A Guide to Labeling Martian Frost in Visible Observations

Serina Diniega[1], Gary Doran[1], Steven Lu[1], Kiri L. Wagstaff[1],
Jake Widmer[2], Mark Wronkiewicz[1]

[1]Jet Propulsion Laboratory, California Institute of Technology
[2]University of California Los Angeles

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1 Overview

The purpose of this labeling guide is to aid in the construction of a dataset consisting of examples of indications that frost is present on the surface of Mars within orbital imagery in the visible spectrum. Observations in this dataset are taken from northern mid-latitude regions where frost has been previously studied and identified using the HiRISE and CTX cameras onboard the Mars Reconnaissance Orbiter. The labeling task consists of identifying polygonal regions within images where we think there is frost on the surface. Some additional information will also be collected for diagnostic and explanatory purposes that describes the context of the frost and dominant visible indications (i.e., the evidence we may use to identify frost) as well as estimates of confidence in our detection of frost. We employ the LabelBox labeling platform (`https://labelbox.com/`) to enable the collection of the data labels.

This guide provides a description of the visible indicators of frost (Section 2) and context in which frost occurs (Section 3) to aid a consistent analysis and interpretation of image content. Finally, the guide provides instructions for how to label images using the LabelBox platform (Section 4).

2 Visible Indications of Frost Presence

Definitively determining the presence of frost from visible imagery is a challenging problem, even for experts in the field. Scientists searching for evidence of frost within images often use contextual information such as season (quantified as the position of the planet in its orbit, or solar longitude, denoted L_s), latitude, and even general year-to-year patterns in frost deposition. Scientists might also use data from other instruments, such as surface temperature data, or visible indications of frost at nearby locations that stand out more obviously (e.g., on dunes consisting of relatively dark basalt), to make their determination and bring down uncertainty when the evidence might indicate frost but could also indicate other environments (for example, a covering of either dust *or* frost can make the landscape look smoother and brighter). This type of analysis is done over a range of scales since some indications of frost are small, individual features and some require seeing a pattern over a larger scene.

Using the methodology described above, sites with frost coverage in the northern mid-latitude region have been identified as part of previous studies. Our goal with this labeling task is to capture specific regions within these sites that exhibit the characteristics of frost presence. The task is made somewhat simpler given the contextual knowledge that these image tiles are from observations known to have frost present, versus the more general task of determining the presence of frost only from an arbitrary visible image. The following subsections describe the various visible indications that frost is present within observations; HiRISE images are all from northern mid-latitude sites and CTX images (added in v2) are from either the northern or southern mid-latitudes.

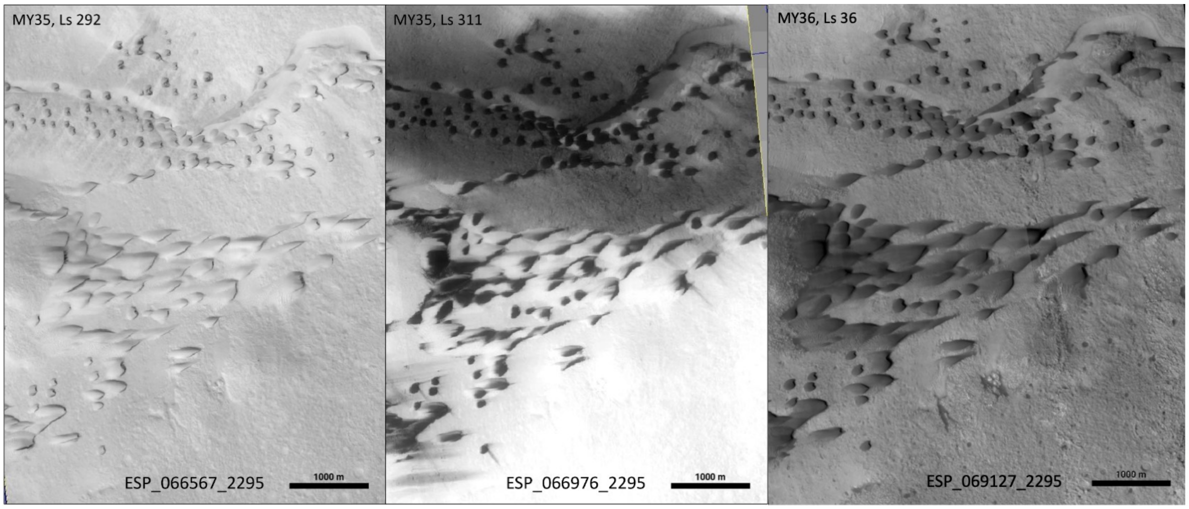

Figure 1: An example series of images with various levels of frost coverage. On the left (Mars Year 35, $L_s = 292$ or early winter), the frost covers the entire scene, exhibiting a uniform, bright albedo. (Variations in brightness are due to shadowing from local topography.) In the middle (MY35, $L_s = 311$ or mid-winter), the relatively darker dunes have started to defrost (see Section 2.4), but much of the region remains covered in a layer of frost. On the right (MY36, $L_s = 36$ or mid-spring), the frost is gone, revealing the natural level of surface albedo variation, in which the dunes stand out as darker than the surface.

2.1 Uniform, Bright Albedo

The term albedo refers to the reflectivity of a surface, which we see in how bright it appears. Surfaces covered with frost tend to have a uniform, bright albedo (for example, left image in Figure 1). However, due to factors such as topography and shadowing, visual brightness can appear to vary (especially at small scales) even when the surface is covered in frost. Examples are shown in Figure 2 and Figure 3 where the scene would still be identified as having a uniform albedo, despite the small albedo variations. Additionally, the presence of small, discrete sublimation markers (discussed more in N) does not count against having an otherwise uniform albedo.

Relatively smooth areas composed of one type of material (i.e., that has consistent optical properties) or a surface covered in dust can also exhibit a uniform albedo, so this visual indicator is not a guarantee of frost (i.e., has a weak association with frost). Confidence in frost detection can be increased if the albedo remains uniform across distinct terrain types and surface features that are known to have a different appearance when defrosted, such as dark sand dunes; an example is shown in Figure 1, which shows the level of albedo variation that can occur with various levels of frost coverage. Confidence that the whole area is covered in frost also increases if more-strongly associated frost markers are present within a portion of the uniform albedo region.

If a surface has a near-uniform appearance, but contains brightness variations that does not appear to relate to topography, then it should not be labeled as having a uniform albedo. A couple of these examples are shown in Figure 4.

2.2 Halos

Bright regions surrounding or filling topographical features such as gullies (Section 3.3) can also indicate the presence of frost. Gullies and other erosional features form along crater walls (Section 3.2); as these features form from the loosening and movement of material downslope and exposure of the subsurface, gullies usually have darker regions within their alcove (the erosional part at the top) and/or their apron (the depositional part at the bottom). When covered in frost, they lack this usual variation; instead, they can appear to have a mostly uniform, bright albedo (Section 2.1). Additionally, slightly higher levels of frost condensing in slightly more shaded or looser surfaces or along edges may give these these features partial brighter outlines

