WATER MOVEMENT AND CAPILLARY BARRIERS IN A STRATIFIED AND INCLINED SNOWPACK

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ABSTRACT: Most avalanche fatalities occur due to dry slab avalanches. However, wet snow avalanches are also dangerous and can be particularly difficult to predict. The rate of change from safe snow conditions to dangerous snow conditions occurs rapidly in a wet snowpack, often in response to water production and movement. This research focuses on the relationship between snow stratigraphy and water movement in an inclined snowpack. Concentrating on the capillary barrier effect and flow finger formation within the snowpack, dye tracer was mixed with water and applied to a stratified snowpack to observe and measure the movement of water in various snow grain types, sizes, densities, and temperatures. Experiments show that even a slight textural change within dry snow grains produce a capillary barrier. The amount of water needed to produce flow fingers depends on the snow structure. Both capillary barriers and flow finger formation may play a large role in wet slab avalanche formation. Increasing global mean temperatures may increase the frequency of wet snow avalanches of all types, so a better understanding of the processes involved is important.

1. INTRODUCTION

Snow avalanches threaten life and property in mountainous areas worldwide. Most avalanche fatalities occur due to dry slab avalanches. However, wet snow avalanches are also dangerous and can be particularly difficult to predict because they are relatively poorly understood (Kattelmann 1984; Baggi and Schweizer 2004; Reardon and Lundy 2004). Though most scientific literature addresses dry snow avalanches, nine percent of U.S. avalanche fatalities since 1950 have resulted from wet snow avalanches (Atkins, pers. comm., 2005; Westwide Avalanche Network 2006). Since 1950, there were only 50 individuals killed by wet slabs. However, within the 50 wet slab fatalities, 47 percent were naturally triggered compared to 35 percent human triggered slides. Wet slab avalanches are more likely to be natural slides compared to dry snow avalanches.

Wet snow avalanches impact recreationists, transportation corridors, and ski areas. Reardon and Lundy (2004) documented extensive wet slab activity on roads in Glacier National Park, USA, and reported several wet avalanche accidents in 71 seasons of clearing and opening of Going-to-the-Sun Road, including a 1964 wet slab that carried a bulldozer and an operator off the road. In some ski areas, such as Bridger Bowl, Montana, poorly understood wet snow avalanches sometimes create more difficulty for the ski patrol than better-understood dry snow avalanches because of unpredictability (Johnson, pers. comm., 2006). An increase in global mean temperature may also lead to a higher frequency of wet snow avalanches in the future. As snow may be precipitated at warmer temperatures, rain-on-snow events might become more frequent. The above examples illustrate the need to achieve a more thorough understanding of wet slab avalanches.

The manner in which water flows through a snowpack has many implications for avalanche hazard. Forecasting wet slab avalanches requires considering the complexities of water percolation through the stratified snowpack, and the interaction of that water with various snowpack layers (Conway 2004; Baggi and Schweitzer 2005). While research has focused on water flow in snow and wet snow metamorphism (Colbeck 1973, 1976, 1978, 1979; Marsh & Woo 1984), few studies exist relating to wet slab avalanches (Kattelmann 1984; Reardon and Lundy 2004). Water flow occurs because of melting within the snowpack or a rain-on-snow event (Heywood 1988; Conway 2004; Waldner et al. 2004). Both situations, under optimal conditions, have the tendency to cause wet slab avalanches.

The theory behind capillary barrier effects in snow is adapted from the concept of liquid flow in porous media (Morel-Seytoux 1969). It involves a change in the infiltration rate of water within a

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snowpack due to a textural difference between two layers (Colbeck 1979). Waldner and others (2004) showed the effect of stratigraphy on water movement in an artificial snowpack. They showed that a microstructural difference of fine grained snow types over coarse grained types created the capillary barrier effect. They found that capillary barriers changed water percolation, and suggested that capillary barrier effects may be more pronounced in a natural snowpack with varying grain size, shape, and metamorphism rates. Thus, there is a need to determine if such impermeable layers or capillary barriers do affect the formation and stability of wet slabs in a natural snowpack.

