Controlled Irradiative Formation of Penitentes

Vance Bergeron,[1] Charles Berger,[2] and M. D. Betterton[3]

[1]*Ecole Normale Supéreiure, Laboratoire de Physique, UMR 5672, 46 allée d'Italie, 69364 Lyon Cedex 07, France*

[2]*Ecole Normale Supéreiure, Laboratoire de Physique Statistique, 24 rue Lhomond, 75231 Paris Cedex 07, France*

[3]*Department of Physics, 390 UCB, University of Colorado, Boulder, Colorado 80309, USA*

(Received 11 July 2005; published 7 March 2006)

Spike-shaped structures are produced by light-driven ablation in very different contexts. Penitentes 1–4 m high are common on Andean glaciers, where their formation changes glacier dynamics and hydrology. Laser ablation can produce cones 10–100 μm high with a variety of proposed applications in materials science. We report the first laboratory generation of centimeter-scale snow and ice penitentes. Systematically varying conditions allows identification of the parameters controlling the formation of ablation structures. We demonstrate that penitente initiation and coarsening require cold temperatures, so that ablation leads to sublimation. Once penitentes have formed, further growth of height can occur by melting. The penitentes initially appear as small structures (3 mm high) and grow by coarsening to 1–5 cm high. Our results are an important step towards understanding ablation morphologies.

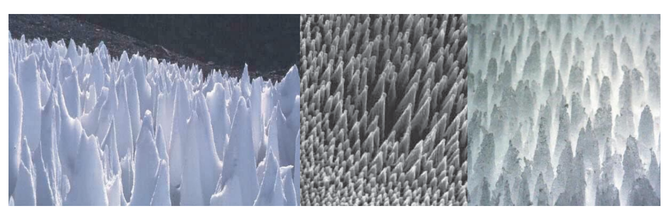
DOI: 10.1103/PhysRevLett.96.098502 PACS numbers: 92.40.−t, 81.16.Rf, 89.75.Kd, 92.70.Ha.

Penitentes 1–4 m high are found on glaciers in high mountain regions; laser ablation of materials can produce similar structures 10–100 μm high (Fig. 1). These structures are initiated by the same underlying physics: ablation caused by direct and reflected radiation. When radiation illuminates a surface, small surface depressions receive more reflected light than high points, leading to greater ablation in troughs and surface instability [1–3]. Penitente formation alters glacial energy balances and therefore affects local water runoff and flooding, feedback in climate dynamics, and paleo-climatic reconstruction [4,5]. In materials science, surface micropatterning via laser ablation can produce problematic surface roughness [6,7], but also has several proposed applications, including improved solar cells and electron-field emitters [8,9].

Here we report the first laboratory generation of snow penitentes 1–5 cm high (Fig. 1). We characterize lab penitente formation and measure penitente coarsening. The lab setting allows controlled environmental conditions, and we can measure the evolution of lab penitentes visually in real time. Our experiments provide a model system for studying ablation morphologies.

Penitentes occur on high-altitude snowfields exposed to intense sunlight, particularly in South America [10]. Expeditions studying penitentes have invoked the importance of sunlight [4,5,10,11] and cold, dry conditions (dew point below 0 °C), where melting is disfavored and ablation proceeds by sublimation [4,10]. Concentrated reflections and protection from wind increase penitente growth; higher temperature and humidity in the troughs of penitentes allows melting in the troughs [10]. This effect accelerates penitente growth, because sublimation of ice at 0 °C requires 7.8 times more energy than melting an equivalent volume, while the sublimating surface is evaporatively cooled, further lowering the surface temperature. Thus initiation of penitente growth requires a low dew point, but melting can occur during later height growth.

Centimeter-scale penitentes similar in appearance to those we describe have been observed in field work, where they are called micropenitentes and are believed to be precursors to large Andean penitentes [4,10,12]. Thus our experiments may mimic the initial stages of penitente development on high-altitude glaciers, and allow further understanding of the conditions necessary for penitente development. Our observation contrasts with reports on the formation of suncups, an ablation morphology found on lower-altitude glaciers and snowfields with a typical initial wavelength of 5–10 cm [1,2]. Suncups typically form in melting snow, where the uniform temperature of melting means that no temperature gradients along the surface are present. This effect may be responsible for the large difference in initial feature size between micropenitentes and suncups.



