NEAR-SURFACE FACETED CRYSTALS AND AVALANCHE DYNAMICS IN HIGH-ELEVATION, TROPICAL MOUNTAINS OF BOLIVIA

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ABSTRACT: The importance of near-surface faceted crystals in forming weak layers associated with snow avalanches has recently received greater attention. However, there is still much to be learned concerning the formation and growth of these crystal types, their geographical extent, and related avalanche activity. Here we report on a spatially extensive avalanche cycle that occurred during late September 1999 at high-elevations in the Bolivian Andes, claiming two lives. Climbers released one slide at about 5,300 m in the Cordillera Apolobamba (on El Presidente), and four days later snow scientists servicing a high-elevation meteorological site triggered another at 6,300 m near the summit of Illimani (Cordillera Real). Both slab avalanches followed lateral fracture propagation through 25-50 cm of relatively new snow; deeper pockets existed due to wind redistribution. Analysis of a snowpit on Illimani, from a nearby and safe location, showed that the avalanche ran on a thick layer of near-surface faceted crystals overlying the austral winter dry-season snow surface. Average size of the crystals was 5-7 mm, and individual crystals exceeded 10 mm in diameter. We evaluate local and regional meteorological information in an effort to understand what caused the growth of these large crystals and the resultant snowpack instability. Insights are offered regarding the avalanche hazard due to near-surface faceted crystal growth in high-elevation areas of the Tropics, where avalanches are not generally recognized as a significant hazard during the climbing season.

KEYWORDS: avalanches, avalanche formation, snow, snow stratigraphy, mountains

1. INTRODUCTION

In late September 1999, climbers at high-elevations in the Bolivian Andes released at least two slab avalanches, as snowfall and wind loading onto the dry-season snow surface led to instability over a large region. Avalanches are not among the widely recognized hazards of climbing in Bolivia, because the climbing season is heavily concentrated in the dry southern (austral) winter months of May through September. In the most recent publication on climbing in Bolivia, Brain (1999) states that "*serious accidents are rare in part because of the consistently stable and good weather during the climbing season*". Avalanches receive no mention in this climbing guide, consistent with the opinion of a guide-in-training recently that "*[avalanches] don't happen in Bolivia*" (Arrington, 1999).

On 25 September 1999, two climbers triggered a slab avalanche at an elevation of 5,200 m on Cerro Presidente, Cordillera Apolobamba, Bolivia (Table 1). Two members of the party witnessed the slide but were not involved. There was one partial burial and one complete burial, killing both climbers including the aforementioned Yossi Brain. Four days after the avalanche on Cerro Presidente, we triggered a slab release at 6,300 m near the summit of Illimani (Cordillera Real), while servicing a high-elevation meteorological station. Both slab avalanches followed lateral fracture propagation through 25-75 cm of relatively new snow, with deeper pockets due to wind redistribution (Table 1). Meteorological, weather, and snow conditions were similar between Illimani and the Apolobamba Range where the fatalities occurred.

Table 1. Characteristics of two avalanches in the Bolivian Andes, September 1999

	Cerro Presidente[a]	Nevado Illimani
Date	9-25-99	9-30-99
Time	0830	1700
Elevation (m)	5,200	6,300
Incline (°)	30-40	30-40
Type	Slab	Slab
Width (m)	100	100
Avalanche Trigger	climbers	snow scientists
Activity	Climbing	Climbing
Party size	2	3
Partial Burials	1	0
Complete Burials	1	0
Fatalities	2	0

[a] For further details see: http://www.csac.org/Incidents/1999-00/19990925-Bolivia.html

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Analysis of a snowpit on Illimani, from a nearby and safe location, showed that the avalanche ran on well-developed faceted crystals located just below the new snow. We evaluate snowpit observations, along with local and regional meteorological information, in an effort to understand what caused the growth of these large crystals and the resultant snowpack instability. Insights are offered regarding the potential avalanche hazard in high-elevation areas of the Tropics, where avalanches are not generally recognized as a significant hazard during the climbing season.

