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MODE OF FORMATION OF "ABLATION HOLLOWS" CONTROLLED BY DIRT CONTENT OF SNOW

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ABSTRACT. A contradiction has existed in the literature as to the conditions favoring formation of "ablation hollows" ("suncups") on a melting snow surface. Some experiments find that these features grow under direct sunlight and decay in overcast, windy weather; whereas others find just the opposite result, that they grow best under cloudy, windy conditions and decay if exposed to direct sunlight. We find that the hidden variable in past experiments, which acts as a switch to determine which mode of formation can operate, is the absence or abundance of dark insoluble impurities in the snow. Direct sunlight causes ablation hollows to grow in clean snow and to decay in dirty snow (for dirt content below a critical value), because the dirt migrates to the ridges between the hollows, lowering the albedo at the ridges. By contrast, when ablation is dominated by turbulent heat exchange, the presence of dirt favours development of ablation hollows because the dirt migrates to the ridges and insulates them; albedo reduction has a negligible effect on ablation.

This hypothesis is supported by an experiment which showed that the presence of a thin layer of volcanic ash on the snow inhibited formation of ablation hollows under direct sunlight.

THE NATURE OF "ABLATION HOLLOWS"

Small-scale relief features often form on ablating snow and ice surfaces, taking on a somewhat regular geometric arrangement. These features typically develop as an assemblage of hollows bounded by ridges, forming a honeycomb-like pattern on the snow surface. The ridges of snow represent zones of slowed ablation relative to the hollows; hence the forms arise due to the consistency and regularity of differential ablation on a snow surface.

The networks of polygonal, cuspate hollows with a ridge-to-hollow relief of 2–50 cm have been referred to by a variety of terms. Matthes (1934) proposed the terms "suncups" for the individual hollows and "honeycombed snow" for the assemblages. The features have also been called "ablation polygons" (Richardson and Harper, 1957), "ablation hollows" (Jahn and Klapa, 1968), and "tortoise-shell patterns" (Takahashi and others, 1973). In this paper we call them "ablation hollows" rather than "suncups", because they are not always caused by the sun, but sometimes we use the short-hand term "cups".

Ablation hollows are found at different elevation ranges in different locales wherever the micro-climate is favourable for their formation. Ablation hollows can occur on snow surfaces regardless of exposure, inclination or aspect, though reports of favoured locations sometimes disagree.

In many mountainous areas, the depth of the ablation hollows increases with elevation. In their extreme form, these features have been termed "sunpits" (Matthes, 1934), "*Büsserschnee*" (Troll, 1942), or "penitents" (Lliboutry, 1954), with ridge-to-hollow relief of 0.3–3 m. Frequently, the hollows are completely melted out, exposing the underlying soil and leaving only the spikes. We will use "penitent snow" for a snow field with these features and "spike" and "trough" for the specific parts of the individual forms. Penitent snow is geographically not as widespread as ablation hollows. It is found only in areas of intense solar radiation and small turbulent heat transfer (Matthes, 1934; Lliboutry, 1954; Hastenrath and Koci, 1981), and is best developed in tropical latitudes at high elevations (maps given by Troll (1942)).

Because ablation hollows are a common, though not geographically ubiquitous, ablation feature, there have been many attempts to understand the mechanisms responsible for their formation. Previous work led to one or the other of two contradictory conclusions: (1) ablation hollows form when turbulent heat transfer is the dominant energy source, whereas intense solar radiation degrades the formations (Richardson and Harper, 1957; Jahn and Klapa, 1968; Takahashi and others, 1973); (2) ablation hollows are formed under direct sunlight (hence the name "suncup") (Matthes, 1934; Lliboutry, 1954; Post and LaChapelle, 1971, p. 70-73), whereas large amounts of turbulent heat transfer degrade the formations.

We do not here assess the viability of the various formation theories; rather we seek to reconcile the contradictory observations concerning the type of energy budget most favorable for formation of ablation hollows. It appears that energy budgets dominated either by solar radiation or by turbulent heat exchange can create and maintain the ablation features. We will show that the keys to reconciliation are (1) a hidden variable: the absence or abundance of detritus at the snow surface, and (2) the normal trajectory theory of Ball (1954), which has repeatedly been shown to describe accurately the migration of soil particles to the ridges of ablation hollows.

