Glaciology
On the morphology of glaciers

Group 1

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1 Classification of glaciers

Glaciers are classified into two major groups, ice sheets and ice caps. Ice sheets are glaciers that cover an area of over 50.000 km^2 and may actually cover and entire continent (such as the Antarctic). They may further be divided into land-based and marine-based ice sheets. For land-based ice sheets most of the base lies above sea level but for the marine-based ones most of the base lies below sea level. Marine based sheets are also called ice shelfs. Ice caps are smaller than ice sheets.

Depending on velocity glaciers may be classified as ice domes, ice streams (also called outlet glaciers) and ice shelfs. Ice domes are large areas of relatively slow moving ice. Outlet glaciers flow faster and may be confined by topography, such as mountains, or by ice rises, slow moving ice surrounding the outlet glacier. As before ice shelfs are ice streams that float on sea and are unconfined. Therefore the are relatively slow moving.

Furthermore glaciers may be classified by shape. The five main types are ice fields, cirque, valley, piedmont and transection glaciers. Ice fields have no dome-like shape and the flow is influenced be topography. Circue glaciers are located within a semicircular basin at glacier heads. Valley glaciers are elongatet glaciers that flow down a valley, confined by mountains on either side. Piedmont glaciers are formed when a valley glacier reaches an unconfined plain. Lastly, transection glaciers are systems of interconnected valley and cirque glaciers.

2 Crevasses

As glaciers flow they encounter some changes in the bedrock and surroundings. This affects the glacier as in response to changes underneath it the ice must deform in order to continue on its path. On picture 1 this is shown schematically as the ice moves down a steep section of the bedrock, causing tension (green) and compression (red) in the ice. These external features of the bed and surroundings also affect the velocity of the ice, which may eiter accelerate or slow down. All this contributes to fracturing of the ice.

For a valley glacier there are three major types of crevasses, transverse-, marginal- and longitudinal crevasses. These are shown in figure 2 along with whats happening in the glacier at for each type respectively (e.g. extension). Also shown are spalying crevasses.

2.1 Types of crevasses and formation

All types have in common that they are tensional fractures in the ice but the different patterns arise from the different situations this tension is applied. Fractures form where the principal stress, σ_1, defined by the bulk stress exceeds the effective tensile strenght of the ice.

To start with the marginal crevasses, which are the simplest type with regards to stress components, they form when the ice flows past a stationary body. This causes friction between the ice and the stationary body which causes shear stress in the ice. Note however that the friction is applied at the sides of the glacier so the shear stress decreases as you move further away from the sides. Therefore the marginal crevasses do not reach the center of the glacier. The principal axis of stress is aligned at 45° relative to the movement of the ice (as seen on figure 2) where tensile stress acts to tear the ice apart.

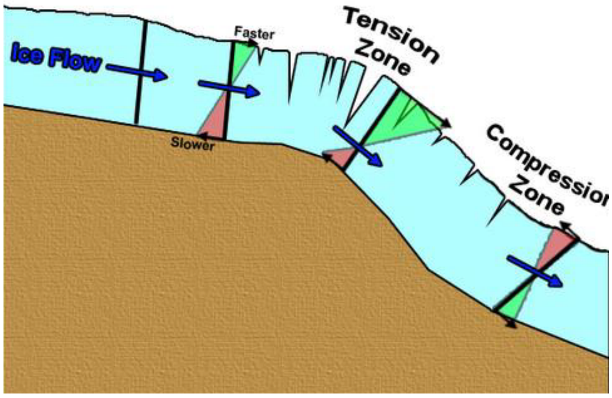

Figure 1: Ice moving over uneven bed.

