Effects of an Early Season "Rain" Crust on Snow Pack Stability within the Continental Climate.

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Abstract

On January 6th and 7th, 2002, the central and northern mountains of Colorado, and Copper Mountain ski resort, experienced a "freezing rain" weather event. This deposited a 4 – 8 mm solid ice crust upon the surface of an 80cm deep, mostly faceted snow pack. This layer affected snow pack stability throughout the season culminating in a large explosives triggered avalanche cycle starting on April 1, 2002 lasting through April 7, 2002. This event involved open terrain which had 3 months of light to heavy skier compaction along with avalanche mitigation measures. Fracture line depths ranged from 1.25 to 2.5 m with widths exceeding 40 m. Aspects ranged from east to south with fracture line elevations from 3767 to 3700m with vertical fall exceeding 180m. Fifteen medium to large slides produced extensive debris fields with depths of 4 to 7m.

Differential creep rates within the upper layers of the snow pack (which occurred after a rapid warm up late March), was a major contributing factor. Water percolation within these layers produced interesting liquid conduits and ice layering evident at the fracture lines. A combination of multiple planer layering and vertical water flow contributing to differential creep stress between adjacent layers will be discussed. Finally, a 6-10cm faceted snow layer which was sandwiched between the "rain crust" and a melt freeze layer produced a very weak shear failure plane above the "rain crust" bed surface.

Discussion

Late in the afternoon on January 6, 2002 a "freezing rain" precipitation event started at Copper Mountain Ski Resort, Colorado. This 18 hour event started about 4:30 pm and was noticed by the author while participating in the end of the day mountain sweep by the ski patrol. The precipitation at the start was of a wet needles variety which instantly froze on any surface especially your goggles making skiing difficult. The air temperature was about (-3.5 Celsius) with very light westerly winds. The event was occurring at a greater rate at the top of the mountain and less evident at lower elevations. By the next morning an ice crust had formed on all surfaces upwards of (5cm) thick. On snow surfaces this crust was about (8mm) thick and very supportive to the weight of a skier. As expected, the crust was thicker at higher elevations and windward aspects, but evident on all aspects and elevations.

Copper Mountain ski resort is located approximately 121km due west of Denver, Colorado. It is about 16 km west of the continental divide with a base elevation of 2960 km with 3 summits reaching 3767 km. Avalanche areas are mainly located within 3 high alpine bowls; Spaulding, Union, and Copper Bowls, with base elevations above 3300 km.

Copper Mountain's bowls in foreground

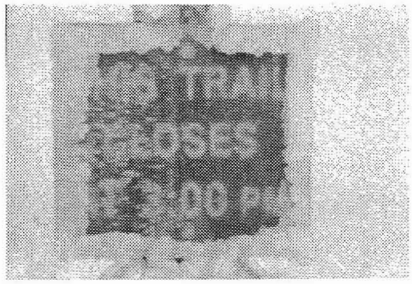
Aspects range from south to east to north with loading winds being predominately cold, dry northwest with significant events also occurring from the southwest with warmer temperatures and greater moisture content.

Copper Mountain's weather is a good example of the continental climate. Winters usually start cold and dry with minimal snowfall per storm (10 - 25 cm), low moisture content (5 to 10 %), and brisk, cold, northwest winds. This produces a shallow, faceted, snow pack with widespread surface wind slabs on lee slopes. Midwinter begins a slow warming as winds shift to the west - southwest bringing occasional heavier, warmer, and wetter storms. Nighttime temperatures still fall well below freezing with southern exposures getting above freezing mid morning. Multiple melt - freeze layers will form on southerly aspects with the northern aspects remaining cold and dry with surface faceting. A substantial (15 – >30cm) basilar depth hoar layer is usually found on most aspects. In spring, the temperatures will produce isothermal conditions on southerly aspects with colder snow packs on non-exposed sun aspects. Liquid precipitation is rare even in the spring months.

As information started to be received by the Colorado Avalanche Information Center, this "freezing rain" event occurred in a band from Steamboat Springs to the north, the west aspect of the continental divide, Crested Butte to the south, and Beaver Creek Resort to the west. The areas of greatest accumulation was the Copper Mountain to Vail area with thickness rapidly thinning as one traveled away from this area.

