Seasonally active slipface avalanches in the north polar sand sea of Mars: Evidence for a wind-related origin

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Abstract: Meter-scale MRO/HiRISE camera images of dune slipfaces in the north polar sand sea of Mars reveal the presence of deep alcoves above depositional fans. These features are apparently active under current climatic conditions, because they form between observations taken in subsequent Mars years. Recently, other workers have hypothesized that the alcoves form due to destabilization and mass-wasting during sublimation of CO_2 frost in the spring. While there is evidence for springtime modification of these features, our analysis of early springtime images reveals that over 80% of the new alcoves are visible underneath the CO_2 frost. Thus, we present an alternative hypothesis that formation of new alcoves and fans occurs prior to CO_2 deposition. We propose that fans and alcoves form primarily by aeolian processes in the mid- to late summer, through a sequence of aeolian deposition on the slipface, over-steepening, failure, and dry granular flow. An aeolian origin is supported by the orientations of the alcoves, which are consistent with recent wind directions. Furthermore, morphologically similar but much smaller alcoves form on terrestrial dune slipfaces, and the size differences between the terrestrial and martian features may reflect cohesion in the near-subsurface of the martian features. The size and preservation of the largest alcoves on the martian slipfaces also support the presence of an indurated surface layer; thus, new alcoves might be sites of early spring CO_2 sublimation and secondary mass-wasting because they act as a window to looser, less indurated materials that warm up more quickly in the spring.

Introduction: The north polar erg of Mars is one of the largest sand seas in the solar system, with an estimated area of 8.4x10^5 sq. km [Hayward *et al.*, 2010], and appears recently active, as most dunes exhibit crisp to minimally degraded brinks, low dust cover (suggesting recent saltation), and a minimum crater retention age [Kreslavsky, 2010]. In support of these observations, high-resolution analyses of dunes throughout the north polar sand sea have revealed changes in the edges of some stoss and lee slopes as well as ripple movement consistent with migration rates on the order of 1 meter per year [Hansen *et al*., 2011; Bridges *et al*., 2012]. However, long-term migration rates of this magnitude have not been observed in over 35 years of orbital imaging [Schatz *et al*., 2006], suggesting that dune migration may be a sporadic process. Migration rates might be limited by the infrequency of strong winds coupled with ice induration of the dune cores, which is predicted based on dune morphology as well as thermal and neutron remote sensing of the dunes [Schatz *et al*., 2006; Feldman *et al*., 2008; Putzig *et al*., 2010; Horgan *et al*., 2010].

Recently, Hansen *et al.* [2011] reported observations of seasonally active mass-wasting on dune slipfaces in the north polar sand sea concurrent with springtime CO_2 sublimation, as well as the appearance of features on the slipfaces with alcove and fan morphologies. Because the features are apparent on the slipfaces after the CO_2 frost is gone but not in images from early in the previous summer, and because new alcoves are often sites of early and enhanced CO_2 sublimation, they attributed the origin of the features to mass-wasting during sublimation. In this study, we have used high-resolution images (25 cm/pixel) from the Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (MRO/HiRISE) [McEwen *et al*., 2007] to show that the alcoves and fans are apparent under the CO_2 frost prior to sublimation, and that the morphology and orientations of the features are instead more consistent with aeolian activity in mid- to late summer.

Alcove and fan morphologies: Alcoves are the most common slipface modification features that we have observed in the north polar sand sea. Alcoves are wedge-shaped and occur above fan-shaped deposits [Hansen *et al*., 2011]. Alcoves are typically several to ten meters across, but combinations of these features can occur in complex dune modifications several hundred meters across. As shown in Figure 1, small alcoves (~ a few meters wide) are usually isolated, shallow, and symmetric. Intermediate alcoves (~10 meters wide) commonly cluster or overlap on slipfaces, producing a shallow, sawtooth morphology (Figure 1b). The much rarer large alcoves often exhibit numerous deep channels (Figure 1d). Features similar to these largest alcoves have been identified in several intracrater dune fields near ~45°S [*e.g.*, Bourke, 2005; Fenton, 2006]. Regardless of size, the alcoves are easily identifiable under favorable lighting conditions because of their steep sides. Most fan deposits appear to be conical, smooth, and symmetric, without evidence for lobate flow features or multiple flow events, and generally do not extend far beyond the base of the slipface. Exceptions include some fan deposits on the shallower slopes of transverse dunes in Olympia Undae, which extend up to 100 meters beyond the alcove, sometimes with overlapping lobate deposits (Figure 1c). Fan deposit length appears to be related to slope length: as slope length decreases, fan deposits are more likely to be short and symmetric. While the gradient of these specific slopes is unknown, photometric measurements of slopes with similar morphologies in central Olympia Undae [Ewing *et al*., 2010] suggest that the upper portions of the slopes where the alcoves have formed likely are steeper than lower portions of the slopes.

