GRAUPEL, CRUSTS, PERSISTENT INSTABILITY, AND UNUSUAL SLAB BEHAVIOR: TWO CASE STUDIES FROM MOUNT SHASTA, CALIFORNIA, USA

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ABSTRACT: These case studies examine two large natural avalanches attributed to graupel/crust combinations on Mount Shasta, California. The first case study details an avalanche in February 2026 which released on a layer of buried graupel above a melt-freeze crust after a major loading event. The graupel layer provided limited feedback before failing ten days after burial – one of the longest documented cases of persistent instability associated with this grain type. A second notable avalanche in April 2026 highlights a graupel/crust combination as a problematic weak layer with wide-propagation potential. These case studies provide further evidence that graupel can act as a persistent weak layer, result in widely-propagating avalanches, and challenge forecasting operations.

KEYWORDS: Graupel; Persistent Weak Layer; Persistent Slab; Melt-Freeze Crust

1. INTRODUCTION

Graupel is a relatively common precipitation type in mountainous areas, formed when ice particles – such as snowflakes – contact supercooled water droplets in clouds (Whiteman, 2000; Birkeland, 2025). This process eventually results in rimed and rounded particles as water droplets freeze onto the ice crystals (Whiteman, 2000). The graupel formation process is typically associated with warm air, convection, and maritime climates (Steenburgh, 2015; Birkeland, 2025; Whiteman, 2000).

Once it reaches the ground, graupel is well known as a potential weak layer in the snowpack. However, graupel's behavior has seen limited research when compared with other weak layers, such as facets. While weak layers associated with precipitation particles like graupel are typically short-lived (Brown and Jamieson, 2006), previous research indicates that graupel can act as a persistent weak layer (PWL) capable of producing avalanches up to eight days post-burial in maritime climates (Reynaud, 2018).

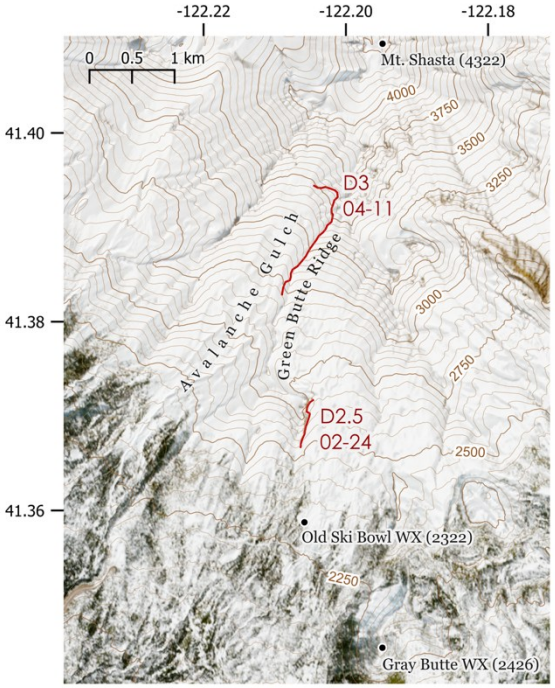

Figure 1. Southwest side of Mount Shasta. Avalanche crowns associated with graupel/crust combinations are outlined in red. The Old Ski Bowl weather station (elevation 2322 m/7617 ft) is located approximately .95 km (.59 mi) south of the February 24 avalanche site and 3.2 km (2 mi) south of the April 11 avalanche site. Satellite imagery from March 6, 2026.