The objective of this research is to identify measurable snow stratigraphy factors that might indicate wet slab conditions, specifically capillary barriers. Since wet slab avalanches result from the interaction of specific snow stratigraphy with free water in the snowpack, this research focuses on how stratigraphy affects water movement. Through field experimental methods we investigate the density, hand hardness, grain size, grain type, and temperature of snow layers surrounding capillary barriers to better understand the role of these variables in water flow through the snow.

2. METHODOLOGY

2.1 Study Sites

The study sites for this research consist of two different geographic areas in Montana. The first study areas are in the mountain ranges surrounding the town of Bozeman, Montana, USA including the Bridger Range, Madison Range, and Gallatin Range. The Bridger Range, in southwest Montana, runs from about 5 km northeast of Bozeman to 45 km towards the northwest, and is a relatively narrow mountain range (10km). We collected data along the northern and southern boundaries of the Bridger Bowl Ski Area, 24 km north of Bozeman, Montana where elevation ranges from 1860 m to 2650 m. The Bridger Range exhibits an intermountain snow climate (Mock and Birkeland 2000).

The Madison Range is located 56 kilometers south of Bozeman, Montana. We collected data in and near the boundary of Moonlight Basin Ski Area. The elevations at this area range from 2070 m to 3400 m, and exhibit a combination of intermountain and continental snow climates as well.

The second study site for this research took place in Glacier National Park, Montana. The study site in Glacier National Park includes the Going-to-the-Sun Road, a two-lane, 80-kilometer roadway traversing through Glacier that is closed each winter because of avalanche hazards, inclement weather, and heavy snowfall (Reardon and Lundy 2004). The northern Rocky Mountains within Glacier National Park also exhibit an intermountain snow climate (Mock and Birkeland 2000).

2.2 Field Data Collection

Seligman (1936) first documented the use of dye tracer in snow, and it has been used extensively in numerous other experiments to determine preferential flow paths in a snowpack (Woo, Heron, and Marsh 1982; Heywood 1988; Schneebeli 1995; Waldner et al. 2004). We utilized red food coloring to determine timing events of water flow and creation and persistence of capillary barriers and preferential flow paths. We mixed the dye with water, and then applied it with a spray bottle to simulate rain or meltwater production within the snowpack. The spray bottle was a hand-pump pressurized 1L bottle that allowed for a more uniform flow to the snow surface than a standard hand spray bottle. To test relative uniformity over a 30 cm x 30 cm surface, we sprayed water into ice cube trays of that dimension, then siphoned and measured the amount in each “cube”.

Utilizing dye tracer allowed us to determine where water came in contact with capillary barriers, and to measure the snow density, grain type, grain size, hand hardness, and snow temperature associated with those barriers. We excavated a total of 5 snow pits of 30cm x 30cm x 100 cm on each slope. Each pit was spaced ~30cm apart, and we completed a vertical pit profile to locate layer transitions before experiments (Figure 1). We sampled on slopes between 27 and 34 degrees to ensure uniformity of water flow, and measured the following: 1) density at every layer using a 250cm^3 stainless steel cutter and a small cylindrical cutter for thin (1-4 cm thick) layers, 2) temperatures every 5cm from the surface to the vertical location of water within the snowpack (linearly extrapolating temperatures for capillary barriers if they existed between these measurements), 3) grain type and size of each layer, 4) air temperature, and 5) applied water temperature.

We cooled the water added to each plot to slightly above 0º C, so as to minimize the amount of meltwater produced by the actual snow grains. Preliminary experiments conducted in the

Figure 1: After applying dye, the author marks the slope parallel cuts that are conducted 10 minutes after dye application. Photo by Karl Birkeland.

Montana State University College of Engineering Cold Laboratory showed that sifted snow with density ranging from 300-355 kg/m^2 requires ~60-100 ml of applied water to begin to form preferential flow paths. Thus, with less dense snow in a field situation, we began with water applications of ~50 ml.

