UNUSUAL DRY SLAB AVALANCHE RELEASES INVOLVING DUST-ON-SNOW LAYERS IN COLORADO

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ABSTRACT: In recent decades, dust-on-snow events are increasing in both frequency and geographic extent in the Western U.S. Although dust layers have gained a reputation for creating unusual avalanche conditions, especially with wet avalanches, there has been little research on the effects of dust layers on dry slab avalanche release. Landry (2014) presented several observational and theoretical processes on how dust layers can affect dry snow via faceting and crust formation. In this paper, we present several case studies of dry slab avalanche events that were unusual or challenging to predict during the past several seasons in Crested Butte, CO. We describe snowpack, weather, and avalanche observations leading to several near misses or surprising avalanches involving dust layers. For each case, we hypothesize on the effects of the dust layer and how it contributed to unusual or long-live instabilities. These events demonstrate several unique metamorphic and rapid change processes involving dust on snow, with the goal of improving avalanche forecasting. We hope these unusual and interesting avalanche occurrences will inspire further research in the field and laboratory setting and promote an increase in the documentation of dust observations and avalanche events involving dust layers.

KEYWORDS: dust, slab avalanches, metamorphism, forecasting

1. INTRODUCTION

1.1 Dust on snow

Recent years have seen an increase in deposition of desert dust on the mountain snowpacks in the southern Rocky Mountains (Neff, et al., 2008; Brahney et al., 2013; Landry, 2014; Skiles et al., 2015; Clow et al., 2016). Deposited primarily during spring events, but also in midwinter, the dust increases the absorption of solar energy and speeds the warming and/or melt of the snowpack, altering snow metamorphism and resulting in faster snow melt. The majority of studies to-date have focused primarily on hydrologic importance, with enhanced snowmelt rates leading to early snow disappearance, rapid streamflow increases, early runoff peaks, and reduced runoff volumes (Painter et al., 2007; 2010; 2012; Skiles et al., 2012; Deems et al., 2013).

The primary effect of dust stems from its low albedo (reflectivity) compared to snow, and the resulting enhanced absorption of solar energy. Due to penetration of solar energy into the snowpack, dust layers can enhance absorption of solar energy even when buried by 30 cm or more of snow. Depending on the snow temperature and the amount of solar input (strongly terrain-dependent), this additional absorption can provide a heat source leading to altered temperature and vapor pressure gradients and enhanced cold snow metamorphism, and to melt production, melt-freeze processes, and wet snow instability (e.g. Birkeland, 1998; Landry, 2014).

1.2 Previous work

Several case studies and observations of processes have explored the role of dust layers in avalanche formation. Toepfer et al. (2006) detail the deposition environment and avalanche impacts of a midwinter dust event in 2006, noting specifically the contribution of the dust to a February wet avalanche cycle and repeated avalanche occurrence on the dust layer with every storm throughout the spring. Landry (2014) provides a comprehensive discussion on potential pathways for dust-influenced processes to impact avalanche formation and occurrence, along with observations conducted around both accumulation and melt season events. As Landry (2014) observes, while dust on and in the snowpack can be seen as enhancing processes already familiar to snow observers, such as near-surface faceting processes, the intensity and rate of energy and mass fluxes can lead to “quite exotic” and complex snow structures and surprising avalanche events.

