FACETED MELT FORMS, A DEADLY AND UNPREDICTABLE WEAK LAYER

Bill Glude*
Alaska Avalanche Specialists, Juneau, Alaska, USA

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

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

1. INTRODUCTION

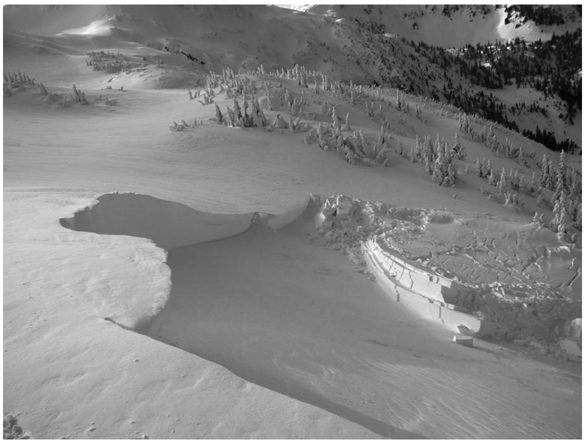

Figure 1. Natural release propagating into slope angles less than 25°, day 40 of 2000-01 layer.

This is an informal report on work in progress. We are sharing our preliminary results now because these layers keep killing people as our studies go on, and because 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, beginning in the late 1960s.

We know of three processes where facets form within and in association with melt layers:

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 and creates a locally intense temperature gradient in the overlying snow, rapidly changing it to faceted grains. (summarized in Birkeland, 1998)
   - This is a classic and dramatic weak layer setup that is very common in cold maritime snow climates.
   - What is not well-described in the literature is that the faceting often produces a rough but weak and spatially variable sugary texture in the top of and occasionally throughout the melt layer.

2. Strong Gradient Across Frozen Melt Layer

   - The melt layer freezes on the surface, no new snow falls before it is frozen.
   - Cold weather creates a strong gradient across the layer and it becomes faceted. Its bond to subsequent snow layers is similarly weak and variable.
   - This process is not well-described in the literature.

3. Facets Below Melt Layer

   - This weak layer is widely reported from the field and is described in the literature, but the process is still poorly understood.
   - What is not well-described in the literature is that the melt layer itself often becomes faceted and weak, especially if it is thin.

This paper's focus is on faceted melt forms, facets that develop in the melt layer itself.

2. METHODS

We will look first at some case histories, then at general characteristics drawn from a spreadsheet tally of 129 field profiles and our

* Corresponding author address:
Bill Glude, Alaska Avalanche Specialists, LLC., PO Box 22316, Juneau, AK 99802 USA;
tel & fax: 907-523-8900; email: aas07@mac.com

records from the last 14 years.

3. JUNEAU, AK, FEBRUARY - MARCH 1995
Late December through January was a long period of unusually dry, mild weather for midwinter, with temperatures reaching as high as 10°C and forming a thick surface melt layer. In early February the weather turned cold and the snowpack refroze solidly.

A light wet snowfall February 10 was followed by a week of cooling, dry weather with sea level temperatures dropping from -2° to -12°C. The new wet snow went through the melt-layer recrystallization process, becoming 0.05 m of sugary early faceted grains topped by a thin, breakable faceted melt form crust 0.02 m thick, all over the underlying refrozen melt layer.

On February 18 through 22, 0.30 m of new soft dry snow fell. Many slopes slid during the snowfall on the now eight to 12 day-old weakness, wiping away the looser faceted grains and allowing a better bond between the old melt layer and the new snow. Slopes that did not slide remained in a hair-trigger state, with the upper faceted melt form crust just strong enough to transmit fracture over large areas. Whumphing and collapse fractures propagating from flat areas to adjacent slopes were common.

The weather cleared on day 13 and stayed clear and in the -2 to -12°C (sea level) range through the last avalanche of the cycle on day 19. The cycle included at least seven human-triggered slab avalanche incidents involving skiers, snowmachiners, and snowboarders.

In one case, a snowboarder hopping to move on a flat knoll triggered an R4 D3 size (see Greene et al, 2004 for size coding) avalanche that released the entire bowl below him. In another, two snowmachines traversing on a mid-slope bench triggered a 300 m wide series of slabs on the slope beneath and 100 m away from them.

There was one fatality. An R4D3 size avalanche on the south face of False Troy buried and killed telemark skier Alex Iliev early in the afternoon of February 24, day 14.

In March, the weak layer gained enough strength to hold the load it had and new snow loading was minimal until the snowpack finally strengthened in the spring thaw.

4. JUNEAU, AK, APRIL - MAY 1999
There were no major thaws in the winter of 1998-99 until April 16-18, when an unusual warm air mass pushed far north, bringing sunny midday sea level temperatures of 14°C and turning even high-elevation, north-facing slopes to mush. The crust had not refrozen solidly when it was buried by new snow and temperatures dropped back below freezing.