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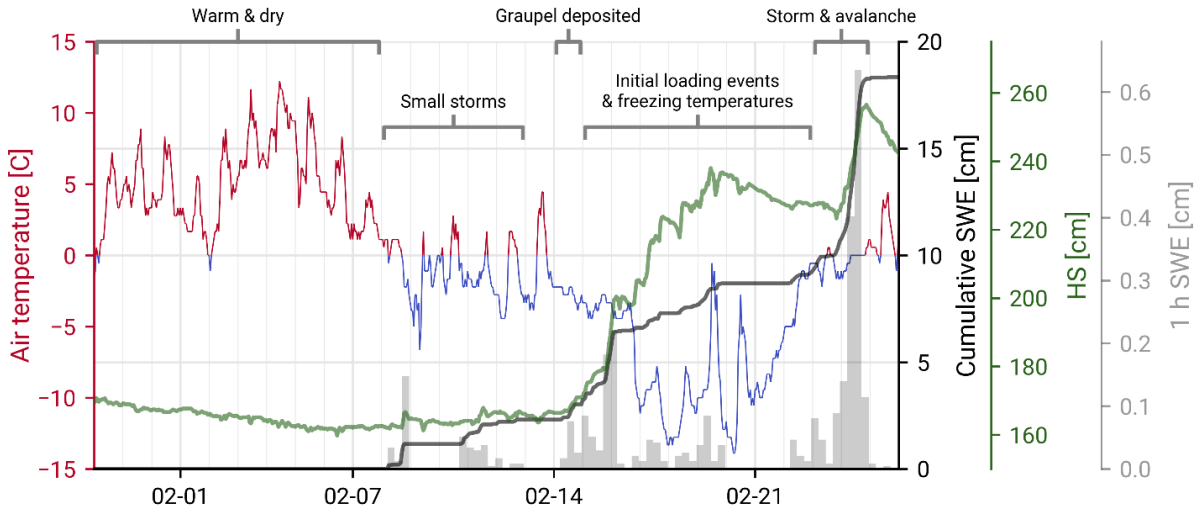

Figure 2. Air temperature, snow water equivalent (SWE) precipitation, and height of snowpack (HS) at the Old Ski Bowl weather station (elevation 2322 m/7617 ft) from January 29 through February 25, 2026. Noted are several significant weather events. Timezone is PST (UTC-8).

The consequences of graupel acting as a persistent weak layer are significant. This characteristic is anomalous for precipitation particles: every other PWL is associated with faceting resulting from well-studied and often easy to recognize snowpack and weather conditions; and yet, slabs breaking on persistent weak layers are responsible for a substantial fraction of the avalanche fatalities in North America as a whole, and likely a majority in its intermountain and continental climates (Bair et al., 2012). A precipitation particle, like graupel, whose formation and spatial distribution is difficult to predict and that persists within the snowpack beyond a few days is also a recipe for accidents. Additionally, some research indicates graupel occurrence may increase in a warmer climate, potentially increasing the frequency of graupel associated snowpack instabilities in the future (Michibata, 2024).

These case studies examine two large natural avalanches attributed to graupel/crust combinations on Mount Shasta, California (Figure 1) in 2026, which demonstrate graupel's potential to produce persistent instability and widely-propagating avalanches.

2. FEBRUARY 24, 2026 CASE STUDY

2.1 Weather and Snowpack

In early February, warm and dry weather produced widespread surface crusts on solar aspects in the Mount Shasta Avalanche Center forecast area (Figure 2). A weak system Feb-ruary 10-11 broke the dry-spell, delivering .94cm (.37in) of snow water equivalent (SWE) at the Old Ski Bowl weather station (elevation 2322 m/7617 ft) and 5-15 cm (2-6 in) of snow near and above treeline on Mount Shasta, with deeper totals on wind-drifted westerly aspects.

February 12 brought an additional .2 cm (.08 in) of SWE (trace of snow). Above-freezing temperatures on February 13 – reaching a high of 4.4°C (40°F) at the Old Ski Bowl – followed by sub-freezing temperatures on the morning of February 14, produced widespread surface melt-freeze crusts near and below treeline on the southwest side of Mount Shasta.

On February 14, a low-pressure system off the coast of Northern California brought southerly, upslope flow to the region and directed precipi-tation into the Mount Shasta area. Observers reported consistent graupel showers throughout the day on the south side of Mount Shasta, accumulating up to an inch deep.

In some areas, primarily southerly aspects near and below treeline, the February 14 graupel fell directly above melt-freeze crusts. In other areas, the graupel fell above soft snow from earlier in the week. Observers reported a high degree of spatial variability in the location of the graupel/crust setup, even across individual terrain features. Southerly aspects commonly held the graupel/crust combination, while westerly and northerly aspects held graupel above soft snow.

