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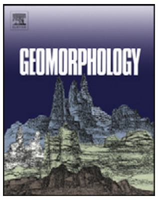

Friction and dynamics of rock avalanches travelling on glaciers

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ABSTRACT

Rock avalanches travelling on glaciers often exhibit effective friction coefficient lower than those on a rocky terrain. After briefly considering some data of rock avalanches on glaciers, the physics of sliding of solid objects on icy surfaces is reviewed, and a model is put forward for the mechanics of rock avalanche sliding on ice accounting for the formation of a natural lubricating layer. It is suggested that at the beginning of the flow of a rock avalanche, friction results from rocky blocks ploughing on ice. As the erosion continues, a gouge of ice particles results, which clogs the interstices between blocks and may partially melt as a consequence of the production of frictional heat. This conceptual model is numerically investigated for a slab travelling on ice. The results show an increase in mobility as a function of slab thickness, travelled length, and the gravity field, in agreement with case studies. The results are useful to interpret the peculiar features of rock avalanches travelling on icy surfaces such as digitations, out-runner blocks, and longitudinal furrows. The lubrication theory for landslides on ice proposed here may provide a framework for understanding landslides on Earth and for future modelling; in addition, it may help elucidate the presence of similar landslide deposits on the surface of Mars.

1. Introduction

The consequences of the increased warming are particularly evident in the mountain environment, where glaciers have been retreating for decades. One of the consequences on glaciers and permafrost is a reduction of support on rocky walls, which may favour the onset of catastrophic landslides. Global warming need not be the sole effect responsible for landslides in glaciated terrain. Young mountain ranges are normally high and steep, often rich in large glaciers; at the same time, such areas are often tectonically and seismically active. These features in combination may result in a higher rate of production of landslides on glaciers in the future (Haeberli et al., 1997; Kaab et al., 2005; Geertsema et al., 2006; Francani et al., 2011).

Cases of rock avalanches travelling on glaciers have been documented in numerous field investigations. Well studied are the Nevados Huascaran slide in the Peruvian Andes, and the 1964 swarm of rock avalanches on the Alaskan glaciers, of which the Sherman glacier landslides are the best known. The former, which claimed 18,000 lives, was initiated when a strong earthquake caused the collapse of an estimated 10–50 Mm^3 volume of rock onto Glacier 511. Probably lubricated by melting water and ice, the material acquired huge speed (Plafker and Ericksen, 1978; Erismann and Abele, 2001). The main slide on Sherman (Fig. 1) collapsed from Shattered Peak after a strong earthquake and travelled several kilometres entirely on the wide Sherman glacier (Shreve, 1966; Marangunic and Bull, 1968; Post, 1968; Tuthill, 1968; McSaveney, 1978). It developed characteristic lobes and stripes indicating the flow direction that seems to be associated mostly with landslides travelling on glaciers (Shreve, 1966; Dufresne and Davies, 2009; De Blasio, 2011b). The same earthquake caused a swarm of rock avalanches on other Alaskan glaciers, even though not all the deposits on these glaciers are related to the earthquake of 1964; others might predate the earthquake or be successive to the seismic event (Post, 1968). Further examples of landslides onto glaciers have been presented, for example, by Fahnestock (1978), Evans and Clague (1988), Evans et al. (1989), Barla et al. (2000), Bottino et al. (2002), Huggel et al. (2005), Sosio et al. (2008), Evans et al. (2009), and Hewitt (2009). Detailed compilations of such events are provided by Schneider et al. (2011) and Sosio et al. (2012). A recent landslide in Alaska occurred on 11 June 2012 when the collapse from Glacial Bay National Park sent a huge mass along the valley glacier; no scientific accounts are available yet. Table 1 reports a very small selection of data.