We applied the dye tracer to each column beginning with 50 ml over a 2-3 minute period ensuring uniform application. Ten minutes after all of the water was applied, we made a slope parallel cut 5 cm down from the snow surface. This allowed us to determine the existence or absence of capillary barriers and preferential flow fingers throughout each plot. The 10 minute lag time and 5 cm cut allowed for flow finger formation based on findings in other lab experiments that finger front traveled with a velocity between 0.1 and 1 cm/s (Waldner et al. 2004). We then made horizontal cuts at 15 cm to identify water movement deeper in the snowpack, and continued every 15 cm until dye tracer was not observed. We replicated this process with increments of 100 cm^3 of water up to the equivalent of ~5 cm of water added to a dry winter snowpack on the 30 cm x 30 cm plot.

2.3 Data Analysis

Statistical analysis focused on the variables that likely lead to capillary barrier formation within the snowpack. We classify a non-capillary barrier as any observable transition between two layers where water moved through that boundary and did not pool or move laterally. We collected data on 42 capillary barriers and 32 non-capillary barriers. We first determined the normality of snow grain size, snow temperature, snow hand hardness, and snow density of capillary barriers and layers transitions that were not capillary barriers. Since the distribution of our data are largely non-normal, we used the nonparametric Mann-Whitney U Test to compare the difference in our variables between capillary barriers and non-capillary barriers.

When characterizing snow grain type, we examined the frequency of each grain type as both a top and bottom layer in capillary barriers and non-capillary barriers. Then we partitioned the data based on crystal type and examined the frequency of top and bottom layers, and performed a one-sample Wilcoxon one sample signed rank test for capillary barrier variables. For instance, we examined all capillary barriers and non-capillary barriers where new snow was present as either a top or bottom layer (or both), and calculated the frequency of each crystal type when new snow is present. The partitioning of data based on grain type allowed for a more detailed characterization of individual crystal types in capillary barriers.

3. RESULTS AND DISCUSSION

3.1 Partitioning Data Based on Crystal Type

No statistically significant difference in density, hardness, grain size, and temperature between the top and bottom layers of all capillary barriers exists. Since the nature of a capillary barrier varies depending on the grain type, we partitioned the data based on grain type. We separated the data into 5 categories based on whether that particular grain type was present either above or below the interface: new snow crystals (crystal type1 as classified by Colbeck et al., (1990)), rounded grains (crystal type 3), faceted crystals (crystal type 4), wet grains (crystal type 6), and crusts (crystal type 9). All of the crystal types except decomposing and fragmented precipitation particles (crystal type 2) observed in our experiments can be classified into these categories. Some interfaces are used for more than one category; for example, facets overlying a crust are used for both our facets category and our crusts category. For the analysis we included decomposing precipitation particles with new snow crystals because they are recently deposited crystals.

Of the capillary barriers observed in this study, new snow particles are the most common layer above capillary barriers (29%) and fragmented precipitation particles are the most common layer below capillary barriers (26%) (Figure 2). Conversely, these two types of crystals are also the least common layers in interfaces that were not capillary barriers (6% and 6%, respectively for top layers and 0% and 3% for bottom layers). Wet grains and rounded grains were not prevalent as either a top or bottom layer in capillary barrier composition, and our results showed no significance in density, hardness, crystal type, and crystal size when these grain types were present in capillary barriers (Table 2).

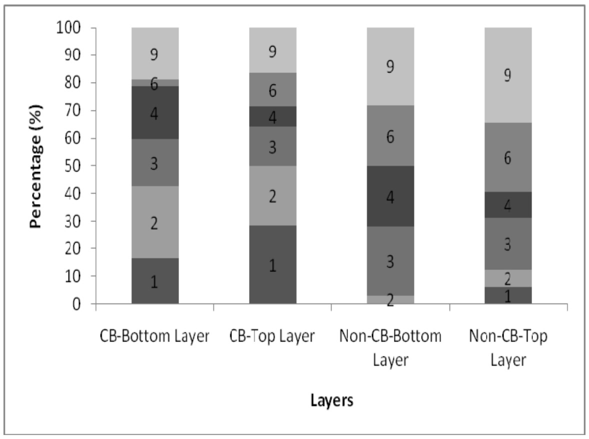

Figure 2: Proportions of crystal types comprising the layers above and below capillary barriers (CB) and non-capillary barriers (Non-CB) of all samples.