A subsequent stormy period February 15-16 brought 3.38 cm (1.33 in) of SWE and 33 cm (13 in) of snow to the Old Ski Bowl. On February 16, forecasters documented a large avalanche on a southwest aspect of Green Butte Ridge and hypothesized the slide released naturally on the February 14 graupel/crust interface but were unable to reach the site to verify. On the same day, on a southeast aspect near 2469 m (8100 ft), an

observer reported a Rutschblock 4 score at 30 cm (12 in) on a thin graupel layer above a melt-freeze crust.

From February 17-22, over 30 cm (12 in) of additional snow accumulated with 2.59 cm (1.02 in) of SWE. Observers continued to find buried graupel/crust combinations on southeast through southwest aspects near and below treeline, with no additional avalanches or propagating results in ECTs or PSTs, but one notable sudden planar result in a modified deep tap test.

From 5pm on February 23 through 9pm on February 24, the Old Ski Bowl weather station received 8.3 cm (3.26 in) of SWE, translating to about 30 cm (12 in) of heavy, wet snow along with strong westerly winds (Figure 3).

2.2 Avalanche Investigation

On the morning of February 25, observers reported a large (D2.5), natural, and widely-propagating avalanche on a wind-loaded, southeast aspect of Green Butte Ridge, at 2682 m (8799 ft) in elevation (Figure 4). The lowest-angle of the starting zone measured 35 degrees. A lack of fresh snow on the bed surface and debris pointed to a late-storm release on February 24.

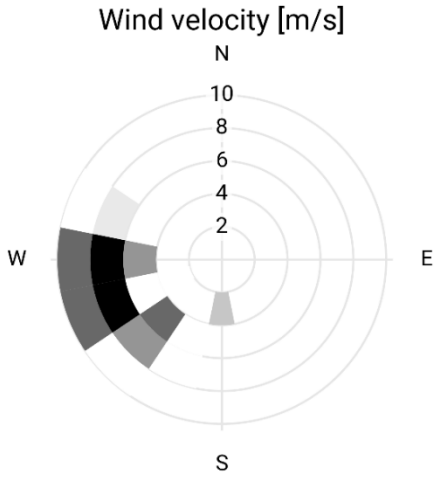

Figure 3. Histogram of wind velocity during the storm from February 23 through February 24 at the Gray Butte weather station (elevation 2426 m/7958 ft).

Figure 4. A large (D2.5), natural, and widely-propagating avalanche on a wind-loaded, southeast aspect of Green Butte Ridge. The avalanche failed on a layer of graupel buried on February 14, and released approximately ten days after burial during a significant loading event.

Figure 5. The crown of the avalanche indicated that it most likely started as a shallower wind slab and stepped down to a deeper layer. The deeper crown was measured at over 91 cm (36 in) in places and failed on a graupel/crust layer.

