FACETED MELT FORMS, A DEADLY AND UNPREDICTABLE WEAK LAYER

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ABSTRACT: Faceted melt forms are a particularly persistent and difficult-to-predict weak layer commonly found in Alaska and in the Japanese Alps. This layer is probably much more geographically widespread, but is not well-described in the literature and thus generally goes unrecognized in the field. We have compiled our observations and case histories from 14 years of study, analyzed characteristics and conditions of formation, summarized what we know about faceted melt form identification and stability evaluation, and made recommendations for further studies and notation.

KEYWORDS: avalanche, case histories, persistent weak layer, facets, faceted melt forms

1. INTRODUCTION

Figure 1. Natural release propagating into slope angles less than 25°, day 40 of 2000-01 layer.

This is an informal report on work still in progress. We are sharing preliminary results now because layers associated with faceted melt forms keep killing people, and we hope that other workers' observations and studies will help all of us to better understand the process.

Faceted grains have been identified as key weak layers in slab avalanches since the 1930s (Seligman, 1936). Understanding of near-surface faceting processes has developed more recently, (Adams and Brown, 1988 and 1990, Birkeland, 1998, Colbeck 1991 and 2001, Colbeck and Jamieson, 2001, Fierz, 1998, Fukuzawa and Akitaya, 1993, Greene and Johnson, 2002, Jamieson and van Herwinjin, 2002). While most works focus on facets in surface layers and adjacent to melt layers, one paper discusses faceting within melt layers (Moore, 1988), and one discusses field observations of faceting in melt forms (Jurica and Witsoe, 2008).

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We know of four situations where faceted melt forms are created:

1. Melt Layer Recrystallization

   - The melt layer forms through thaw, rain on snow, or slush fall and is buried before it freezes, as precipitation turns to snow.
   - As the liquid water in the melt layer freezes, the phase change releases heat. The locally intense vapor pressure gradient causes rapid facet growth. (summarized in Birkeland, 1998)
   - This is a classic and dramatic weak layer setup that is very common in cold maritime snow climates.
   - It is not well-described in the literature that faceting often occurs in the top few centimeters of and sometimes throughout the melt layer, making for unusually weak, unpredictable, and variable bonding.

2. Strong Gradient Across Frozen Melt Layer

   - The melt layer freezes while it is still on the surface. It is not buried.
   - Cold weather creates a strong temperature and vapor pressure gradient across the layer and it becomes faceted.
   - The layer's bond to subsequent snow layers is again very weak and variable.
   - This process is not well-described in the literature.

3. Facets Below Melt Layer

   - This weak layer is widely reported and there are theories in the literature, but it is still incompletely understood.

- It is not well-described in the literature that the melt layer often becomes faceted and weak, especially if it is thin.

4. Radiation Recrystallization

    - Solar radiation warms the snow just below its surface to the melting point.
    - The snow surface continues to lose heat via longwave radiation.
    - Strong vapor pressure gradients cause rapid facet growth over a melt form crust.
    - This is another weak and spatially variable snowpack setup.
    - It is not well-described in the literature that this process can create facets within the thin melt layer. It is rare in Alaska, so we have few observations. Low-latitude, high-altitude snow climates are ideal for study.

This paper's focus is on faceted melt forms, facets that develop within the melt layer as or after it freezes, rather than above or below it.

2. METHODS

We will begin with some case histories, then discuss characteristics and conclusions drawn from our compilation of 130 field profiles, and our records and observations from the last 14 years of fieldwork, mostly in Alaska and Japan.

3. JUNEAU, AK, FEBRUARY - MARCH 1995

Late December through January brought a long period of unusually dry, mild weather, with temperatures reaching as high as 10°C, forming a thick melt layer. In early February the weather turned cold and the snowpack refroze solidly.

Light moist snowfall February 10 was followed by a week of cooling, dry weather with sea level temperatures dropping from -2° to -12°C. By day seven, the new snow had become a breakable faceted melt form crust 0.01 m thick over 0.04 m of sugary early faceted grains.

On February 18 through 22, days eight through 12, 0.30 m of new dry snow fell. Many slopes slid during the snowfall, removing the weak layer and allowing a better bond between the lower melt layer and the new snow. Slopes that did not slide remained in a hair-trigger state. The thin faceted melt form crust was just strong enough to transmit fracture over large areas. There was widespread whumphing and fracture propagation from flat areas to slopes.