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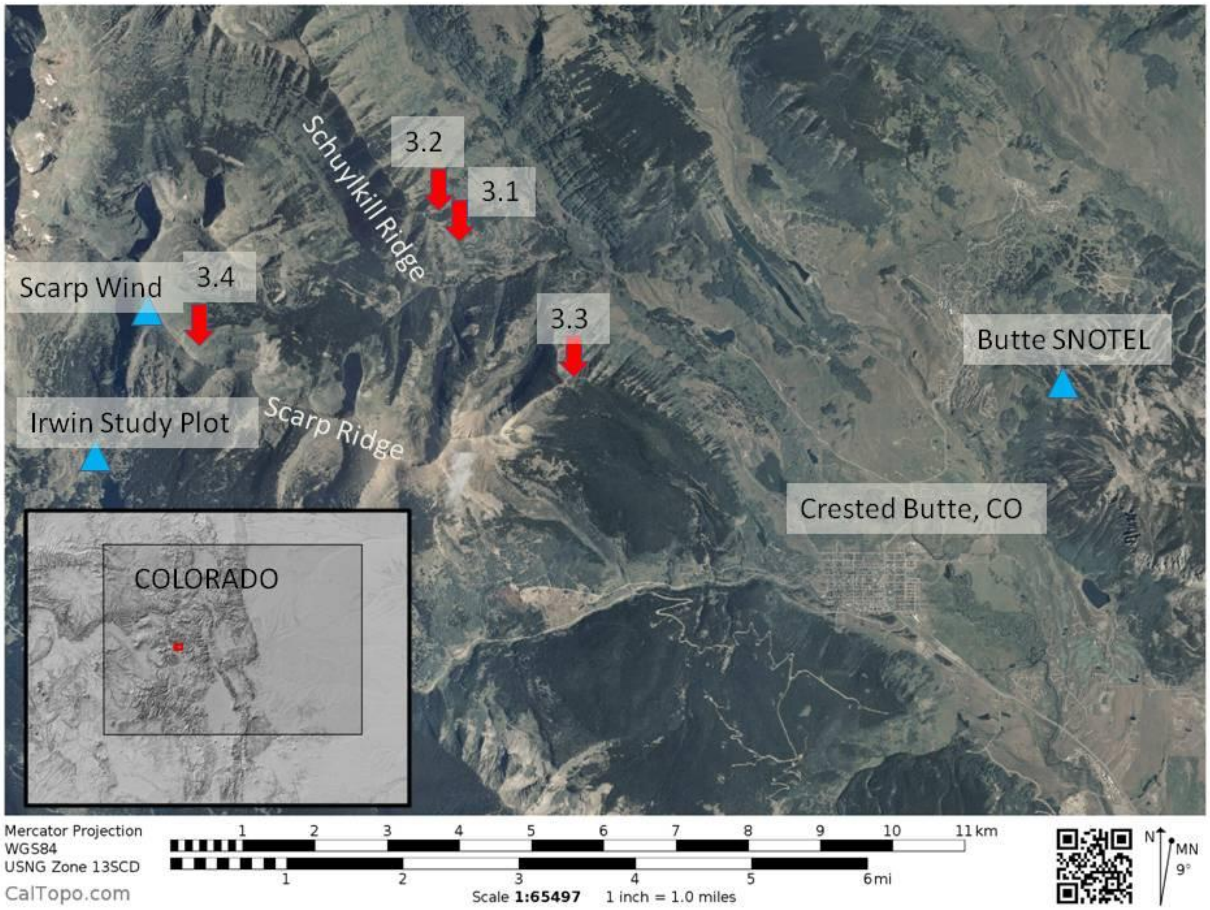

Fig. 1: Location of the study area near Crested Butte in Central Colorado, northeast of the Colorado Plateau. The avalanche incidents described in sections 3.1 to 3.4 are labeled accordingly. Temperature, wind, and snowfall data are from the three sites labeled above.

In this paper we explore several dust-related avalanche case studies from the Crested Butte region in central Colorado. We hope both to add to the body of observations detailing dust on snow avalanche events and to renew the call for new and sustained observations and research into this important and highly dynamic set of avalanche processes.