3.2 *<u>New Snow</u>*

Of 14 interfaces involving new snow, 12 of those interfaces acted as capillary barriers while two of them did not (Table 1). The crystals above the capillary barrier were columns (33%), plates (17%), or stellar dendrites (50%), while those below the barrier were columns (8%), plates (8%), stellar dendrites (33%), graupel (8%), partly decomposing crystals (17%), small facets (8%), and melt-freeze crusts (17%) (Figure 3). The crystal types below and above the interface differed with the exception of only one case (interface CB8). Only three of the 12 interfaces (CB10, 11, and 12) involved grain types other than new or precipitation particles. The interfaces involving melt-freeze crusts consisted of a few centimeters (≤ 5 cm) of new snow over the crust. Though crystal type generally varied, densities typically did not; seven of ten interfaces with complete density measurements had the same – or nearly the same – measured density above and below the capillary barrier, and statistical tests showed no significant difference in density between the layers above and below capillary barriers (p-value=1). Changes in hardness and crystal size were also subtle, but some patterns existed. Hand hardness was either the same, or the upper layer was softer than the lower layer, a relationship that is significant at the 0.10 level (p-value=0.089). Further, with the exception of one layer (CB12) the upper layer had smaller grained crystals than the layer below the interface (p-value=0.10)). Thus, capillary barriers in new snow can be created from extremely subtle changes in the crystal type. Those changes can often be identified through careful investigation of crystal types with a 30X hand microscope, and subtle changes in hardness and crystal size may be evident. However, there is no set rule for the crystal types involved in these barriers. For example, our data show that sometimes a capillary barrier can consist of columns over plates, while other times it can consist of plates over columns.

We observed only two cases where new snow interfaces did not act as a capillary barrier, so we cannot comment extensively (Table 1). In both cases, the layer above the barrier consisted of stellar dendrites while the layer below the barrier was an older layer of snow. In one case it was mixed rounds and in the other it was small facets. This is interesting because we never observed a situation where a subtle change in crystals within new snow did *not* act as a capillary barrier. It is possible that we missed some of these subtle interfaces. However, this emphasizes that any change in crystal type with new snow layers may be capable of acting as a capillary barrier.

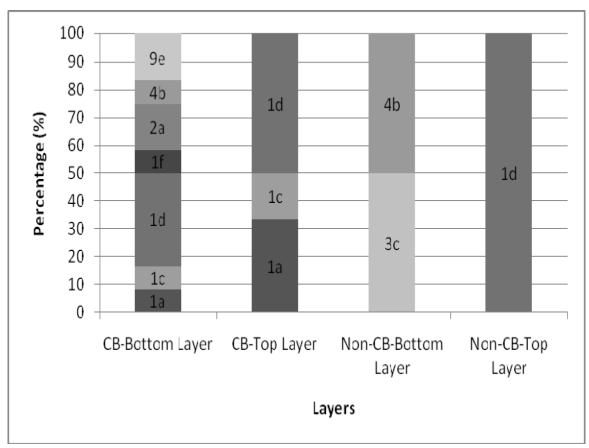

Figure 3: Bar chart displaying the proportions of crystal types in all capillary barriers and non-capillary barriers involving new snow crystals as either the layer above or below the capillary barrier.