April 19-26 was mostly showery and stormy. Snowfall in the mountains was heavy, and southeast storm winds in the 10 m/sec range and higher, gusting to 30 m/sec, built soft slabs. The winds ended as instability showers behind the last front dropped 0.30 m of light dry snow.

The weather broke on April 26, day seven. While the author was digging a test block to the melt layer 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 a deep R2D3 size slab avalanche, 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 test results but did not trigger slides.

Looking for the source of the weakness, what was most strikingly apparent was the sugary, granular, faceted nature of the top few centimeters of the refrozen melt layer.

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

Persistent instability from the same layer continued for about 25 days at mid elevations and for at least 33 days at higher elevations, producing several more near misses from meter-deep skier-triggered soft dry slabs before the spring thaw ended the cycle.

5. JUNEAU, AK, JANUARY - MARCH 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 the -1 to -6°C range. We found melt-layer recrystallization and faceting in the underlying melt layer in the field on the fifth day of the cooling trend as the top 0.20 m of the melt layer froze.

The faceted melt forms again behaved in a highly inconsistent manner. Sometimes, shear and slope tests would indicate 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 11, after the first storm loading on the faceted melt forms, we found unusually pronounced 0.6 to 1.0 m deep natural cracking, as well as widespread soft dry slab avalanching.

A second storm on days 12 to 14 brought heavy snow and southeast winds, triggering a major avalanche cycle of R2-3D2-3 size soft dry slabs. Fieldwork revealed widespread avalanche activity and extreme instability as the storm ended. Slabs were 0.5 to 2.0 m thick.

Ongoing storms on days 24 to 33 brought more snow and southeast winds which caused a moderate natural avalanche cycle of deep R2-3D2-3 size soft dry slabs on the same layers.

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 one resulted in a near-miss skier burial and companion rescue from an R3D3 size slide. We profiled this one and noted that it was triggered after at least ten other skiers descended the slope, in a thin spot where the slab was only 0.55 m thick rather than the 1.25 m thickness where the previous skiers' tracks were. The skiers involved in the burial had done numerous block tests in the area over the prior week without detecting unusual weakness.

On day 30 a skier triggered an R2D2 size soft dry slab in the backcountry near Eaglecrest, but skied away without getting caught. On day 31, a snowmobiler on Mt. Troy triggered and was caught in an R2D2 size soft dry slab, but rode out of it.

On day 35, another snowboarder triggered an R2D2 size soft dry slab in the Heavenly Valley backcountry near Eaglecrest, and rode away without getting caught. We investigated the slide immediately after it occurred. This avalanche was triggered after all the adjacent chutes had been ridden without incident, in a thin spot where the slab thickness was only 0.60 m. We noted highly variable test results here including tap compression tests as weak as CTV to 4 Q1 (see Greene et al, 2004 for coding) near the trigger point on the 50° slope.

The fresh bed surface was similar to those of the Hogsback slides, highly spatially variable with some sugary areas, some hard and icy areas, and a generally rough surface. We hypothesized that the rough surface provided mechanical keying that allowed new snow to bond well enough to accumulate but that the sugary texture propagated fracture widely once it was initiated.

The next and final avalanche cycle to release on the faceted melt forms was a widespread series of naturally-releasing R2-3D2-3 size hard dry slabs in March, on days 40 through 51. These 1.0 to 3.5 m thick slabs were triggered by clear-weather northeast windloading. 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. In April, the weakness finally strengthened and stabilized.

Figure 2. Natural release 3.5 m deep on faceted melt forms from day 40 of the 2000-01 layer.

6. CORDOVA, AK, MARCH 2008

The final case history comes from Kirsti Jurica and Steve "Hoots" Witsoe's (Jurica and Witsoe, 2008) report on their observations of the March 8th, 2008 avalanche on Mt. Eyak that killed avalanche forecaster Michael O'Leary and broke another party member's femur.

The snowpack section of the report indicates that they noticed 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.*"

They also note 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 process and stability evaluation with Michael O'Leary previously, but does not know if that information was remembered or factored into the day's decision-making.

By the time of the March 8 avalanche, on day 22 since the faceted melt forms developed, the weak layer was about 145 cm below the surface, deeper than the bottom of the party's test pits. They reported that most of the overlying snow was moist melt forms from subsequent snowfall and rain, with a 0.20-0.40 m layer of dry rounded grains on top.

The report discusses the role of persistent weak layers in deep slab instability and goes on to say that "*In this case, the weak layer was created weeks before the avalanche and persisted for months after.*"

7. CHARACTERISTICS OF FACETED MELT FORMS

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

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 0.47°C, with lows of 0.0°C and highs on one day varying between 5 and 10°C.

Daytime temperatures taken when we happened to be doing snow profiles do not accurately represent the conditions that create faceted melt forms. Overnight temperatures would be lower, and vapor pressure gradients produced by phase changes as melt layers freeze would be stronger. The key point is that mildly cool temperatures appear to be sufficient to develop and preserve faceted melt forms.