(a) (b) (c)

FIG. 1 (color). Images of ablation spikes. (a) Penitentes in the Andes, approximately 2 m high [reused with permission from Javier Corripio] [4]. (b) Silicon spikes created through laser ablation [Reused with permission from Tsing-Hua Her, Richard J. Finlay, Claudia Wu, Shrenik Deliwala, and Eric Mazur, Applied Physics Letters. Copyright 1998, American Institute of Physics.] [8]. The largest spikes are approximately 15 μm high. (c) Laboratory penitentes approximately 5 cm high.

Once penitentes are formed, feedback by multiple reflections and evaporative cooling preserves their shape [4]. Here we study the initial stages of the instability, when penitentes are most vulnerable to disruption. Simulations of an Andean glacier basin suggest that penitentes lower the net ablation rate, preserving glacier mass. Global warming is expected to increase the minimum elevation of penitente formation, accelerating the disappearance of Andean glaciers and depleting water resources [4]. Particulate pollution could further accelerate Andean glacier disappearance, because snow optical properties are significantly altered by surface debris [13–15]. Small dirt particles adhere to the ablating surface and migrate toward its peaks [1]. A thin debris layer suppresses reflections and disrupts penitente formation, while a thicker layer forms an insulating sheath and promotes formation of different structures [1,2].

Laser ablation of surfaces can produce a variety of surface patterns [6], including arrays of conical spikes that bear a striking resemblance to penitentes. The enhanced light capture due to multiple reflections on such micropatterned silicon surfaces has led to the suggestion that they could form improved solar cells [8]. Conical spikes have been demonstrated in metals and semiconductors [8,16–20], polymers [21–25], composites [26], and ceramics [6,27,28]. The formation mechanism of ablation spikes shares common features with penitente formation. The spikes tilt toward the illumination direction [8,16,22] and multiple reflections are believed to be important for their growth [3,16,18]. Other variables are also important in the formation of microstructures by high-intensity laser pulses, including light interference, hydrodynamics of melted surface material, refreezing of material at cone tips, surface impurities, and chemical interactions with ambient gas.

Our apparatus allows controlled air temperature down to $-50\,^{\circ}\mathrm{C}$ with a relative humidity $<5\%$ (Fig. 2). Illumination is provided by a flood lamp. We produce artificial snow with controlled particle radius by freezing water droplets [29]. In our experiments, penitentelike structures

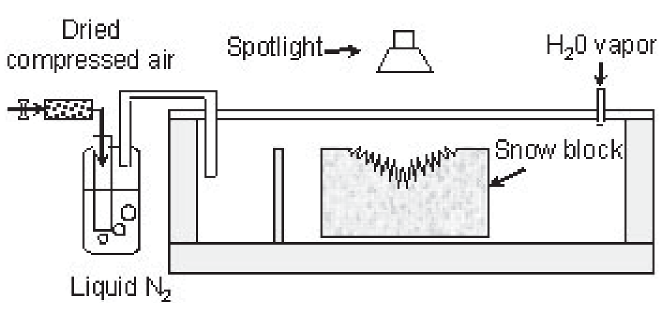


FIG. 2. Experimental apparatus. A horizontal freezer with Plexiglas cover serves as the environmental chamber. Temperature control is achieved by passing dried compressed air through liquid nitrogen and into the chamber. Humidity control is achieved by introducing water vapor. For further details, see Ref. [29].

1–5 cm high were produced after a few hours of illumination. The direction of penitente growth is always aligned with the incident angle of our radiation source as observed in laser ablation and on glaciers. Furthermore, at normal incidence we were able to etch the conical irradiation profile of the lamp into the snow (as shown in Figs. 2 and 4).

Filtering the light or creating wind eliminates penitente formation in our experiments. The absorption of light by snow is much higher for near-infrared and infrared wavelengths than for other spectral regions [13]; therefore, the intensity of these wavelengths controls the ablation rate. Selectively filtering out infrared wavelengths inhibits penitente formation in our setup. Similarly, using a fan to provide a steady breeze of $2.5\ \mathrm{m\,s^{-1}}$ over the snow surface eliminates penitente production. The wind may prevent temperature gradients along the surface needed for penitente formation through a reduction in the thickness of the water-vapor boundary layer.

