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Near-surface faceted crystals, avalanches and climate 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 two avalanches that occurred during late September 1999 at high-elevations in the Bolivian Andes. Climbers released one slide at about 5200 m in the Cordillera Apolobamba (on El Presidente), which claimed two lives. Four days later and 200 km to the southeast, snow scientists servicing a high-elevation meteorological site triggered another at 6300 m near the summit of Illimani (Cordillera Real). Both slab avalanches fractured through 25–50 cm of relatively new snow, with deeper pockets of wind redistributed snow. Snowpit analyses on Illimani showed the avalanche ran on a thick layer of near-surface faceted crystals overlying the austral winter dry-season snow surface. Average crystal size 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. Dust and chemistry profiles indicate that the crystal growth occurred through the austral winter, prior to a snowfall event in the days prior to the avalanche. Temperature profiles measured just above and just below the snow surface indicate that bi-directional, large gradients of temperature and vapor pressure exist through the dry winter season. 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 may have 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 austral winter months of May through September. Avalanches receive no mention in the most recent publication on climbing in Bolivia (Brain,

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1999), 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 5200 m on Cerro Presidente, Cordillera Apolobamba, Bolivia (Table 1). One partial burial and one complete burial resulted, and both climbers were killed. Two members of the party witnessed the slide but were not involved. Four days after the avalanche on Cerro Presidente, we triggered a slab release ~200 km to the southeast, at 6300 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). Weather and snow conditions prior to the avalanches were similar on Illimani and in the Apolobamba.

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). Birkeland (1998) proposed the terminology "near-surface-faceted crystals" as snow formed by near-surface vapor pressure gradients resulting from temperature gradients near the snow surface. Furthermore, he identified the predominant processes leading to the formation of near-surface faceted crystals. This work has built upon considerable work investigating 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 h. Of importance to the understanding of near-surface faceted crystal growth at high elevations is the mathematical treatment of the issue by Col-

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

	Cerro Presidente[a] (Cordillera Apolobamba)	Nevado Illimani (Cordillera Real)
Date	25 September 1999	30 September 1999
Time	0830	1700
Elevation (m)	~5200	6300
Incline (°)	30–40	30–40
Type	Slab	Slab
Width (m)	100	100
Canadian size classification	2–3 (?)	2
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.

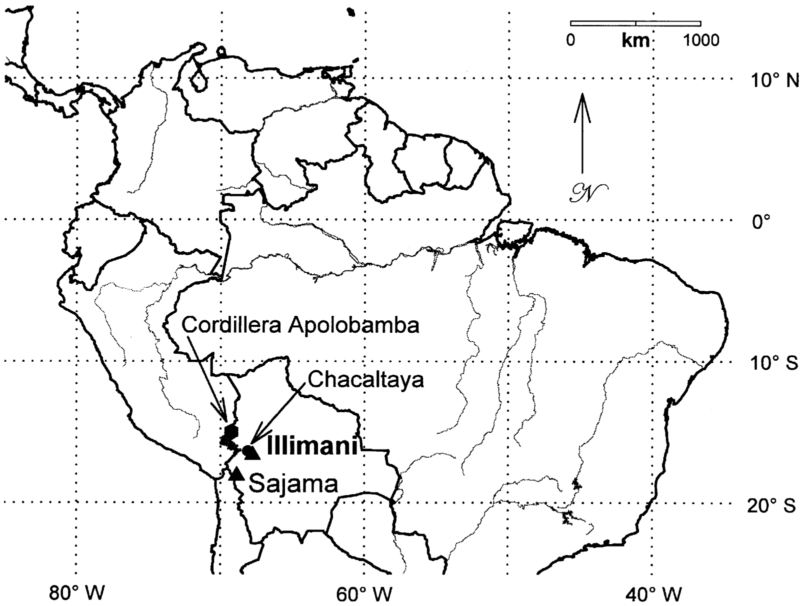

Fig. 1. South America north of 25°S, showing locations discussed in text; all are within Bolivia. From Illimani, Nevado Sajama is ~200 km to the southwest, and Cerro Presidente (Cordillera Apolobamba) is ~200 km to the northwest. The University of Massachusetts maintained high-elevation meteorological stations near the summits of Sajama and Illimani.