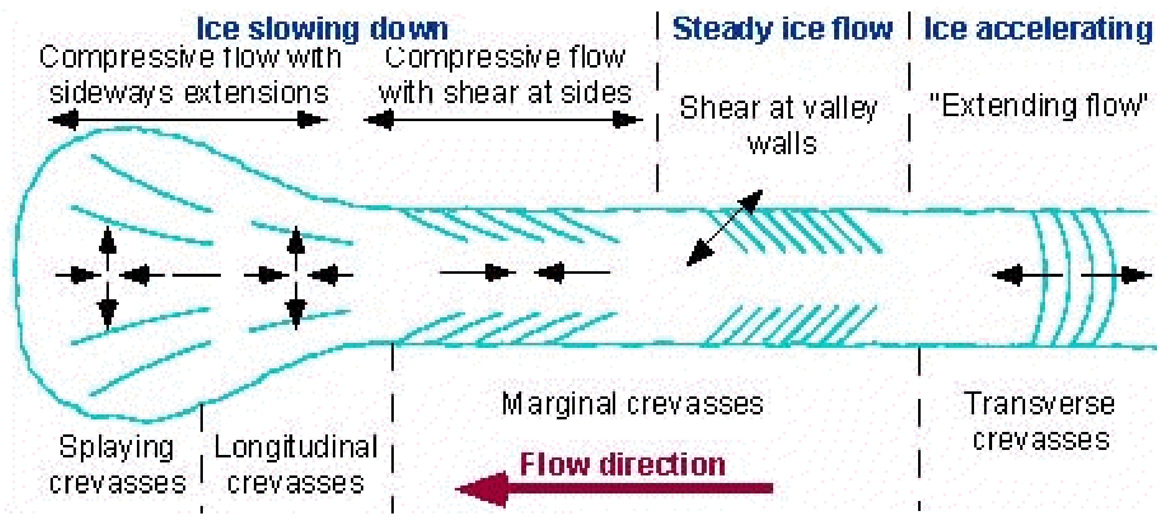

Figure 2: The main types of crevasses for a valley glacier, transverse-, marginal- and longitudinal crevasses. Also shown are splaying crevasses or radial patterns.

Transverse crevasses form when the ice accelerates downstream. This adds tensional stress along the flowline of the glacier so crevasses form perpendicular to the flow. This tensional stress is coupled with the shear stress closer to the edges of the glacier so the alignment of the crevasses changes to an inclined angle. The angle can however not reach 45° as with the marginal crevasses due to the additional tensile stress.

Last of the three main types of crevasses are longitudinal crevasses. In contrast to the transverse crevasses, longitudinal crevasses form when the ice decelerates, i.e. slows down. Keeping in mind that crevasses form due to tensile failure in the ice this may seem odd. When the ice is compressed in the flow direction it expands prependicular to the flow [1]. Near the edges of the glacier, the compressive stress is coupled with the shear stress so crevasses form at an angle less than 45° to the flow. The shear component decreases as mentioned before closer to the center of the glacier so the crevasses align closer to the direction of flow near the center.

Splaying crevasses are a subset of longitudinal crevasses formed when a valley glacier comes out from its valley and starts spreating out. This forms radial patterns because the flow lines are diverging. That causes tension parallel to the glacier margin which opens crevasses perpendicular to the margin.

[1] Typical Poisson's ratio for ice is 0.33 [Erland M.Schulson, 1999].

Crevasses have sharp tips because of the force from the far-field stress [2] is not able to be transmitted across the fracture. This intensifies the stress near the ends, making the tips sharp and the crevasse long compared to its width.

There are some other types of crevasses, such as *bergschrunds* and *rifts*. Bergschrunds are irregular crevasses that form when a moving glacier detatches itself from a stagnant piece next to a mountain side. These crevasses can even reach down to the bed of the glacier and is at a right angle to the flow. Rifts are gigant cracks in ice shelfs. They propagate from the sides of the shelf and into the shelf throughout the entiredeepens thickness of the ice. Rifts can have significant effects on the dynamics of an ice shelf.

2.2 Depth of crevasses

For temperate glaciers crevasses are usually no deeper than 25-30m. In polar glaciers deeper crevasses have been recorded.