The optical extinction length determines the initial size structures that form, except in the case of particle sizes comparable to the extinction length. We created artificial snow particles with radii between 25 μm and 2.5 mm. In the field, snow flakes age to become quasispherical with age-dependent particle radii of 20 μm–1.5 mm, and snow optical properties change with age [13,14]. The size of the smallest ablation structures is limited by the optical extinction length: points on the snow within one extinction length experience the same light intensity and therefore ablate at the same rate [2]. The optical extinction length is proportional to r/v, the particle radius divided by the ice volume fraction in the snow [13]. For our dry, fine-grained snow, we estimate that the extinction length is 0.5–1 mm for particle radii 25–500 μm. The snow density increases with particle size. Therefore as the particle radius increases the volume fraction also increases and the extinction length is approximately constant. An extinction length of 1 mm is consistent with our observation of an initial feature wavelength of approximately 3 mm, which we observe for all but very large ($r = 2.5$ mm) particles. For 2.5 mm radius particles, the formation of initial structures requires a much longer time, and structures initially appear on the scale of the particle size (5 mm wavelength).

Formation of penitentes does not require granular snow; we also studied structure formation using a solid ice block. Similar penitentes formed, but the initial development of structure required approximately 2 times longer than for experiments with snow particles (at the same temperature and relative humidity). An opaque, frosty layer formed on the ice surface before the formation of ablation spikes. This layer may form when surface ice sublimates and the resulting evaporative cooling of the surface causes a portion of the water vapor to recondense. The surface roughness produced by the recondensation may be important for the initial development of ice surface structure.

After the initial instability forms surface structure, penitente growth enters a nonlinear regime. The penitentes

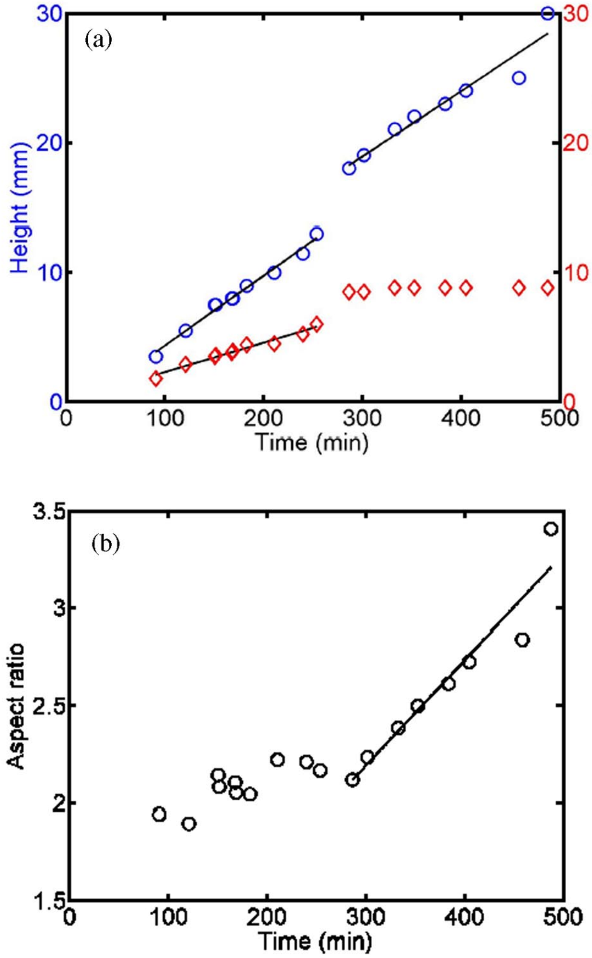


FIG. 3 (color online). Coarsening data. (a) Measurements of penitente height (circles) and peak separation (diamonds) versus time. (b) Penitente aspect ratio (height/peak separation) versus time. After an initial coarsening phase ~300 min in length, the dynamics transition from sublimation throughout the structures to melting at the troughs and coarsening ceases. In this experiment the initial particle radius was approximately 50 μm, infrared radiation intensity approximately 300 W m^{-2}, temperature $-15\,^{\circ}$C, and relative humidity 10%.