2. STUDY AREA

2.1 Crested Butte

These case studies are from the backcountry surrounding Crested Butte, Colorado (Figure 1). Crested Butte is located in the Elk Mountains of central Colorado, which are generally characterized by a continental snowpack (Mock and Birkeland, 2000). Gothic, CO, located 9.6 km north of Crested Butte, has averaged 1092 cm of snow annually since 1974 (Barr, 2016). The Elk Mountains rise above the eastern edge of the Colorado Plateau, and they form one of the first downstream barricades to storms tracking from the southwest across the desert regions of Arizona and Southern Utah. Dust-on-snow events in the Elk Mountains are becoming increasingly common each year due to land use and modification on the Colorado Plateau (Neff et al., 2008; Skiles et al., 2015). They typically occur in the spring, when strong southwest wind events transport red or brown desert dust and deposit it onto the surface of the snowpack. Though the majority of detailed dust on snow studies have been conducted in the San Juan Mountains to the southwest, the Elk Mountains are situated downwind of the same dust source regions, and manual and satellite observations indicate that the annual pattern of dust deposition has closely followed that monitored in the San Juan Mountains to the southwest of the Crested Butte region (Burgess, 2014; Center for Snow and Avalanche Studies, 2016).

2.2 *Observations*

This paper presents case studies of several unique or unexpected avalanche events involving dust layers from 2013 and 2016. Narratives describing the weather, the snowpack's evolution, and pattern of avalanches come from the Crested Butte Avalanche Center's (CBAC) field notes and public advisories, and discussions and observations from the Colorado Avalanche Information Center. The parties involved with triggering these avalanches initially reported the details of the event to the CBAC, or in one case the author remotely triggered one of the slides. Specific snowpack and avalanche characteristics presented here come from subsequent site visits made from CBAC forecasters within several days of the avalanche occurrences.

Snow and snow water equivalent (SWE) data are manually collected twice per day from Irwin's snow study plot, located near Lake Irwin 10.6 km west of Crested Butte at 3108 m. Due to orographic effects, the amount of snowfall typically decreases eastward from this study plot; the eastern-most Climax incident site commonly sees half of the amount of measured snowfall or less. Temperature data come from the Butte SNOTEL site, located on Mt. Crested Butte approximately 4.3 km northeast of Crested Butte at 3097 m. All wind data is from the Scarp Ridge wind station, 10.3 km northwest of Crested Butte at 3647 m (Figure 1).

3. CASE STUDIES

3.1 *3.1 April 14, 2013 - Schuylkill Ridge*

From April 8th to April 9th, 2013, a closed low steering from the desert southwest brought 53 cm of new snow and 2.9 cm of SWE to Irwin's snow study plot. A diffuse layer of dust accumulated in the lower few centimeters of fresh snow. As anticipated under a relatively large and rapid load, storm instabilities were observed within and above this dust layer during the storm. Sunny weather on April 10th and April 11th consolidated the new snow into a supportive crust on solar aspects and into settled powder or thinner crusts on shadier slopes. The snow depth decreased from 191 cm to 157 cm over these two days, bringing the April 8th dust layer closer to snow surface. Apart from shallow wet loose avalanches involving the recent snow, the pattern of short-lived spring storm instabilities played out as expected, and signs of slab instabilities disappeared. Unsettled weather brought light snow flurries and no noteworthy changes to the snowpack over the next two days

Fig. 2: The crown of a remotely triggered soft slab avalanche on Schuylkill Ridge on April 14, 2013. The trigger was near the gladed ridgeline in the background, at least 30 m away. Dusty and friable wet grains comprise the weak layer and bed surface.

before another 46cm of snow (2.5 cm SWE) fell overnight on April 13th. Alpine winds during the storm averaged 11 m/s from the WSW, gusting to 36 m/s. Temperatures fell from a high of 7° C to -6° C overnight, but the snow initially began falling at 0.5° C at the onset of the storm. On April 14th, the skies began clearing through the morning.

