Investigating the bedrock topography effect on the ice flow ablation using the analogue modelling technique

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Summary Three-dimensional laboratory physical experiments have been used to investigate the influence of bedrock topography and ablation on ice flow. Different models were tested in a Plexiglas box, where a transparent silicone simulating ice in nature was allowed to flow. Experimental results show how the flow field (both in terms of flow lines and velocity) and variations in the topography of the free surface and internal layers of the ice are strongly influenced by the presence and height of bedrock obstacles. In particular, the buttressing effect forces the ice to slow down, rise up and avoid the obstacle; the higher the bedrock barrier, the more pronounced the process. Only limited uplift of internal layers is observed in these experiments. In order to exhume deep material embedded in the ice, ablation (simulated by physically removing portions of silicone from the model surface to maintain a constant topographic depression) must be included in the physical models. In this case, the analogue ice replenishes the area of material removal, thereby allowing deep layers to move vertically to the surface and severely altering the local ice flow pattern. This process is analogous to the ice flow model proposed in the literature for the origin of meteorite concentrations in blue ice areas of the Antarctic plateau.

Citation: Corti G., A. Zeoli, A. Deponti and L. Folco (2007), Investigating the bedrock topography effect on the ice flow ablation using the analogue modelling technique, in Antarctica: A Keystone in a Changing World--Online Proceedings of the 10th ISAES X, edited by A.K. Cooper and C.R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 181, 4 p.

Introduction

The Antarctic ice sheet is the most productive region for the discovery of meteorites on Earth thanks to the cold, arid polar climate. Besides being well preserved from alteration, meteorites are concentrated in specific regions by ice flow dynamics, as described in the ice flow (or conveyor belt) model (Cassidy et al., 1992; Harvey, 2003a). In this model, extra-terrestrial material is embedded within the ice mass and transported downstream of snow accumulation zones (Nagata, 1982; Whillans and Cassidy, 1983). Meteorite traps typically occur in areas of negative mass balance where deep, ancient ice is exposed at the surface, i.e. in blue ice fields (BIFs; e.g., Bintanja, 1999). In BIFs the meteorite-bearing ice slows down, and is deformed and uplifted by the buttressing effect due to submerged or emerged bedrock obstacles; wind ablation then exhumes and concentrates meteorites trapped in the ice. As a consequence, low surface temperatures (preventing sinking due to radiation-induced ice melting), high ablation rates (allowing the exhumation of deep ice and its meteorite content), low horizontal surface velocities and outcrops of ancient ice characterise nearly all meteorite-bearing BIFs.

The development and evolution of BIFs and meteorite traps is part o the more general problem of flow and deformation of ice masses and their response to boundary conditions such as bedrock topography (presence of submerged or emerged obstacles) and ablation. These processes have been extensively investigated through numerical and analytical modelling.

In this work we analyse the influence and the relative weight of these two basic factors (bedrock topography and ablation) claimed by the ice flow model to control the formation of meteorites stranding surface through three-dimensional physical laboratory models. In particular, we present two experimental series that were designed to address 1) the influence of emerged/submerged bedrock obstacles on the ice flow trajectories and velocity fields and 2) the control exerted by surface melting/sublimation on the vertical movement of ice and exhumation of englacial material. The experimental results have a more general significance and improve the understanding of the mechanisms of glacier flow and deformation.

Analogue modelling

Physical (or analogue) modelling has been widely used to simulate geological and geomorphological processes since the nineteenth century. The evolution of a correctly constructed dynamic scale model simulates exactly that of the prototype at a more convenient geometric scale (smaller) and rate (faster). In minutes or hours, processes lasting thousands or millions of years and involving hundreds of square kilometres can be reproduced in the laboratory through centimetre- or decimetre-scale models.

Previous physical models were used to investigate ice flow dynamics at the Frontier Mountain meteorite trap, Antarctica (Corti et al., 2003). These models clearly showed the potential of physical modelling in analysing glacial flow and internal deformation and the processes of meteorite trapping and exhumation.