beck (1989), who determined that formation could occur due to either temperature cycling or solar radiation input—but "...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 (Fig. 1), as part of a project to better understand the climatic signal recorded by tropical ice cores. Each station has an array of sensors to measure aspirated air temperature and humidity, pressure, wind speed and direction, solar radiation and snow accumulation/ablation (distance to snow surface). Additional instrumentation on Sajama provides measurement redundancy, as well as profiles of air and snow tem-

Table 2
Selected sensors and measurements intervals, at high-elevation weather stations in Bolivia. Variables unique to Sajama are shown in italics. Heights changed constantly as the snow surface changed; those shown here are for Sajama on approx. 1 July 1997

Variable	Sensor model	Height (m)	Sampling interval
Wind speed and direction (upper)	R.M. Young 05103	3.7	60 s
Wind speed and direction (lower)	R.M. Young 05103	2.7	60 s
Air temperature	Vaisala HMP35C	3.7	10 min
Relative humidity	Vaisala HMP35C	3.7	10 min
Snow accumulation *($n=2$)*	Campbell SR50 acoustic	2.47 and 2.57	1 hr
Snow surface temperature	Everest Interscience 4000B	2.3	10 min
Air temperature gradient	Type E thermocouples	0.03, 1.03, 2.03, 3.7	10 min
Snow temperature	Thermometric thermistors	0.15, −1.85	10 min
Snow temperature gradient	Type J thermocouples	0, −0.01, −0.06, −0.11, −0.16	10 s

Fig. 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 location of the avalanche that occurred 14 days prior. Illimani (6458 m) is the highest peak in the Cordillera Real, a massive mountain with three summits over 20,000 ft, visible from hundreds of miles out on the Altiplano to the west and from far out into the Amazon Basin on the east.

perature (Table 2). Measurements are processed and stored on-site, as well as transmitted to the GOES East satellite. Data are obtained from NOAA in near real-time at the UMass Climate Systems Research Center. The meteorological station on Illimani was not fully functional in September; we were there to service the station and collect snow samples. Data from Sajama are therefore used in our analysis of the

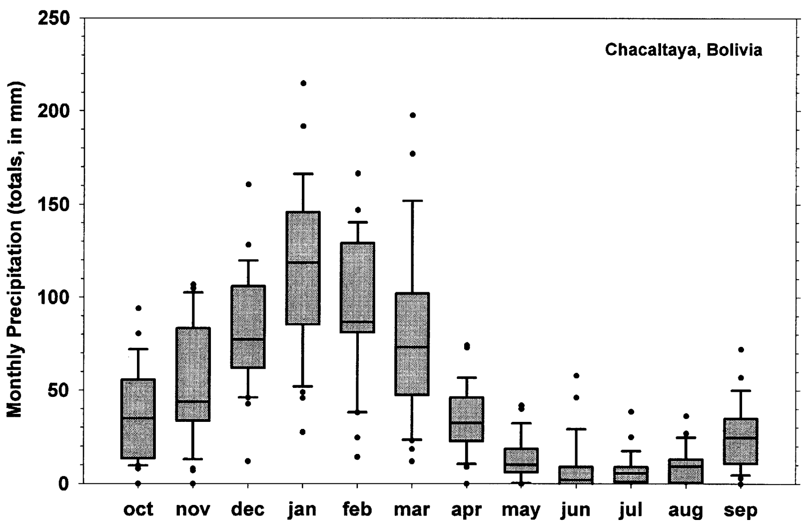

Fig. 3. Monthly precipitation at Chacaltaya, Bolivia (5220 m), 1967–1997. Whisker plot boxes illustrate the median (line) and enclose the 25th and 75th percentiles. Error bars enclose the 10th and 90th percentiles, with extremes indicated by circles. Annual precipitation averaged 560 mm during this period.