Reports from people driving over nearby Vail Pass (elevation 3250 km) later that night stated that precipitation froze on windshields and the road surface making driving extremely hazardous. Snow cat operators also reported difficult conditions as equipment froze up during the night. Detachable chair lifts had great difficulties in morning start up as the rubber wheels of the detachment apparatus were slipping with the ice accumulations.

Tim Shinn, a ski patroller who resides at the top of the ski resort at one of the duty stations, came down the mountain and had the first reports of the ice crust for the ski patrol. The snow mobile he was using had been outside during the event and had a clear ice crust approaching 3 - 5cm thick on the windward side. He reported that the entire upper zone of the ski resort was covered with greatest thickness on the windward aspects and side of any object above the snow surface. As the ski patrol worked its way up the mountain the ice crust was very evident covering chairs, towers and the snow's surface.



2cm clear ice layer over sign with 8cm rime edges.

Since Copper Mountains inception in 1972, very few freezing rain events of this nature have occurred and almost always early season in November. They have become a very significant sliding layer within the snow pack which would become evident months later as a bed surface of widespread avalanche activity or an impedance layer causing faceted layers to form above and below. One example occurred in Spaulding Bowl in 1999 when a large portion of the bowl slid when triggered by a patroller approaching a shot placement. Knowing that this "freezing rain event" had occurred, it would have to be closely monitored for the rest of the season.

Several days after the freezing rain event, a cold mid- mountain snowfall of 20cm with strong northwest winds occurred. It had remarkably good adhesion to the rough surface of the rain crust and promptly buried the rain crust to a level not easily affected by ski cutting. A brief warm day followed which formed a 1-2mm melt – freeze crust upon this new snow. Subsequent management of snowfall and snow pack allowed Spaulding Bowl and most of the other bowls to be opened to the public by late January. Moderate to heavy skier compaction helped stabilize the new snowfalls further burying the rain crust.

As the 2001-2002 seasons progressed it was below average in temperatures, snowfall and water content. Storms had prolonged periods of high winds with small accumulations. Wind redistribution of surface layers along with cold was a common weather occurrence. March was an especially cold month and brought below normal temperatures remaining well below freezing and light snowfalls. The overall snow pack remained in a mid winter regime. Wind events further buried the rain crust and its associated faceted layers under one to two meters of snow. In wind exposed areas the rain crust remained uncovered throughout the season. Avalanche activity during the winter occurred well above the rain crust and seldom affected the associated faceted layers although several large events did occur. However, we knew that eventually spring and warmer temperatures would occur which would greatly effect the deep slab instability. Melt freeze water percolation and warming of the snow pack to isothermal conditions would significantly weaken the stronger layers above the now isolated rain crust and faceted layers.

Snow pit study would identify the rain crust and faceted areas of concern above and below caused by the impedance nature of the rain crust under high temperature gradients (exceeding 1-2 degrees c. per 10cm). Depth hoar and facets soon became the snow pack below the crust as the overall base measurements (< 1 meter), air and snow pack temperatures all remained below normal. A 6 - 10cm layer of 1-2mm faceted grains had also formed between the rain crust and the melt freeze layer. Due to moderate skier traffic, 1 meter deep moguls were the norm on most slopes within Spaulding Bowl well above the rain crust.