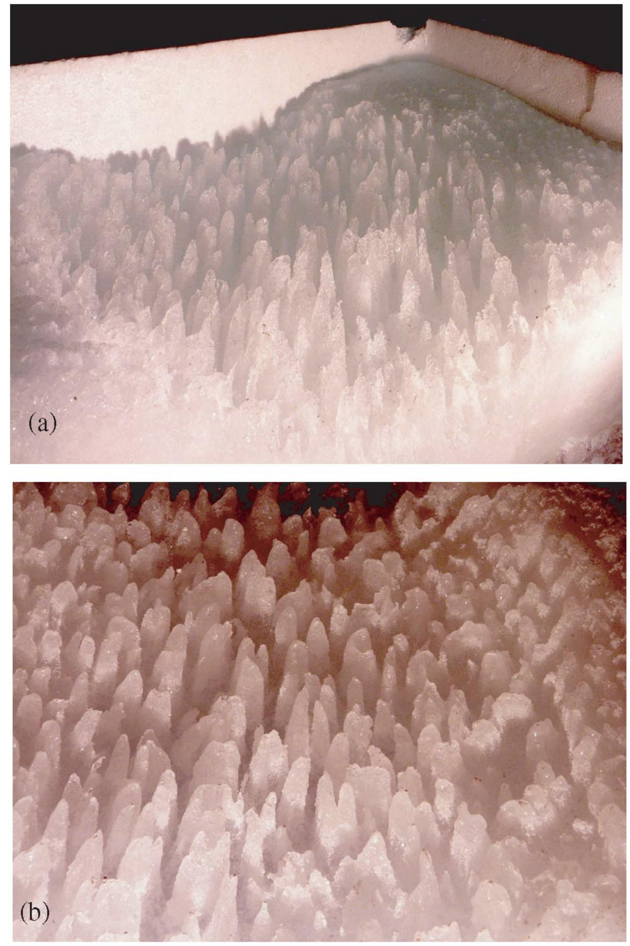


FIG. 4 (color). Images of penitentes. (a) A snow block showing larger penitentes in the center where the light illumination is most intense. The curved shape of the surface is caused by the conical irradiation profile of the flood lamp. The snow block is 80 by 50 cm and the largest, central penitentes are 6 cm high. (b) Field of penitentes after the transition to melting in the troughs has occurred. The penitente aspect ratio increases and the tips become more rounded. The largest penitentes are 3 cm high.

increase in size by coarsening (Fig. 3), as predicted in a previous model of penitente growth [2]. In our experiments, penitente height and peak separation increase linearly, while maintaining an approximately constant aspect ratio of 2. This value is comparable to aspect ratios of 1.5–1.7 measured for Andean penitentes 1.35 m high [30].

In many experiments, we observe that coarsening stops after a certain time. This dynamical transition occurs near $t = 300$ min for the experiment shown in Fig. 3. After the transition, penitente height continues to increase while the peak separation remains constant. In addition, we observe a rounded shape at penitente tips after the transition (Fig. 4). We hypothesized that the end of coarsening behavior is associated with a transition to melting in penitente troughs. Because larger penitentes capture a greater fraction of the illuminating radiation, the reflected intensity in penitente troughs increases with time during coarsening. This hypothesis was confirmed by experiments with a temperature-sensitive dye added to the snow [29]. In these experiments, the surface layer was blue, corresponding to a warmer temperature than the pink snow below the penitentes. The transition to height increase without coarsening was accompanied by a transition to melting: we observed both downward seepage of warmer (blue) material and the elimination of observable temperature gradients along the surface. This behavior is expected for uniformly melting snow. The transition to melting did not occur for experiments at colder temperatures.

Humidity changes have little effect on structure formation in our experiments, while changes in temperature significantly alter the growth of penitentes. For the conditions of Fig. 3, addition of water vapor to the chamber to increase the relative humidity up to 70% does not significantly change penitente growth. However, temperature changes significantly affect the process. Under melting conditions (above −4 °C), the snow ablates and meltwater accumulates beneath the snow without structure formation. Between −10 and −20 °C penitentes appear within two hours of irradiation and coarsen as in Fig. 3. Below −35 °C we could not produce penitentes after ten hours of irradiation. The strong temperature dependence suggests that glacial penitentes are sensitive to temperature increases induced by climate change: as global temperatures increase, regions where penitentes currently form may become too warm for their growth.

The large change in vapor pressure with temperature is likely responsible for the variations we observe. The sublimation rate is proportional to the difference between the saturated vapor pressure near the surface and the ambient partial pressure far from the surface. The vapor pressure of water decreases approximately exponentially between 0 and −35 °C, with a decay constant ~10.5° [31]. Presumably, at −35 °C the low saturated vapor pressure (20 Pa) impedes sublimation because the air near the ice surface is saturated with water vapor. The thickness of the boundary layer of water vapor near the ice surface also affects the ablation rate.

To investigate the effects of surface debris on penitente formation, we spread carbon black powder over half the surface of the snow block. The powder layer thickness was comparable to the snow particle size, the limit of the thin-dirt regime of Ref. [2]. In the debris-covered region, we observed earlier formation of penitentes with larger peak separations than in the clean-snow region. In addition the particulate material accumulated at the tips of the penitentes. It is known that small dirt particles typically adhere to an ablating surface and migrate toward its peaks [1]. These observations are consistent with a model of how dirt influences ablation-structure formation [2].