September avalanches to supplement the Illimani observations.

Nevado Illimani (6458 m) is the highest peak in the Cordillera Real, a massive mountain with three summits over 20,000 ft (Fig. 2). The meteorological station on Illimani is located approximately 200 m below the summit (16°39′S; 67°47′W at 6265 m (20,555 ft)), in a large bowl oriented to the southwest. Nevado Sajama is located in Parque Nacional Sajama, within the Cordillera Occidental, on the eastern side of the Altiplano (Fig. 1). This extinct volcano is the highest peak in Bolivia (6542 m), and higher elevations of the mountain are covered by an ice cap. The meteorological station on Sajama is located about 27 m below the summit (18°06′S; 68°53′W at 6515 m (21,376 ft)).

The Bolivian Andes experience a marked seasonality in precipitation, with an extended summer wet season and a dry winter. The 30-year record from Chacaltaya, just west of Illimani (Fig. 1), illustrates the pronounced dry period June–August, when less than 5% of the annual precipitation is delivered (Fig. 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.

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 10-m 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 triggered on 29 September 1999. We measured snow properties and snowpack stratigraphy using standard protocols (e.g., Colbeck et al., 1990; Williams et al., 1999). We used a 100-cm^3 stainless steel Taylor–LaChapelle cutter and an electronic scale (±1 g) to measure snow density. Snowpack temperatures were measured with 20-cm-long dial stem thermometers. A 16× hand lens (18 mm diameter) and gridded plate were used to determine grain shape and estimate grain size.

The chemical and dust content of individual strata in the snowpack were also analyzed. These values have the potential to provide information on snowpack development (e.g., Hardy et al., 1998b), and on conditions at the snow surface, such as evaporation amounts (Eichler et al., 2000). Snow samples were collected in EPA-certified containers for chemical and isotopic content following methods such as those of Williams et al. (1996), and kept below −4 °C during transport to the lab. Laboratory analyses were conducted at the Byrd Polar Research Center at Ohio State University.

Here we analyze the climatological and snow conditions that led to the two avalanches, using information from the high-elevation meteorological stations on Nevado Illimani and Sajama. A comprehensive discussion of the station's design and configuration has been published (Hardy et al., 1998a). For this report, we emphasize measurements of air temperature, snow accumulation, snow surface temperature, and internal snowpack temperatures. Instruments and sampling frequency for these measurements are presented in Table 2.

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 6300 m on the afternoon of 29 September en route to a weather station on the mountain. 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 to the weather station, on a gentle slope of perhaps 10°. 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 collapsed with a "whoomph" noise on the gradual slope, a phenomena one of us (CE) recalls experiencing only five times in 13 years of climbing in Bolivia. We were in a dense whiteout at the time, proceeding toward the meteorological station by reckoning. Suddenly a larger whoomph (or "firn quake") occurred, representing a widespread collapse of the snowpack. Simultaneously, we 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 to the saddle and set up camp, as in the whiteout it was impossible to assess the danger of additional slides.

Visibility improved shortly thereafter, revealing the avalanche we had released (Fig. 2), about 200 m 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 (size 2, Canadian classification), 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) enhance wet-season precipitation on the Altiplano (Vuille et al., 2000), and a large La Niña event peaked during the 1998–1999 wet season. At the Illimani weather station, 240 cm of snow accumulated by early April of 1999, which buried the snow depth sensor. Station visits on 7 April and 17 June document the same snow depth, although without the sensor we have no record of variability between those dates. On 29 September, the snow surface 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°. Stratigraphic analysis and sample collection were conducted from about 1300 to 1600 h on that day. Weather was clear, bright, and brisk, with the sun almost directly overhead. Snow temperatures were isothermal at 0°C in the first 9 cm, decreasing to -30°C for the remainder of the snowpack observed (Fig. 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 layers.