The weather cleared on day 13. It was clear and -2 to -12°C (sea level) through the end of the cycle. At least seven human-triggered slab avalanche incidents involved skiers, snowmachiners, and snowboarders.

In one case, a heliskiing snowboarder hopping on a flat summit triggered an R4D3 size (see Greene et al, 2004 for size coding) slab that released the entire bowl below. In another, a snowmachine traversing on a mid-slope 20° bench triggered three R3D3 size slabs, each 80 m wide, on the slope 100 m below.

On day 14, February 24, an R4D3 size avalanche on the south face of False Troy killed and buried backcountry skier Alex Iliev.

The last slabs released on day 19. New snow loading was minimal until the snowpack strengthened with spring warming.

4. JUNEAU, AK, APRIL - MAY 1999

There were no major thaws in the winter of 1998-99 until April 16-18, when a warm air mass brought sea level temperatures of 14°C and thawed even high-elevation, north-facing slopes. The crust had not refrozen when it was buried by new snow and temperatures cooled.

April 19-26 was showery and stormy. Snowfall in the mountains was 0.7 - 1.0 m, and southeast storm winds in the 10 m/sec range, gusting to 30 m/sec, built soft slabs. The winds ended as post-frontal showers dropped the final 0.30 m of light dry snow.

The weather broke to clear, calm, and cool on April 26, day eight. While the author was digging a test block for a heliski party just below the ridge of Mt. Olds, a 0.75 m deep fracture propagated from the corner of the pit for 150 m across the slope and released an R2D3 size slab, leaving him standing behind in the pit. The block tested AK4 Q1 on 45° (see Glude and Mullen, 2008 for information on the AK Block test). Other parties reported AK4-6 Q1-2 results, rode freely, and did not trigger slides that day.

Looking for the source of the weakness, we found the top few centimeters of the melt layer were strikingly sugary, granular, and faceted.

On April 27, day nine, heliskiing snowboarder Matt Brakel triggered a meter-deep R3D3 size soft dry slab on McGinnis Mountain. He and would-be rescuer Kat Winchell both went over cliffs and died as a result of the slide.

Persistent instability continued for 25 days at mid elevations and for at least 33 days at higher elevations. There were several more close calls from meter-deep skier-triggered soft slabs before the spring thaw ended the cycle in May.

5. JUNEAU, AK, JANUARY - APRIL 2001

A thaw in the second half of January ended February 1 with snow showers as the snow level dropped and sea level temperatures fell to -1 to -6°C. On the fifth day of the cooling trend as the top 0.20 m of the melt layer froze, we found melt-layer recrystallization above and faceting in the underlying melt layer.

On day 11, after the first storm, we found widespread soft dry slab avalanches and dramatic 0.6 to 1.0 m deep natural cracks.

On days 22 to 25, storms triggered a moderate natural cycle of 0.5 to 2.0 m thick R2-3D2-3 size soft dry slabs. As the storm ended, instability and human-triggered slides were ongoing.

On day 26, a series of three skier-triggered hard dry slab avalanches released on the Hogsback, in the backcountry near the Eaglecrest ski area. The largest avalanche totally buried a skier in an R3D3 size slide. Partner rescue was rapid and the skier was lucky to escape with no injuries.

We profiled this slide. It was triggered after at least ten other riders descended the slope, in a thin 0.55 m spot rather than the 1.25 m thick slab where the previous tracks were. The skiers involved had done numerous block tests in the area over the prior week without detecting any unusual weakness.

This faceted melt form layer was characterized by highly inconsistent behavior. Shear and slope tests often indicated good stability, yet the entire slope would fracture massively on the next person to load it. The usual risk management protocols could not be trusted.

On day 28, a skier triggered an R2D2 size soft dry slab in the backcountry near Eaglecrest and rode out of the slide without getting caught. On day 29, a snowmachiner on Mt. Troy triggered and was caught in an R2D2 size soft dry slab, but rode out of the avalanche.

On day 33, a snowboarder triggered an R2D2 size soft dry slab in the Heavenly Valley backcountry near Eaglecrest, but rode fast enough to get off the slab and was not caught.