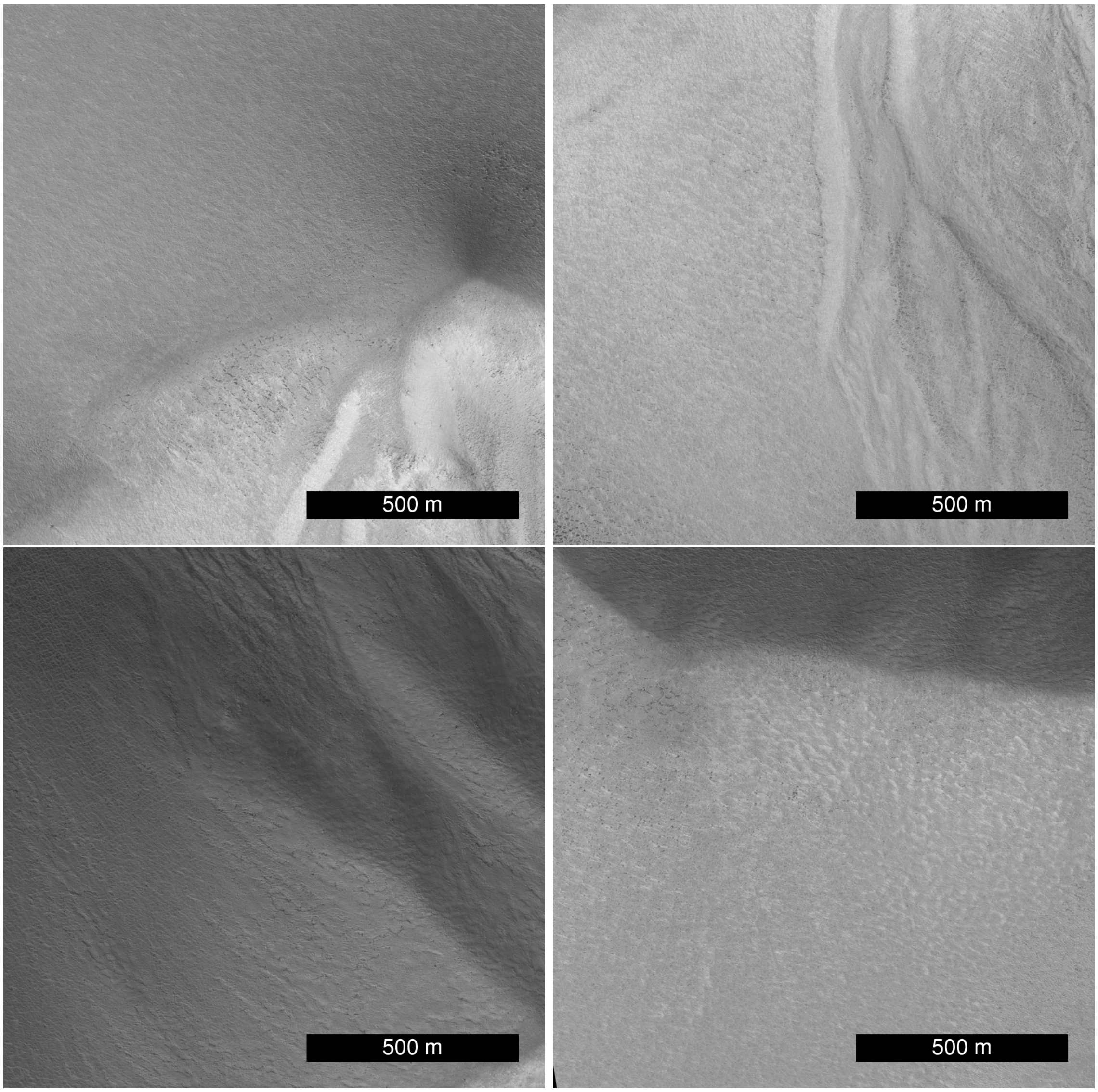

Figure 2: HiRISE examples showing scenes considered to have a uniform albedo despite some degree of variation in apparent brightness within `ESP_033141_2450`. As seen in all images, small ripples or a textured ground underlying the frost can yield a stippled pattern. Larger changes in slope, such as those in the bottom two images, can yield a gradual (bottom left) or sudden (bottom right) darkening across a larger area due to large shadows.

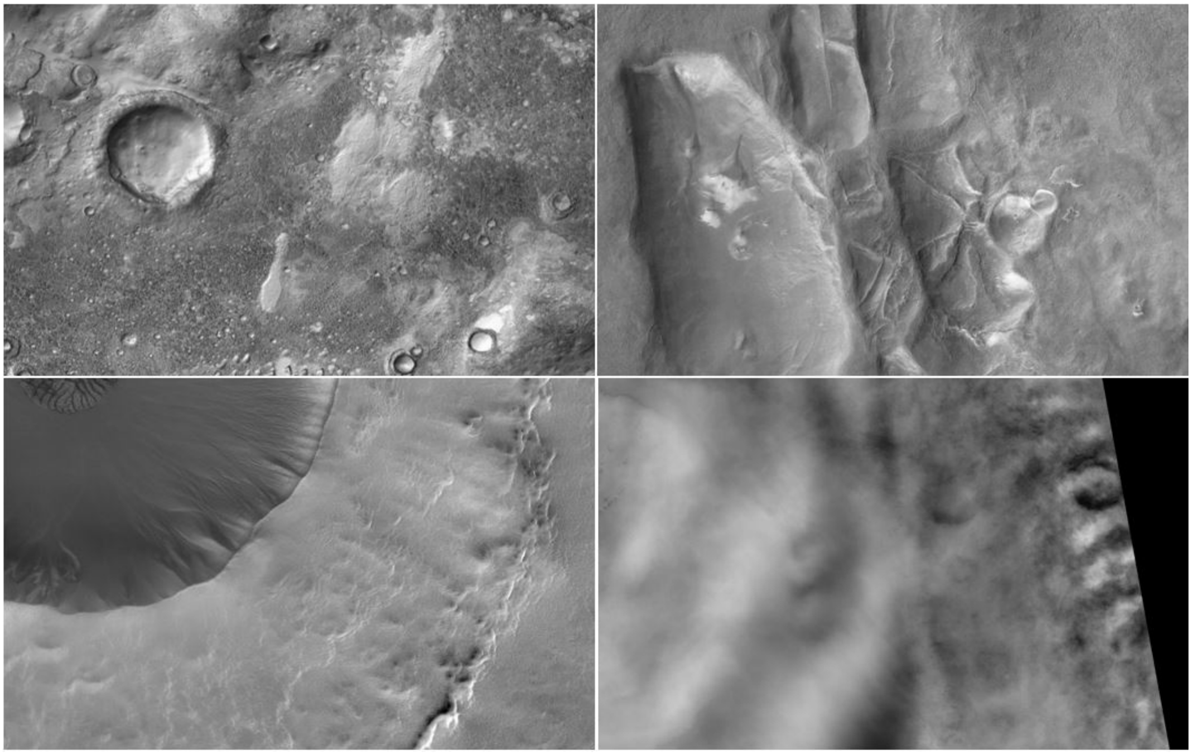

Figure 3: A few examples from CTX images with uniform albedo. Especially as CTX images have lower resolution and broader footprint, there many be many small variations in brightness (but that appear to due to topography/shadowing rather than compositional differences).

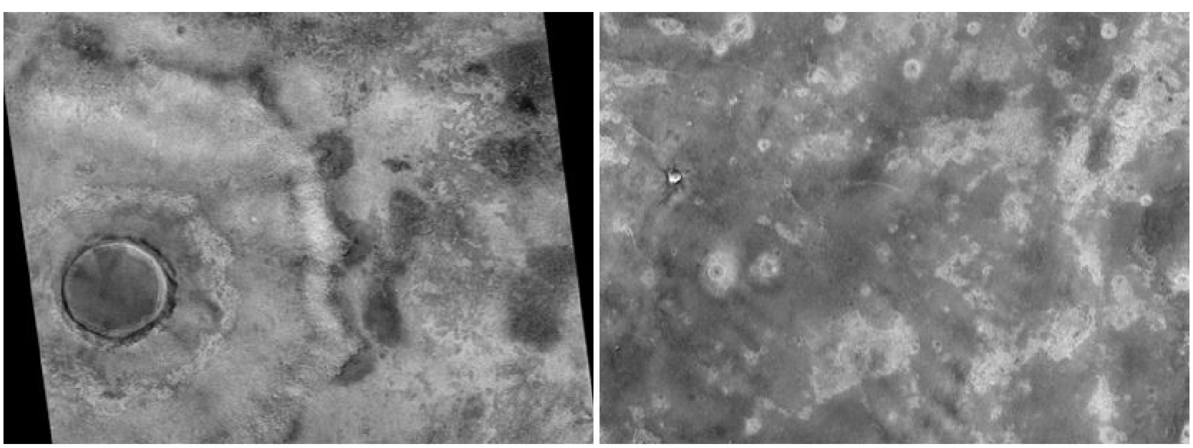

Figure 4: Two examples from CTX images that should not be labeled as having a uniform albedo. Although the range of brightness across each surface is comparable to those shown in Figure 3, the variations do not appear correlated with topography. In the left example, a portion of the image including the crater and its ejecta ring might be labeled as uniform albedo, but the right-half of the image has extensive defrosting marks and other variations. In the right image, the full surface is mottled.