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 is consistent with subsurface melting and re-freezing. 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 throughout the 27–37 cm depth layer 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, and the density was 230 kg m^{-3}. Dust was visible throughout this layer, with much higher concentrations in the upper 3 cm. Hardness was measured by the hand test as low (Fig. 4). The layer from 37–64 cm was similar to that above, except that faceting was not as well developed. Grains sizes of 2–4 mm were smaller than in the layer above, and it was slightly harder. There was no visible dust in this layer. A well-bonded ice lens was at 65–73 cm, composed of melt–freeze polycrystals.

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 larger, and more diverse in form, than those previously reported either in the avalanche literature or informally among avalanche professionals. We believe that these differences are the result of unique meteorological conditions at high elevations in the tropical Andes.

4.3. Snow chemistry and dust content

The chemical and dust content of the snowpack provides insight into the meteorological history of the snowpack development. Dust concentrations from the bottom of the snowpit at 180 cm to a depth of 37

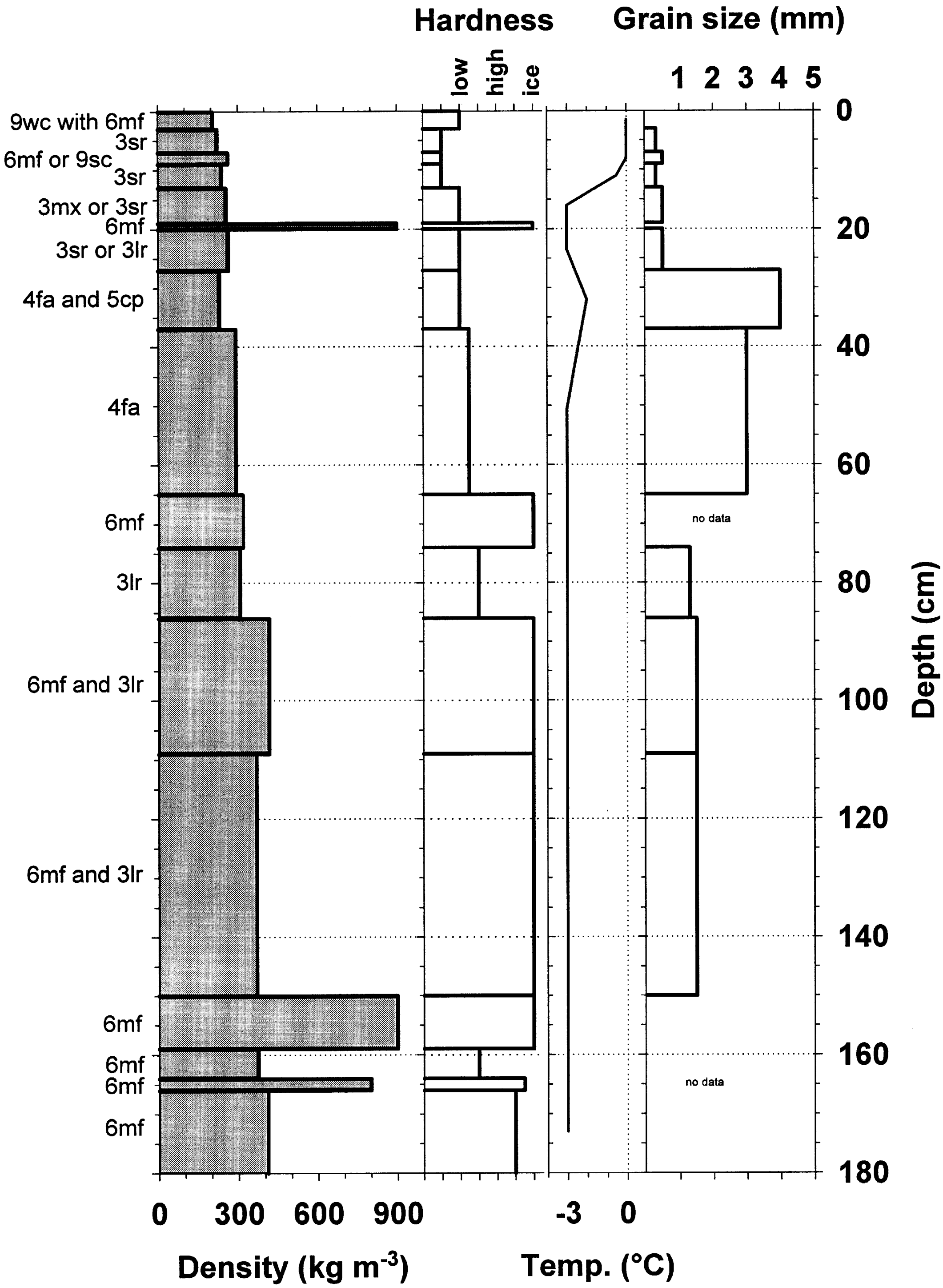

Fig. 4. Snowpit profile sampled at 6300 m near the summit of Nevado Illimani, Bolivia on 30 September 1999. Note the presence of near-surface faceted crystals from 27–64 cm.