Faceted melt forms are exceptionally persistent weak layers. Our data set includes skier-triggered avalanches up to 1.0 m deep on 33 day-old layers and 0.6 m deep on 35 day-old layers, natural releases ranging from 2.25 up to 3.5 m deep on 40 day-old layers, weak block test results (AK3 Q2 on 38°) on 99 day-old layers, and identifiably sugary faceted textures in 119 day-old layers.

8. DEVELOPMENT OF FACETED MELT FORMS

Faceted melt forms require thaw, rain, or slush to produce the melt layer, followed by below freezing weather to make facets. They can form in any snow climate, but coastal Alaska is ideal.

The author has long characterized our snow climate as "high-latitude maritime", with much colder and more variable weather than the stereotypical maritime, but "cold maritime" is a more accurate description, since our data set includes multiple instances of faceted melt forms from the relatively low-latitude Northern Alps of Nagano Prefecture, Japan.

The case histories cited above give a general idea of conditions that create faceted melt forms, but the most complete example we recorded was in 2003-04.

On December 23, we recorded a 0.37 m thick 360 kg/m^3 wet and unfrozen melt layer under 0.19 m of 120 to 100 kg/m^3 slightly moist new snow and rounded grains at an air temperature of -1°C with no temperature gradient yet present.

On December 25, the melt layer was still unfrozen and moist but the air temperature had dropped to -4°C, the snow surface temperature was -2.5°C, and a temperature gradient of 0.5°C/0.10 m had developed at 0.30 m depth.

On December 26, the melt layer was still not frozen but with an air temperature of -6°C and a snow surface temperature of -8°C, a temperature gradient of 3°C/0.10 m had developed just above it and was just reaching the top of the layer. The top 0.10 - 0.20 m of the overlying snow had become very sugary faceted grains and the rest of the new snow was beginning to facet but was not yet sugary.

On December 27, the top 0.07 m of the melt layer had frozen but was not yet sugary or visibly faceted. With an air temperature of -10°C and a snow surface temperature of -15°C, a temperature gradient of 2°/0.10 m had reached the melt layer, and all the overlying snow was now faceted grains.

On December 28, the top 0.20 m of the melt layer was frozen and the top 0.03 m of the layer was sugary faceted melt forms. This was five days after the onset of below-freezing weather. Both the air and snow surface temperatures were -6°C, and the gradient in the top of the melt layer was 0.75°C/0.10 m. The overlying snow was very sugary faceted grains.

On December 29, freezing had progressed to 0.55 m below the top of the melt layer and the top 0.04 m of the layer was faceted melt forms. The air temperature was -5°C, the snow surface temperature was -4°C, and the gradient in the top of the melt layer was 0.5°C/0.10 m. The overlying snow was all sugary faceted grains.

This faceted melt layer remained essentially unchanged until it was destroyed by a thaw on January 15, 23 days after the facets developed. It showed up as a weak layer in block tests but was never loaded enough to produce an avalanche cycle.

9. SUMMARY AND CONCLUSIONS

9.1. <u>Significance</u>

- Melt layers bond much more weakly and unpredictably when they become faceted.

- Spatial variability increases.
- Tests results are unreliable.
- Triggering often occurs near rocks or thin spots.
- They are very persistently weak.

9.2. __Identification__*:*

- Faceted melt forms are a common weak layer in cold maritime snow climates but will occur anywhere that thaws, rain, or slush are followed by colder weather.
- Watch for weather sequences that may produce faceted melt forms or facets in association with melt layers.
- Check pit profiles for facets in and around melt layers. Look for sugary texture, confirm faceting with a hand lens.
- Rub suspected faceted melt layers with a gloved hand. If the top few centimeters is sugary and falls apart, do not trust that layer regardless of what pit or slope tests tell you!

9.3. ***__Stability Evaluation__***

- Facets in association with melt forms, whether they are over, within, or under a melt layer, are difficult weak layers to evaluate.
- Facets within the melt layer are particularly unstable, spatially variable, persistent, and unpredictable.
- Tests results are unreliable. Slope and block tests may show strength, yet large slabs release when the right spot is triggered. One slope may fracture catastrophically even though adjacent slopes are ridden all day with no sign of instability.
- These layers often trigger near rocks or thin spots.
- Faceted melt forms are exceptionally persistent weak layers. We have recorded skier-triggered avalanches on five week-old layers, natural releases on six week-old layers, weak block test results on 13 week-old layers, and identifiably sugary faceted textures in 17 week-old layers.

10. FURTHER STUDIES AND RECOMMENDATIONS

Our purpose in presenting the results of our studies to date is in part to spur other workers to look for and study faceted melt forms. We welcome observation and research. Let us know what you find!

There is no ICSI symbol for faceted melt forms. Rather than continuing the proliferation of individual symbols which are difficult to remember and to draw with cold fingers in wet or snowy fieldbooks, we suggest that combined forms like these be represented by doubling up the basic symbols, in this case using facet and melt form symbols side by side like this: □○

11. REFERENCES

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

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