On April 14th, several natural D2 wind slabs were observed below alpine ridgelines, apparently failing within the new snow. In more sheltered locations, several observers, including myself, found the warm-arriving, cold-exiting storm had bonded well to the crusty storm interface. I was traveling on Schuylkill Ridge, where the overnight storm snow was 40-50 cm deep. I could not find any signs of instability on northerly aspects, but as I worked towards more easterly and southerly facing slopes, I experienced widespread collapses, even in wind-sheltered terrain. On these sunnier aspects, the April 8th dust layer was about 6 – 8 cm below the crusty storm interface. Large, friable, unfrozen wet grains surrounded this dust layer. As we approached the first avalanche path from the ridgeline, we remotely triggered a D2.5 slab avalanche from 30 m away. The crown was on a SE aspect near treeline, ranging from 45-60 cm deep, 120 m wide, and the slide ran about 610 vertical meters (SS-ASr-R3/D2.5-O). Although the slab was dry, the weak layer was the large, wet grains surrounding the dust layer, which held an unusually airy and porous appearance (Figure 2).

In this case, the behavior of the avalanche was surprising for a late-spring storm like this. That day, we expected to find storm or wind slab instabilities, confined to specific features without the potential for wide propagation and remote triggering. Yet this dust layer exhibited unusual behavior, with audible collapses and a remotely triggered avalanche.

Due to its lower albedo and its insulated position within the snowpack, it appears that the dust layer gained and retained more heat on these sunnier aspects than on slopes with less solar exposure. This caused the surrounding grains to melt into poorly bonded wet grains before the overlying crust was buried. The high porosity of the dust-containing layer (relative to nearby layers) indicates that the extra solar absorption created very high melt rates within that layer, resulting in a loss of mass through meltwater. Additionally, this layer may not have completely refrozen before burial (air temperatures were above freezing at onset of snowfall), and/or there may have been enough solar gain that day for the dust layer to weaken the bonds below the slab. The aerated nature of the wet grains surrounding the dust was unusual compared to what we observe with clean, wet snow grains, but is consistent with other observations of layers subjected to dust-enhanced metamorphism and melt (e.g. Landry, 2014). We have observed unusually porous or angular wet grains when dust layers are at the surface. It appears that this process can also occur below the surface, and these exceptionally weak wet grains likely produced the facet-like behavior observed that day.

3.2 Schuylkill Ridge - March 27, 2016 and 3.3 Climax Chutes - March 28, 2016

A record setting wind event on February 18th, 2016 flattened hundreds of trees and brought a layer of desert dust with a few cm of new snow. Scarp Ridge recorded gusts to 52 m/s out of the south-southwest. A month-long dry spell ended on March 6th, and a series of three storms arrived on weekly intervals through the rest of March. Irwin's snow study plot recorded 28cm of snow with 2.4 cm SWE on March 7, 50 cm of snow with 4.6 cm of SWE from March 14th - 16th, and 109 cm of snow with 5.6 cm of SWE from March 22nd - 26th. The dust layer marked the end of our month-long dry spell, and this March 6th dust/facet layer on due northerly aspects or dust/crust/facet layer on northeasterly aspects continued to plague us through the month. With each storm, we saw a handful of slabs failing on that layer, and these slabs became increasingly larger with each storm. Our forecasters continued to find propagating extended column test results all month on the same layer on shaded aspects (where the facets had formed and been preserved prior to burial).

In the last few days of March, there were two close calls involving this dusty persistent weak layer. On March 27th, a skier was caught and partially buried in a persistent slab avalanche on a northeast aspect of Schuylkill Ridge. The slab failed on the March 6th dust/facet/crust layer, 61 cm deep, 30 m wide, and ran approximately 300 vertical meters (SS-ASu-R2-D2-O; Figure 3). The group of experienced skiers was on their 4th lap in that bowl that day, and that particular path had dozens of tracks from days prior.

The second close call was with another group of highly experienced riders in the northeast-facing

Fig. 3: Crown profile of the near-miss on Schuylkill Ridge on March 27, 2016. The March 6th dust/facet/crust layer can be seen at the bed surface, and the March 22nd dust layer (See section 3.4) is also visible in the middle of the slab.