Table 1. Characteristics of Layer Transitions Involving New Snow Crystal Types (1)									
(*ρ*=kg/m^3, *R*=scale (Fist=1, Fist+=1.33, 1F-=1.67, 1F=2.00, etc.), *E*=mm, *T*=°C, NA=Not Available)									
Interface	**CrType abv**	**CrType below**	***ρ* above**	***ρ* below**	***R* above**	***R below***	***E* above**	***E below***	***T***
CB1	1a	1d	72	72	1.00	1.00	2.00	2.00	-7.2
CB2	1a	1d	72	72	1.00	1.00	2.00	3.00	-7.2
CB3	1d	1a	64	64	1.00	1.33	2.50	2.50	-6.8
CB4	1a	1d	80	80	1.00	1.33	1.00	1.00	-12.6
CB5	1a	1c	68	68	1.00	1.00	0.75	0.75	-10.1
CB6	1c	2a	68	100	1.00	2.00	0.75	1.25	-9.8
CB7	1d	2a	138	138	1.00	1.00	1.00	2.50	-0.7
CB8	1d	1d	186	NA	1.00	1.33	0.88	0.88	0.4
CB9	1c	1f	116	112	1.00	1.00	0.38	1.13	0.0
CB10	1d	9e	120	NA	1.33	4.00	1.00	2.00	-4.7
CB11	1d	9e	53	239	1.00	4.33	1.50	2.00	-2.8
CB12	1a	4b	64	144	1.00	2.00	2.00	0.38	-11.3
NONCB13	1d	4b	64	124	1.33	2.00	2.50	0.50	-7.3
NONCB14	1d	3c	116	192	1.33	2.00	1.00	0.75	-10.3

3.3 Melt-Freeze Crusts

Crusts, especially melt-freeze crusts, are commonly considered to act as a barrier to water flow. Our work showed that in capillary barriers where crusts were present as either the top or bottom layer of the transition, melt-freeze crusts indeed were prevalent (53%) as the bottom layer, yet also comprised the upper layer of capillary barriers (20%) as well (Figure 4). Of 35 interfaces involving crusts, 15 of those interfaces acted as capillary barriers while 20 did not (Table 2). The crystals above the capillary barriers were stellar dendrites (13%), rounded particles (14%), facets (6%), wet grains (20%), and melt-freeze and wind crusts (47%). The bottom layer was comprised of precipitation particles (20%), rounded grains (13%), facets (14%), and crusts (53%). Nine of the 15 interfaces had a top layer that was harder *and* denser than the bottom layer. Yet, our statistical analysis show no significant difference for hardness between the layers above and below the interface (p-value=0.65) or for density (p-value=0.29). Also, in nine of the 15 cases the top layer was comprised of crystals of smaller or equal sized grains than the bottom layer, but our tests again showed no significant difference (p-value=0.19). Thus, our conclusion is that crusts can be both above and below capillary barriers.

Melt-freeze crusts were the most common of the crust layers present, but buried wind crusts were also present in our experiments. Interestingly, of the interfaces with buried wind crusts, this type of crust always served as the top layer in the capillary barrier.

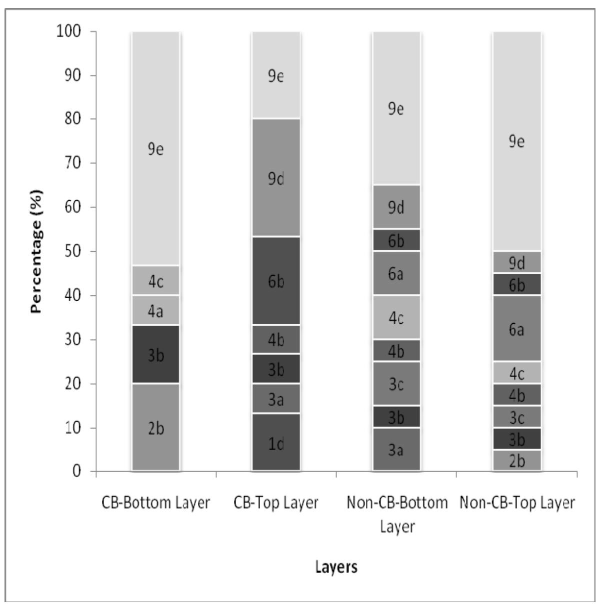

Figure 4: Bar chart displaying the proportions of crystal types associated with capillary barriers and non-capillary barriers involving all types of crusts.