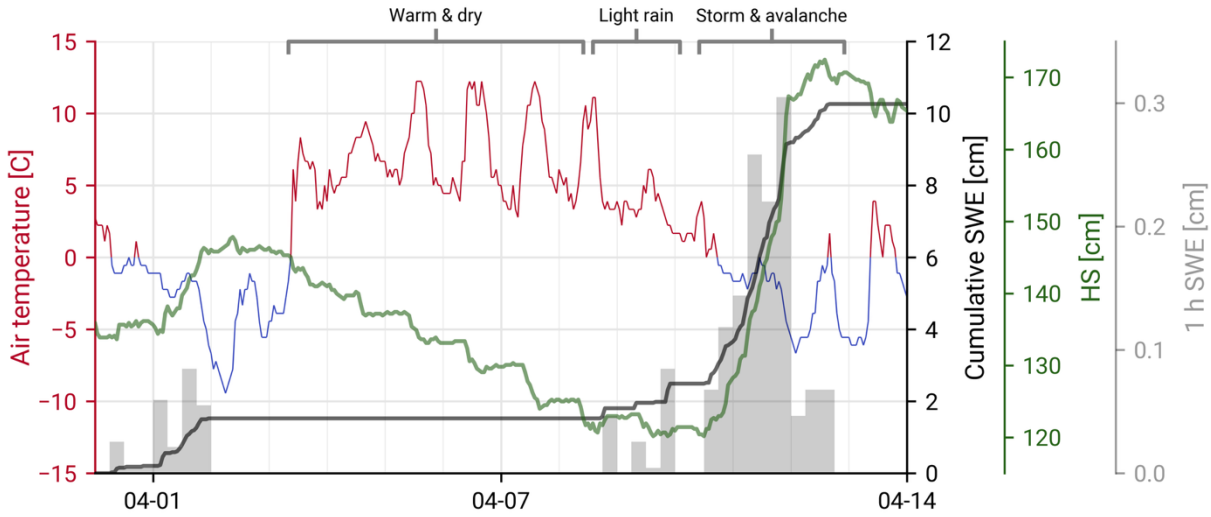

Figure 6. Air temperature, snow water equivalent (SWE) precipitation, and height of snowpack (HS) at the Old Ski Bowl weather station (elevation 2322 m/7617 ft) from March 31 through April 13, 2026. Noted are several significant weather events. Timezone is PDT (UTC-7).

Further investigation by Mount Shasta Avalanche Center forecasters revealed that the avalanche likely started as a shallower wind slab (Figure 5) and stepped down to the February 14 graupel layer above a stout melt-freeze crust. The slab averaged over 60 cm (24 in) deep and exceeded 91 cm (36 in) in places and was approximately 518 m (1700 ft) wide. The graupel layer had been buried for ten days prior to failure – one of the most persistent graupel instabilities documented.

3. APRIL 11, 2026 CASE STUDY

3.1 Weather and Snowpack

The forecast area experienced a warm and dry early-April (Figure 6). On April 8-9, a small storm delivered .97 cm (.38 in) of rain to the Old Ski Bowl, along with above-freezing temperatures.

Temperatures dropped heading into the next precipitation event later that week, producing widespread surface crusts. On April 10-11, an upper-level low brought heavy showers and convective activity to the region. An observer documented hail below treeline as the precipitation began on April 11. From 12pm on April 10 to 12am on April 12, the Old Ski Bowl weather station received 6.71 cm (2.64 in) SWE and about 48 cm (19 in) of snow, accompanied by consistently strong southeast winds (Figure 7).

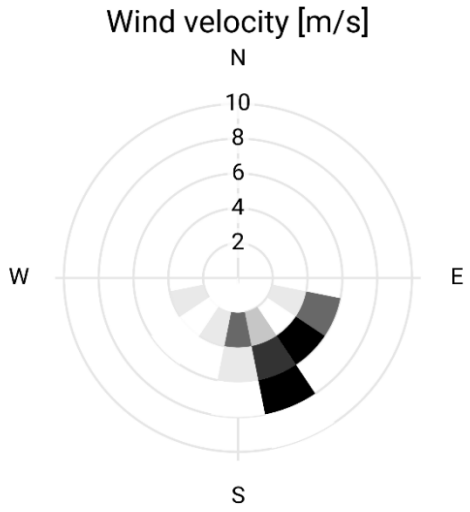

Figure 7. Histogram of wind velocity during the storm from April 10 through April 11 at the Gray Butte weather station (elevation 2426 m/7958 ft).

3.2 Avalanche Investigation

On April 12, observers reported a very large (D3) avalanche on a west/northwest aspect in Avalanche Gulch near 3600 m (11800 ft). The slab failed 76-91 cm (30-36 in) deep on a layer of 2-3 mm graupel grains above a melt-freeze crust, and broke about 1.4 km (.87 mi) wide (Figure 8), wrapping around rocky terrain features on Green Butte Ridge.

