Near Crust Faceting in a Dry Alpine Snowpack and the Implications on Avalanches

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For a number of years, avalanche professionals have been observing large dangerous slab avalanches release on and near buried crusts across all snow climates. In a significant portion of these dangerous avalanches a thin facet layer has been observed above and/or below the crust within the snowpack. Numerous papers have been published on this phenomenon and how it has killed or injured many backcountry users across all snow climates. In the more recent years a few papers have been published shedding light on the exact cause of how these dangerous avalanches have been happening on buried crusts. Though there are still many questions to be answered and much research to still be done to fully understand this phenomenon, the avalanche industry has begun to understand and prove why and how these buried crusts are reacting to the surrounding snowpack and causing dangerous avalanches in all snow climates, as well as other effects a buried crust has on a dry alpine snowpack.

Section 1: Water Vapor Movement in the Snowpack

The snowpack is defined as by the atmosphere above its surface and the substrate it rests on, typically Earth or glaciers. Stored heat at the ground surface and geothermal heating combine to keep the ground surface existing at or near 0℃ while near-surface temperatures fluctuate greatly from day-to-night called diurnal fluctuations. (The Avalanche Handbook) This effect causes a temperature gradient that is defined as a temperature over a distance ($\Delta T/\Delta D$) typically in the vertical direction but can be in the horizontal direction when thermal bodies are present such as rocks or brush. The reason temperature gradient is so important is it can be easily measured in the field and used to help us understand the influence vapor pressure plays in metamorphism. In a dry alpine snowpack, the movement of water vapor through the pore space, or the vapor pressure gradient (ΔV/ΔD) is the primary cause of snow grain metamorphism, along with grain curvature and mass of the overlying snowpack in combination with gravity and ΔT/ΔD. Sublimation of snow grains supplies water vapor to increase the vapor pressure in the pore space. As the water vapor moves through the snowpack due to the temperature gradient in the snowpack, it tends to condense on larger grains encouraging the growth of larger particles while reducing the size of smaller ones. Since saturated warm air can hold more water vapor than saturated cold air, typically higher water vapor exists in the pore space at the bottom of the snowpack moving upward towards the snowpack surface by leaving the surface of one grain and condensing onto a grain above (Colbeck S. and Jamieson B., 2001). The rate of this motion determines the type of crystal formation [snow grain and snow crystal being used interchangeably] and the rate is determined by the temperature, pore space, and temperature gradient. High rates of this vapor pressure movement produce faceted grains that may develop angular striations ultimately resulting in large cupped crystals known as depth hoar.

The high crystal growth rates typically form the most persistent and unstable snow grain type due to poor bonding with adjacent layers, lack of settlement and strength because of their anisotropic structure, and are often responsible for avalanches. These grain types include surface hoard, facets, and depth hoar. Facets have been frequently observed to form immediately above or below crusts in the snowpack.

Section 2: Crust formation

The International Classification for Seasonal Snow on the Ground [ICSI] identifies three types of crusts and three types of ice layers (ICSI, 2009). Melt-freeze crusts, rain crusts, and sun crust all form on the surface of the snowpack under the right meteorological circumstances, while ice layers, ice columns, and basal ice all form within the snowpack.

Rain crusts result from the snow surface being wetted by rain then freezing into a crust either before or after being buried by new snow. Major terrain factors affecting rain crusts include elevation, aspect of the slope if there is wind present during a rain event, and incline of slope since liquid water typically does not penetrate as deep in the snow on steeper slopes (Wankiewicz, 1979). Sun Crusts form when absorbed short-wave radiation exceeds outgoing long-wave radiation and causes melting of the surface snow and easily identified by solar aspects, and slope angle tilting more perpendicular to the sun. A melt-freeze crust, sometimes called a temperature crust, happens when air temperatures are above freezing and the snow surface melts due to sensible heat. Elevation is typically the primary terrain effect of a melt-freeze crust. (Jamieson B., 2006) Ice layers, ice columns, and basal ice all form from liquid water percolating through the snowpack and freezing by heat conduction into surrounding snow or onto a cold substrate. These crusts and ice layers form the bed surface to many slab avalanches (Atwater, 1954). With the crust acting as a bed surface and an overlying slab present, there still has to be the presence of a weak layer or interface for an avalanche to occur (Schweizer et al 2003).