Table 2. Characteristics of Layer Transitions Involving Crusts (9)									
(ρ=kg/m^3, *R*=scale (Fist=1, Fist+=1.33, 1F-=1.67, 1F=2.00, etc.), *E*=mm, *T*=°C, NA=Not Available)									
Interface	**CrType abv**	**CrType below**	**ρ above**	**ρ below**	***R* above**	***R* below**	***E* above**	***E* below**	***T***
CB1	1d	9e	120	NA	1.33	4.00	1.00	2.00	-4.7
CB2	9d	4a	392	240	4.00	1.00	0.75	1.00	-6.7
CB3	9d	2b	144	144	1.33	1.67	0.15	0.15	-1.0
CB4	3b	9e	NA	NA	NA	NA	0.75	NA	NA
CB5	4b	9e	144	NA	2.00	4.00	0.38	0.50	-2.4
CB6	1d	9e	53	239	1.00	4.33	1.50	2.00	-2.8
CB7	9e	3b	378	640	4.33	3.00	1.00	0.75	-1.0
CB8	9e	3b	172	378	3.67	2.00	1.00	0.75	-1.2
CB9	9e	2b	186	112	3.67	1.00	0.75	0.50	-0.8
CB10	3a	9e	280	NA	1.33	3.00	0.50	NA	-2.3
CB11	9d	2b	NA	152	3.00	2.00	0.20	0.38	-6.5
CB12	9d	4c	239	216	3.00	2.00	0.75	0.50	-3.5
CB13	6b	9e	371	391	1.33	3.00	0.50	1.00	0.0
CB14	6b	9e	420	420	1.67	3.33	1.75	2.00	0.0
CB15	6b	9e	434	528	2.67	2.67	0.25	1.00	0.0
NONCB16	9e	3c	NA	NA	4.00	2.00	2.00	1.25	-5.5
NONCB17	2b	9d	NA	392	1.00	4.00	0.38	0.75	-5.4
NONCB18	3c	9d	280	280	2.00	4.00	1.25	0.75	-5.6
NONCB19	9d	3c	280	NA	4.00	1.67	0.75	NA	-5.6
NONCB20	9e	4c	265	244	4.00	2.00	0.88	0.75	-3.0
NONCB21	6a	9e	184	358	1.00	3.67	0.50	1.00	-1.2
NONCB22	9e	3b	378	160	4.33	3.00	1.00	0.75	-1.0
NONCB23	9e	4c	358	172	3.67	2.00	1.00	0.40	-1.2
NONCB24	3b	9e	160	NA	3.00	3.67	0.75	0.88	-0.4
NONCB25	4c	9e	172	378	2.00	4.33	0.40	1.00	-1.1
NONCB26	9e	4b	358	159	4.00	3.00	NA	NA	-2.5
NONCB27	9e	3a	159	232	3.67	2.67	0.75	0.38	-1.9
NONCB28	4b	9e	159	398	3.00	4.00	NA	NA	-2.5
NONCB29	9e	3a	398	164	4.00	2.00	NA	NA	-2.5
NONCB30	6a	9e	380	380	1.33	3.33	1.25	1.25	0.0
NONCB31	6b	9e	456	NA	2.00	4.00	1.00	NA	0.0
NONCB32	9e	6b	380	420	3.33	1.67	1.25	1.75	0.0
NONCB33	9e	6a	NA	484	4.00	2.00	NA	0.25	0.0
NONCB34	6a	9e	484	NA	2.00	4.00	0.25	NA	0.0
NONCB35	9e	6a	NA	434	4.00	3.00	NA	0.25	0.0

We observed 20 layer transitions that contained a crust layer in which water moved directly through without being impeded (Table 2). In these cases, crusts existed as both top (50%) and bottom (45%) layers adjacent to varying crystal types (Figure 4). The most prominent crystal type (aside from crusts) in this category as a top layer is wet grains (20%); rounded grains serve as the most common type bottom layer (25%). Differences in layer density, hardness, and grain size also vary. Thus, it is difficult to draw any strong patterns that emerge as to whether the crust will form a capillary barrier, and, if so, whether it tends to be the top or bottom layer.