Alcoves are found throughout the north polar sand sea, but their distribution is not uniform. Very high alcove densities (many alcoves per slipface) occur in all barchan dune fields adjacent to polar scarps. Intermediate densities (isolated alcoves on most slipfaces or many alcoves on a few slipfaces) occur in some regions within Olympia Undae. Low densities (isolated alcoves on a few slipfaces) are most common elsewhere. Overall, the relative freshness of the alcoves and fans mimics that of the slipfaces on which they occur, where fresh slipfaces are indicated by sharp crestlines and fresh-looking (*e.g.*, un-rippled) slipfaces. Most alcoves exhibit signs of degradation through modification by ripples, perhaps indicating less recent formation. Exceptions include fresh-looking alcoves and fans in Tenuis Cavus, which have been recently active [Hansen *et al*., 2011].

Seasonal changes: Slipface alcoves are actively forming under modern climatic conditions. Horgan *et al*. [2010] reported observations of new, isolated alcoves forming between consecutive summers in Mars Years (MY) 28 and 29 in the mid-sections of Chasma Boreale, and Hansen *et al*. [2011] reported observations of abundant new alcoves forming in Tenuis Cavus between early summer of MY 29 and spring of MY 30. Based on a strong association between these new alcoves and spring mass-wasting on slipfaces at L_S = 59°, Hansen *et al*. [2011] hypothesized that the alcoves form during this time period (mid-spring) due to mass-wasting triggered by CO_2 sublimation. However, analysis of a sequence of images bracketing this date (Figure 2a-b) shows that the alcoves clearly are already present under the CO_2 frost prior to exposure of the underlying sand and initiation of mass-wasting, as identified by the outlines of their sharp sides and associated fan deposits. To verify this observation, we searched for new alcoves in a subset of 228 slipfaces in the Tenuis Cavus dune field by comparing a sequence of co-registered HiRISE images from MY 29 and 30, and then noted when the new alcoves first become visible. As shown in Figure

2c, of the 228 slipfaces examined, 170 (75%) exhibited new alcoves, and in 140 (82%) of the changed slipfaces, the new alcoves are visible under the CO_2 frost. Thus, while CO_2 sublimation appears to be causing additional mass-wasting and minor modification of these features during the spring, our survey reveals that the primary formation mechanism for the alcoves does not appear to be related to CO_2 frost sublimation. Because the new alcoves are apparent underneath the frost, they most likely formed prior to deposition and annealing of the thick CO_2 slab, which begins near L_s = 170-180° (early fall) at the 84°N latitude of Tenuis Cavus [Kelly *et al.,* 2007]. The last MY 29 image of this dune field prior to formation of the new alcoves was at L_s = 102° (Figure 2), placing the formation of the alcoves sometime during the middle to late summer. Observations of future alcove formation may help to narrow down this time range.

***Alcove orientations**:* The association noted above between fresh slipfaces and fresh alcoves suggests a possible relationship between alcove formation and aeolian activity. Furthermore, the sudden increase in alcove density on dunes in Tenuis Cavus between early summer of MY 29 and spring of MY 30 (*e.g.*, Figure 2a-b) implies that the alcove formation process does not consistently recur and instead may be related to isolated events. Strong winds and subsequent aeolian activity are also thought to be intermittent on Mars, as supported by observations of ripple movement in Gusev Crater [Sullivan *et al.*, 2008], the general lack of observed long-term dune migration on the planet [*e.g.,* Zimbelman, 2000; Schatz *et al.*, 2006], and the paucity of winds above the saltation threshold resolved in global circulation models [*e.g.*, Bridges *et al.*, 2012].