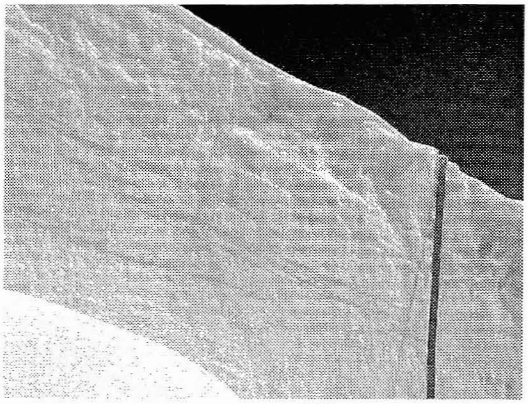
Late March and early April saw a rapid warm up with well above normal temperatures with no precipitation. Starting March 26 and extending through April 10 daytime temperatures averaged 5 to 12 degree Celsius in the upper elevations of the resort. Southern exposures experienced an extremely rapid warm up with free water percolating within the upper layers. Overnight temperatures remained close or above freezing with minimal solidification and strengthening of the upper snow pack. Geological ground warming was also occurring within the basal layers resulting in shallow areas becoming isothermal alarmingly fast. Around rock outcroppings, thin areas, and scree fields, snow conditions deteriorated to the point where a skier was no longer supported. As these areas were closed to the public, access out of the remaining open non sun aspects of the bowl forced skiers to traverse below, and well within the run out zones of the now unstable slide areas. Explosives were recommended as a safe way to test stability and mitigate avalanche potential along with curtailing hours of operation within the bowl.

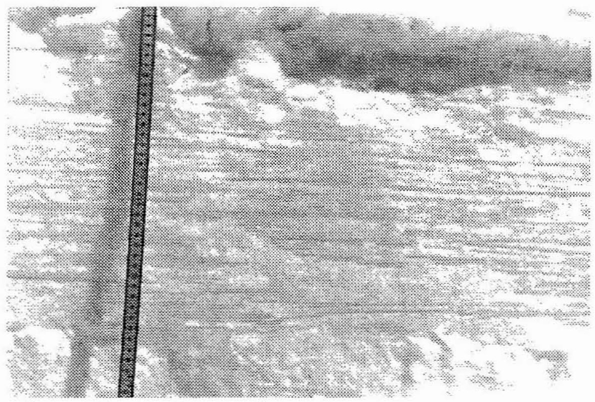
Explosives including 1 kg PETN cast primers but mostly 2 - 4 liter plastic jugs (2-3kg) of ANFO (ammonia nitrate and fuel oil) with their slower detonation velocity and more "heave" were used. Immediate results occurred with multiple WS-AE-3-0 slides occurring with fracture line depths around 1.25 – 2.5 meters and about 20 to 50 meters in length. The bed surface appeared to be at the depth of the rain crust with the weak failure layer being the faceted grains directly above. As explosive testing moved into areas which were deeper and non isothermal, a colder (-4.5degree c.) and dry 40 - 75cm thick midpack layer existed. This contributed to the avalanche debris being a combination of wet and dry slab material. Each charge released a large volume slide. Debris piles were 4 to 7 meters in depth which would cover the exit traverse for the open areas within Spaulding Bowl. Snow cats would rebuild this traverse on a nightly basis as temperatures cooled and stability increased.

Northeast aspects within the bowl which didn't have such rapid warming and solar radiation would be open for several hours in the morning then closed as the more southerly aspects warmed up. Control work would start early afternoon with dramatic results occurring. Slope angles averaged about 34 to 38 degrees with vertical drops about 180m, with linear distances exceeding 350m. Skier compaction ranged from low to moderate in the initial release zones but involved areas of moderate to high compaction by the time the 6 day cycle was over. In all, 15 slides occurred involving over 500 linear meters of fracture lines and thousands of tons of debris. The cycle ended as suitable avalanche terrain and conditions were exhausted.

The slide cycle was closely monitored for suspect characteristics which would give us clues to the mechanism of release. From data collected before, during, and after it was concluded that perhaps differential creep rates between the rapidly warming surface layers on top of colder mid pack layers induced shear stress within the layers above the rain crust. With a nearly non-cohesive 6 - 10cm layer of facets directly above the rain crust, capped by a thin melt freeze layer, the upper layers were isolated and reacted independent of the basal depth hoar layers or the rain crust itself.

A very curious phenomenon was noted within the surface and immediate layers below with water percolation flow patterns. Multiple ice lenses (10 to 20) formed within the top 30 – 50cm layers. It appeared that water would percolate downward until it hit a slightly colder layer and spread horizontally. Percolation channels were noted where a layer would melt through and the process would occur directly below. This would repeat itself many times until there were multiple ice lenses 2 to 4mm thick with very small grain layers sandwiched in between. At the fracture lines these layers could be easily followed and photographed.