3.4 Faceted Crystals

Of 19 interfaces involving faceted crystals, nine of those interfaces acted as capillary barriers while 10 of them did not (Table 3). The crystals above the capillary barrier were columns (11%), highly broken particles (11%), small rounded grains (11%), large rounded grains (11%), small facets (22%), mixed forms (11%), and wind crusts (22%), while those below the barrier were solid facets (33%), small facets (33%), mixed forms (22%), or melt-freeze crusts (11%) (Figure 5). All of the crystal types differed between the top and bottom layers, and only two contained one type of facet over another (CB5 and 7). Eight of the nine interfaces have faceted crystals as the bottom layer, while one (CB3) has a melt-freeze crust as the bottom layer. Three of the layer transitions involved a crust as a top or bottom layer. Reardon and Lundy (2004) describe this “funny business” layer (a mix of faceted grains and a crust) as the failure layer in a large wet slab avalanche cycle in the spring of 2003 in Glacier National Park.

When facets are present, they comprise the bottom layer in all but one of our capillary barriers (CB3). This may be due to the “coarseness” of facets compared to the overlying layer. Density, hardness, and grain size varies between the top and bottom layer in these capillary barriers. We observed cases where the top layer is denser, harder, and with larger grain sizes than the bottom layer, as well as cases with the bottom layer exhibiting the same characteristics as the top layer. Statistical results show no significant difference between the layers above and below the capillary barriers at the 0.10 level for density (p-value=0.35), hardness (p-value=0.90), or grain size (p-value=0.81). Thus, classifying capillary barriers with facets based on these variables is difficult.

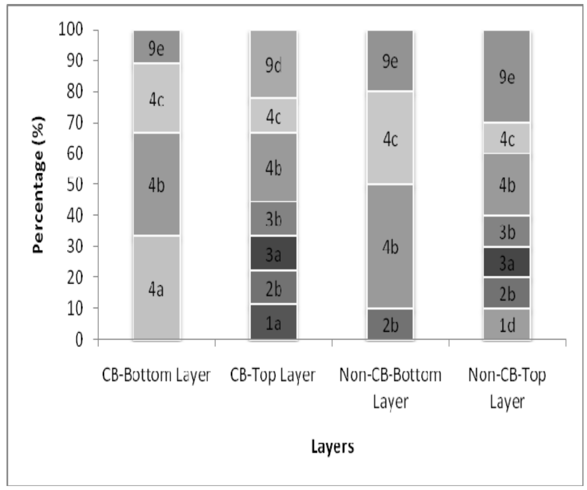

Figure 5: Bar chart displaying the proportions of crystal types associated with capillary barriers and non-capillary barriers involving all types of facets.

We observed 10 interfaces with facets that were not capillary barriers (Table 3). Of these interfaces, the top layer consisted of stellar dendrites (10%), fragmented particles (10%), rounded grains (20%), facets (30%), and melt-freeze crusts (30%), while the bottom layer consisted of fragmented particles (10%), facets (70%), and melt-freeze crusts (20%). Facets are almost as evident as the bottom layer in non-capillary barriers as they are in capillary barriers. Further, the adjacent crystal types to these facets in both capillary barriers and other layer transitions are nearly identical making it difficult to predict what may or may not serve as a capillary barrier. Therefore, careful examination during periods of water flow through interfaces involving facets is the best means of identifying capillary barriers.

3.5 Wet Grains and Rounded Crystals

A more complete explanation of our results for wet grains and rounded crystals will be included in Peitzsch (In preparation). Our most prominent conclusions are: 1) where wet grains comprise one of the two layers around the 5 capillary barriers we investigated, the crystal size was smaller in all the top layers than in the bottom layers (p-value=0.058), and 2) where rounded crystals comprise one of the two layers around the 10 capillary barriers we investigated, the top layer is always less dense (p-value=0.034). This second result is surprising since we typically would consider a denser layer over a less dense layer would act as a capillary barrier, while the opposite would not.