If alcove formation is related to recent aeolian activity, we should expect to see some correlation between alcove orientations and recent local wind directions indicated independently by other data. In Olympia Undae, alcoves have a strikingly uniform orientation within each HiRISE image, as shown in Figure 3a, consistent with contemporaneous formation during the most recent strong wind event(s). In eastern Olympia Undae (locations 1-3 in Figure 3a), the alcoves often appear degraded, with clear modification by ripples, missing fan deposits, and a lack of steep sides. These alcoves face SE-SSE, and occur in two locations (Figure 1c): larger, isolated, and often more degraded alcoves occur near bedform intersections, while smaller, often fresher alcoves occur on slipfaces of secondary bedforms. In central Olympia Undae (locations 4-5), the complex dune patterns in the east transition to clear primary and secondary bedforms [Ewing *et al*., 2010], and alcoves occur primarily on the SSE-S facing slipfaces of the secondary bedforms. In western Olympia Undae (locations 6-8), there is no clear pattern of secondary bedforms, and alcoves are found on the W-WNW facing slipfaces of the primary bedforms.

The dominant wind direction in the interior of Olympia Undae is thought to be easterly, based on primary bedform morphology [*e.g.*, Tsoar, 1979], so alcove orientations in western Olympia Undae are consistent with formation related to easterly winds. However, a study of ripple orientations in central Olympia Undae has suggested that more recent winds have had other orientations, resulting in the complex dune patterns observed throughout eastern and central Olympia Undae [Ewing *et al*., 2010]. This conclusion is supported by regional circulation models, which indicate a complex summer wind regime in Olympia Undae [Masse *et al*., 2012]. In both eastern and central Olympia Undae, sharp brinks, ripple-free slipfaces, and fresh-looking, SW-SE trending ripples on the stoss slopes of some secondary bedforms with alcoves (*e.g.*, Figure 1c) all suggest that recent winds have been trending in the same direction as the alcoves in these areas. To verify this observation, we conducted a systematic comparison of the crestline orientations of alcove-bearing slipfaces and adjacent stoss slope ripples in one HiRISE image near 210°E, between eastern and central Olympia Undae. As shown in Figure 3b, of the 169 alcove-bearing slipfaces examined, the crestlines of the slipfaces and ripples differed by less than 15° in nearly half (46%) of the slipfaces, and by less than 45° in the vast majority (84%) of the slipfaces. Overall, there appears to be a strong correlation between alcove and ripple orientations, confirming that recent winds did flow over the alcove-bearing slipfaces.

Discussion: The morphology of alcoves observed on north polar dune slipfaces is not consistent with erosional features thought to result from volatile-rich flows, which are characterized by narrow, sinuous channels, complex alcove morphologies, and extensive, lobate debris aprons [*e.g.*, Costard, *et al*., 2002]. Periglacial processes also do not appear to be involved, as these processes result in slump and pit morphologies distinctly different from alcoves and fans [Horgan *et al*., 2010; Bourke, 2012]. Instead, the summer timeframe of formation, association with dune activity, and possible relationship with recent winds that we demonstrate above all suggest an origin for the alcoves related to aeolian processes. Indeed, the morphology of the alcoves is consistent with a dry granular flow created during localized collapse of the slipface, which on terrestrial dune slipfaces is triggered by over-steepening caused by deposition of saltating sand. A very small flow initiates on the slipface, creating an initial breakaway scarp, which expands laterally and moves upslope, forming an alcove at the dune brink [Lindsay, 1973; Hunter, 1977]. The sand flowing away from the scarp often forms a bottleneck at the point of steepest gradient on the slipface [Anderson, 1988]. At this point, the morphology of the flow most resembles the martian alcoves (Figure 1e-f). However, alcoves are unstable on active terrestrial dune slipfaces, because their sides are often near the static angle of repose. Collapse of the alcove sides, often coupled with additional input of saltating sand, triggers further collapse of adjoining areas, so that the region of failure extends across the slope (Figure 1f).