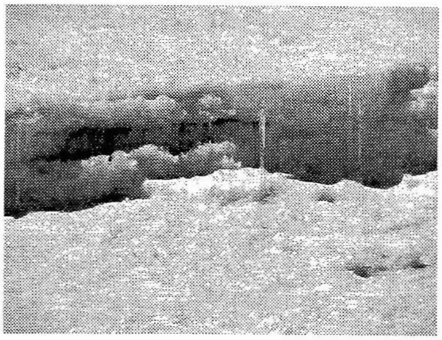




Water percolation channels and layering.

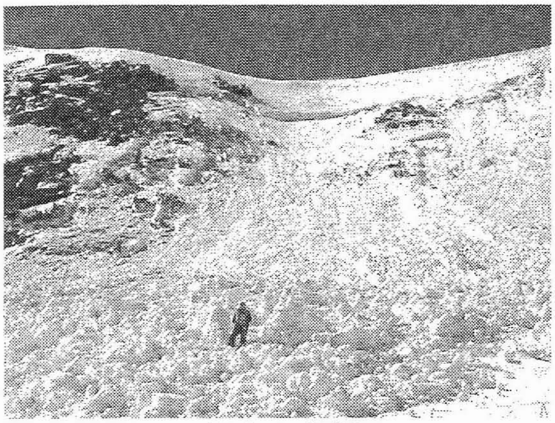
The areas of occurrence were heavily wind affected with almost constant surface transport of cold broken grains from a northerly fetch over the course of the winter. Multiple thin layers of wind transported grains formed. Snow temperature profiles showed that temperatures decreased from 0.0c within the level of solar influence, to a low temperature of – 4.5c 50cm down. During the rapid warm up of late March, this process may have produced a more vicious, well lubricated, easily deformable upper snow pack layer which could induce higher levels of shear stress on the layers directly below. At the point of maximum mid day warmth, this differential creep rate (along with deeper snow pack instabilities) was then influenced to the point of failure with the use of explosives which could have contributed to the resulting large avalanches.

It was noted that before the avalanche activity occurred, 2-4cm wide and 20 - 40cm deep creep cracks were observed in some areas where subsequent fracture lines later occurred. After the ensuing avalanches, much larger creep cracks formed above and adjacent to these fracture lines in the following days. Water freely flowed out of the fracture lines 10 – 20 cm down from the surface (extent of daily warming as solar heating occurred). This made fracture line investigation in some areas impossible due to suspected wet slab instability. Fracture lines also occurred lower than traditional starting levels where wind loading would taper off and a thinning of the overall snow pack occurred.



Icicles evident of flowing water at a fracture line

All but one slide occurred much lower than normal. The one exception was the last slide to occur where the mid tract area released first, removing any compressional strength and releasing a slide with a 2.5 meter deep fracture line within the traditional starting zone. It occurred within a large wind drifted area which was formed from deceleration behind our patrol headquarters. (This sizable drift is a new loading feature due to the building's construction only 3 years prior).



Debris field.

Adjacent fracture lines with exit traverse.

Conclusion

The effects of an early season freezing rain event upon the surface of a very thin continental snow pack produced a deep slab hazard which lasted until sufficient loading and spring warming occurred. It is believed, with a very rapid warm up of the surface layers, differential creep rates produced high shear stress within the snow pack above the rain crust. A very weak faceted layer which formed above the rain crust, isolated the upper skier compacted snow layers from the rain crust and lower layers, developing a very precarious situation. During daily warming of the upper layers, stability greatly decreased as snow temperatures increased. With the introduction of explosives, widespread avalanching occurred.

Also, with extremely rapid surface warming of a cold snow pack, unusual ice layers and percolation channels had occurred. Multiple conduits for water percolation and planar flow developed which followed grain and temperature boundaries. This decreased adhesion between layers when wet, but greatly increased stability when frozen. This phenomenon needs to be investigated more closely in the future as a possible contributing factor for wet slide activity. By providing heat within a layer and lubrication between layers, percolating water could allow a layer to deform more readily producing differential creep rates. The above could increase stress between the upper and mid layers of the snow pack leading to possible mid pack or deeper failure resulting in large volume spring slides.