Rock avalanche masses travelling on glaciers or glaciated terrain exhibit different mechanical behaviours compared to the ones travelling on a rocky terrain. The first difference is often a lower H/R ratio between the fall height H of the rock avalanche and the runout R as a function of the volume (Fig. 2). This ratio represents the efficiency of conversion of gravitational energy into kinetic energy: the lower the ratio, the more mobile the landslide. For purely frictional materials, H/R should be equal to the friction coefficient of the rock involved in the mass movement (Scheidegger, 1973; Middleton and Wilcock, 1994), which is fairly constant as a function of load and velocity (Scholz, 2002). In contrast to this simple prediction, data for landslides on rock exhibit an apparent decrease of the H/R ratio as a function of the volume (e.g., Scheidegger, 1973; Middleton and Wilcock, 1994; De Blasio, 2011a). The significance of this effect, termed the 'volume effect', is still

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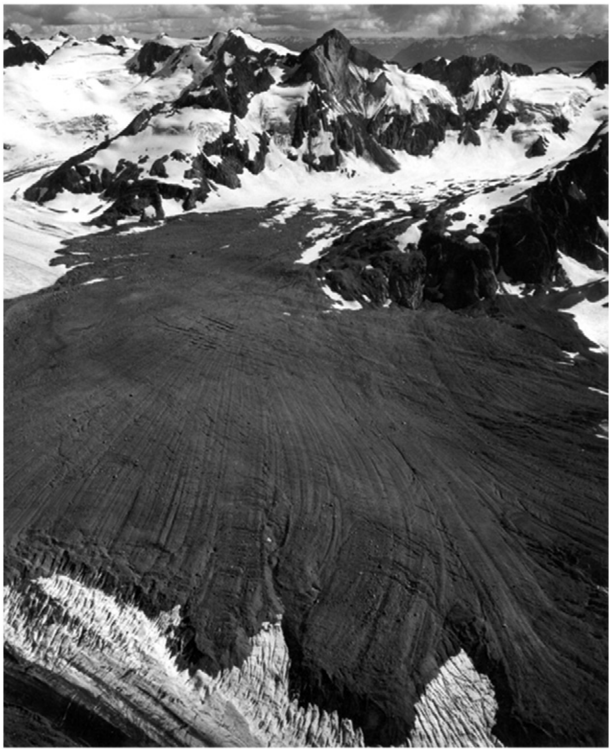

Fig. 1. A famous example of rock avalanches travelling on glaciers: the Sherman landslide, Alaska. Image courtesy USGS.

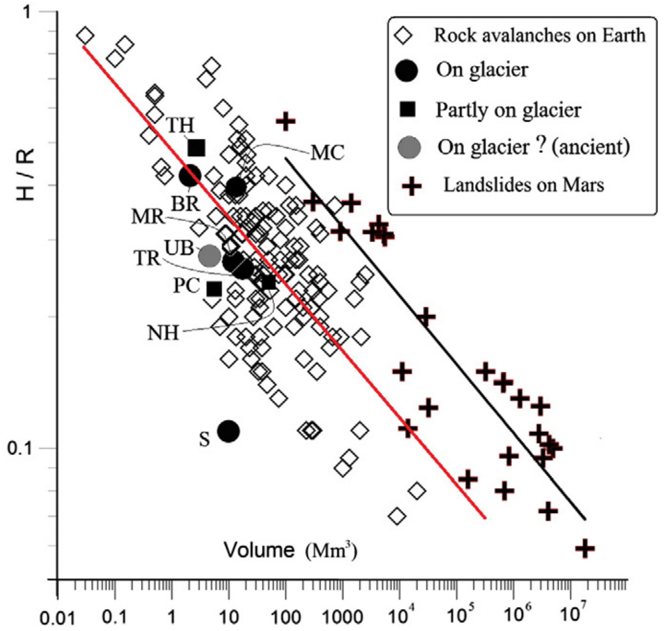

Fig. 2. The ratio between the fall height of some rock avalanches H and the horizontal distance R is shown as a function of the volume for terrestrial and for landslides on Mars. Because the movement of the centre of mass is seldom measured, a proxy for the ratio H/R that works fairly well consists in measuring the positions of the front of the deposit and the highest point of the landslide scar. The decrease of the fitting curves with volume embodies a discrepancy from the hypothesis of constant friction coefficient for bare rock. The data points report data for rock avalanches on glaciers. S: Sherman; NH: Nevados Huascaran; PC: Pandemonium Creek; TR: Triolet; UB: Urdbø ura; MR: Mount Rainier (Little Tahoma Peak); BR: Brenva; TH: Thurwieser; MC: Mount Cook.