FORMATION OF ABLATION HOLLOWS BY TURBULENT HEAT TRANSFER

Some researchers have found that ablation hollows form best in regions protected from direct sunlight (Richardson and Harper, 1957; Jahn and Klapa, 1968). Consequently, these authors concluded that direct-beam sunlight was unnecessary and possibly inhibiting for cup formation, whereas turbulent heat exchange caused the cups to grow. Both papers noted the segregation of detritus on the snow surface on to the ridges, in agreement with the normal-trajectory theory.

Takahashi and others (1973) performed comprehensive and detailed experiments on ablation hollows. They measured cup profiles over time concurrently with wind velocity, air temperature, and relative humidity. They found that ablation hollows developed best under conditions of high air temperatures and wind velocities, when melt was mainly due to turbulent heat transfer. When solar-radiation absorption was greater than turbulent heat transfer, the cups decayed. Ashwell and Hannell (1966) had also found that

cup forms decayed during sunny periods subsequent to the formation of thin dirt concentrations on the ridges.

Takahashi and others (1973) also performed experiments in a temperature-controlled wind tunnel, which corroborated the results of their field studies. They found that wind speeds greater than 4 m s^{-1} and air temperatures greater than 5°C were required for development of ablation hollows. They also concluded that vapor pressures at or near saturation accelerated the development of ablation hollows. These results were substantially confirmed by further experiments of Takahashi (1978). It is thus well documented that ablation hollows can be formed solely by turbulent heat transfer.

FORMATION BY SOLAR RADIATION

Matthes (1934) may have been the first to assert that ablation hollows and penitentes were formed solely from the effect of the sun. Many subsequent researchers have verified this, observing these features to grow under direct sunlight. Under a direct solar beam, differently oriented surface elements will be exposed to quite different irradiances, and this situation can cause initially small surface irregularities to grow.

Post and LaChapelle (1971, p. 70-73) observed that suncups "migrated" to the north (in northern latitudes) a few centimeters per day while deepening. They ascribed this to the orientation of the direct beam at these latitudes. In the Northern Hemisphere, south-facing slopes receive the most solar radiation. Other factors being equal, these slopes will undergo the most ablation. Thus the north walls of the cups (south-facing) continuously melt away faster, causing northward migration of the ablation hollows as the snow surface lowers.

The orientation of the spikes and troughs of penitent snow also suggest that direct sunlight plays a dominant role in their formation. Matthes (1934) noted that, at any latitude, the spikes of penitent snow were oriented parallel to the direct-beam radiation at solar noon at that latitude. The spikes tilt to the north in the southern latitudes (Lliboutry, 1954; Amstutz, 1958; Hastenrath and Koci, 1981) and to the south in the northern latitudes (Matthes, 1934; Post and LaChapelle, 1971, p. 70-73; Kotlyakov and Lebedeva, 1974). Additionally, the troughs coalesce along an east–west line, leaving blades of spikes. Several photographs of these blades or wedges were shown by Lliboutry (1954, figs 4–8; 1964, pls 21–23). Hastenrath and Koci (1981) measured the blade angles in Peru and found good agreement with the zenith angle of the Sun at solar noon, as did Kotlyakov and Lebedeva (1974) in Central Asia. A structure thus evolves in which the surviving snow surfaces (the blade walls) have minimal exposure to solar radiation, and most of the sunlight is absorbed in the troughs, as pointed out by Lliboutry.

Both Matthes (1934) and Lliboutry (1954, 1964, p. 372-79) noted that penitentes decay during times when turbulent heat transfer is dominant. Lliboutry found that penitent snow formed only on leeward sides of mountain slopes, where turbulent heat transfer is reduced. Of special interest to our argument is Matthes's claim that "sunpits and suncups attain typical forms only in clean snow. Rock fragments and wind-blown dust interfere with their orderly development and tend to produce irregular forms."