Table 3. Characteristics of Layer Transitions Involving Faceted Grains (4)									
(*ρ*=kg/m^3, *R*=scale (Fist=1, Fist+=1.33, 1F-=1.67, 1F=2.00, etc.), *E*=mm, *T*=°C, NA=Not Available)									
Interface	**CrType abv**	**CrType below**	***ρ* above**	***ρ* below**	***R* above**	***R below***	***E above***	***E below***	***T***
CB1	9d	4a	392	240	4.00	1.00	0.75	1.00	-6.7
CB2	1a	4b	64	144	1.00	2.00	2.00	0.38	-11.3
CB3	4b	9e	144	NA	2.00	4.00	0.38	0.50	-2.4
CB4	2b	4b	124	176	2.67	1.33	0.50	0.38	-8.4
CB5	4b	4a	176	240	1.33	2.67	0.38	2.50	-7.3
CB6	3a	4b	119	204	1.67	2.00	0.15	0.28	-1.8
CB7	4c	4a	264	264	2.33	2.00	1.50	1.25	-4.2
CB8	9d	4c	239	216	3.00	2.00	0.75	0.50	-3.5
CB9	3b	4c	164	240	2.00	3.00	0.50	1.00	-2.2
NONCB10	1d	4b	64	124	1.33	2.00	2.50	0.50	-7.3
NONCB11	2b	4b	72	256	1.00	3.00	0.75	0.15	-4.8
NONCB12	4b	2b	256	136	3.00	2.33	0.15	1.50	-5.9
NONCB13	9e	4c	265	244	4.00	2.00	0.88	0.75	-3.0
NONCB14	3b	4c	332	264	2.67	2.33	1.25	1.50	-6.5
NONCB15	9e	4c	358	172	3.67	2.00	1.00	0.40	-1.2
NONCB16	4c	9e	172	378	2.00	4.33	0.40	1.00	-1.1
NONCB17	9e	4b	358	159	4.00	3.00	NA	NA	-2.5
NONCB18	4b	9e	159	398	3.00	4.00	NA	NA	-2.5
NONCB19	3a	4b	232	280	2.67	3.00	0.38	0.50	-2.3

4. CONCLUSIONS

Snow crystal types helped to effectively characterize capillary barriers in our data. The relationships between the snow crystal types, as well as factors such as layer density, hardness, and crystal size all play a role in determining whether a layer transition is a capillary barrier or not. Our results illustrate the complexity of capillary barrier formation. Though we investigated 51 capillary barriers, we found it difficult to unearth distinct patterns in those layers. For new snow these transitions are exceedingly subtle, but they still served to allow downhill water transport for many meters of slope distance, a finding consistent with past work (Kattelmann 1986). Our findings suggest that rain or meltwater on new snow is likely to move water downslope and laterally along quite subtle textural changes within that new snow.

We found that crusts can form either the layer above or the layer below capillary barriers. We also observed the same conditions in non-capillary barriers suggesting that the presence of crusts does not always imply that it will be a capillary barrier. Also, water not only flows along the top of crusts but also below the crusts. While both wind and melt-freeze crusts may form the layer above capillary barriers, we observed only melt-freeze crusts below our capillary barriers.

In only one out of nine cases were facets found above a capillary barrier. In all other cases where facets were associated with these barriers, they were below the barrier. This makes sense because facets typically form porous, loosely compacted layers, so we would expect other adjacent layers to better hold the water. This emphasizes the importance of carefully monitoring faceted layers when free water starts moving through the snowpack. Water flowing along strong capillary barriers may weaken bonds at grain boundaries or lubricate the transition between two layers, thereby increasing the potential for wet slab avalanches.

More work is needed to better understand the complexities of capillary barriers and their role in wet slab avalanche formation. While we applied varying amounts of water in our experiments, it was constructed as a test plot, not a slope-scale experiment. The amount of water flow on a large scale might also be critically important as to whether or not a capillary barrier will form at specific interfaces. Therefore, it is a complex problem with no simple answers, but this work provides a start for understanding capillary barriers in the inclined snowpack and aids practitioners and researchers alike in identifying the location where free water within the snowpack may move downslope laterally and identify potential failure layers in a wet slab avalanche scenario.

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