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Two-dimensional numerical modeling of fracturing and shear band development in glacier fronts

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ABSTRACT

In this contribution we present a two-dimensional numerical model of a deforming glacier front. The model is based on a hybrid lattice spring network approach where particles in the model can deform in a volume conservative visco-elastic manner but at the same time they can be compressed elastically and fracture by discrete failure. We restrict ourselves to a simple setting where the glacier sits on a frictionless slope that dips with 5–10°, the ice block is fixed on one side and has a free surface on the other. The glacier varies in viscosity and can flow at the base, whereas it is brittle at the top. Results show that the head of the glacier is unstable. Failure happens as a combination of extension fractures (crevasses) at the top surface of the glacier and shear fractures that are dipping toward the glacier head. Once the shear fractures intersect with the free side-wall of the glacier a triangular ice block is carving from the glacier head. During successive flow of the glacier the failure is stepping backwards into the glacier and large shear planes develop that connect the sliding ice at the base with crevasses at the top. Variations of overall viscosity of the glacier indicate that higher viscosities (and thus a more brittle glacier) lead to larger spacing of shear surfaces and thus to larger ice blocks that are carving from the head of the glacier. In addition the geometry of the deformation structures within the glacier does not vary significantly with the height of the ice indicating that larger glaciers carve larger blocks. A higher tilt of the ground surface, however, leads to tighter spacing of shear surfaces and a more pronounced crevasse development. This indicates that glacier heads that lie on steeper slopes will carve smaller blocks than glacier heads that lie on shallower slopes. Failure and carving of ice from the model glaciers is a combination of early developing closely spaced extension fractures (crevasses) and later developing wider spaced and more localized shear fractures or shear zones.

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1. Introduction

The interaction of elastic deformation, fracturing and ductile flow in materials is still a phenomenon that is not well understood. One of the major shortcomings is the difficulty to model the long-term time-dependent flow as well as the buildup of elastic strain and successive failure. The discontinuous nature of fracturing itself poses a problem when it is modeled in combination with flow of material that can be simulated with continuum models. However the interaction of these processes is important and can be observed in many geological structures in the Earth's crust (Passchier and Trouw, 2005) as well as on the Earth's surface in materials that flow easily, for example glaciers (Nye, 1951; Hambrey and Milnes, 1975; Marmo and Wilson, 1999; Pralong et al., 2003; Fitzsimons et al., 2008).

Crustal examples of the interaction of flow and brittle deformation that have been the focus of recent work are flanking folds where discontinuities develop in a harder more brittle layer and the layer is then folded and displaced at the fault or vein (Passchier, 2001; Passchier et al., 2005; Grasemann and Stüwe, 2001). Another example is foliation boudinage where fractures develop in relatively ductile material. Layers deflect around the discontinuity and the fracture may actually open and form a hole in an otherwise ductile material (Hambrey and Milnes, 1975; Platt and Vissers, 1980; Lacassin, 1988; Mandal and Karmakar, 1989; Aerden, 1991; Swanson, 1992; Goscombe et al., 2004; Arslan et al., 2008; Birtel and Stöckhert, 2008). On the crustal scale the interaction of brittle and ductile processes becomes also very important. Many discontinuous as well as continuous codes have been used to study this interaction (Buiter et al., 2006; Gölke and Mechie, 1994; Li et al.,

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2009; Regenauer-Lieb et al., 2006, 2008; Regenauer-Lieb and Yuen, 2003). Some numerical models are layered such that the brittle crust is modeled with a more discrete approach, whereas the ductile flow in the lower crust is modeled with a continuum approach. However, such an approach does not account for the interaction between brittle and ductile processes especially if the interaction takes place across a wide zone in the crust. Recent comparisons between different codes and physical experiments illustrate the complexity of being able to model brittle–ductile interactions in a satisfactory way (Buiter et al., 2006).