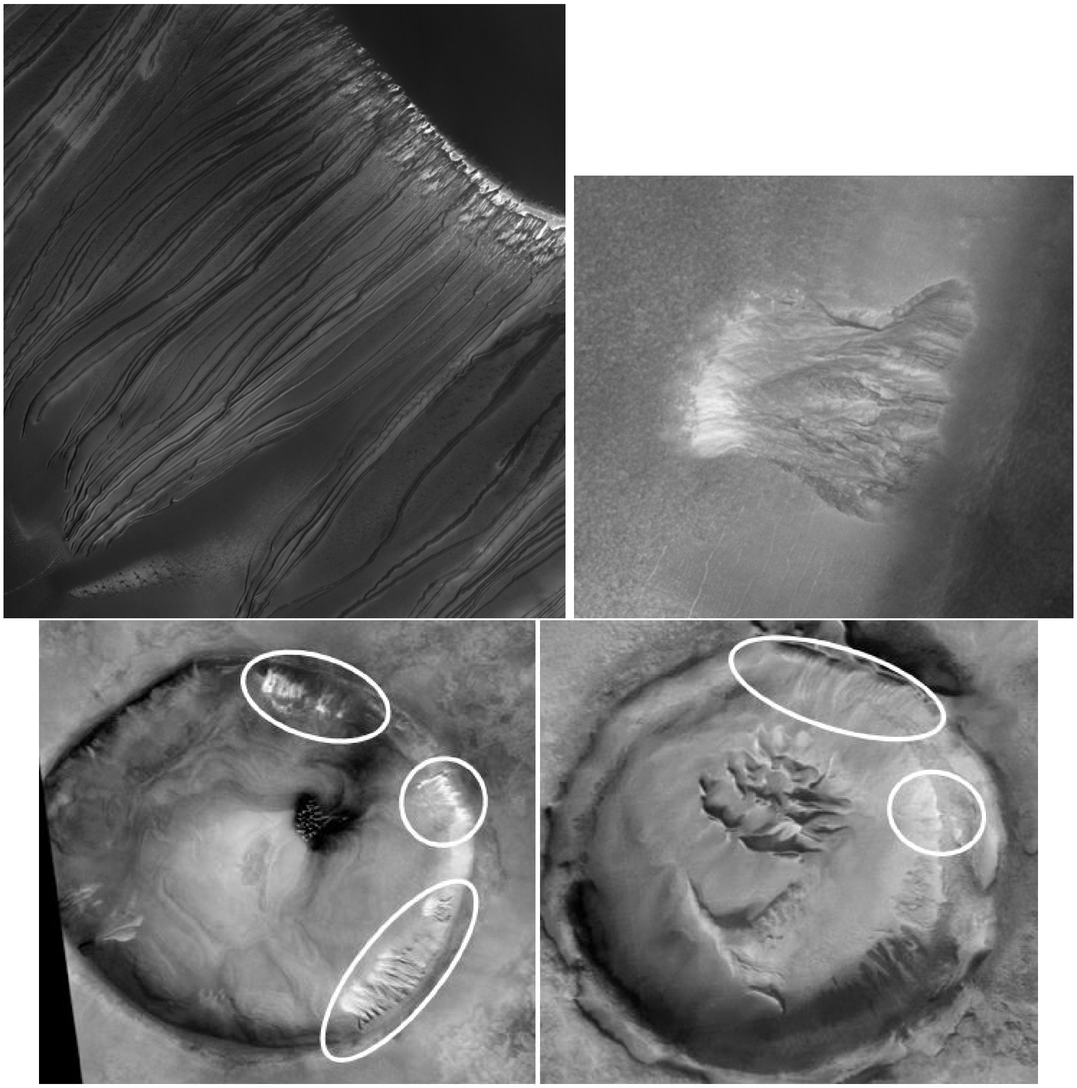

Figure 5: Examples showing halos around gully and linear gully features in crater walls. In the top left HiRISE image (ESP_047078_1255), the entire dune slope, which extends downslope towards the bottom left, is covered in frost. The ∼2 km long linear gullies are outlined with brighter frost, especially within their alcoves (top right). In the top right HiRISE image (ESP_032912_2385), the top of the gully or the alcoves are on the right and the aprons are on the left, with short channels between them. The halos are around the edges of the alcoves and channels, as well as the brighter deposit over parts of the aprons. Similar features are sometimes visible in CTX images, as shown in the bottom images (with the halo'd gullies circled).

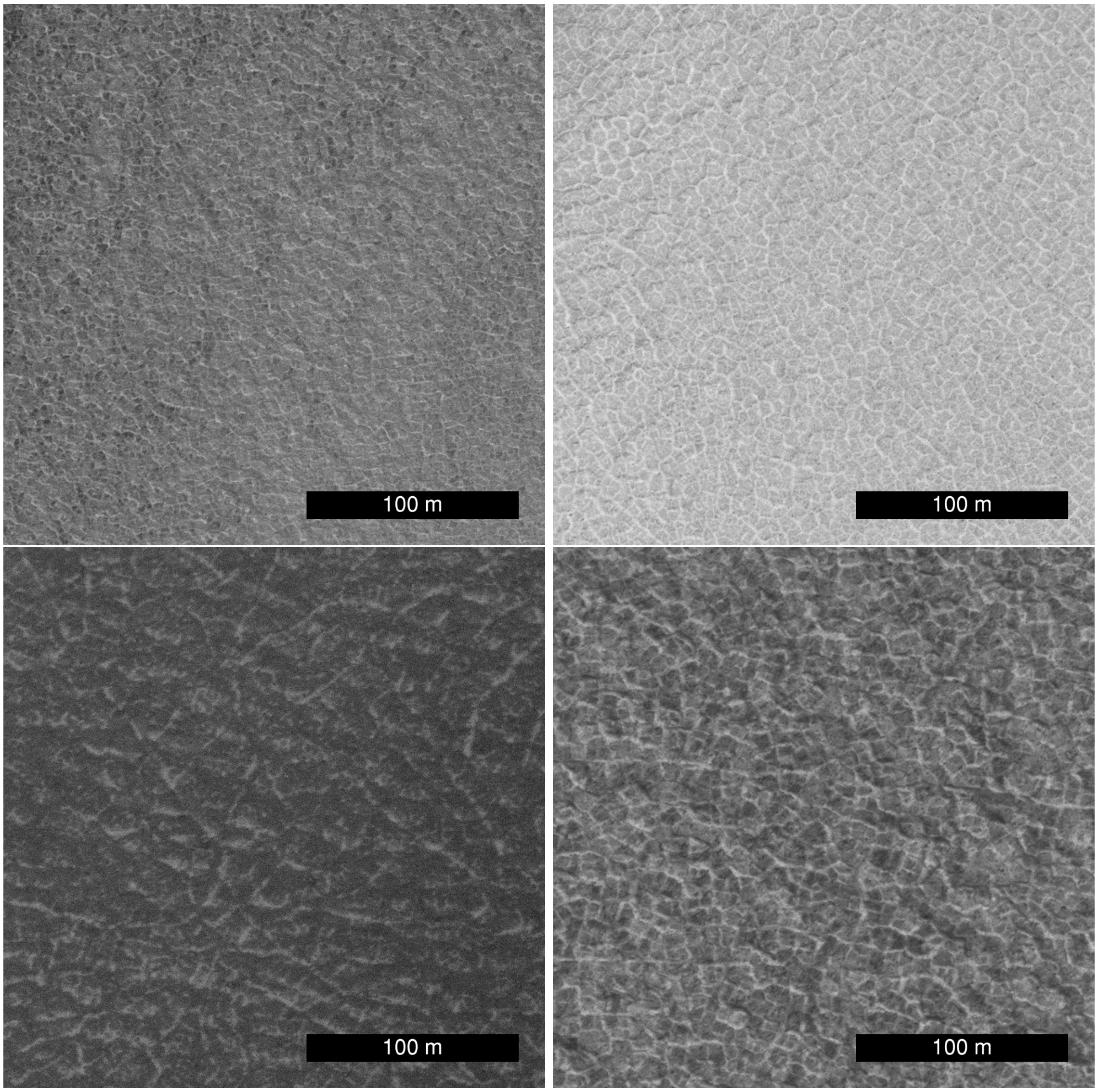

Figure 6: Examples showing a surface polygonal texture with bright outlines, due to frost in the cracks.

(looking like halos) or filled areas (see Figure 5). Halos have a medium association with frost, with confidence potentially higher or lower depending on clearness of its definition and whether it's proximal to other frost markers.

2.3 Polygonal features

There are two types of small-scale polygonal features that can be identified: those that appear to be in the ground (and may be covered by frost) and those that appear to be in a surficial ice layer. We will refer to the first as "polygonal cracks" and the second as "slab ice cracks." In both cases, the outlined polygons are usually a few-meters to ten-meters in diameter, and they occur over a large patch (i.e., there are many polygons abutting each other) but need not extend over the full scene.