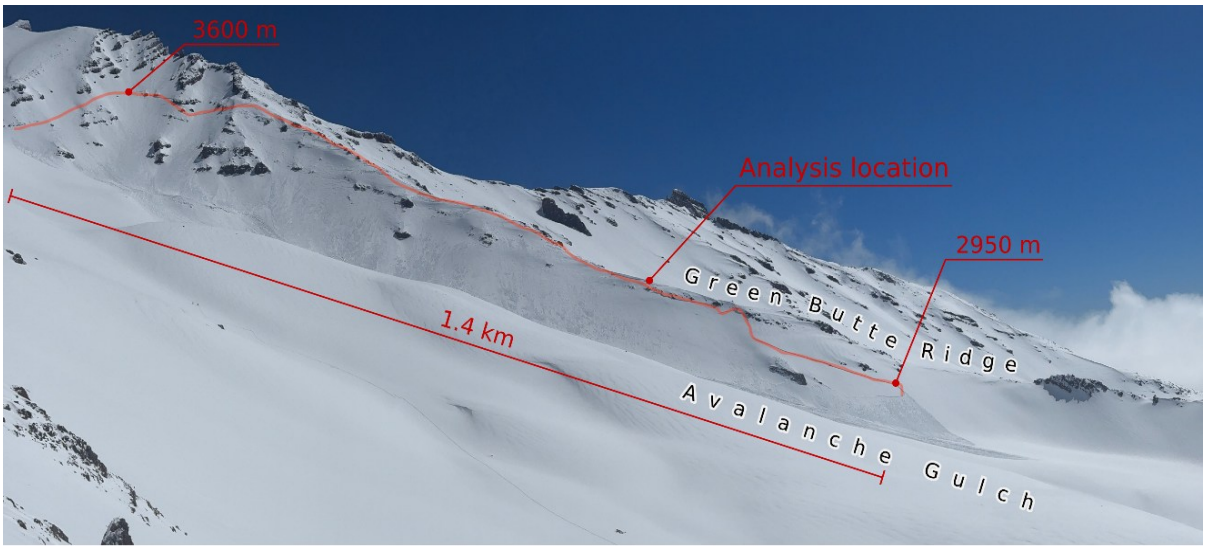

Figure 8. The widely-propagating crown of the April 11 avalanche in Avalanche Gulch. The very large (D3) slide failed approximately 1.4 km (.87 mi) wide on a graupel/crust layer after a significant loading event.

4. SNOWPILOT DATA

SnowPilot data provides a broader context for these case studies.

An initial query for all snow profiles with graupel above a crust – either melt-freeze (MFcr), sun (IFsc), or rain (IFrc) – or an ice layer (IFil), returned 525 profile results (Figure 9). Of the 525 pits with graupel above a crust, 193 profiles included a shear test failure somewhere within the graupel or crust layer. Of the initial query, 94 snow profiles, or ~18%, identified the graupel/crust layer as the "Layer of Concern." Also of the initial query, 34 profiles included recent avalanche activity on similar slopes. By examining snowpack structure, observer notes, and test results, we screened out 23 profiles in which weak layers other than the graupel/crust combination appeared most likely responsible for the avalanche activity, leaving 11 profiles with avalanche activity on similar slopes most likely attributable to the graupel/crust layer. Six of these profiles were located in the maritime climate of the Sierra Nevada range, in California and Nevada, USA.

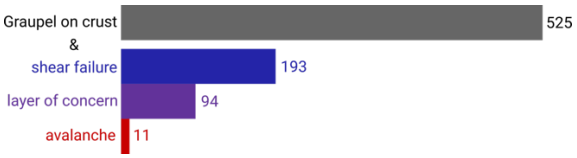

Figure 9. Summary of SnowPilot data, showing 525 snow profiles with graupel above a crust (melt-freeze, sun, rain) or an ice layer. 193 profiles included graupel above a crust and a shear test failure somewhere within those two layers; 94 profiles identified the graupel/crust layer as the "Layer of Concern"; and 34 profiles noted avalanche activity on similar slopes. However, we screened out 23 profiles in which weak layers other than the graupel/crust combination appeared most likely responsible for the avalanche activity, leaving 11 profiles with avalanche activity on similar slopes reasonably attributable to the graupel/crust combination.