We investigated immediately after the slide. The rider triggered this avalanche after all the adjacent chutes had been ridden without incident, in a thin 0.60 m spot near some rocks and small trees. We had highly variable but all Q1 test results near the trigger point on the 50° slope. Tap compression tests ranged from CTV to 14 (see Greene et al, 2004 for coding).

The bed surface was similar to the Hogsback slides' bed: generally rough and highly spatially variable with sugary areas and hard, icy areas.

We theorized that the rough surface of these layers provides mechanical keying for new snow to bond well to, but the sugary texture propagates fracture widely once it is initiated.

An alternate theory is that faceted melt forms do not propagate fracture more readily at all, but the conditions that create them happen to create weaker facets or weaker bonds in the layers above and below. Though there are cases of faceted melt form cycles without neighboring facet layers, an effect that weakens adjacent snow is possible.

We know that there is a strong correlation of faceted melt forms with unpredictable weakness, spatial variability, persistence, and human involvements, but at this point our theories on cause and effect are still speculative.

The final avalanche cycle, a widespread series of deep natural R2-3D2-3 size hard dry slabs, came in March on days 38 to 49. These 1.0 to 3.5 m thick slabs were triggered by clear-weather northeast wind-loading. Again, the pattern was highly variable. Some slides ripped out over 2.0 m deep into slope angles below 25° while adjacent 40° to 50° slopes remained intact. The weakness finally strengthened with spring warming in April, 60-some days after formation.

Figure 2. Natural release 3.5 m deep on faceted melt forms from day 39 of the 2000-01 layer.

6. CORDOVA, AK, FEBRUARY - APRIL 2008

The final case history comes from Kirsti Jurica and Steve “Hoots” Witsoe’s (Jurica and Witsoe, 2008) report on the March 8th, 2008 avalanche on Mt. Eyak that buried and killed avalanche forecaster and backcountry skier Michael O’Leary, and partially buried and broke the femur of another party member.

The crown was 1.5 - 4 m deep. The slide was an R4D4 size, 150 - 200 m wide hard slab that fell about 500 m. It buried Michael four meters deep.

The snowpack section of the report notes that they found faceted melt forms in the weak layer: "*The rain during the Valentine's storm saturated the snow in turn creating a thick, hard layer of melt freeze polycrystals when it refroze ... At the end of this storm, the temperature dropped bringing 20 cm of snow. The transition at the end of the storm, from warm to cold, produced a localized, near surface faceting of the preexisting polycrystals. A fine layer of 3 mm faceted polycrystals sat loose between the melt freeze and the new snow.*"

The report also notes that "*Stability tests at 600 m produced moderate to hard but good quality (Q1) results.*" These are typical test results for faceted melt forms, which often test relatively strong before fracturing spectacularly. The author had discussed his observations of faceted melt form processes and stability evaluation with Michael O'Leary, but does not know if that information was remembered or factored into the day's decision-making.

The slide released on day 22. The weak layer was about 1.45 m down, deeper than the party's test pits. They reported that most of the overlying snow was moist melt forms from subsequent wet snowfall and rain, with a recent 0.20-0.40 m layer of dry rounded grains on top.

The report quotes Atkins 2008 on the common roles of persistent weak layers and triggering from thin spots in deep slab releases and notes that "*In this case, the weak layer was created weeks before the avalanche and persisted for months after.*"

7. SIGNIFICANCE OF FACETED MELT FORMS

Faceted grains are common in our field areas, comprising 42% of the weak layers in a recent study of 357 large blocks over more than 120 field days (Glude and Mullen, 2008). But most of those are near-surface facets not associated with faceted melt forms.

Faceted melt forms are much less common. Despite being weak layers in only 12% of the profiles with weak layers studied here (n= 510), they cause a disproportionate share of problems. They were involved in all three Juneau-area fatalities during our period of study, in 39% of the near-miss incidents (n=49), and 54% of the near-miss slides (n= 69). In the field we consistently noted them as exceptionally-persistent, spatially variable, and difficult to evaluate and predict.

8. CHARACTERISTICS OF FACETED MELT FORMS

The average faceted melt form density measured in our data set for this study was 335 kg/m^3, with a low of 100 kg/m^3 and a high of 480 kg/m^3. The relatively high density of melt layers does not appear to limit faceting within the layer.