The growth of near-surface faceted crystals, and their role in the formation of weak layers within the snowpack, has recently received attention by Birkeland et al. (1996, 1998). Furthermore, Birkeland (1998) proposed a terminology and identified the predominant processes associated with the formation of weak layers in mountain snowpacks caused by near-surface faceted crystals. This work has built upon considerable work investigation the growth of faceted snow crystals in response to vapor pressure gradients resulting from temperature gradients, primarily in basal snowpack layers (*e.g.*, Akitaya, 1974; Marbouty, 1980; Colbeck, 1982; Sturm and Benson, 1997). Research focusing upon the growth of faceted crystals close to the surface has also demonstrated the importance of these gradients. Armstrong (1985) for example, determined that faceted crystal growth is initiated when the vapor pressure gradient exceeds 5 hPa m^{-1}. Birkeland et al. (1998) document bi-directional gradients five times larger, resulting in very rapid growth of near-surface faceted crystals. In the latter case study, a significant weak layer formed in less than 48 hours. Of great importance to the understanding of near-surface faceted crystal growth at high elevations is the mathematical treatment of the issue by Colbeck (1989), who determined that formation could occur due to either temperature cycling or solar radiation input – but that "…solar input definitely increases the sub-surface growth rate".

2. SITE DESCRIPTION

The University of Massachusetts maintains two high-elevation meteorological stations near the summits of Illimani and Sajama in Bolivia (Figure 1), as part of a project to better understand the climatic signal recorded by tropical ice cores (Hardy et al., 1998). The meteorological station on Illimani was not fully functional in September; we were there to service the station and collect snow samples. Meteorological records from Sajama are used in our analysis of the September avalanche cycle to supplement the Illimani observations.

Nevado Illimani (6458 m) is the highest peak in the Cordillera Real (Figure 2). The meteorological station on Illimani is located approximately 200 m below the summit (16°39' S; 67°47' W at 6,265 m (20,555 ft)), in a large bowl oriented to the southwest.

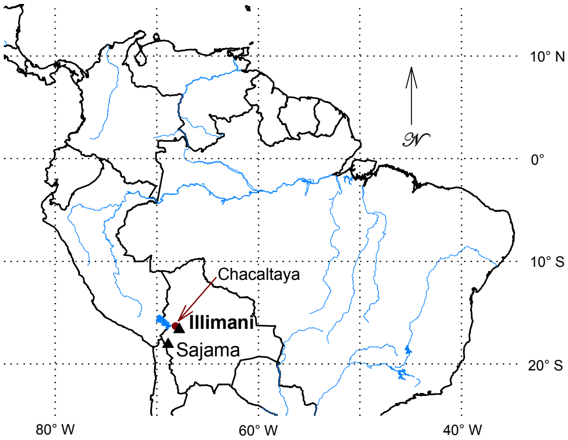

Figure 1: Map showing the location of Bolivia, Nevados Illimani and Sajama, and Chacaltaya. The University of Massachusetts maintains high-elevation meteorological stations near the summit of both mountains.

Nevado Sajama is within the Cordillera Occidental, on the eastern side of the Altiplano (Figure 1). The meteorological station on Sajama is located about 27 m below the summit (18°06' S; 68°53' W at 6,515 m (21,376 ft)).

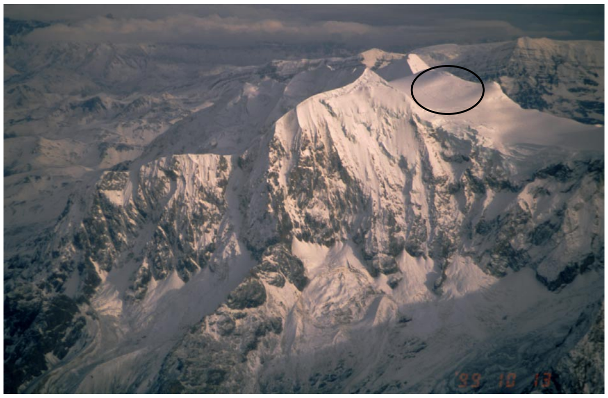

Figure 2: Nevado Illimani as seen from a commercial airline flight between La Paz, the capital of Bolivia, and Santa Cruz. An oval on the image, east of the summit, indicates the 14-day old avalanche path. Illimani (6,458 m) is the highest peak in the Cordillera Real, a massive mountain with three summits over 20,000 feet, visible from hundreds of miles out on the Altiplano to the west and from far out into the Amazon Basin on the east.

The Bolivian Andes experience a marked seasonality in precipitation, with an extended summer wet season and a dry winter. The 30-year record fromChacaltaya, just west of Illimani (Figure 1), illustrates the pronounced dry period June-August, when less than 5% of the annual precipitation is delivered (Figure 3). Precipitation over the entire Bolivian Altiplano (including Sajama) originates almost exclusively from the east, and annual totals decrease to the west of the Cordillera Real.