Section 3: Near crust energy balance and faceting

When crusts form within the snowpack, or on the snowpack surface and are buried, they become a barrier for water vapor transport throughout the snow pore space below and above the crust (Colbeck and Jamieson, 2001). For an extended period of time, faceted snow crystals were observed directly above and below crusts in many locations spanning all types of snow climates across the globe with numerous papers published on these observations and subsequent avalanche cycles with little explanation of the process of above or below crust faceting (Greene, 2007) until Bruce Jamieson's paper Formation of Refrozen Snowpack Layer and Their Role in Slab Avalanche Release(2006) which discusses at length the theoretical explanations and field observations explaining near crust faceting and weak interfaces between crusts and overlying slabs. It likely wasn't until Greene (2007) when quantifiable research was done to help identify the effects of buried ice lenses and crusts in the snowpack and confirm theory and field observations with laboratory experimentation, followed by Hammonds et al, (2015). Local Temperature gradients on a sub-millimeter scale both above and below an artificial ice lense of 2mm, 4mm, and 8mm thickness within a model snowpack can be nearly 40 times larger than the macroscopic imposed temperature gradient, the macroscopic temperature gradient being field temperature measurements typically measured as T every 10cm (Greene et al, 2004, SWAG) to determine ΔT/ΔD. (Hammonds et al., 2015) The same study finds that new ice crystal growth from deposition on the bottom of an ice lens occurs simultaneously with sublimation from the top surface which helps to show exactly how a crust in the snowpack can act as a water vapor barrier (Hammonds et al., 2015). Further analysis of this study was conducted to ultimately identify which mechanism was primarily responsible for observed enhancement in temperature gradient near an ice-snow interface, and thus faceting on a sub-millimeter scale (Hammonds and

Baker, 2016). It was found that out of the mechanisms thought possible for heat and mass transfer including thermal contact resistance, thermal conductivity, latent heating/cooling, and imposed temperature gradients, thermal contact resistance was the primary contributor to the ΔT/ΔD enhancement both above and below an artificial ice lens. Thermal contact resistance is the ratio of the temperature drop that occurs at the interface of two materials when heat flows from the warmer material to a cooler material and the average heat flow across the interface (Madhusudana et al, 1997). These results suggest that taking field measurements every 10cm to determine ΔT/ΔD may be misleading due to the fact that crusts or ice layers can cause sub-millimeter temperature gradients much larger than an otherwise thermodynamically homogeneous snowpack may suggest. These results also conclude that faceting can occur above or below the ice lens in a matter of hours. Though this experiment was conducted using an artificial ice lens and controlled snow grains that may not fully be indicative of a natural snowpack, the results confirm and shed more light on what has been observed in the field and theorized to occur for many years.

Section 4: Implications of near crust faceting for Avalanches

It has been well known and documented that buried crust and ice layers often form the bed surface of slab avalanches (Atwater, 1954, Jamieson and Langevin, 2004, Jamieson, 2006, Schweizer et al, 2003). Many avalanches have also been observed where the layer of failure is the weak grain type immediately below the crust. With the drastic vapor and temperature gradient on a sub-millimeter level that occurs above and below crusts we have a persistent layer in the snowpack that creates its own weak layer. There were many notable avalanche cycles that have been published about avalanches on crusts. From 1990 to 2004 the University of Calgary collected a data set of 335 snow pits near dry slab avalanches and wumphs in the Columbia Mountains and of these 335 snow pits 70 had crusts as the bed surface (Jamieson and Langevin, 2004). Another extensive study was completed in the Columbia Mountains where 17% of natural avalanches were recorded to be a facet-on-crust combination with 7% occuring on crusts without any observed facets on the crust (Hägeli and McClung, 2003) thus concluding that using a dataset including 4500 avalanches observations over 5 winters 24% of those avalanches occur on a crust. The MLK crust on Crystal Mountain became the bed surface of several separate avalanche cycles throughout the winter including one of the largest avalanche cycles observed on Crystal Mountain (Morin C., 2012). This event in particular shows how a persistent crust in the snowpack can cause several dangerous avalanche cycles throughout a season.

Though we now understand a great deal more about the energy balance of a snowpack with a buried crust in it, we still have a gap in knowledge about many aspects of buried crusts. A commonly observed danger of buried crusts is the large temperature gradient and vapor pressure gradients above the crust and subsequent faceting of snow crystals which, with an overlying slab structure, can create very dangerous avalanches. The weak layers below a crust can also act as the weak layer for large and dangerous avalanches without the crust acting as a bed surface, which is another area for further research to be done. Is there a certain hardness or thickness of crusts where the snowpack is more likely to fail in the weak layers above or below the crust? The implications of different types of crusts is still a large area of speculation that further experimentation could shed light on. We could still benefit a great deal by conducting similar experiments as Hammonds Ice Lens experiment but with naturally collected crusts from an alpine snowpack rather than an artificial ice lens. Field observations have confirmed that buried crusts can erode with time but what is the time scale that certain crusts will lose their mass and the large temperature and vapor pressure gradients no longer exist immediately above and below the eroded crust. How long can a crust sustain large temperature and vapor pressure gradients before losing mass due to sublimation? Further experiments with more natural snowpacks may help answer these questions as well as to shed light on the implications of snow grain, size, and porosity above and below the crusts. Further understanding of the energy balance the buried crusts have in a dry alpine snowpack can greatly increase avalanche forecasters ability to properly inform the public on how to stay safe when specific crusts have been observed in their backcountry zones, as well as countless other applications in avalanche forecasting.

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