Climax Chutes of Mt. Emmons on March 28th. A skier triggered the slide low on the slope but escaped getting caught. The crown was 35 m wide, averaged approximately 51 cm deep, and ran approximately 550 vertical meters, gouging to the ground on its way down (SS-ASu-R3-D2.5-O/G, Figure 4). It also failed on the dusty March 6th interface with an audible collapse, on a weak layer of 0.5mm rounding facets, capped by a thin crust in places.

Long-lived persistent slab instabilities are common in Colorado, but this dust/facet layer was unusually active and prolonged for a mid-snowpack facet layer buried in March. Although the entire state experienced a facet-forming dry spell in February, other parts of Colorado were seeing few, if any, signs of instability with this facet layer by late March. Yet in the Crested Butte backcountry, we were consistently finding propagating extended column tests and seeing avalanche results to support them. This can certainly be attributed to spatial variation of other snowpack factors on a regional level, but the Crested Butte area was one of the few locations in the state that saw the combination of a significant dust event followed by continued dry weather that kept the dust at the surface. For instance, the neighboring Northern San Juan Mountains saw the same dust event on February 18th above a widespread facet layer, but saw 15 – 25 cm of new snow bury the dust four days later. This likely diminished the effects of the dust compared to the Crested Butte area, where it remained at or just below the surface until March 6th.

The most unusual observation from this dust layer came from our site visit to the Climax Chutes avalanche. The crown of this avalanche appeared atypically low in the starting zone of this path, 60 to 90 vertical meters below where it commonly starts. When we investigated the crown, the March 6th dust layer was evident on the bed surface below the crown (Figure 4), but wasn't apparent above the crown or along the flanks of the avalanche, based on hasty pits and hand pits while traversing above and along the skier's left edge of the slide. Because this dust layer was deposited with snow during a major wind event, it displayed localized drifting patterns, which could explain why it was found only in parts of the path. The dust pattern in the bed surface shows evidence of longitudinal striping, as might be caused by cross-slope winds and dune formation, consistent with the SSW winds during and after dust deposition. There was no apparent change in slope angle or slab thickness above the crown, two critical contributors to slab fracture arrest (Simenhois and Birkeland, 2014). Empirical evidence from this slide suggests that the dust contributed to enhanced weakness or longevity with its surrounding facet layer, or potentially contributed to the formation of a thin crust above the facets that promoted fracture propagation. The apparent absence of the dust elsewhere along the flanks and above the crown could explain the crown location and extent of the slide, or it could be that a more extensive search (via trenching or systematic pits) would have revealed dust elsewhere on the slope. Though the exact distribution of the dust and its specific contribution to the Climax Chutes event are not well understood, the weak layer and collapse mechanism clearly indicate that dust played a role in the formation of this avalanche, and likely contributed to the location and extent of the release.

Fig. 4: The Climax Chutes avalanche that nearly caught a skier on March 28, 2016. Note the March 6th dust layer on the bed surface. In a subsequent site visit, we did not find this dust layer present above the crown or along the skier's left flank.

3.4 *Scarp Ridge - April 3, 2016*

On March 22nd, 2016, another layer of dust was deposited at the onset of a period of extended snowy weather. Irwin's snow study plot reported 109 cm and 5.6 cm of SWE from March 22nd through March 26th. The March 22nd dust layer marked the end of a 6-day dry spell, and was deposited on top of settled powder, crusts, or small-grained near surface facets. Sunny spring weather returned on March 27th and 28th, with highs reaching 2.8°C and 7.8°C, respectively. This allowed for good views of numerous storm related slab and loose snow avalanches in this area, none of which appeared to fail on the dust layer, but rather, on mid-storm density differences. Given the potentially problematic dusty interface, CBAC forecasters monitored the March 22nd layer closely in snow profiles over the next week, but found weaknesses to be indistinct and well-bonded in all but one isolated pit location. From March 29th to March 30th, another 30 cm and 1.4 cm of SWE fell at Irwin under light wind speeds, averaging 6 m/s. No signs of instability were observed with this new snow other than small wet loose avalanches as the sun came out over the next 3 days. April 1st through April 3rd brought clear skies and a warming trend, with temperatures rising to 0.6°C, 6.7°C, and 7.8°C. Winds were light with no snow transport during these three days. The snow depth at the Irwin study plot decreased from 203 cm on March 31st to 183 cm by April 4th, with 7.6 cm of settlement on April 3rd.