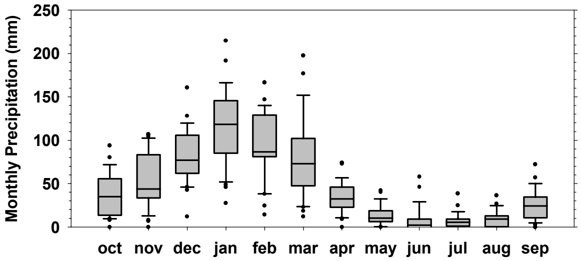

Figure 3: Monthly precipitation at Chacaltaya, Bolivia (5,220 m), 1967 – 1997. Whisker plot boxes illustrate the median (line) and enclose the 25th and 75th percentiles. Error bars enclose the 10th and 90th percentiles, with extremes indicated by circles. Annual precipitation averaged 560 mm during this period.

Mean annual temperature (MAT) near the Illimani weather station is –7.6°C, as indicated by the borehole temperature at 10 m (Zweifel, personal communication). MAT on Sajama is 3.0°C lower by our station measurements and by the 10m borehole temperature (Zagoradnov, personal communication).

3. METHODS

On 30 September 1999 a snowpit was dug and analyzed in a location adjacent to the avalanche we initiated on 29 September 1999. We measured snow properties using standard protocols (e.g., Williams et al., 1999). We used a 100 cc stainless steel Taylor-LaChapelle cutter and an electronic scale (± 1g) to measure snow density. Snowpack temperatures were measured with 20-cm long dial stem thermometers. Grain type, size, and snowpack stratigraphy were also recorded, following the protocols in Colbeck et al. (1990). The chemical and dust content of individual strata in the snowpack were also analyzed, providing additional information on the snowpack history (Hardy et al., submitted).

Here we analyze the climatological and snow conditions that led to the avalanche cycle using information from the high-elevation meteorological stations on Nevado Illimani and Sajama. For this report, we emphasize measurements of air temperature and snow accumulation.

4. RESULTS and DISCUSSION

4.1 Avalanche on Nevado Illimani

We released a slab avalanche near the summit of Nevado Illimani on 29 September 2000, similar to the slab release on Cerro Presidente 4 days earlier (Table 1). We were at about 6,300 m on the afternoon of 29 September en route to a weather station on Nevado Illimani in the Cordillera Real. Snow was well-sintered and supported steps and front-pointing on the 45-50° west-facing approach to a saddle below the summit of Illimani Sur. We began descending from the saddle below the summit of Illimani Sur to the weather station, on a very gentle slope of perhaps 10 degrees. As the slope began to steepen the walking became more difficult in deepening snow. We started to post-hole with every step. Twice the snow whoomphed on the very gradual slope, a phenomena one of us (CE) had experienced only five times in 13 years of climbing in Bolivia. We were in a dense white-out at the time, proceeding toward the meteorological station by reckoning. Suddenly a larger whoomph (or "firn quake") occurred, obviously representing a widespread collapse of the snowpack. Simultaneously, we actually heard a fracture propagate to our left, followed by a dull roar. Visibility was minimal, but a fresh fracture line was visible in the snowpack underneath our feet and extending to our left, where we had heard what we thought was an avalanche release. We retreated back to the saddle and set up camp, as in the whiteout it was impossible to assess the danger of additional slides.

Shortly thereafter the clouds thinned and the avalanche we released became visible (Figure 2) about 200 meters to our left. The slab originated from a distinct fracture, 1-2 m thick. We estimate the slide path at 100-200 m in both width and length, although we did not have time to inspect it more closely. The runout zone of the avalanche was within 100 m of our meteorological station and snowpit.

4.2 Snow Accumulation and Snowpit Stratigraphy

Negative sea-surface temperature anomalies in the central equatorial Pacific (i.e., La Niña) are known to enhance wet-season precipitation on the Altiplano (Vuille et al., 2000), and a large La Niña event peaked during the 1998-99 wet season. At the Illimani weather station, 240 cm of snow accumulated by early April of 1999, which buried the snow depth sensor. Visits to the station on 7 April and 17 June revealed no change in surface height, although without the sensor we have no record of variability between those dates. The snow surface on 29 September was 25-30 cm above that of 17 June, representing 270 cm of accumulation since the previous November.