debated (Legros, 2002). The volume effect appears also for landslides on glaciers. Thus, if the H/R ratio is a good proxy for the friction coefficient, then it can be stated that rock avalanches on glaciers typically travel with reduced friction. In particular, of the data collected in Fig. 2, the lubrication of the Sherman landslide has been particularly significant. In other cases, however, no improvement of mobility is seen like for the Thurwieser rock avalanche, identified with 'TH' in the figure; note, however, that only 20% of this rock avalanche occurred on glacier, the rest having taken place on rock. Whereas some researchers have invoked air lubrication to explain the high mobility of Sherman and other landslides (Shreve, 1966), Erismann and Abele (2001) convincingly assumed that the landslide showed reduced resistance because of the effect of ice melting. Because of the discrepancy between the coefficient of friction and the ratio H/R not only for landslides on glaciers but also for those on rock, H/R is often called the 'effective friction coefficient'; this usage will be retained here.

A second peculiarity of landslides sliding on glaciers is the predominance of inertia in the style of flow. Longitudinal grooves, well visible in Sherman as well in other landslides (Fig. 1), are like natural indicators of flow, demonstrating that the movement has occurred parallel to the surface without much vertical detachment from the base. This is consistent with low coefficient of restitution for the impact of rock against the snow–ice surface and also of reduced friction compared to rock avalanches running on rock. In order to visually demonstrate an inertia-dominated style of flow, Fig. 3A shows again an aerial view of the Sherman landslide, and Fig. 3B is a simple kinematic simulation of the flowage on the Sherman glacier. The simulation starts with 100 dots placed in the position of the black rectangle on the right of Fig. 3B. The initial velocity given to the dots before reaching the glacier (72 m/s), which gives the observed runout, is intermediate between the one reported by Shreve (1966) for the Sherman landslide material (51.4 m/s) and that would be acquired from free fall from the scar (108 m/s). Dots slide with constant friction coefficient on a curved surface modelled as a tilted cylinder, introduced as a proxy for the shape of the Sherman glacier. Note how the trajectories are compatible with the furrows on the Sherman glacier landslide. Some of the dots cross the axis of the glacier where slope changes sign and reach the end of the

Table 1
A short list of landslides travelling on glacier or icy surface[a].

Name of landslide	Year	Volume (millions of m^3)	Locality	Measured ratio H/R (Scheidegger, 1973)	Reference
Sherman	1964	10	Alaska, USA.	0.11	Shreve (1966); McSaveney (1978)
Pandemonium Creek	1959	5 (only partly on glacier)	Canada	0.23	Evans et al. (1989)
Nevados Huascaran	1970	50 (only partly on glacier)	Peru	0.24	Plafker and Ericksen (1978)
Mount Rainier	1963	11	Washington, USA.	0.246	Fahnestock (1978); Sheridan et al. (2005)
Mount Cook	1991	12	New Zealand	0.40	McSaveney (2002)
Brenva	1997	2	Monte Bianco (Italy)	0.42	Barla et al. (2000)
Triolet	1717	18	Val D'Aosta (Italy)	0.26	Bottino et al. (2002)
Thurwieser	2004	2.5	Italian central Alps	0.49	Sosio et al. (2008)
Urdbø	Ancient	5	Southern Norway	0.275	De Blasio (2009)

[a] The table shows also the ratio H/R between the fall height and the runout length. The Sherman landslide, considered in more detail in this work, collapsed from Shattered Peak in Alaska following an earthquake and travelled several kilometres entirely on the wide Sherman glacier.