The slope of concern in this case study is a northeast facing pitch above treeline at 3596 m, below a cliff band of Scarp Ridge. On April 2nd, a pair of experienced ski guides descended the slope with no signs of instability. At the CBAC and CAIC, we were discussing dropping the danger to low during this period: the March 22nd layer was seemingly a non-issue, and the March 6th layer (described in the previous case studies) was trending towards an unlikely avalanche problem. On April 3rd, a D2 dry slab avalanche ran naturally on the same slope that was skied the day prior (SS-N-R2-D2-O). CBAC forecasters viewed the site from above the next day, and it does not appear that a cornice fall, rock fall, or loose snow avalanche triggered the slide (Figure 5). The majority of the bed surface was comprised of the March 22nd dust layer, with a very small portion of the slide “stepping up” to a clean snow layer a few cm higher. The crown was roughly 46 cm thick, up to 60 m wide, and ran 215 vertical meters.

This slide was surprising for a number of reasons. It failed naturally during a period of relatively benign weather, absent of additional loading or a dramatic temperature or solar change from the day prior. It also failed on a layer that we had been observing as non-problematic, and we continued to find this layer to be well bonded in snow profiles through the rest of spring. This was the only observed avalanche that failed on the March 22nd dust layer, and it failed naturally during a period of seemingly stable avalanche conditions.

Fig. 5: A natural avalanche that occurred below Scarp Ridge during a period of relatively good stability on April 3, 2016. The March 22nd dust layer is visible on the bed surface; this layer had not displayed any avalanches or alarming pit results prior to this avalanche.

This avalanche brings to question the mechanics of failure as well as the reason for this anomalous instability. We hypothesize that the dust layer was near enough to the surface to cause additional solar gain in the upper snowpack, leading to rapid snow settlement and slab deformation. The dust layer may have contributed to unusual metamorphism at the failure interface, either enhanced faceting or crust formation.

4. DISCUSSION

The case studies presented here serve to highlight several important challenges with assessing the impacts of dust on snow stability. While the exact processes and mechanisms in each case are not clear, several features are worthy of note and further study.

Consistent with observations elsewhere, and with details presented in Landry (2014), dust layers can enable the formation of a very porous, friable, and poorly bonded snow layer, often underneath a thin crust, that can result in widespread collapsing – a behavior akin to that seen with surface hoar or depth hoar faceted layers, but in a spring snowpack where this failure mechanism is often unexpected. It is unclear whether a faceting process is present in all dust/collapse cases, or whether faceting even plays much of a role when it is present – dust-enhanced melt is possibly extreme enough to cause mass loss from the coincident layer, and render the remaining grain structure extremely weak.

Dust can absorb solar energy even when buried by 30 cm or more of clean snow. Thus a buried dust layer can contribute to warming of the snowpack whether or not melt is generated. The presence of dust under a new snow slab should be expected to increase slab temperatures, especially at the layer interface, more rapidly than anticipated for clean snow, potentially increasing creep rates and stress within the slab.

The spatial pattern of dust will exert a primary control over melt/freeze crust and facet formation patterns, with the result being that the spatial distribution of dust on a slope can define the stability pattern. While the exact mechanisms are sure to exhibit slope-specific characteristics, it would appear that efforts to characterize the dust variability, through wide-area photography, could yield important results for research as well as to help document conditions leading to avalanche activity. The Climax Chutes event highlights this assertion – a photograph of the surface dust distribution on that slope prior to burial would help address several unknowns in regards to the dust contribution to the avalanche location and extent.