Polygonal cracks in the surface can be filled with frost earlier than the rest of the ground; thus they appear brighter than their surroundings. (Surroundings may be covered in frost and thus also bright – just a bit less bright, or may be defrosted and thus much darker.) Examples are shown in Figure 6. However,

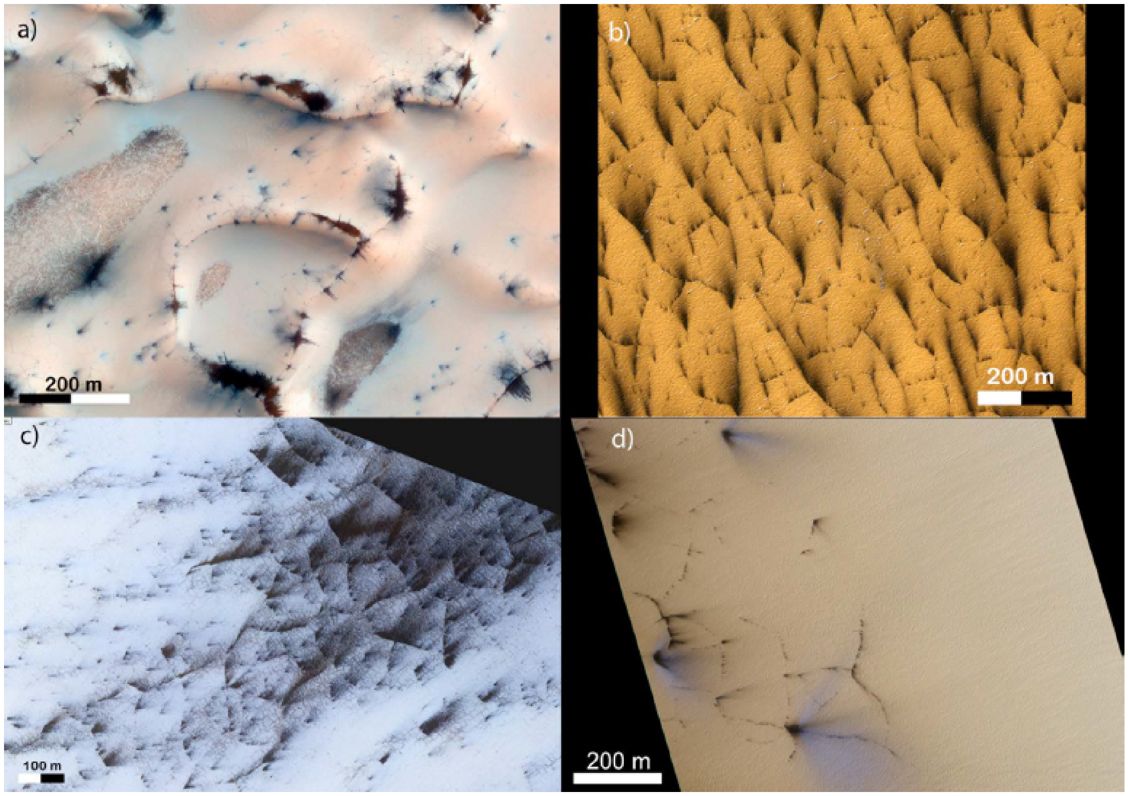

Figure 7: Slab ice cracks, identified in a study of these features by Portyankina et al. (2012). Caption from that paper: "Examples of various polygonal cracks observed by HiRISE in the southern and the northern polar areas. All images are false color images produced by separately stretched infrared, red, and bluegreen filters. (a) PSP-008396-2610 - defrosting north polar dunes (81°N, 156°E); (b) ESP-012680-1000 - the southern polar terrain (79.9°S, 234.1°E); (c) ESP-012081-0930 - the southern polar terrain (87°S, 72.5°E); (d) PSP-003474-0850 - Giza region (85°S, 69.9°E)." Due to their thinness, these types of features are harder to identify in CTX images.

some surface cracks might be filled with bright material other than frost (such as a mineral that is lighter than the matrix), so the presence of this feature alone is a weak indication of frost and does not constrain the type of frost. (Since these cracks are in the ground, under any ice or frost, in a defrosted image the polygonal cracks would still be visible, but would likely be slightly dark due to shadowing.)

Slab ice cracks occur after a thick, brittle layer of CO_2 ice (i.e., CO_2 slab ice) has accumulated through the winter. As the surface warms, this slab ice may destabilize and form defrosting marks (described in the next section) and/or may crack into pieces. In the latter case, cracks usually appear as dark lines within the bright, uniform albedo slab ice layer (see Figure 7). These features may only occur in small areas (such as along dune crests, where the ice layer bends over a change in topography) or may permeate a region. Slab ice cracks – in isolation over a bright surface, has medium association with CO2 slab ice. However, the cracks are likely to be proximal or overlapping with other defrosting markers, such as fans and spots (Section 2.4), and such association would increase confidence in the identification of CO_2 slab ice. (Since these cracks are in the ice layer, in a defrosted image, the lines would not be visible as the ice would have disappeared.)

2.4 Uneven Defrosting Marks

As the surface warms, defrosting can progress unevenly, resulting in a pattern of marks that stand out in contrast to the regions where frost is still present. Examples are shown in Figure 8 and Figure 9 of defrosting marks on dunes, where they are particularly visible. Typical defrosting marks are spots or splotches that

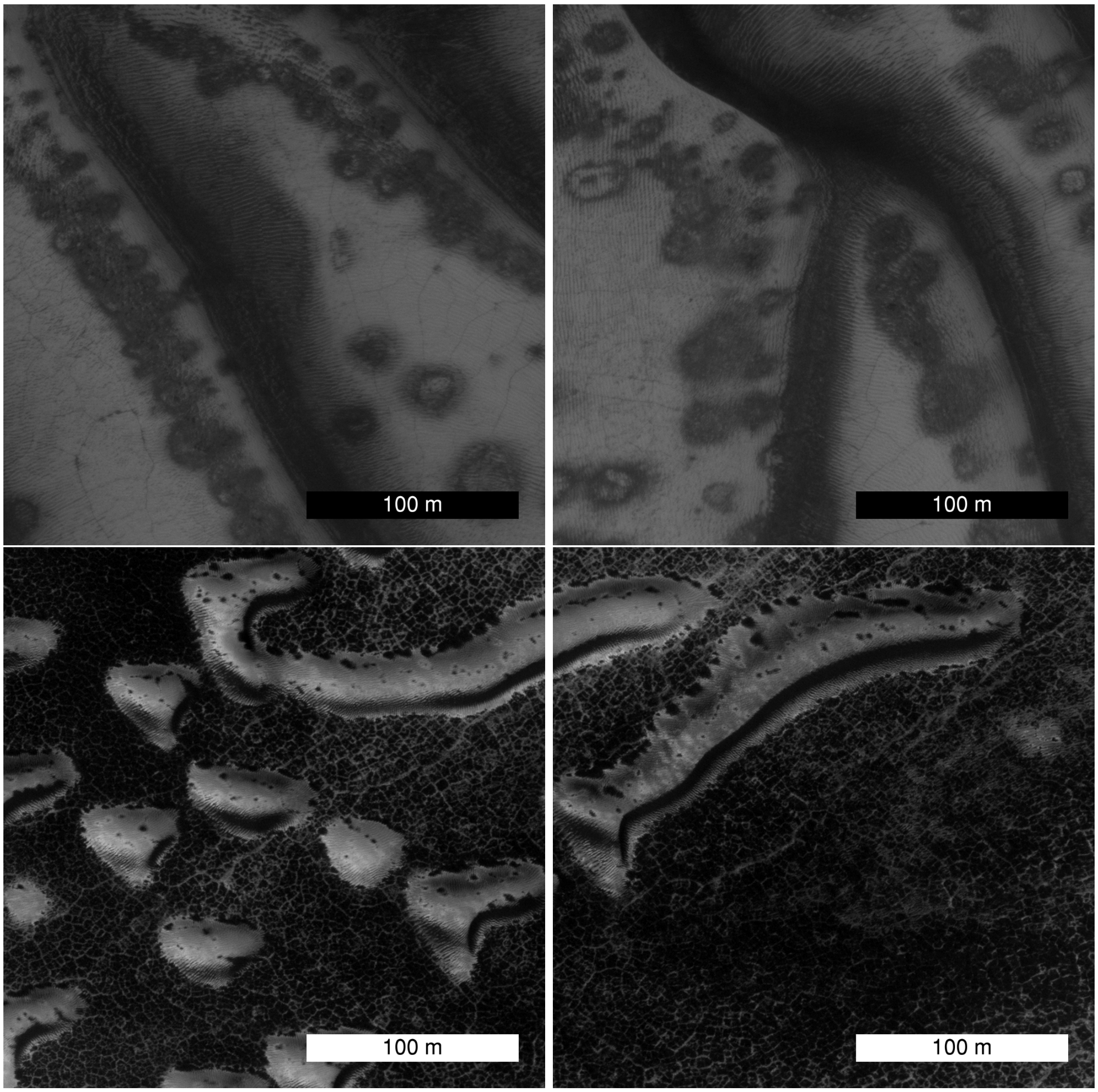

Figure 8: HiRISE examples showing uneven defrosting patterns on dunes. The top two images contain sublimation spots (including "fried eggs" with the concentric bright and dark rings) along with slab ice cracks (Section 2.3). The bottom two images contain sublimation spots over the dunes, with bright polygonal cracks (Section 2.3) throughout the interdune surface; this ground is likely mostly defrosted with only residual frost in the cracks.