The result of our dirty-snow experiment has surprising implications for the effects of particulate pollution on penitente formation. On a relatively flat glacier surface, a thin debris layer accelerates glacier ablation [15]. However, simulated glaciers covered with penitentes ablate more slowly than flat ones, because of shadowing and increased cooling by wind [4]. Large fractions of a penitente-covered glacier are in shadow as the sun moves throughout the day and the solar zenith angle changes from day to day. Although penitentes absorb a slightly larger fraction of the incident radiation than does a flat surface, the shadowing effect dominates the increased absorption. In addition, a penitente-covered glacier has larger surface area and is more effectively cooled by a light wind blowing over the surface. Thus, by accelerating penitente formation and producing larger penitentes, small amounts of particulate matter could help preserve Andean glaciers.

We thank M. Ben Amar and J. Corripio for useful discussions. M. D. B. acknowledges funding from the Alfred P. Sloan foundation.

[1] J. J. Rhodes, R. L. Armstrong, and S. G. Warren, J. Glaciol. **33**, 135 (1987).
[2] M. D. Betterton, Phys. Rev. E **63**, 056129 (2001).
[3] A. Usoskin, H. C. Freyhardt, and H. U. Krebs, Appl. Phys. A **69**, S823 (1999).
[4] J. G. Corripio, Ph.D. thesis, University of Edinburgh, 2002.
[5] V. M. Kotlyakov and I. M. Lebedeva, Z. Gletscherkd. Glazialgeol. **10**, 111 (1974).
[6] S. G. Foltyn, in *Pulsed Laser Deposition of Thin Films*, edited by D. B. Chrisey and G. K. Hubler (John Wiley and Sons, New York, 1994), pp. 89–114.
[7] *Laser Ablation and Desorption*, edited by J. C. Miller and R. F. Haglund, Experimental Methods in the Physical Sciences Vol. 30 (Academic Press, San Diego, 1998).
[8] T. H. Her *et al.*, Appl. Phys. Lett. **73**, 1673 (1998).
[9] H. C. Lo *et al.*, Appl. Phys. Lett. **83**, 1420 (2003).
[10] L. Lliboutry, J. Glaciol. **2**, 331 (1954).
[11] C. Troll, *Büsserschnee in den Hochgebirgen der Erde*, Patermanns Geographische Mitteilungen Ergänzungsheft Vol. 240 (Justus Pertes, Ghota, 1942).
[12] L. Lliboutry, *Traité de Glaciologie* (Masson, Paris, 1965).
[13] W. J. Wiscombe and S. G. Warren, J. Atmos. Sci. **37**, 2712 (1980).
[14] S. G. Warren and W. J. Wiscombe, J. Atmos. Sci. **37**, 2734 (1980).
[15] S. G. Warren, Ann. Glaciol. **5**, 177 (1984).
[16] S. I. Dolgaev *et al.*, Appl. Phys. A **73**, 177 (2001).
[17] Y. Kawakami and E. Ozawa, Appl. Phys. A **74**, 59 (2002).
[18] A. J. Pedraza, J. D. Fowlkes, and Y. F. Guan, Appl. Phys. A **77**, 277 (2003).
[19] F. Sanchez, J. L. Morenza, and V. Trtik, Appl. Phys. Lett. **75**, 3303 (1999).
[20] E. Gyorgy *et al.*, J. Mater. Res. **18**, 2228 (2003).
[21] Y. Novis *et al.*, J. Appl. Phys. **64**, 365 (1988).
[22] D. J. Krajnovich and J. E. Vazquez, J. Appl. Phys. **73**, 3001 (1993).
[23] B. Hopp *et al.*, Appl. Surf. Sci. **110**, 232 (1997).
[24] X. Y. Zeng *et al.*, Appl. Surf. Sci. **140**, 90 (1999).
[25] Z. B. Wang *et al.*, J. Appl. Phys. **93**, 6375 (2003).
[26] S. Ono *et al.*, Appl. Surf. Sci. **129**, 821 (1998).
[27] Y. S. Jeong *et al.*, Appl. Surf. Sci. **110**, 424 (1997).
[28] J. Heitz *et al.*, Appl. Phys. A **65**, 259 (1997).
[29] See EPAPS Document No. E-PRLTAO-96-123605 for methods and additional images. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.
[30] J. G. Corripio, B.sc. thesis, University of Edinburgh, 1999.
[31] *CRC Handbook of Chemistry and Physics*, edited by D. R. Lide (CRC Press, Boca Raton, FL, 2005), http://www.hbcpnetbase.com.