cm were relatively low (Fig. 5). At the 27–37 layer, characterized by large and well-developed near-surface faceted crystals, the dust concentration increased by more than two orders of magnitude to almost 3,000,000 particles/mL. Calcium, which is a major component of dust, increased by more than an order of magnitude from 50 ppb at a depth of 50 cm to 1500 ppb at the layer at 27–37 cm. These dust and calcium concentrations indicate that the meteorological conditions were much different while the layer at 27–37 cm was exposed at the snow surface, compared to all other layers.

Comparison of our results to those from the Quelccaya Ice Cap in Peru illustrates the climatic conditions on Illimani that preceded the avalanche release. Dust concentrations from snowpits on the Quelccaya Ice Cap in Peru exhibit a distinct seasonal variation, with high concentrations during the dry season similar to those we report for the layer at 27–37 cm and with concentrations during the wet season near zero (Thompson, 1980). The association of high particle concentrations at Quelccaya with the dry season is a function of: (1) high radiation receipt with little accumulation (e.g., lots of clear days with little cloud cover); (2) dominant wind direction from the west, transporting material from the high, dry Altiplano; and (3) higher wind speeds during the austral winter (Thompson et al., 1988).

The large increase in dust particles in our snowpit suggests that little precipitation occurred for an extended period of time while the layer at 27–37 cm depth was exposed at the snow surface—perhaps since early April. Additionally, the lack of grain rounding or re-frozen meltwater in that layer is