The Scarp Ridge natural event highlights an important consideration – how to factor in the presence of dust layers when forecasting avalanche danger ratings? Does the mere presence of dust layers hint at increased danger potential, even in the absence of conclusive test results? The morning that the Scarp Ridge slide occurred, CBAC and CAIC forecasters were considering changing the danger rating from moderate to low. While neither danger rating precludes the occurrence of large natural avalanches, these events should be extremely unlikely under low avalanche danger. The size of the Scarp Ridge event suggests that if this instability was related to this widely distributed dust layer, it may not have been an isolated problem that day. It is likely, however, that a rule-based approach to dust considerations in danger ratings will not be a reliable solution. Instead, systematic, targeted observations that can capture rapid changes in snow temperatures and structure could provide appropriate data to support danger assessment over wide areas.

Dust accelerates the influence of sun on the snow energy balance, can induce spring-like conditions in winter months, and provokes rapid changes in snow dynamics in all seasons. To better characterize the processes associated with dust on snow stratigraphy, and their contribution to individual avalanche events, more observations are needed, and we recommend that a set of standardized dust observations be included in standard procedures for avalanche operations active in dust-prone regions. In particular, the following observations would be valuable:

- Dust presence/absence, both in snowpit, hasty pit, and crown line observations as well as wider area observations.
- Snow temperatures near and within dust layers, on solar exposed and shady slopes.
- Monitoring grain metamorphism in and near dust layers during and after burial.
- Energy balance observations, particularly incoming and outgoing solar radiation for snow albedo monitoring and to allow high resolution snowpack modeling. Operational implementation of a snow physics model (e.g. SNOWPACK; Lehning et al., 2002) with the ability to simulate dust processes, could be a valuable tool for anticipating dust impacts within the snow stratigraphy.

During the 2016 snow season in particular, the CBAC regularly included discussions of dust observations in forecast products. In addition to the evident need to communicate the role of and uncertainty associated with dust layers for backcountry users, this also encouraged the general public to submit dust-related observations to the center. Increased awareness of the potential roles of dust in avalanche formation, and their contribution to unusual or unanticipated avalanche conditions, will serve both our evolving understanding of the dust phenomenon, as well as the needs of backcountry users and avalanche professionals.

5. CONCLUSION

This paper provides specific examples of unusual dry slab avalanche events involving dust-on-snow layers in the Crested Butte, Colorado backcountry. These case studies, several of which involved close calls with backcountry skiers, point out the importance of understanding how dust layers affect the stability of the snowpack. These avalanches suggest empirically that dust contributes to the formation or persistence of weakness in the snowpack, as well as enhance slab deformation above them.

It is clear from these cases that several research and observation needs exist. The processes by which dust affects snow stratigraphy and stability appear to extend beyond a simple nuance or acceleration of conventional near surface faceting processes to include rapid mass loss and bond weakening and potentially enhanced deformation rates from rapid warming.

Future research in a controlled environment would further our understanding of dust-on-snow effects. In a laboratory or controlled field setting, the growth rates and size of facets or buried wet grains around dust layers could be compared against clean snow. The rate of slab settlement or deformation when dust layers are buried in dry snow could also be compared to clean snow.

The spatial pattern of dust deposition, burial, and metamorphic influences likely has a strong impact on subsequent stratigraphy and stability evolution and therefore on weak layer and slab patterns on individual slopes. Increased attention to dust observations, perhaps through inclusion of dust observations in the SWAG manual or in the standard procedures of specific operations, is sure to benefit our understanding of dust phenomena and to increase public safety. We hope this study inspires careful documentation of dust-related avalanche events for further research and improved avalanche forecasting.

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