A 180-cm deep snowpit was dug on 30 September 1999, the day after the avalanche, on a slope angle of about 10 degrees. Stratigraphic analysis and sample collection were conducted from about 1300 to 1600 hrs on that day. Weather was clear, bright, and brisk, with the sun almost directly overhead. Snow temperatures were about 0°C in the first 9 cm, then about -3.0°C for the remainder of the snowpack (Figure 4). Density generally increased with depth, from about 210 kg m^{-3} at the snow surface to 410 kg m^{-3} at a depth of 180 cm, with the exception of several ice lenses.

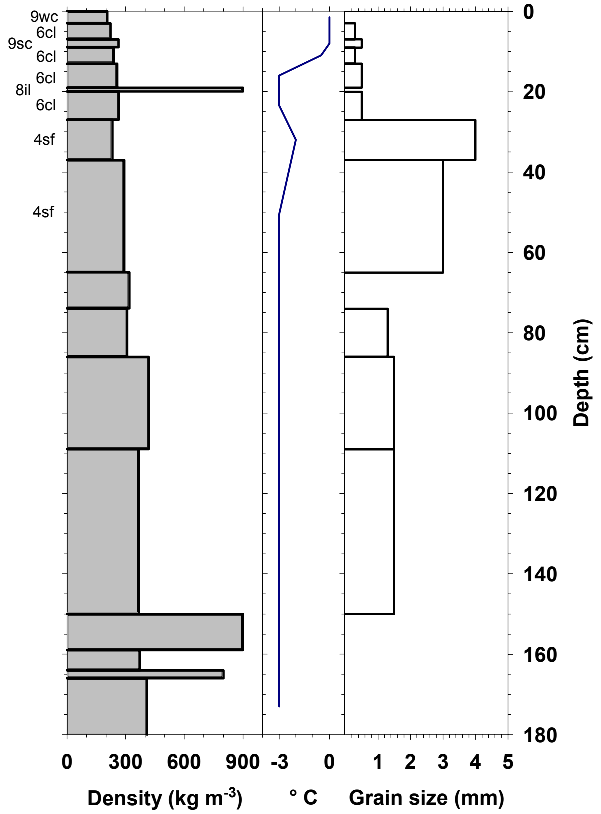

Figure 4: Snowpit profile sampled at 6,300 m on 30 September 1999, near the summit of Nevado Illimani, Bolivia. Note the presence of near-surface faceted crystals from 27-64 cm.

The stratigraphy of the snowpit contained some interesting surprises. Snow grains in the first 19 cm were rounded, suggesting the presence of some liquid water and wet snow metamorphism *(e.g.* Colbeck, 1979). The small grain size of 0.3 mm along with the absence of polycrystalline grains suggests that conditions consisted of snow with low water content and little if any percolation. A thin ice layer at 19-20 cm was consistent with either subsurface melting and refreezing (e.g., Liston, 1999), or refreezing of draining meltwater. Snow grains from 20-27 cm were similar to grains at 0-19 cm, though slightly larger at 0.5 mm in diameter.

Below a depth of 27 cm, the stratigraphy suggested a different snow environment. Snow grains at a depth of 27-37 cm were heavily faceted. Many of the grains showed well-developed cups and scroll patterns similar to kinetic growth or depth hoar grains that develop at or near the bottom of the snowpack (Colbeck, 1983). Average grain size was 3-5 mm, with several grains larger than 10 mm. Dust was visible throughout this layer, with much higher concentrations in the upper 3 cm of this layer. Sintering was particularly poor in this layer. The layer from 37-64 cm was similar to the above layer, with the exception that faceting was evident but not as well-developed. Grain sizes of 2-4 mm were smaller than in the layer above. There was no visible dust in this layer. A well-bonded ice lens was at 65-73 cm, composed of melt-freeze grains frozen together.

The avalanche that we triggered appeared to run on the faceted grains located at a depth of 27-37 cm in our snowpit. We believe that the faceted grains we report for layers from 27-64 cm are near-surface faceted crystals, formed by the process Birkeland (1998) terms diurnal re-crystalization. To our knowledge, these near-surface faceted grains are the largest ever reported, either in the avalanche literature or informally among avalanche professionals. Their presence suggests unique meteorological conditions at high elevations in the tropical Andes.

4.3 Meteorological Conditions

4.3.1 Precipitation

Direct measurements of precipitation on Illimani are not available through the 1999 dry season. From observations, we know that 25-30 cm of snow accumulated sometime between 17 June and 29 September, and snowpit evidence indicates that this increment fell within days to weeks prior to 29 September. Such winter precipitation events have been recorded in prior years on Illimani, including two snowfalls in August 1997 (19 and 12 cm), 15 cm in September of that year, and one 10 cm event during June of 1998.