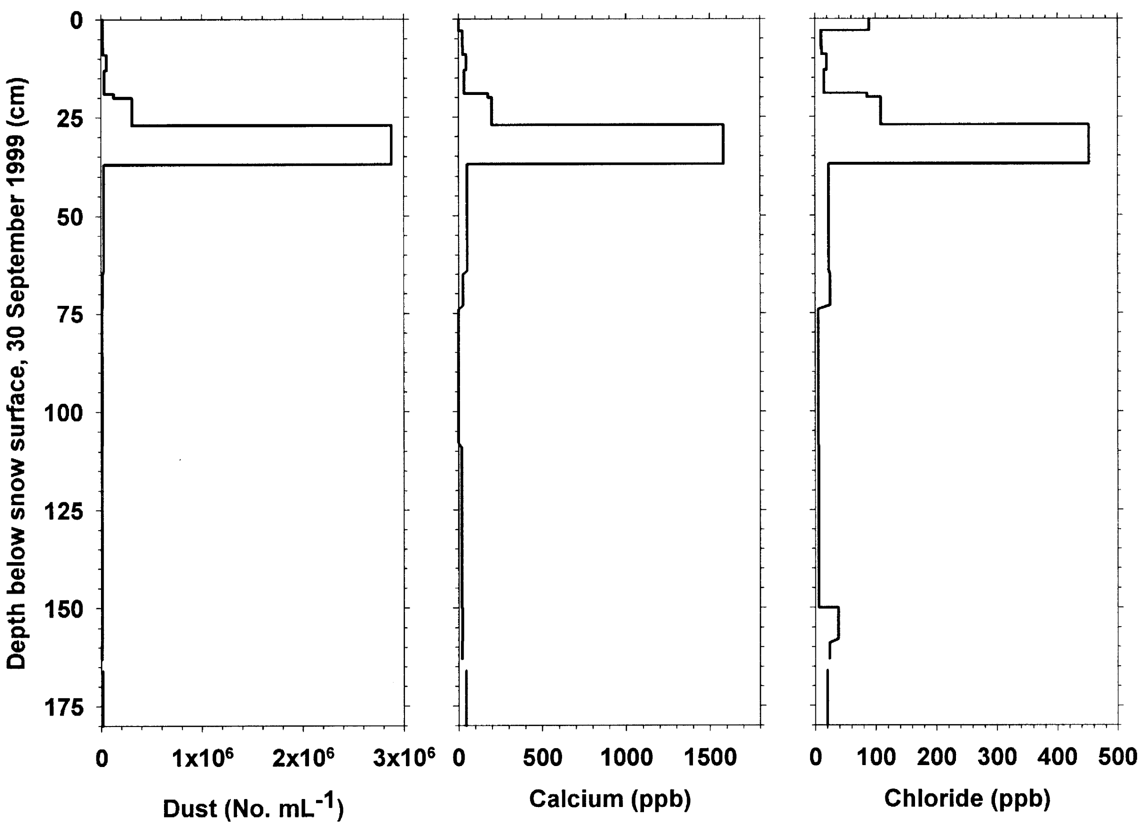

Fig. 5. Dust and chemical content of the snowpit profile sampled at 6300 m near the summit of Nevado Illimani, Bolivia on 30 September 1999. Note the large increase in dust, calcium, and chloride concentrations in the snowpack within the sample taken between 27 and 37 cm.

evidence that air temperatures were low enough that no liquid water was produced at or just below the snow surface.

Chloride concentrations can be used to evaluate the possibility of sublimation/evaporation at the snow surface in high-elevation environments (Eichler et al., 2000). Chloride concentrations increase from 25 ppb at a depth of 50 cm to 450 ppb in the layer at 27–37 cm. The large increase in concentration of chloride at a depth of 27–37 cm suggests that large amounts of sublimation occurred while this layer was exposed at the snow surface.

The dust and chemistry data suggests that the surface at 27 cm depth was exposed to clear and cold conditions during the austral winter. Meteorological conditions during this exposure appear to have driven the formation of near-surface faceted crystals.

4.4. Meteorological conditions

4.4.1. 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 the snowpit evidence suggests that this increment fell within days to weeks to 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 precipitation 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 snow 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 m s^{-1}, because the reflected solar radiometer was buried beneath the snow surface on 23 September. Indeed, for the 2-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, probably accompanied by sufficient wind to cause redistribution of the new snow.

4.4.2. 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., 1998a). However, the mean temperature at the summit of Sajama (~460 hPa) during the winter is only −12.8 °C (1996–1999). In contrast to mid-latitude mountain environments, the average diurnal temperature range of 7.8 °C is larger than the annual temperature range. Monthly mean measurements on Sajama from July through September 1999 show increasing solar radiation, and increases in both mean air temperature and the daily temperature range (Table 3). Illimani temperatures

Table 3
Monthly temperatures and incoming solar radiation (K-down) on Sajama, June–September 1999

Month	Mean minimum aspirated daily *T* (°C)	Mean maximum aspirated daily *T* (°C)	Mean daily temperature range (°C)	Mean 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
Sepetember 1999	−15.2	−6.9	8.3	950

are generally slightly higher, due to the 250 m elevation difference and higher humidity, but unavailable for this time period.