The minor difference between static and dynamic angles of repose helps limit the sizes of grain flow alcoves on active terrestrial dune slipfaces. However, the reduced gravity experiments of Kleinhans et al. [2011] predict that differences between static and dynamic angles of repose at martian gravity should be larger. If this is true, it should result in larger regions of failure, longer grainflow runouts, and shallower runout slopes compared with original, pre-avalanche, gradients. Some characteristics of dunes in the north polar sand sea might be consistent with this scenario, including the long-runout fans and slipface slope breaks in Olympia Undae mentioned previously. We also do observe a major difference in size between scarp retreat flows on Earth (typically tens of centimeters wide [*e.g.*, Lowe, 1976]) and even the smallest martian alcoves that we have identified (a few meters wide). However, these gravity-dependent effects may not be necessary to explain the size difference between terrestrial and martian alcoves, as major variations in size are also observed across Mars. Alcove widths vary by several orders of magnitude within the north polar sand sea, and large alcoves have not been reported outside of the north polar sand sea. In other martian dune fields, alcoves and fans are rare, and if they are present, they are often small and poorly preserved (*e.g.*, HiRISE image ESP_020384_1650). Indeed, slipface activity at lower latitudes is dominated by meter-scale rectilinear flows without obvious alcoves [Fenton, 2006; Silvestro *et al.*, 2011]. While a combination of rectilinear and channelized flows is not uncommon on terrestrial slipfaces [Breton *et al.*, 2007], this observation suggests that other processes may be affecting the polar dunes. One possibility is that the large sizes (10 meters and larger), steep walls, and multi-year preservation (even after spring mass-wasting) typical of the alcoves in the north polar erg may be caused by partial induration of the slipface, which would lead to less frequent and therefore larger failures [Breton *et al.*, 2007], and would also help to preserve alcoves and to create steep walls [*e.g.*, Bourke, 2005]. This would suggest that the rectilinear grainflows elsewhere are more typical of less indurated or unindurated martian dunes. The surface of the north polar erg may be indurated due to chemical agents, perhaps similar to the weak surface crusts observed at many landing sites [*e.g.*, Sullivan *et al.*, 2008], and facilitated by the sulfates (~10-40 wt.%) found throughout the north polar sand sea [*e.g.,* Horgan *et al.*, 2009]. If surface induration is present, then new alcoves may be revealing looser, less indurated material. A difference in induration between alcoves and undisturbed dune surfaces could help explain why new alcoves appear to be loci for early spring CO_2 sublimation: less indurated surfaces would be expected to have lower thermal inertias and would heat up more quickly in the spring.

Conclusion: We have demonstrated that the origin of new slipface alcoves and fans in the north polar sand sea of Mars by CO_2 frost sublimation processes is inconsistent with observations from our extensive spatial and temporal survey of these features. Instead, their formation time and correlation with recent wind directions supports an alcove origin related to aeolian processes in the mid- to late summer season. We propose that alcoves and fans form by a sequence of aeolian deposition during strong wind events, super-critical steepening of slipfaces, localized failure, and enhanced collapse compared to terrestrial alcoves due to added cohesion, and potentially, reduced gravity. Surface induration, perhaps due to sulfate cementation, likely promotes the large alcove sizes observed in places throughout the north polar erg.

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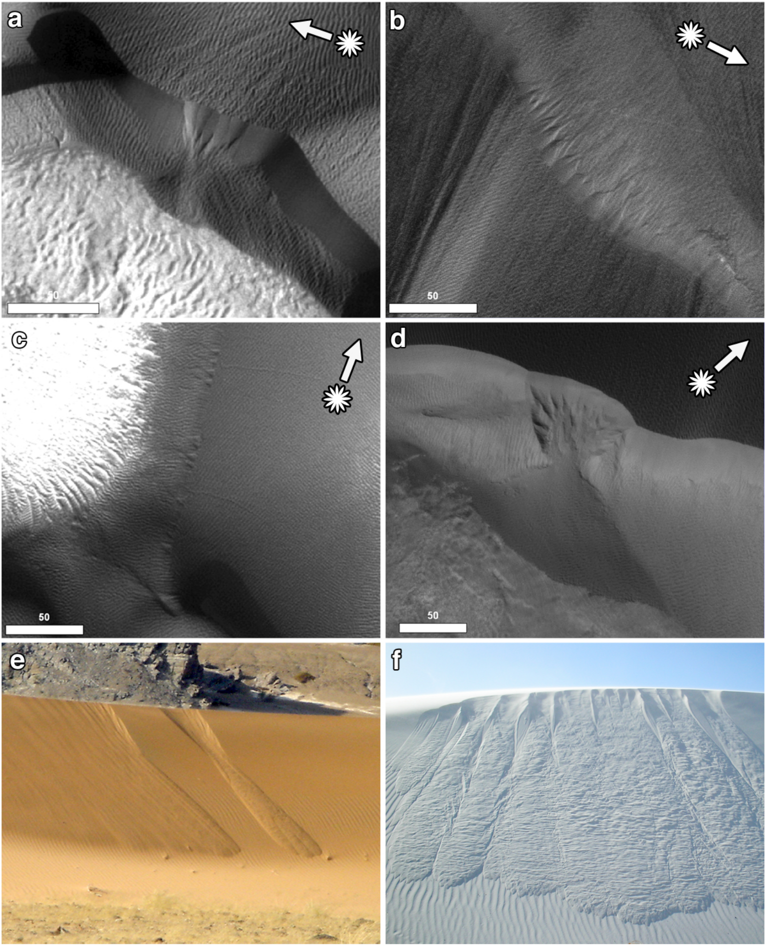
Figure 1: (a-d) Example alcove and fan morphologies from throughout the north polar sand sea. (a) Slipface alcoves with steep sides (Chasma Boreale: PSP_010682_2650); (b) Overlapping alcoves producing a sawtooth pattern (Olympia Cavi: PSP_9252_2640); (c) Small alcoves on a secondary slipface and one intermediate alcove with extensive fan deposits at the intersection of the primary and secondary bedforms (Olympia Undae: PSP_009904_2795); (d) Large, complex alcove (Tenuis Cavus: PSP_9905_2650). All scale bars are 50 meters in length. Lighting directions are indicated by arrows. (e-f) Examples of terrestrial dune slipface scarp retreat flows. (e) Slipface failure in the Cunene Sand Sea (Namibia) showing both a laterally extended and flattened failure surface and an isolated alcove/fan, which is about 40 cm across at maximum width (M. Bourke). (f) Formation of alcoves and lateral migration of slipface flows in the White Sands (New Mexico) dune field. Region of failure is about 3 m across, and typical alcove depths are a few centimeters (R. Sullivan).