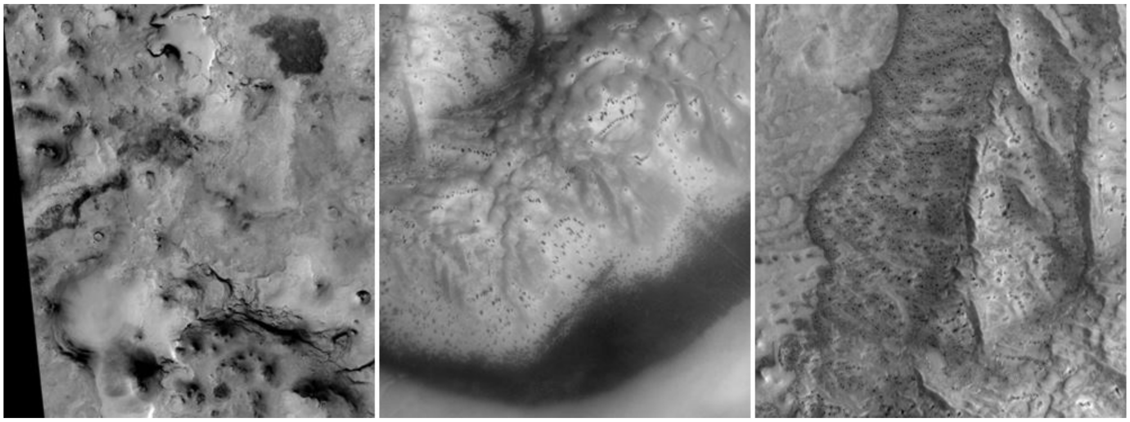

Figure 9: Examples of CTX images showing uneven defrosting patterns, also mostly on dunes. These features are still very distinctive, even if less discrete in the lower-resolution images.

are much darker than the frost (as they expose the darker surface material), and sometimes they are aligned around topography (e.g., dune face) or focused within a particular material. Dark fans can also appear (these are a variation of the sublimation spots), as shown in Figure 7. These features are fairly distinctive, even within CTX images, and are strongly associated with CO_2 slab ice.

3 Geologic Context of the Frost

The visual appearance of frost differs depending on the geologic context. In order to quantitatively diagnose this difference, we ask labelers to also record the context in which the frost was observed. The northern mid-latitude sites from which these observations were taken are typically dune fields within the centers of craters. Therefore, the three main geologic contexts of relevance for these images are the dune fields, the crater rim, and gullies or gully-like features along the crater walls. Each context is described in more detail below.

3.1 Dunes and Dune Fields

Dunes and dune fields on Mars are typically composed of dark basalt sand grains and so usually are darker than the surrounding terrain. When covered in frost, these dunes will appear much lighter in albedo than when unfrosted, and they usually will have an albedo much more similar to their surroundings (because everything is covered in frost). During frosting and defrosting, an even covering of frost can be interrupted with defrosting marks (described above) or become patchier in coverage. Occasionally, dark sand can slide down the frosted dune face to create a dark patch superimposed on the frosted surface. Figure 10 shows some examples of dune fields. On the left, isolated dunes with some frost covering and defrosted marks are visible, over a surface that is also covered with frost. On the right is a large patch of dunes that are merged together to form a single dune field. Dune slopes in this one have defrosting marks and in some cases appear mostly defrosted. Again, the surrounding terrain is also likely covered in frost.

In some cases, as shown in Figure 11, there may be dunes or sandy material with a lighter toned albedo. This may be due to a different composition or a covering a dust. In the example referenced above, light dust devil tracks are an indication that the covering on this smooth, sandy material is not frost.

3.2 Crater Rims

Crater rims are the raised external edges of a crater, and they are usually circular. Craters can be formed by impact or volcanic explosion. Due to these formation processes, crater rims may have different material and thermal properties from the surface inside or around the crater which can cause frost to accumulate at different rates. Additionally, the rim's topography will create shadowing (especially on the poleward slope)

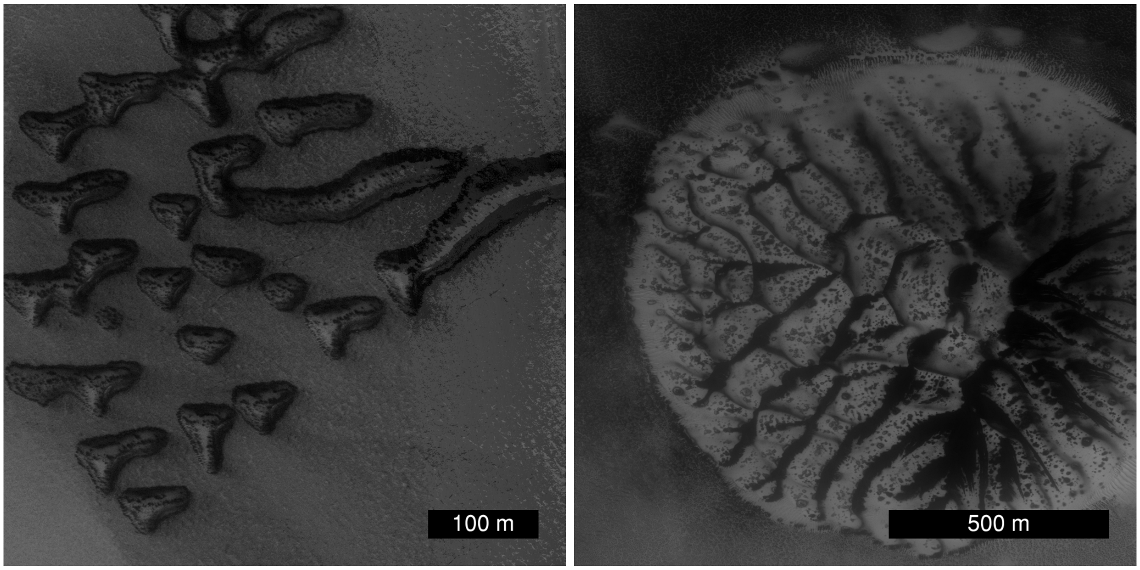

Figure 10: Examples of two dune fields, with and without isolated dunes.

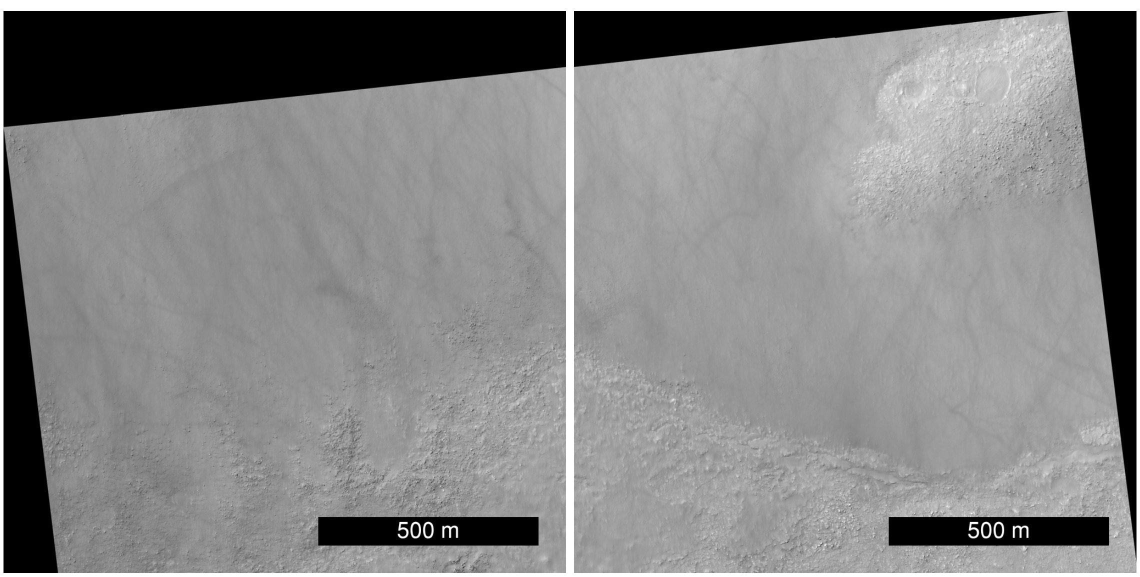

Figure 11: Examples of two unfrosted dunes with a lighter albedo.