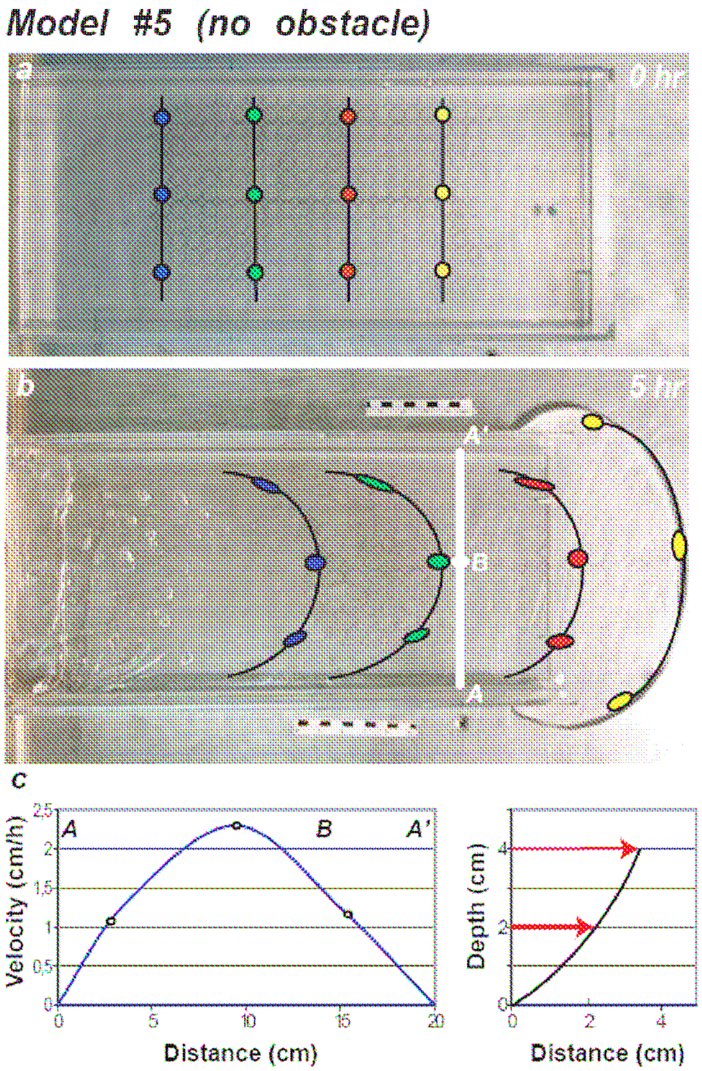

Figure 1: Deformation of model #5 (no obstacle). a) Initial conditions (the line drawing on the model surface indicates the shape of passive markers); b) final overhead photo; c) transverse velocity profile (trace of the cross-section indicated in b); d) vertical velocity profile (position of the measurement point indicated in b).

Scaling

The physical experiments were scaled following the concept of geometric, dynamic, kinematic and rheologic similarity outlined by Hubbert (1937), Ramberg (1981) and Weijermars and Schmeling (1986). In particular, models were built with a geometric scaling ratio of $L^* \sim 2 \bullet 10^{-5}$ (where the asterisk denotes the ratio between model and nature, $L^* = L_{model}/L_{nature}$), such that 1 cm in the model represented about 500 m in nature (Table 1). The scaling factor of stress (s*) is given by:

$$s^* \sim r^* g^* L^*$$

where r is density and g is gravity. Since PDMS and ice have similar densities, r*~1; similarly, since experiments were performed in the terrestrial gravity field, $g_{model} = g_{nature}$ and g*=1. Thus, $s^* \sim 2 \bullet 10^{-5}$. The following relations describe the scaling velocity (v) and viscosity (h) of Newtonian materials:

$$*\sim t^*/h^* \sim s^*/h^* \text{ and } *\sim v^*/L^*$$

where is the shear strain rate and t is the shear stress. The reduction factor of velocity can therefore be calculated starting from the scaling ratio of viscosity and vice-versa. Considering $h^* \sim 3 \bullet 10^{-12}$ (Table 1), v*~130; this implies that a velocity of 1 cm/hr in the model corresponds to ~66 cm/yr in nature. Based on the scaling ratio of velocity, the time reduction factor (T*) can be expressed as:

$$T^* \sim L^*/v^*$$

Considering that $T^* \sim 1.5 \bullet 10^{-7}$, 1 hour in the models corresponds to ~800 years in nature and the total duration of one experiment (5 hours) corresponds to ~4000 years (Table 1).

Experimental set-up

Analogue experiments were performed at the Tectonic Modelling Laboratory of the Institute of Geosciences and Earth Resources (National Research Council of Italy) at the Earth Science Dept. of the University of Florence.