A number of models have been proposed the calculate the depth of a crevasse. One such model derived by Nye in 1957 assumes that a crevasse penetrates to the point where the principal stress changes from tensile to compressive. This gives a simple relation for the depth d:

$$d = \frac{2}{\rho g}[\frac{\dot{\epsilon}}{A}]^{1/n}$$

Here A is a parameter positively correlated with temperature. That means that crevasses can get deeper in colder areas. This relation is however a great simplification. It does not include the fracture toughness of the ice nor is it valid for a water filled crevasse. If a crevasse is filled with water, the added pressure from the water can make the crevasse considerably deeper, even penetrate through the entire thickness of the ice. For this, however, much water is needed so the crevasse is always full of water as it deepens.

One attempt at a better model, including the fracture toughness, was derived by van der Veen, and gives a maximum depth of:

$$d \approx \frac{2.6}{\rho g}[2\tau_{xx} - \frac{K_{1c}}{\sqrt{\pi d}}]$$

where K_{1c} is the *critical stress intensity*. This formula gives a much greater depth, even as much as 2.5 times deeper. It is also limited to dry conditions.

3 Icefalls

An icefall is a part of the glacier where the flow of ice is very rapid and the surface is heavily crevassed. It is an analogous phenomena to the waterfall of a river, but obviously much slower. Icefalls usually form where the glacier falls of a pronounced step in the bedrock. This can also be accompanied by a narrowing, further increasing the speed of the ice. Below the icefall, the ice slows down and pressure builds up, closing the crevasses. The surface below the icefall can be relatively flat. In some cases pressure ridges form below icefalls.

As the ice accelerates rapidly massive transverse crevasses form but soon the ice breaks completely. This makes the surface extremely uneaven and chaotic. The velocity of an icefall can be up to an order of magnitude higher than the average velocity of the glacier. This high speed is much greater that plastic deformation can account for so the ice breaks completely.

This violent process destroys all layers in the ice. However, some icefalls produce *ogives* which are alternating bands of dark and light ice. The ogives often appear as thin crests and valleys. This happens because the darker areas have lower albedo than the light ones and therefore the absorb more heat from sunlight, making the melt faster. Each pair of light and dark bands represents one year of flow. This makes the ogives give a good approximation of the flow rate of the glacier in question.

Massive intersecting crevasses form so called *seracs*. These are very large towers of ice. They are generally very unstable and can collapse without warning. Sustained cold weather does however stabilize them to some degree. Seracs can be found in other places besides icefalls, such as on the lower edge of a hanging glacier.

[2] That is, the average stress in the area.

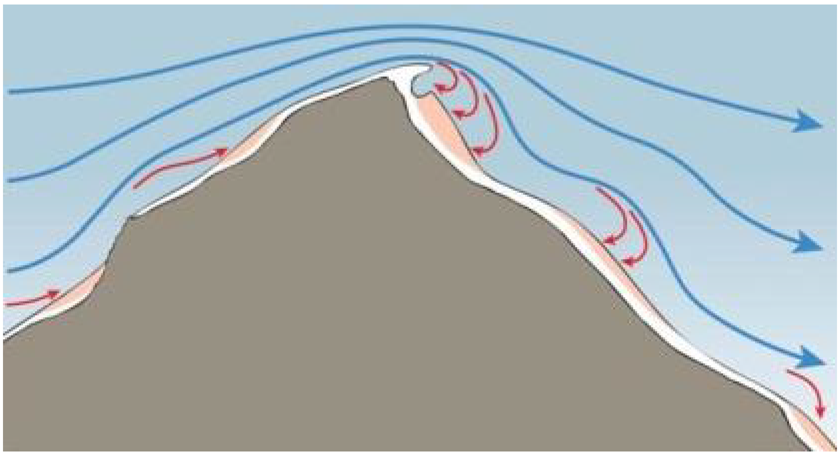

Figure 3: Flow lines of wind over a cliff and the formation of a cornice. Red arrows show slower windspeed.