Although Lliboutry (1954) found that direct sunlight was responsible for the formation of both ablation hollows and penitentes, he attributed their qualitative difference to the dominant mode of mass loss: penitentes were sublimating at the spikes and melting in the troughs, whereas ablation hollows were melting at all points on the surface. Penitentes have enhanced relief because, for a given amount of energy absorbed, the mass loss by melting is greater than by sublimation. Lliboutry found that the transition from ablation hollows to penitentes occurs as one moves to higher elevations where the day-time air temperature drops below 0°C. Hofmann (1963) and Kraus (1966) have made initial attempts toward modeling these processes.

NORMAL TRAJECTORY OF PARTICLES ON MELTING SNOW

Fine organic and mineral detritus on the snow surface is usually observed to be segregated on to the ridges during the process of ablation-hollow formation. This is well documented with photographs by Jahn and Klapa (1968) and Takahashi and others (1973), and has been observed repeatedly by us in the mountains of Colorado, Washington, and Alaska. The normal-trajectory theory was proposed by Ball (1954) to explain how an initially uniform thickness of particles on the snow surface became concentrated on the ridges and removed from the hollows. Ball asserted that the particles would follow a path normal to the retreating snow surface rather than parallel to gravity. His illustration of particle paths along the normal trajectory during surface lowering is reproduced here as Figure 1.

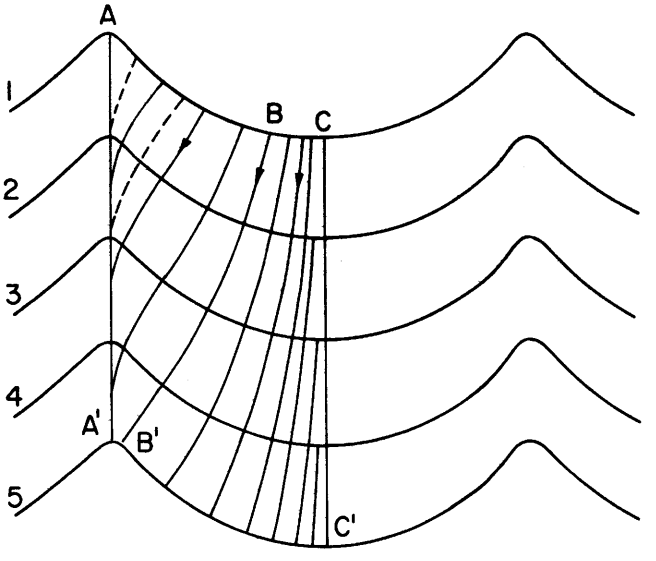

Fig. 1. Diagram to show how dirt initially uniformly distributed through snow is concentrated at the ridges of polygons as ablation proceeds. The curves 1–5 represent the successive positions of the snow surface. Dirt initially at B *is later located at* B'*; similarly for* A *and* C. *(Figure and caption from Ball (1954, fig. 1).)*

The normal trajectory of particles is due to the adhesive forces between the snow and the particles (Jahn and Klapa, 1968). Particles which have gravity forces acting on them that are greater than the adhesive forces will not follow the normal trajectory, but rather a path along the resultant of the adhesive- and gravity-force vectors. Thus, for the fairly constant density of minerals, there is probably a threshold volume-to-surface ratio (V/S) for particles following the normal trajectory. Indeed, it has been observed that the dirt on the ridges consists only of fine particles (Richardson and Harper, 1957; Ashwell and Hannell, 1966; Jahn and Klapa, 1968), whereas coarser particles sink vertically into the snow. For approximately spherical particles, the threshold size is probably close to 0.6 mm diameter, the largest size found in "dirt cones" (Drewry, 1972), because the normal-trajectory mechanism also operates in dirt cones. This corresponds to a V/S ratio of 0.1 mm. Non-spherical particles can be much larger for the same V/S ratio, so that, for example, blades of grass will also migrate to the ridges (Jahn and Klapa, 1968, fig. 8).

The accuracy of normal-trajectory theory has been verified by field experiments. Both Ashwell and Hannell (1966) and Jahn and Klapa (1968) found that thin soil accumulations placed on flat snow were segregated to ridges after cups formed. In their more detailed study, Takahashi and others (1973) mapped soil deposits and measured soil

thickness over time as cups developed. Their calculations of dirt concentration based on the normal-trajectory theory gave reasonable agreement with the measured dirt accumulations.

