see Weijermars, 1986); previous experimental works have shown that the rheology of PDMS well approximates that of natural ice (Corti et al., 2003, 2008).

Each experiment consisted of an initial stage in which the silicone (analogue ice) was poured inside the upper Plexiglas box and allowed to escape from the front end of the box and to flow through the valley into the lower water tank to form a floating platform (simulating the ice shelf). This stage lasted at least three days, 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 was under water, the remaining one third was above the water level (Fig. 1). During both the pre-collapse steady conditions and the perturbed post-collapse stage, the base of the PDMS layer was stuck to the analogue bedrock, simulating frozen bed conditions typical of cold glaciers (e.g., Benn and Evans, 1998). In these conditions, 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; Corti et al., 2003). Only in one experiment (see below, Exp 11), the base of the channel was lubricated with Vaseline in order to minimize basal friction at the interface between the analogue bedrock and the PDMS. This allowed reproducing conditions in which the entire glacier slides over its bed (e.g., when meltwater is prevalent at the base of the glacier and/or this latter on beds of deformable sediments) and thus analyzing the effect of basal sliding on the flow perturbations induced by ice shelf collapse.

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 both the pre- and post-collapse phases the velocity of the surface of the models 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 (Corti et al., 2003). No seasonal processes have been reproduced in the modeling, such that the time progression of flow perturbations must be taken as a proxy only. Also, differently from previous analogue models (Corti et al., 2003, 2008), no ice supply on the ice sheet was modeled, allowing to better highlight the effect of ice sheet collapse on the flow perturbations.

2.2. Scaling

Following Ramberg (1981), the condition for dynamic similitude between models and nature for the viscous deformation has been calculated on the basis of equality of dimensionless ratios of gravitational to viscous forces acting on the brittle–ductile systems:

$$\left[\frac{\rho g h}{\eta \dot{\gamma}}\right]_{\text{model}} = \left[\frac{\rho g h}{\eta \dot{\gamma}}\right]_{\text{nature}}$$

where ρ, h and η are the density, thickness and viscosity of the ice analogue, respectively, and g is the gravitational acceleration. $\dot{\gamma}$ is the shear strain rate that is given by $\dot{\gamma} = \frac{V}{h}$ where V is the ice velocity. Considering the imposed geometrical scaling ratio ($\sim 2 \cdot 10^{-5}$) and the physical parameters of PDMS and natural ice ($\rho \sim 920$ kg m^{-3}, $\eta \sim 1 \cdot 10^{13}$ Pa s), a

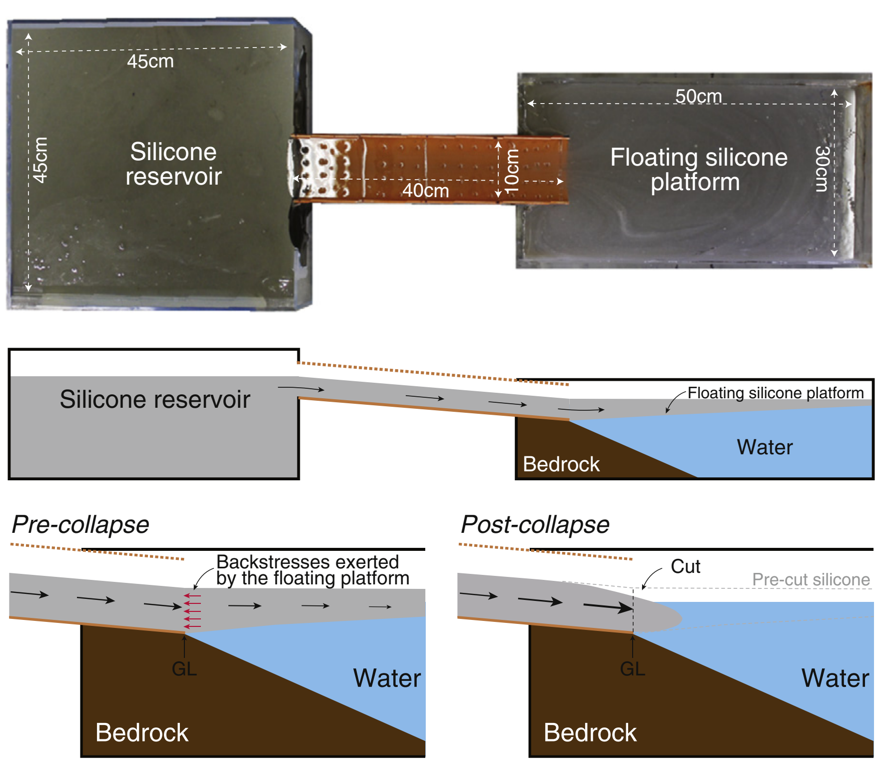

Fig. 1. Sketch of the experimental apparatus. Upper panel: top view scheme of the apparatus, showing the flow of the silicone from the upper reservoir into the lower water tank through a connecting channel. Central panel: lateral view scheme of the apparatus. Bottom panels: close-up of the grounding line (GL) area showing the pre- and post-collapse conditions. Note that the removal of the floating platform corresponds to the removal of the buttressing effect on the flowing silicone, inducing its acceleration and thinning close to the grounding line.