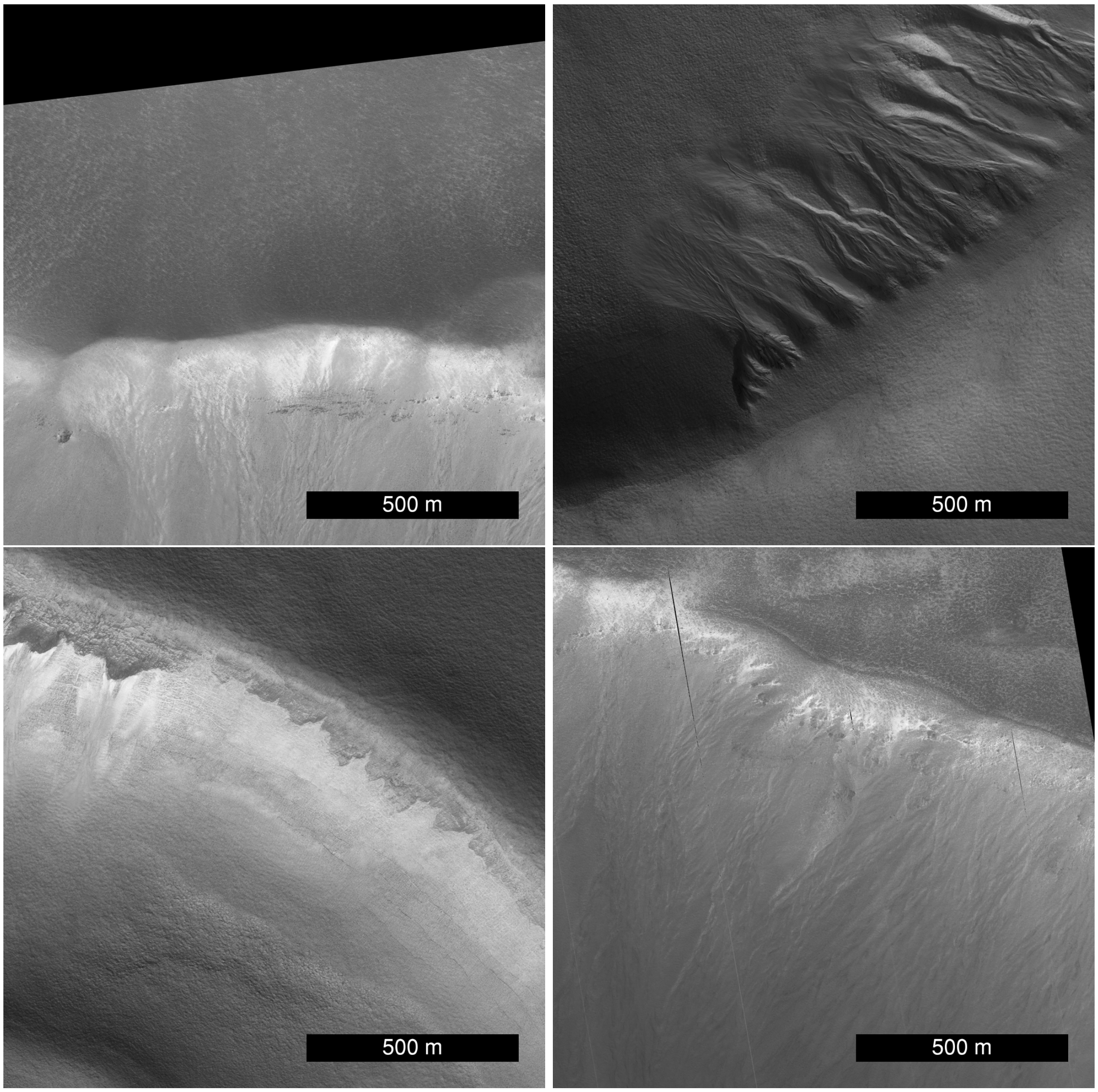

Figure 12: Examples showing partial crater rims within observation subframes. Depending on the size of the crater relative to the subframe, the rim may appear curved, straight, or slightly sinuous. All of of these examples are likely covered in frost, based on the uniform albedo (Section 2.1). Additional interesting frost patterns, such as halos (Section 2.2) or frost patches (as seen in the two images on the left and in the bottom-right), may be seen along the crater rim, and there may be erosional features just under the rim. For example, very clear gullies (such as gullies; Section 3.3) are shown in the upper-right image and more degraded erosional alcoves are seen in the upper-left and lower-right images.

which will cause earlier and longer-lasting frost accumulation. Thus, the frost on these crater wall and inner slope may look different from the region outside the crater rim or deep within the crater. Figure 12 shows a few crater rims. These rims can be identified based on the bright/dark change as one goes over the ridge (i.e., shadowing on one side and illumination on the other) that makes up the rim. For labeling purposes, we are only interested in relatively large craters (on the order of several hundreds of meters or larger in diameter) with significant topography.

3.3 Gullies

As on the Earth, martian gullies are features carved into rocky or sandy slopes, such as those found along crater walls, hillsides, and sand dunes. Gullies typically have an hourglass-appearance, with the "triangular" zone of erosion on top (the alcove), a "triangular" zone of deposition at the bottom (the apron), and often a zone of transport connecting them (the channel). As these features may contain zones with different material and thermal properties (such as looser areas of the apron where material was very recently deposited) as well as well-shadowed areas (such as along the bottom of the alcove or channel), frost will deposit unevenly across them. Eventually they may be fully covered by frost and thus have a more uniform albedo, but even then there may be some brighter or darker areas or outlines due to shadowing or differences in frost distribution. Figure 13 shows four frosted gully examples, including one where the aprons and some channels are distinctly brighter than the rest of the area, likely due to slightly different frost amounts or characteristics over the aprons and lower channels.

4 Labeling Instructions

LabelBox provides a visual interface for viewing the images and annotating them with frost indicator labels (Figure 14). Each image is a subframe of the original source image to provide an image of manageable size for labeling. The labeling goal is to create a polygon that encompasses each region with indicators of frost and to annotate the polygon with descriptors and context elements. All regions in which frost appears and covers at least 25% of the surface (if patchy) should be enclosed with a polygon. **Polygons should not overlap.**

Each image is accompanied by metadata that includes the observation identifier, time of year (L_s), solar incidence angle (angle of the sun above the horizon), solar azimuth (direction of illumination, measured in degrees clockwise from the right, indicated with an arrow pointing to the sun's location), local time of day, map scale (size of a pixel), the latitude and longitude the image spans, and the total subframe extent in kilometers. Such information may be useful for interpreting the image, such as identifying which direction shadows would extend and thus which direction is likely upslope. Click the small square "Asset Description" box in the upper left of the screen to toggle on/off the metadata window (see Figure 15).

The "Overlay" button (Figure 16) can be used to toggle a grid overlay on top of each image subframe (Figure 17, Figure 18). This overlay is meant to help determine how precise to be annotating frost outlines. When drawing polygons below using the guidance below, do not spend time annotating details that are smaller than the individual squares in this grid. Only frost features that appear at least as big as one grid square are necessary to annotate. Additional overlay notes:

- When zoomed out, sometimes the full resolution grid will not appear. Make sure to zoom in until the 50m resolution grid is visible; use the scale bar in the upper left corner can be used to check whether the grid has been rendered at this resolution.
- The overlay provides guidance for scale only; the drawn polygons should not conform to this grid.
- It is not possible to label while viewing the overlay. The original subframe (Layer 1 in the overlay list) must be visible before drawing polygons is possible.