The normal-trajectory theory, amply confirmed, thus indicates that surface material will be concentrated on ridges (areas of slower ablation) and removed from hollows (areas of more rapid ablation) over time as ablation hollows are formed and maintained during the lowering of the snow-pack surface. Both Ball (1954) and subsequent researchers (Richardson and Harper, 1957; Ashwell and Hannell, 1966; Jahn and Klapa, 1968) stressed that the normal trajectory of surface particles is not a cause of ablation hollows, but rather a product of their formation. However, Jahn and Klapa (1968, p. 303) noted that, while detrital concentrations on ridges were not necessary for formation, they seemed to *accelerate* the development of ablation hollows.

COMBINED EFFECTS OF THE LOW ALBEDO OF DETRITUS AND ITS MOTION IN THE NORMAL TRAJECTORY

The key to reconciling the contradiction in the literature lies in how the normal-trajectory path concentrates detritus and how detritus thickness affects ablation under different meteorological conditions. Experiments by Ashwell and Hannell (1966) and by Driedger (1981) have shown that, up to a threshold thickness, ablation is increased under layers of detritus with increasing thickness due to albedo reduction. After the threshold thickness is reached, ablation is decreased with further increasing thickness, due to the effects of insulation. The dependence of ablation rate on detritus thickness is determined by the heat conductivity and the albedo of the detritus, but the functional form should be similar for all low-albedo materials and a given heat budget, as first suggested by Wilson (1953). The most detailed measurement of the dependence of ablation (a) on detritus thickness (t) was done by Driedger (1981), for Mount Saint Helens ash on the melting snow of a temperate glacier in summer. Her illustration is reproduced here as Figure 2, but with the addition of two hypothetical curves for other heat budgets. Driedger's curve can be divided into two regimes: the rising limb, $t \lesssim 3$ mm, where $da/dt > 0$; and the falling limb, $t \gtrsim 3$ mm, where $da/dt < 0$.

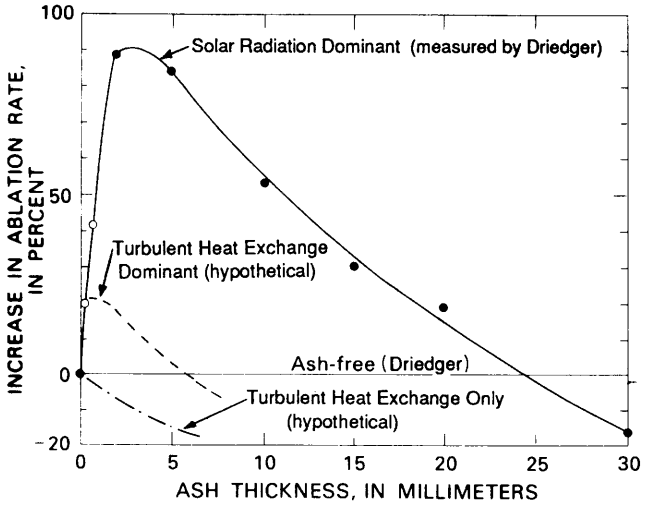

Fig. 2. Data points and solid curve: change in ablation rate of snow on which different thicknesses of volcanic ash from Mount Saint Helens had been artificially spread. The experiment was done on the accumulation zone of South Cascade Glacier, Washington State, U.S.A., in August 1980. Solid circles indicate measured ash thickness; open circles indicate estimated ash thickness. (From Driedger, 1981, fig. 446.) Dashed curves: hypothetical changes in ablation rate for the same materials under energy budgets dominated by turbulent exchange rather than solar radiation.

It is important for our argument to note that the curve would shift to the left or right, and the position and height of the maximum would change, with changes to the components of the energy budget. The increase in a with t is due solely to the fact that soil albedo is lower than snow albedo. Therefore, under conditions of greater sensible heating and less solar radiation, the curve would be shifted left and vertically compressed (dashed curve). With a heat budget composed solely of sensible and latent heating, there would be a monotonic decrease in ablation rate with increasing ash thickness (dot–dash curve), due to the effect of insulation. Thus, with a thicker layer of detritus on ridges than in hollows, ablation on the ridges would be lower than in the hollows during periods of melting dominated by turbulent heat transfer. Once this occurs, soil would subsequently be further concentrated on the ridges via the normal trajectory.