4.4.3. Near surface temperature gradients

Although air temperature is measured only at ‘screen height’ on Illimani, additional temperature measurement instrumentation operated on Sajama (Table 2). During clear-sky conditions, without differences in cloud cover, Sajama provides an excellent analog for the near-surface temperature patterns on Illimani. While we realize the inherent problems in the measurement of near-surface temperatures and calculation of temperature gradients (e.g., Birkeland et al., 1998), our results demonstrate the range of possible temperature (and vapor pressure) gradients available to drive the formation of near-surface faceted snow crystals in this environment. Where appropriate, we use only night-time measurements (2100–0700 h) to avoid potential problems caused by heating of the instrumentation.

To investigate the near-surface *air* temperature gradient, we selected a nearly cloudless 13-day period of data from July 1997. A thermocouple (TC) had just been installed 4 cm above the snow surface during a site visit ending 2 July, and the infrared temperature transducer was functioning well. Given the uniformity of the radiation regime through this

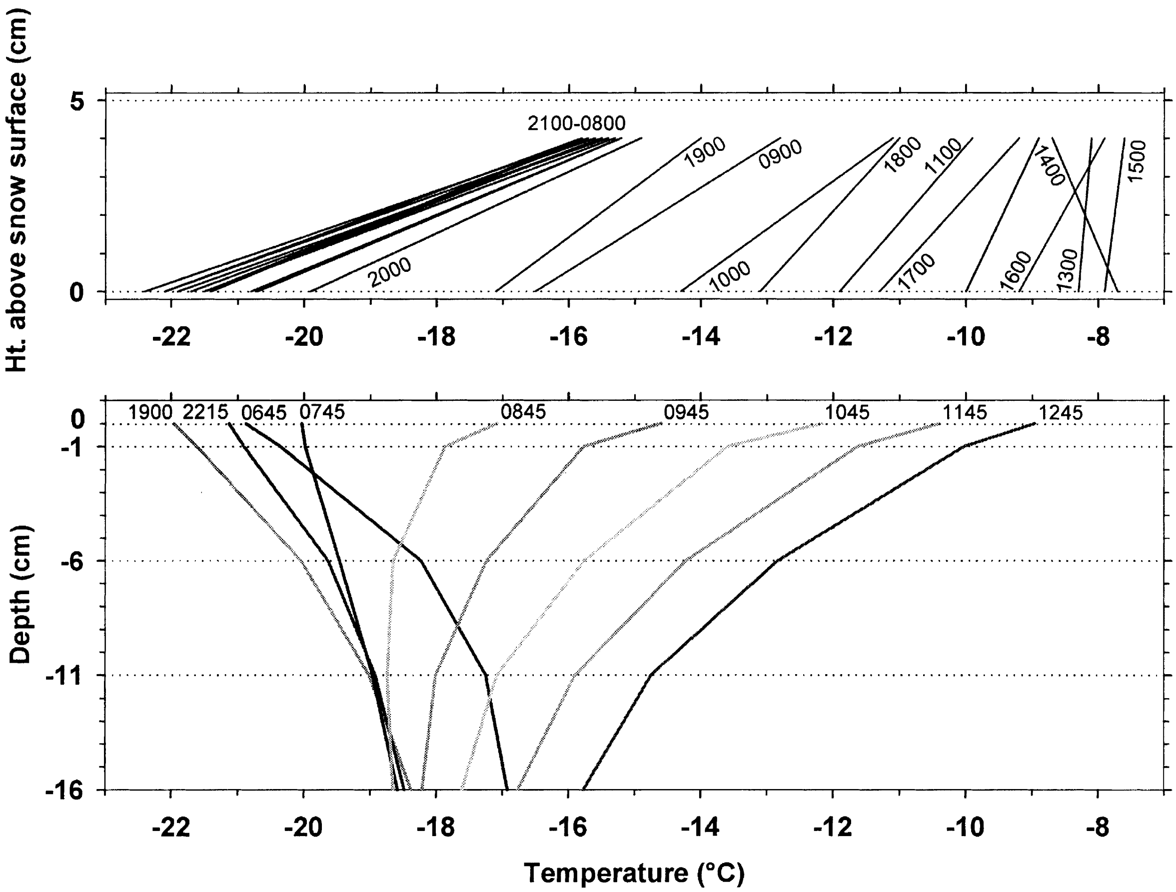

Fig. 6. Temperature profiles just above (upper plot) and below (lower plot) the snow surface on Sajama, during two different time periods. Air temperature profiles represent the mean hourly temperature at about 3.9 cm above the surface (range during period = 3.1–4.9 cm) and at the snow surface, during the period 1–13 July 1997. (The 1400 temperature at 4 cm may not be comparable to those at other times, due to differential shading of solar radiation on the thermocouples.) Lower profiles depict measured temperatures at selected time periods with clear-sky conditions, between 1900 h on 27 June and 1245 h on 28 June, 1997. Measurement depths are 0, 1, 6, 11, and 16 cm.

period, we determined the average temperature at 4 cm and at the surface, for each hour of the day. These pairs of values, for each hour, were used to estimate the temperature gradient in the lowest 4 cm above the snow. The uniformity of the gradient during periods of no solar radiation (i.e., night-time) is quite remarkable (Fig. 6, upper); night-time gradients were not significantly affected by wind speed, which varied between calm and 24 m s^{-1} (not shown). We calculate an average night-time temperature gradient in the lowest 4 cm during these 13 days of 161°C m^{-1}, well within the 100–300°C m^{-1} range others have recorded.