Although the source image identifier is provided for traceability, please do not visit the full source image when labeling the subframe that is presented. The goal is to collect labels that reflect what can be determined from the subframe image alone.

For each subframe, labeling proceeds following the steps outlined below. Refer to Figure 19 as an example that highlights the keys steps of drawing polygons and annotating with context, indicators, and confidence.

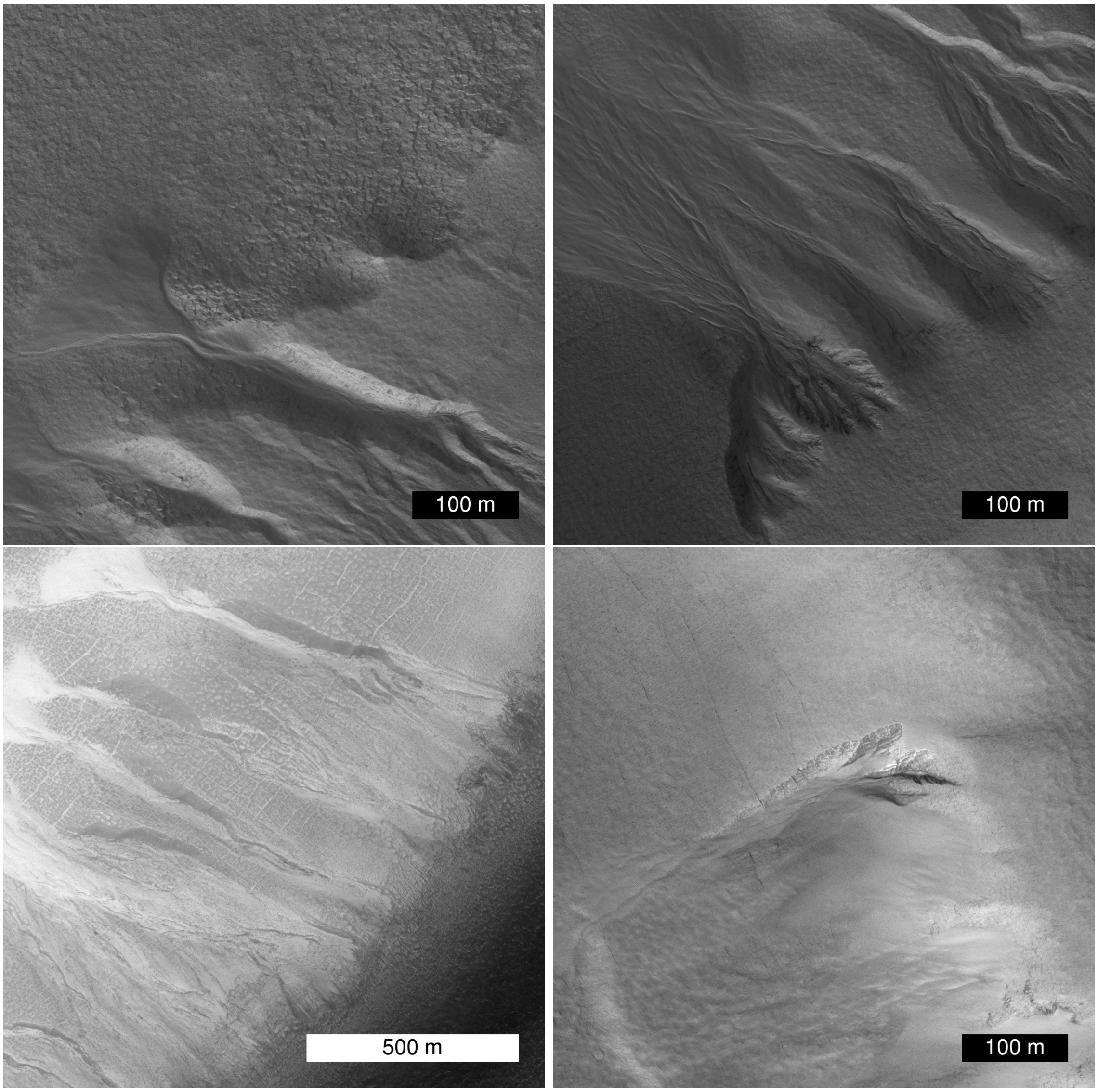

Figure 13: Examples of frosted gullies along crater walls. In the two left and the upper-right examples, the alcoves extend towards the bottom-right of the image and the apron is in the upper-left. In the bottom-right example, the alcove is in the middle of the image and the gully extends downslope, towards the bottom-left. The bottom-left image also contains some nice bright “haloing” (Section 2.2) along and around the channels and aprons.

Figure 14: An overview of the LabelBox labeling interface. Controls are located in the upper-left portion of the interface, annotation tools are on the left, and visual controls are in the upper-right.

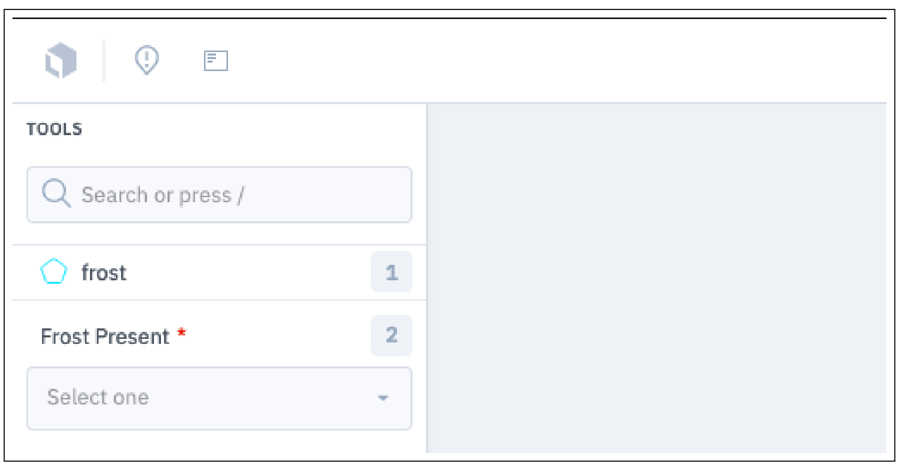

Figure 15: The LabelBox control and tool menus. Along the top are buttons to return to the LabelBox home menu, create an issue (problem/comment on an image), and display the Asset Description (metadata). Along the left-hand side are annotation tools to label frost polygons and indicate the presence or absence of frost within the image.

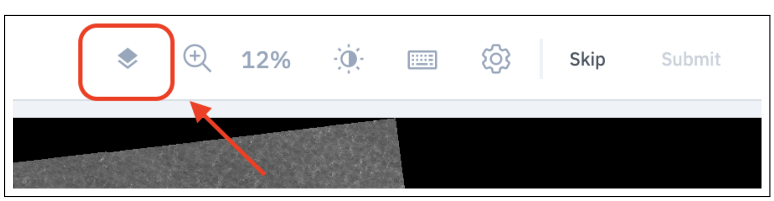

Figure 16: The LabelBox overlay button appears in the the top control bar as two stacked squares (red).

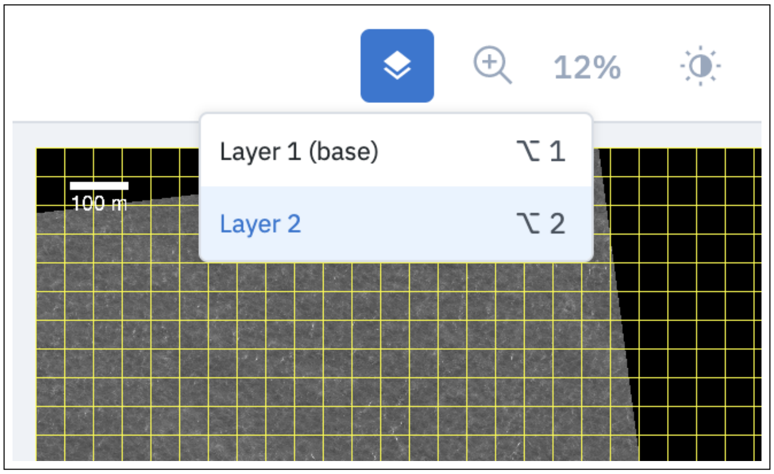

Figure 17: Once clicked, the LabelBox overlay button will display possible image layers to view (e.g., original image and the grid overlay image). Using hotkeys will allow for faster switching.