One very important example of the interaction of brittle and ductile processes at the Earth's surface is the flow and failure of glaciers (Nye, 1951; Hambrey and Milnes, 1975; Pralong et al., 2003; Pralong and Funk, 2005; Benn et al., 2007; Schulson and Duval, 2009; Bassis and Walker, 2011). In contrast to crustal rocks that are mainly deformed by tectonic stresses, glaciers are dominated by gravitational processes, so that ice sheets expand laterally and hanging glaciers flow down hill. Flow of ice and corresponding ice surface structures have been modeled with several approaches where flow of ice is often modeled with non-linear viscous or plastic flow laws (van der Veen and Whillans, 1996; Marmo and Wilson, 1999). However, in order to successfully model fracturing and flow a hybrid model is need that can treat both rheologies, brittle and viscous. This is especially important when studying the stability of the head of a glacier or ice sheet. Fig. 1 shows a cross section through a cliffed glacier tongue after Chinn (1986, 1991) and Holdsworth (1969) and illustrates that the glacier contains several different rheological zones. The upper part and the tongue or head of the glacier are brittle, whereas the lower part of the glacier is semi-plastic to plastic or viscous. The stability of glacier fronts has been the attention of several studies including hanging glaciers, ice sheet fronts on solid ground and ice sheets protruding into lakes or the sea (Fitzsimons et al., 2008). It is of general interest to understand the failure of ice in order to study calving processes and get an understanding of the size of icebergs as well as the stability of glacier fronts (Benn et al., 2007). Failure is quite often studied in analytical or simple numerical models ranging from stability analysis of glaciers that contain crevasses at the top and partly at the bottom as well as full continuum models of failure (Pralong and Funk, 2005). Failure of material is often described by two main modes, mode I extension failure and mode II shear failure. In the case of mode I failure a potential crack develops perpendicular to a tensile stress and the crack is opening. Mode II shear failure leads to the development of two conjugate shear planes that are oriented with an angle of about 30° relative to the main compressive stress direction. The actual failure in glaciers is often modeled by a combination of mode I fracture criteria (i.e. the crevasses) and sometimes the occurrence of shear fractures that connect the mode I fractures. One of the main outcomes is a critical size that the glacier front can have before it collapses giving the height of ice sheets a limit (Benn et al., 2007). The actual size of blocks that carve off the glacier front is harder to estimate but there are good estimates on the actual discharge of blocks, which seems mainly to depend on how fast the ice flows. Pralong et al. (2003) and Pralong and Funk (2005) present a coherent continuum damage model that is used to understand failure of hanging glaciers. In their models they attain relatively large damage zones that represent the actual crevasses or the damage zone below and around a crevasse. A comparison of the surface evolution and failure geometry of the models shown in Pralong and Funk (2005) is in good comparison to natural examples. We present a similar approach to the one taken by Pralong and Funk (2005) using a discrete element description in order to study the interaction of brittle and ductile processes in detail with a special emphasis on the development and interaction of extension and shear fractures. Our modeling looks at the stability of the head of a glacier or ice sheet on a slope (similar to Fig. 1) where brittle and ductile processes interact strongly and the failure is mainly governed by the interaction of both, extension and shear fractures.

2. Model

We use a two-dimensional hybrid lattice-particle model (Latte within the modeling environment Elle; Koehn et al., 2003; Bons et al., 2008) in order to study the interaction between flow and fracturing at a glacier front. These models offer the possibility to study fracturing as well as ductile flow and interactions between the two (Buxton et al., 2001; Koehn et al., 2003; Malthe-Sørenssen et al., 2004; Sachau and Koehn, 2010). The model is based on a lattice-particle approach where single elements in the model are

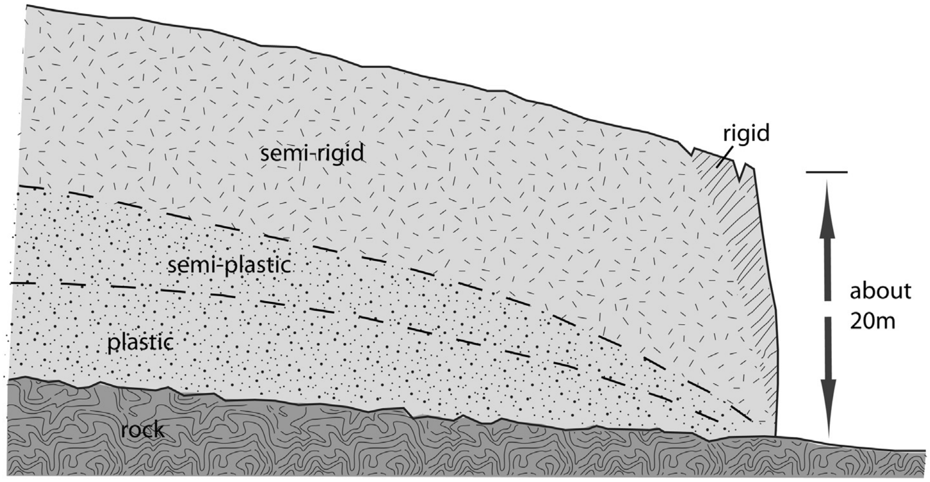

Fig. 1. Figure shows the sketch of a cross section through a cliffed glacier tongue after Chinn (1986, 1991) and Holdsworth (1969) and illustrates that the glacier contains several different rheological zones. Note that the bottom layer is tilted so that the glacier flows down a slope. The glacier head is brittle and has a rigid zone with pronounced crevasses at the top. The upper part of the glacier is semi-rigid and progresses into a semi-plastic zone. The transition between the two represents the brittle–ductile transition in the glacier. At the base the glacier tongue is plastic and the glacier flows.

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