Richardson and Harper (1957), Jahn and Klapa (1968), and Takahashi and others (1973) were all dealing with dirty snow. Dirt and vegetal matter had been concentrated on the ridges, with the hollows relatively free of detritus. If the soil thicknesses they observed on the ridges were below the threshold thickness (~3 mm) of maximum ablation rate, which they appear to be, the relief would decay during sunny periods due to increased ablation on the ridges relative to the clean hollows. However, under a heat budget dominated by sensible heating (hypothetical curves in Figure 2), the same detritus thicknesses on the ridges might cause a reduction in ablation rate. Ablation by sensible heating would then be less on the ridges (because, unlike the hollows, they are insulated by debris), further concentrating detritus there via the normal trajectory and further decreasing ablation rate on the ridges. Hence, for initially dirty snow, melt primarily caused by turbulent heat transfer can result in a positive feed-back loop which can build and maintain the ablation hollows. This explains Jahn and Klapa's (1968) observation that the presence of detritus on the ridges of ablation hollows (in a shaded area) accelerated their development.

With dirty snow, in areas of intense solar radiation, any initial formation of ablation hollows by differential ablation would tend to concentrate detritus on the incipient ridges via the normal trajectory. If the detritus thickness on these incipient ridges were less than the threshold value (maximum of Driedger's curve in Figure 2), any concentration of dirt would lead to increased melting at these incipient ridges relative to the incipient hollows, and the initial slight irregularity would decay. The effect is clearly a negative feed-back which prevents cups from forming. Hence, a physical explanation is provided for Matthes's (1934) observation that dirt on a snow surface hinders the development of ablation hollows in areas with strong solar radiation. The principle of this negative feed-back is very simple and has probably occurred to others. In particular, figure 10.4 of Lliboutry (1964) comes very close to stating this idea.

(If the snow is covered with a layer of dirt thicker than the threshold value (~3 mm), there is no negative feed-back under direct sunlight, and the irregularity can continue to grow. This is the regime of "dirt-cone" formation (Wilson, 1953; Drewry, 1972). Such huge amounts of dirt are much more common in the ablation region of glaciers than in the accumulation regions, so dirt cones are usually features of glacier ice rather than snow.)

FIELD EXPERIMENT

Our hypothesis was inspired by a field experiment. The Snowdome of Blue Glacier, at about 2200 m elevation on Mount Olympus, Washington State, U.S.A. (lat. 48°N., long. 124°W.) is a large snow field of rather clean snow. In summer, it is normally subjected to many consecutive days of clear skies during which deep ablation hollows form under the influence of direct sunlight. (This was the location of the experiment of Post and LaChapelle (1971, p. 70–73) cited above, which found "suncups" to migrate northward several centimeters per day under the influence