Bolivian station data show that a widespread regional event occurred on 17 September 1999 (7.4 to 7.9 mm at La Paz, Cochabamba, and Oruro). On Sajama, after a prolonged period without precipitation, 19 cm of accumulation was recorded on 18-19 September and 23 cm on 28-30 September. These are relatively large events for the more arid Sajama, and the accumulation was not blown away as typically occurs with winter precipitation events on Sajama.

One additional piece of indirect evidence for the timing of precipitation comes from Illimani. During the dry (low humidity) evening of 22-23 September, snow was evidently drifting in response to wind speeds of 4-7

Table 2. Mean monthly temperatures and incoming solar radiation (K-down) on Sajama, June - September 1999.

Month	Minimum Aspirated Daily T (deg. C)	Maximum Aspirated Daily T (deg. C)	Daily Temperature Range (deg. C)	Maximum Daily K-down ($W m^{-2}$)
June 1999	-16.6	-9.6	7.0	817
July 1999	-16.6	-10.4	6.3	763
August 1999	-15.9	-8.1	7.8	861
September 1999	-15.2	-6.9	8.3	950

$m s^{-1}$, because the reflected solar radiometer was buried beneath the snow surface on 23 September. Indeed, for the two week period prior to the Illimani avalanche, winds were consistently from the northwest (blowing downslope) at speeds varying between 2 and 8 $m s^{-1}$. In summary, considerable snowfall apparently occurred within the period 8-12 days prior to avalanches in the Cordilleras Apolobamba and Real, accompanied by sufficient wind to cause redistribution of the new snow.

4.3.2 Solar radiation and air temperature

Solar radiation receipt remains high during the austral winter at high elevations in the Andes, with daily irradiance maxima typically greater than 800 W m^{-2} (Hardy et al., 1998). However, the mean temperature on Sajama during the winter is only –12.8°C (1996-99), due to the low air density at high elevation. In contrast to mid-latitude mountain environments, the average diurnal temperature range of 7.8°C is larger than the annual temperature range. Monthly measurements on Sajama from June through September 1999 show increasing solar radiation, and increases in both mean air temperature and the daily temperature range (Table 2). Illimani temperatures are generally slightly higher, due to the 250 m elevation difference and higher humidity, but unavailable for this time period.

5. SUMMARY

The near-surface faceted crystals observed on Illimani in September 1999 appear to be both better developed (i.e., large) and form a thicker layer than any reported previously. While the best-developed grains were in a layer 10 cm thick, those in the 27 cm thick layer below were also faceted. This thicker layer may have been briefly exposed to the surface prior to the additional 10 cm of accumulation, however, the lack of dust in this layer suggests that the faceting occurred after the layer was buried (i.e., 10 – 37 cm deep). Conditions unique to high-elevation tropical mountains favoring the growth of near-surface faceted crystals include: (1) higher input of incoming solar radiation, due to less atmosphere; (2) greater absorption of solar radiation at the snow surface during the austral winter, due to the relatively high dust concentration (enhancing the temperature gradient); and (3) greater longwave radiation loss due to rapid cooling of the dry, thin atmosphere in the evening.

Development of near-surface faceted crystals during the dry season, at high elevations in the Bolivian Andes, may present a greater avalanche hazard than is generally recognized. Two documented incidents in September 1999 occurred when ‘early season’ snow was redistributed onto leeward slopes, burying a thick, well-developed layer of near-surface faceted crystals. This layer probably formed through the process Birkeland (1998) termed diurnal recrystallization. In this region of the Andes, our results suggest that ideal meteorological conditions for faceted crystal growth persist through the entire climbing season of June-August, and probably occur most years in high-elevation areas. Indeed, we have observed buried near-surface faceted crystals within a previous years snowpack on Sajama. Regional precipitation decidedly increases during September, and relatively large snowfall events are not uncommon in our short record from Illimani. Avalanches may occur when synoptic weather conditions result in dry-season snow events and high wind speeds that produce a slab over this weak layer. La Nina conditions, such as during 1998-99, may favor this situation. Although the resulting instability should be relatively easy to recognize due to audible collapse upon loading (whoomphing), climbers must be alert to the potential threat. Currently, climbers and other users of the Bolivian high-mountain environment are not expecting to encounter avalanche hazards during the climbing season, and many have little experience in evaluating avalanche dangers.

6. ACKNOWLEDGEMENTS

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