Models were built inside a Plexiglas box with internal dimensions of 60cm x 20cm x 10cm. Similarly to the work by Corti et al. (2003), the ice was simulated using Polydimethilsyloxane (PDMS; Weijermars, 1986), a transparent Newtonian silicone with a density of 965 kg m-3 and a viscosity of $\sim 3 \bullet 10^{4}$ Pa s (measured with a coni-cylindrical viscometer) at a room temperature of ~21° C. During each experiment, the temperature was maintained constant (in a range of ±1°C), ensuring that the silicone underwent no significant variations in viscosity (Weijermars, 1986).

This material was poured into the Plexiglas box and allowed to settle in order to obtain a 4-cm thick layer with a flat free surface; the base of the PDMS layer was stuck to the analogue bedrock, so that no basal sliding was involved and glacier flow was only related to internal ductile deformation.

During the experiment, the Plexiglas box was inclined 3° and the PDMS was allowed to escape from the front end of the box (Fig. 1b). In all the experiments, the volume of ice escaping the front end was removed at regular time intervals of 30 minutes and added at the rear end of the box to simulate the constant replenishment of ice. The equilibrium topographic profile of the PDMS free surface was quickly reached through this procedure.

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Model deformation was analysed during the experiment by monitoring (through overhead photos taken at regular time intervals) the progressive displacement of passive markers placed both on the model surface and at a depth of 2 cm within the PDMS layer (see Corti et al., 2003). The markers consisted of carbon-black particles, printed on the model surface using the unbaked photocopy method.

Experimental series

We performed 7 models representative of two different experimental series. Series 1 models investigated the influence of a bedrock obstacle on ice flow dynamics. The obstacle was a parallelepiped placed in the central part of the Plexiglas box. The rectangular base of the parallelepiped was 10 cm x 3 cm, with a variable height of 2 cm (completely submerged obstacle) to 5 cm (completely emerged obstacle). A model with no obstacle was also created for comparison.

The height of silicon was 4 cm in all experiments. Series 2 models investigated the influence of ablation on ice flow. In these models, ablation was simulated by physically removing pieces of PDMS at regular time intervals in order to maintain a constant depression on the free surface of the ice both upstream and downstream of the bedrock obstacle. The height of the latter was kept constant in order to isolate the effect of ablation on local ice dynamics.

Table 1 Scaling parameters

PARAMETER	MODEL	NATURE	MODEL/NATURE
Length, L (m)	0.01	500	2 x 10^{-5}
Density, ρ (kg m^{-3})	960	920	1.04
Gravity, g (m s^{-2})	9.81	9.81	1
Stress, σ (Pa)			2 x 10^{-5}
Viscosity, η (Pa s)	30000	1 x 10^{16}	3 x 10^{-12}
Velocity, v (m s^{-1})	2.8 x 10^{-6} (*)	2 x 10^{-8} (#)	130
Time , T (s)	1.8 x 10^4 (§)	1.2 x 10^{11} ($)	1.5 x 10^{-7}

(*) corresponding to 1 cm/hr
(#) corresponding to 66 cm/yr
(§) corresponding to 5 hours
($) corresponding to 4000 years

Advantages and limitations of the experimental set-up

The experimental set-up adopted in this work has intrinsic advantages but also limitations that must be beard in mind when extrapolating the model results to nature. Particularly, we found PDMS to be a good viscous material to reproduce glaciodynamical processes for several reasons. Firstly, being a high viscosity-fluid, this material has a low velocity of flow at normal room temperature, so that the progressive displacement of passive markers is easy to record and document during each experiment. Its viscosity is not substantially influenced by the small temperature variations that may occur in the laboratory during an experiment. In addition, PDMS is also easy to handle and processes such as material removal to simulate ablation are easily performed during each experiment. Probably the most important characteristic of PDMS is its transparency, which makes possible to analyse the flow trajectories and deformation of internal marker progressively during the model run. This is normally impossible in the majority of analogue modelling studies, since the models must be cut at the end of the experiment to observe their internal deformation.