Figure 2: Seasonality of alcove formation. (a-b) Repeat observations of dune slipfaces over Mars Years (MY) 29 and 30 in Tenuis Cavus (84°N, 1°E) show that new alcoves (white arrows) are apparent beneath the thinning CO_2 frost by $L_s = 52°$ (mid-spring), implying formation prior to CO_2 deposition in the fall. Where they are present, old alcoves (red arrows) appear to undergo overprinting and modification due to formation of new fans. All scale bars are 50 meters. HiRISE images from top to bottom: PSP_009324_2650, ESP_016682_2650, ESP_016893_2650, ESP_017249_2650, ESP_017974_2650. (c) Slipface changes on a subset of dunes in Tenuis Cavus, using HiRISE images from (a). Notably, of all slipfaces with new alcoves (red and green spots), 82% have alcoves apparent under the

CO_2 frost (green spots only).

Figure 3: (a) Variations in alcove orientations measured across Olympia Undae. Rose diagrams indicate facing directions of the dune slipfaces at the locations where alcoves occur (*i.e.*, the direction perpendicular to the crestline). HiRISE images are all from the same summer season: (1) PSP_009540_ 2595, (2) PSP_009764_2600, (3) PSP_009904_2795 and PSP_010049_2795, (4) PSP_009733_2795, (5) PSP_009647_2605, (6) PSP_009832_2615 and PSP_009674_2610, (7) PSP_009912_2620, (8) PSP_009728_2620 and PSP_010071_2615. (b) Histogram of the angle measured between dune crestlines above slipface alcoves and approaching stoss slope ripple crestlines in HiRISE image at location 4 from (a). Bin sizes are 5°, where the labeled value indicates the minimum of the bin.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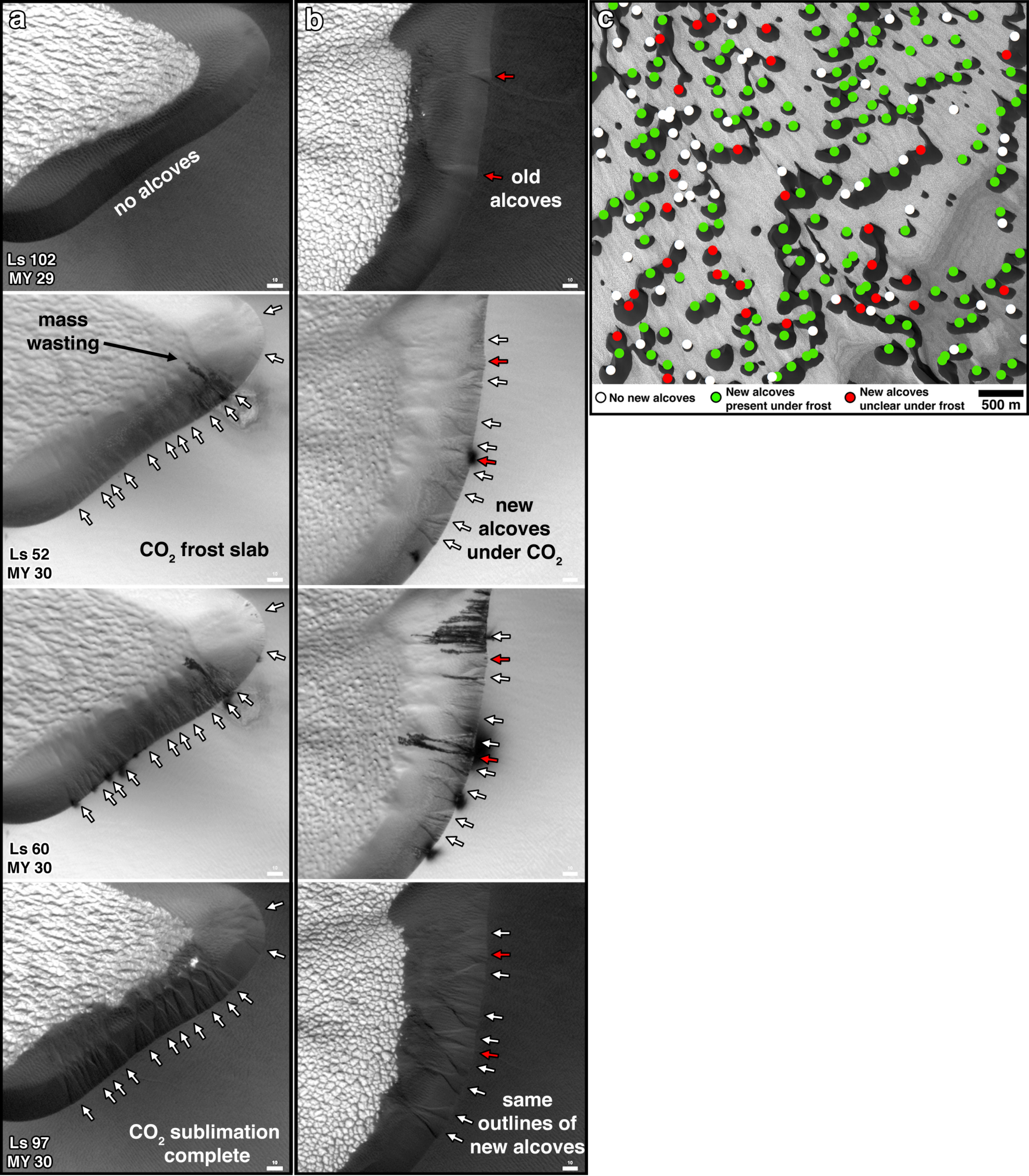
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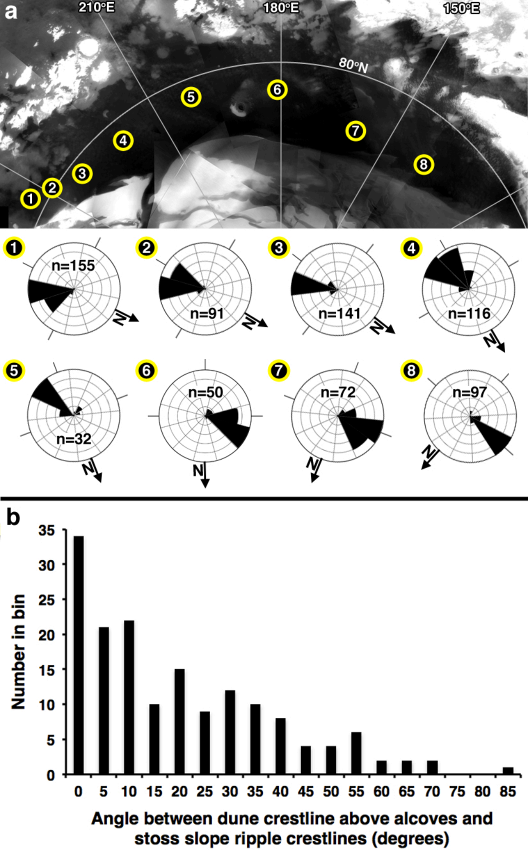
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Angle between dune crestline above alcoves and stoss slope ripple crestlines (degrees)