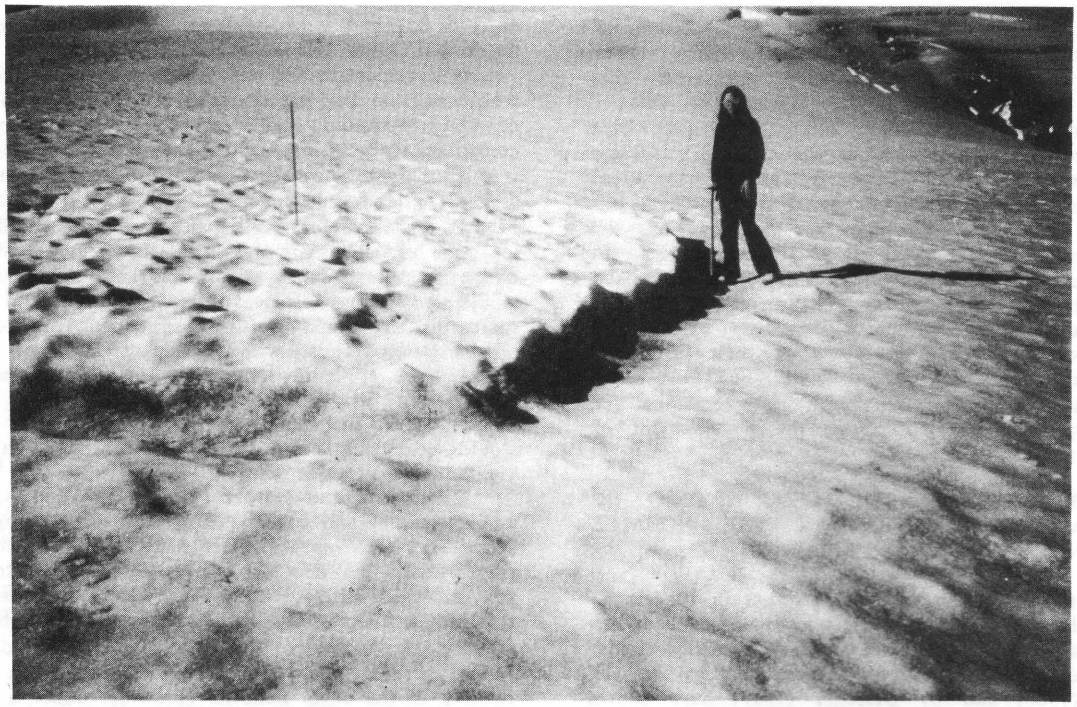

Fig. 3. Experiment performed in the accumulation zone of Blue Glacier on Mount Olympus, Washington State, U.S.A., in July 1980. The thin layer of volcanic ash covering the snowfield was removed from a rectangular plot. This photograph was taken (by R.L. Armstrong) 2 weeks later, showing the development of ablation hollows in the cleaned snow.

of the Sun (personal communication from E. LaChapelle).) The summer of 1980 was unusual. During the course of early summer melting, a thin layer of volcanic ash (from a spring-time eruption of Mount Saint Helens) became uncovered, which then remained on the surface for the remainder of the summer, causing higher than normal ablation rates. The nearly uniform thickness of the ash layer was less than 1 mm. Although the number of sunny days was near normal that summer, there was very little development of ablation hollows. The ash was suspected as the cause of this anomaly. The deposited ash was removed from the surface of the snow on a rectangular plot approximately 3 m by 4 m. The experiment resulted in the situation shown in Figure 3, after 2 weeks of sunny weather (July–August 1980) with ablation due mainly to direct sunlight. The cleaned surface is elevated because its ablation rate was less than that of the darker ash-covered surface. Figure 3 shows that the development of ablation hollows was favoured on the clean snow surface and inhibited on the ash-covered surface, verifying the negative feed-back caused by the tendency of debris to concentrate at the ridges.

We have not determined a threshold value of dirt content *below* which the snow is clean enough that ablation hollows will grow under the influence of direct sunlight. This threshold value must lie somewhere between the values of impurity content in the two parts of Figure 3, which were not measured.

SUMMARY

The apparently contradictory published observations of the conditions leading to growth or decay of ablation hollows can be resolved by noting that the different experimenters were observing one of two different kinds of snow: dirty or clean.

Ablation hollows can be formed either by turbulent heat transfer or by radiative heating. With dirty snow, formation by turbulent transfer is favoured. Under a heat budget dominated by sensible heating, accumulations of detritus and their concentration by the normal-trajectory path can result in the initiation of a positive feed-back mechanism for the formation of ablation hollows; this occurrence is dependent on the thickness of the detritus, its albedo, and its heat conductivity.

Ablation hollows can develop in clean snow in areas of intense direct sunlight. However, the presence of dirt on the snow surface, with dirt thickness less than a threshold value (~3 mm), inhibits the development of ablation hollows in areas of strong solar radiation, if the dirt follows the normal trajectory. Under such conditions, the normal-trajectory path, together with the dependence of ablation rate on detritus thickness, create a negative feed-back mechanism first suggested by Lliboutry (1964, p. 372-79), which prohibits both detritus segregation on to the ridges and the formation of ablation hollows.

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