5. DISCUSSION

Implications, Uncertainties, and Spatial Variability

The first case study – the February 24, 2026 avalanche – provides additional evidence that graupel can behave as a persistent weak layer, especially when above a crust and stressed by a significant loading event. These findings agree with a previous study, in which graupel/crust combinations in a maritime climate resulted in avalanches up to eight days post-burial (Reynaud, 2018). Both cases highlight the potential for graupel to act as a persistent weak layer, a characteristic unique amongst precipitation particles.

Given that persistent weak layers are typically associated with faceting (e.g. Jamieson 1995; Birkeland, 1998) the question of whether facet-ing played a role in this case study arises. A period of extended cold temperatures from February 17-22 (Figure 2) raises the potential that some faceting may have occurred within the graupel/crust layer, particularly near the boundaries of the buried crust layer. Although we can't completely rule out that faceting played a role, observers did not report faceting over multiple observations of the graupel/crust layer before and after the slide. Regardless, the February 14 graupel/crust layer provided limited feedback – both via natural avalanches and on stability tests – before failing dramatically during the major loading event of February 23-24. This type of limited feedback is often associated with persistent and deep persistent weak layers, which can be notoriously difficult for avalanche practitioners and backcountry recreationists to assess. This case study once again raises the question: how do forecasters best approach evaluating and communicating the hazard of layers which appear concerning and provide limited feedback until a significant loading event – in this case, over 7.6 cm (3 in) of SWE – finally tips the scales?

Notably, several of the snow profiles we en-countered within the SnowPilot data included some degree of faceting in the graupel layer, emphasizing the potential for faceted graupel/crust combinations. Overall, the SnowPilot results are subject to human error, such as incorrect layer labeling and the difficulty of identifying graupel when it is a thin layer and/or located within new storm snow. Further, plenty of snow profiles and documented cases exist outside the SnowPilot dataset.

While not a persistent instability, the April 11, 2026 avalanche (Figure 10) provides evidence of surprisingly wide propagation. This type of wide propagation is unusual for storm or wind slabs in the Mount Shasta Avalanche Center forecast area and resembles the propagation behavior typically associated with persistent weak layers.

Finally, graupel can be a highly spatially variable weak layer. On a regional scale, the environmental conditions that produce graupel may exist over some parts of a forecast area and not others. On a smaller scale, aspect and slope-scale characteristics proved critical during the February 14 graupel event. In some areas, the graupel fell onto soft, recent snow from previous wind-loading. On other adjacent slopes, the graupel fell directly onto a melt-freeze crust due to recent warm temperatures and solar input. It was the graupel/crust

combination that proved to be problematic in this instance. Graupel is also known to pool on lower-angled slopes beneath steep cliffs and gullies. The February 24 avalanche site, with steep cliffs above the starting zone, is conducive to deeper graupel accumulations and this factor likely contributed to additional layer variability. Tracking the spatial variability of graupel, and the underlying layers such as crusts, presents another challenge for avalanche practitioners grappling with graupel.

Figure 10. The crown of the April 11 avalanche in Avalanche Gulch on Green Butte Ridge. Crown depth measured 76 to 91 cm (30 to 36 inches). The slab failed on a layer of 2-3mm graupel grains on a melt-freeze crust.

Our literature review and SnowPilot queries highlight that relatively few case studies or datasets exist involving avalanches attributable to graupel on crusts. We hope these case studies will add to the pool of knowledge around this challenging weak layer and inspire further research which focuses on what scenarios lead to PWL behavior, the faceting process within graupel/crust layers, and the spatial variability of graupel distribution. This research may become more relevant as a warming climate could increase the frequency of graupel and crust layers.

6. CONCLUSION

These case studies provide further evidence that graupel can act as a persistent weak layer and result in widely-propagating avalanches. In particular, the graupel/crust combination, when stressed by significant loading events, proved problematic in both circumstances. Limited feedback on the stability of graupel/crust combinations and high spatial variability of graupel deposition can challenge forecasting operations.

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