Air temperatures in our data set averaged -3°C, with a minimum of -20°C and a maximum of 3°C. Temperature gradients in the melt layers averaged 4.7°C/m, ranging from no gradient to one day that varied from 50.0 to 100.0°C/m.

This temperature data is limited because temperatures were taken when we were doing snow profiles. They were not targeted for conditions that create faceted melt forms. Overnight temperatures were probably lower, and vapor pressure gradients from phase changes were probably stronger.

The key finding is that mildly cool temperatures appear to be sufficient to develop and preserve faceted melt forms.

Faceted melt forms are very persistent. Our data includes skier-triggered avalanches 0.6 to to 1.0 m deep on 33 to 35 day-old layers, natural releases 2.3 to 3.5 m deep on 40 day-old layers, weak block tests (AK3 Q2 on 38°) on 99 day-old layers, and identifiably sugary faceted textures in 119 day-old layers.

9. DEVELOPMENT OF FACETED MELT FORMS

Faceted melt forms require thaw, rain, or slush fall to produce the melt layer, followed by below freezing weather to make facets.

The author has long called coastal Alaska's colder, more-variable snow climate "high-latitude maritime" to distinguish it from the stereotypical maritime snow climate, but we also find these layers at low latitude in Japan. "Cold maritime" is a better term for ideal faceted melt form climates. Workers elsewhere should still be wary, faceted melt forms will develop in any snow climate when conditions are right.

Our best formation sequence record is from Juneau, Alaska, December - January 2003-04:

On December 23, day zero, the air temperature was -1°C and no temperature gradient was yet present. The wet, unfrozen melt layer was an average 0.4 m thick and its density was 360 kg/m^3. The slightly moist new snow and rounds averaged 0.3 m thick and 110 kg/m^3 density.

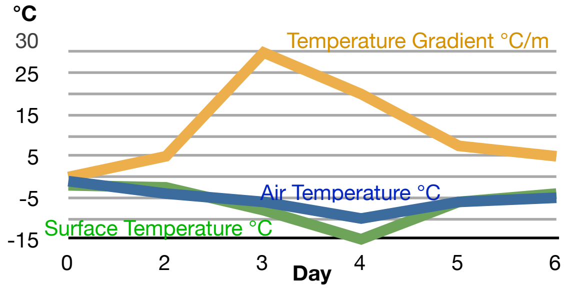

Figure 3. Air and surface temperatures dropped, then moderated. The temperature gradient peaked on day three then decreased as the difference spread out over greater depth.

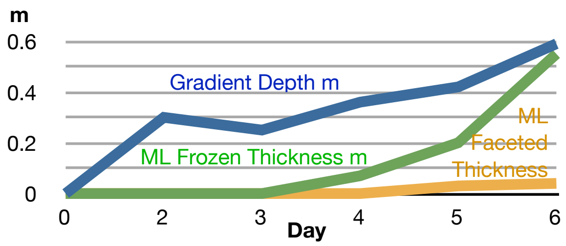

Figure 4. The temperature gradient penetrated steadily deeper. The melt layer (ML) began to freeze by day four, frozen thickness increased daily. Faceted melt forms developed by day five.

The grains in the faceted melt form layer rounded slightly as the temperature gradient moderated but otherwise remained essentially unchanged until the layer was destroyed by thaw on January 15, day 23. It functioned as a weak layer in block tests but never had enough load to produce an avalanche cycle.

10. SUMMARY AND CONCLUSIONS

10.1. Identification:

- Faceted melt forms develop in any climate when colder weather follows thaws, rain, or slush fall.
- Watch for those weather sequences!
- Search for facets in and around melt layers. Look for sugary texture.
- Rub suspected faceted melt layers with a gloved hand. If the top few centimeters is sugary and falls apart, do not trust that layer no matter what pit or slope tests tell you!
- Check with a hand lens or loupe to confirm faceting. Shape is usually angular to sub-angular, will only be crisp and sharp when freshly formed.