The main limitation of this experimental set-up is related to the rheological characteristics of the PDMS and that of natural glaciers. According to the theory of scaling, any analogue material should show a similar rheological behaviour with respect to its natural counterpart. This is practically impossible, due to the lack of perfect knowledge on the rheology of natural materials and to the limited availability of laboratory materials. Consequently, any analogue model is simplification of the natural prototype in terms of rheology. In this experimental series, the PDMS is a Newtonian fluid, with linear stress—strain rate relations; in nature, it is in many cases assumed that ice masses have a power-law stress—strain rate relation, with stress exponent close to three (Glen's law). However, in practice it is unrealistic to think in terms of a single flow law for ice, because several processes contribute to creep, and their relative importance changes in space and time. Depending on parameters as ice thickness, temperature, ice grain characteristics, englacial particles, etc., the behaviour of ice in nature may vary from Newtonian to power-law (Glen's law). Thus, PDMS simulates an end-member in the wide spectrum of complex rheological behaviours shown by glaciers in nature.

Discussion and conclusions

The described physical models were used to investigate the influence of bedrock topography and ablation on ice flow dynamics. The simple experimental set-up allowed us to isolate the effects of these parameters on the dynamics of glacial flow. In particular, Series 1 models highlight the important influence of submerged and emerged bedrock obstacles on the flow field (both in terms of flow lines and velocity) and on variations in the topography of the free surface and internal layers of the ice. As described in the classical ice flow (or conveyor belt) model (Cassidy et al., 1992; Harvey, 2003b), the experiments show how the buttressing effect generated by (submerged or emerged) obstacle forces the ice to slow down, rise up and deviate its flow trajectories.

The higher the bedrock barrier the higher i) the deviation of the flow lines towards the free area, ii) the reduction in velocity upstream of the obstacle, and iii) the uplift of the internal layers; maximum effects are observed in the presence of totally emerged obstacles. However, Series 1 model revealed that the buttressing effect alone is only able to determine a limited uplift of internal layers, which show only small vertical displacement and never reach the surface. Series 2 models integrate these findings by introducing ablation, i.e. the main parameter causing the negative mass balance that characterises blue ice fields (BIFs) in nature. Our experiments show that the passive surface markers are transported towards the area of ablation where deep layers are exhumed. This process works in the case of ablation both upstream and downstream of the bedrock obstacle, although the effects are more pronounced when material removal is coupled with the buttressing effect (i.e., upstream ablation).

Acknowledgements Research was carried out in the framework of the Project on Glaciology of the PNRA-MIUR and performed -for the analogic part- at the Tectonic Modelling Laboratory of the Institute of Geosciences and Earth Resources (National Research Council of Italy). We also thank the Antarctic National Museum, Siena section, for support on this research.

References

Bintanja, R. (1999), On the glaciological, meteorological and climatological significance of Antarctic blue ice areas, Rev. Geophys., 37, 337-359.
Cassidy W.A., R. Harvey, J. Schutt, G. Delisle, K. Yanai (1992), The meteorite collection sites of Antarctica, Meteoritics, 27, 490-525.
Corti G., A. Zeoli, M. Bonini (2003), Ice flow dynamics and meteorite collection in Antarctica, Earth Planet. Sci. Letters, 215, 371-378.
Harvey R.P. (2003a), The origin and significance of Antarctic meteorites, Chem. Erde, 63, 93-147.
Harvey R.P. (2003b), The Broken Belt: meteorite concentrations on stranded ice, Lunar and Planetary Science XXXIV, Abstract #1194.
Hubbert M.K. (1937), Theory of scaled models as applied to the study of geological structures, Geol. Soc. Am. Bull., 48, 1459-1520.
Nagata T. (1982), Search for Antarctic Meteorites, in: Craddock C. (Ed.), Antarctic Geosciences, International Union of Geological Sciences, Series B, Beijing, China, pp. 1049-1058.
Ramberg H. (1981), Gravity, deformation and the Earth's crust (2nd edition). Academic Press, London.
Weijermars R. (1986), Flow behaviour and physical chemistry of bouncing putties and related polymers in view of tectonic laboratory applications. Tectonophysics, 124, 325-358.
Weijermars R. and H. Schmeling (1986), Scaling of Newtonian and non-Newtonian fluid dynamics without inertia for quantitative modelling of rock flow due to gravity (including the concept of rheological similarity), Phys. Earth Planet. Int., 43, 316-330.
Whillans I.M. and W.A. Cassidy (1983), Catch a falling star: Meteorites on old ice, Science, 222, 55-57.