The near-surface *snow* temperature gradient was measured through a brief period just prior to the time period discussed above. While servicing the weather station we installed a TC array in undisturbed snow nearby (as described by Birkeland et al., 1998), and temperature measurements were collected every 15 min over 3 days. Our procedure differed slightly from that of Birkeland et al. (1998) in that the top TC was installed right at the snow surface, so measurements were made at 0, −1, −6, −11 and −16 cm. The resultant measurements do not provide a comprehensive measure of the maximum temperature gradients possible at the site, because some cloud cover is known to have occurred during the night-time hours (altering the longwave radiation balance), and because wind speeds were relatively high (10–20 m s^{-1}) through the period (inducing convection within the snowpack). Fig. 6 (lower) illustrates profiles during largely clear-sky conditions over a very brief period of measurements. These limited data suggest that bi-directional gradients may be roughly symmetrical, reaching at least ±50 °C m^{-1} in magnitude and probably higher close to the surface. At 6515 m on Sajama (~460 hPa), therefore, vapor pressure gradients could typically exceed ±5 hPa m^{-1}.

5. Summary

The near-surface faceted crystals observed on Illimani in September 1999 appear to be both better developed (i.e., larger) and form a thicker layer than those reported from mid-latitude mountain environments. This finding is consistent with Colbeck's (1989) theoretical treatment of near-surface faceted crystals growth. While the best-developed grains on Illimani were in a layer 10 cm thick, those in the 27 cm-thick layer below were also faceted. It is not known when the faceted crystals developed, although the thicker layer was exposed to the surface for less time than the overlying 10 cm of accumulation, based on dust concentrations (Fig. 5). Faceting in the lower layer may have occurred after burial (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 and higher sun altitudes; (2) greater day-time 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 redisturbed 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 Niña conditions, such as during 1998–1999, 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 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 danger.

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