10.2. Stability Evaluation

- Any facets in association with melt layers make evaluation and forecasting difficult.
- Facets may occur over, within, or under a frozen melt layer.
- Facets within the melt layer, as studied here, make prediction particularly difficult.
- Melt layers seem to bond much more weakly when they become faceted.
- Spatial variability increases.
- Tests results are unreliable. Slope and block tests may indicate strength, yet large slabs release when the right spot is triggered.
- The trigger point is often near rocks, trees, or thin spots.
- The weakness is very persistent:
  - Five weeks, skier-triggered avalanches,
  - Six weeks, deep natural releases,
  - 13 weeks, weak block tests,
  - 17 weeks, still identifiable, sugary faceted textures.

11. NOTATION

The IACS suggests doubling up snow classification symbols for mixed snow types with the primary grain type first, like this: □○

The secondary grain type can optionally be enclosed in square brackets for greater clarity.

12. FURTHER STUDIES AND RECOMMENDATIONS

We need more people working on field and laboratory studies of faceted melt form. Studies targeting formation, persistence, strength, predictability, and especially microstructure and role in triggering and fracture propagation would be most useful.

13. REFERENCES

We apologize to the many workers we have left out here. References to faceted melt forms have proven elusive to track down. We would greatly appreciate suggested additions to make a comprehensive faceted melt forms reference list.

Adams, E.E., and R.L. Brown. 1988. *On the Effect of Strong Density Layering on Metamorphism of Seasonal Snowcover*. ISSW 1988 Proceedings, Whistler, BC, 37-40 pp.

Adams, E.E., and R.L. Brown. 1990. *A Mixture Theory for Evaluation of Heat and Mass transport Processes in Nonhomogeneous Snow.* Continuum Mechanics and Thermodynamics 2, 31-63 pp.

Birkeland, Karl W., 1998. *Terminology and Predominant Processes Associated with the Formation of Weak Layers of Near-Surface Faceted Crystals in the Mountain Snowpack.* Arctic and Alpine Research. Vol. 20, No. 2, 1998, pp. 193-199. Includes citations of earlier work.

Colbeck, S.C., 1991. *The Layered Character of Snow Covers.* Reviews of Geophysics, 29, 81-96 pp.

Colbeck, S. C., 2001. *Sintering of Unequal Grains.* Journal of Applied Physics, 89, 4612–4618 pp.

Colbeck, S.C., and Jamieson, J.B., 2001. *The Formation of Faceted Layers Above Crusts*. Cold Regions Science and Technology, 33, 247-252 pp.

Colbeck, S., Akitaya, E., Armstrong, R., Gubler, H., Lafeuille, J., Lied, K., McClung, D., and Morris, E., 1990. *The International Classification for Seasonal Snow on the Ground*. International Commission on Snow and Ice of the International Association of Scientific Hydrology, 23 pp.

Fierz, C., 1998. *Field Observation and Modeling of Weak-layer Evolution.* Annals of Glaciology, 26, 7-13pp.

Fukuzawa, T. and Akitaya, E., 1992. *Depth-hoar Crystal Growth in the Surface Layer under High Temperature Gradient.* Annals of Glaciology, 18, 39-45 pp.

Glude, B. and Mullen, R.,2008. *AK Block Project Status Update 2008.* ISSW 2008 Proceedings, Whistler, BC, 1043-1052 pp.

Greene, E. and Johnson, G., 2002. *Characterization of a Deep Slab Avalanche Cycle.* The Avalanche Review, 21, 2, 1-19 pp.

Greene, E. and The Working Group on Observational Guidelines, 2004. *Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States.* The American Avalanche Association, PO Box 2831, Pagosa Springs, CO 81147.

Jamieson, J.B., and van Herwinjin, A., 2002. *Preliminary results from Controlled Experiments on the Growth of Faceted Crystals above a Wet Snow Layer.* ISSW 2002 Proceedings, Penticton, BC, 337-344 pp.

Jurica, K. and Witsoe, H., 2008. *Deep Slab Instability, Decision making, and Consequences: A Case Study.* ISSW 2008 Proceedings, Whistler, BC, 364-370 pp.

Moore, M.B., 1982, *General Physical Characteristics of Snowpits Showing Crust Weakening and Temperature Gradients Needed to Sustain Weakening*. Technical Memorandum #4, Tech Series, Northwest Avalanche Center, 1-16 pp.

Seligman, G., 1936. *Snow Structure and Ski Fields*. McMillan and Co, Ltd., London, 555 pp.