4 Traveling and safety on glaciers

Traveling on glaciers can be of great interest, for scientific purposes or simply for pleasure[3]. Crossing glaciers can either be done in a vehicle, such as a super-jeep or a snowmobile, or on foot. Here, the focus will be on travel by foot.

Hiking on a glacier can be divided into two categories, that is travelling on a glacier with or without snow cover. On a snow covered glacier travellers often choose to use skis for speed and comfort. In either case some precautions must be made and some specialized equipment is required. This includes, but not limited to, crampons, ice axe, harness and crevasse rescue equipment. Food and clothing goes without saying, but keep in mind that getting caught in a storm on a glacier while wearing a T-shirt is not a good idea. On temperate glaciers below firn line water is in abundance, but above firn line, and in polar regions water is the most valuable resource.

The reason for all this is that traveling on glaciers is not without danger. These might be divided into two categories, namely falling things and falling into things.

Starting by travel on hard ice, i.e. a glacier without snow cover. Here all dangers are clearly visible and danger in any place quite easy to identify. The main dangers are cauldrons and crevasses and, if climbing an icefall, seracs. Climbers who climb in icefalls must be well aware of the constant danger of falling seracs, they can collapse instantly and without warning. Still, mountaineers cilmb icefalls both for the sheer challenge, but also in some cases crossing or climbing an icefall may be the only viable way to a certain destination, e.g. the Khumbu icefall on Mount Everest.

Falling into crevasses or cauldrons on hard ice is always preventable with careful route selection and propper crampon technique. Should a fall or a slip occur near a crevasse stopping may be difficult since the ice is slippery. Still, roped travel is not recommended on hard ice, since if one member of the party falls, the group may not be able to stop the fall on the slippery ice, causing the whole group to fall.

On a snow covered clacier not all dangers may be clearly visible. Crevasses may now be hidden by snow and look like unbroken surface, avalanches are always a possible danger when traveling in mountain areas. Seracs may or may not be present, depending on topography, and cornice may also pose some danger. For travel on snow crampons may not be needed if the snow gives enough traction.

Avalanche risk can be objectively assessed by digging a profile in the snow and estimate the stability. Most avalanches fall in slopes of 30°-45° and are classified in two main categories, loose and slab avalanches.

As wind blows over a cliff (or the sides of a crevasse) the windspeed drops significantly on the leeward side under the top. Figure 3 shows wind blowing over a cliff. Drift rate of snow, i.e. the rate at which snow is moved by wind, is given by $G = 0.03(V - 1.3)^3$ where V is wind speed[4]. This meas that if wind

[3]Sometimes even out of necessity, such as in the Icelandic countryside before the glacial rivers were bridged. Crossing the glaciers was often a better choice than crossing the river.

[4]The rebound mass or the mass of the snow deposited by wind is related to wind speed cubed so windpacked snow may

speed is doubled, the amount of snow moves is multiplied by 8, or if windspeed drops by half, 8 times more snow can be deposited. This mean that as snow is moved by wind from the windward side of a mountain it can accumulate fast on the leeward side. This forms an overhanging mass of snow called *cornice*. Cornices can pose danger to travelers since they are overhanging the can fall abruptly, either is a person stands on it, or naturally. This can often be the trigger of an avalance.

When cornice forms at the side of a crevasse it may grow large enough to reach the other side. When that happens a so called *snow bridge* is formed. Snow bridges are thickest near the edges of the crevasse but thinner in the middle. In good conditions the can support considerable weight. As mentioned before, snow bridges may hide crevasses underneath. Should a person walk accross a snowbridge there is a possibility that the bridge does not support the weight. This is especially a concern in late summer when much snow has melted and early winter before the bridge has gotten full strength. Roped travel is therefore recommended and space between party members should be enought so that at any time only one person could be standing on a snow bridge. Usually 8-10 m suffice, but may be more in colder areas.

be very dense.

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