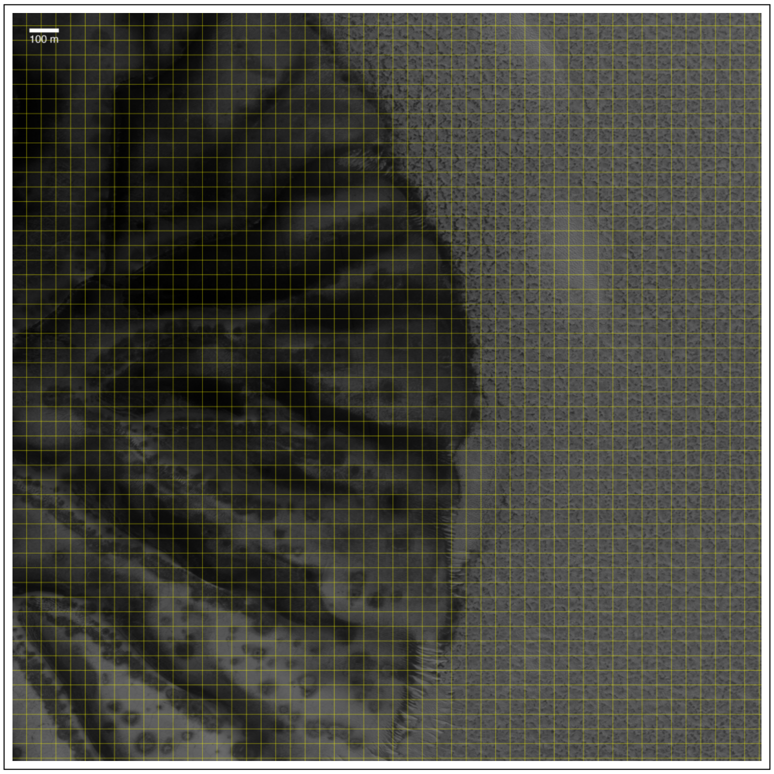

Figure 18: The LabelBox grid overlay can be used to determine the approximate labeling resolution required for this task.

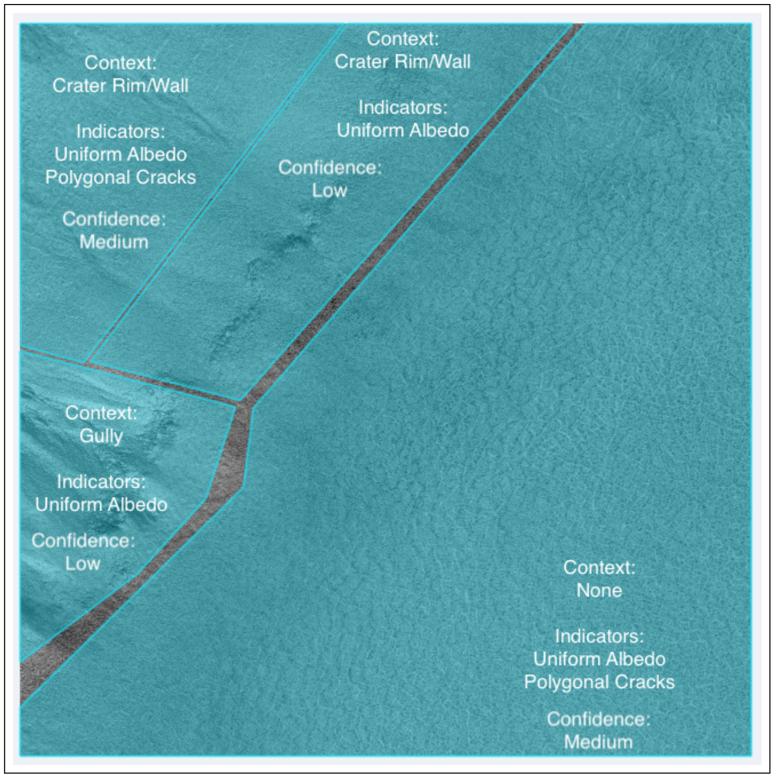

Figure 19: An example subframe annotated with multiple polygons within LabelBox. The geologic context, frost indicators, and confidence values are shown for each polygon.

4.1 Is frost present?

First, determine which portions of the subframe contain valid image data. Because subframes are taken from map-projected images, some portions of the subframe might be completely black (missing), as in the upper left of Figure 12. Polygons should only be drawn within regions with valid (non-missing) image data. In general, only images with at least 25% valid image data will be shown to the user for labeling.

Within valid regions, check whether there are any of the frost indications described in Section 2. If no indications are visible, select "False" under the "Frost Present" tool and assign a confidence value (see Figure 20). Confidence ranges correspond to high confidence ($\geq$ 90%), medium confidence (70–89%), and low confidence (50–69%). Examples are shown in Figure 21. From left to right, there is progressively less of an albedo difference across different exposed materials, which (when present) would help to rule out the uniform albedo that would be apparent in a frost-covered terrain.

If frost is not present, you can complete the task immediately and submit the subframe label. Otherwise, if any frost is present, select the "True" option for the "Frost Present" question and proceed to the step in Section 4.3. If you are unable to complete even this first step, see Section 4.2.

4.2 Unsure how to annotate the image?

If you are unable to determine whether frost is present within the image using these instructions, it is possible to skip the image using the "Skip" button in the upper-right of the interface. You might skip an image due to the presence of extreme image artifacts, or some ambiguity that you cannot resolve. Before skipping, please use the "Issue" button (the exclamation mark in Figure 15) to record a comment where you can describe the issue and why you skipped the subframe. Note that you can also record issues even for subframes that you do not skip, in case there is anything you would like to bring to the attention of the label review team.

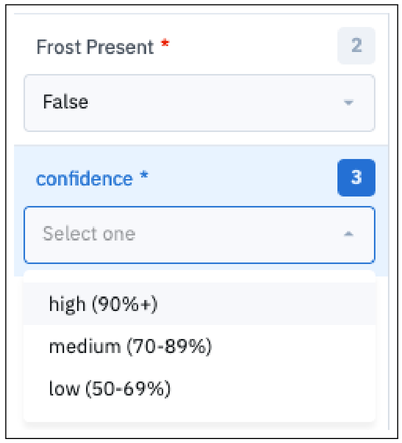

Figure 20: Confidence options when selecting “False” for the “Frost Presence” question.

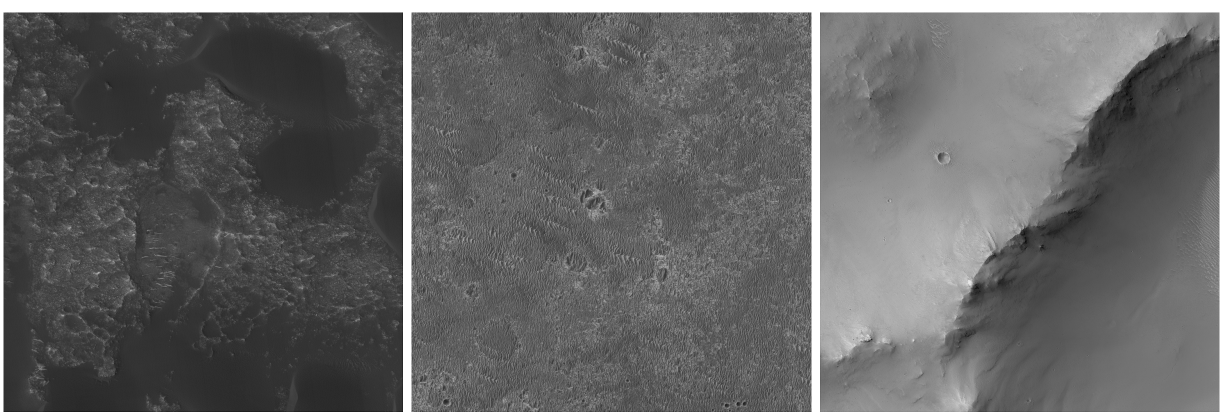

Figure 21: Examples of high (left), medium (middle), and low (right) confidence subframes without frost.

Figure 22: Example of a polygon (blue borders) drawn around the entire subframe.

4.3 Draw frost polygon(s)

If frost is present within an image, you will be asked to provide polygonal labels outlining all regions where its presence is apparent. You will create a distinct polygonal region for each unique combination of frost indicators and geologic contexts. That is, if there are two different indications within a subframe, or a single indication in two different geologic contexts, there should be a separate region drawn for each.

To draw a polygon, click the "Frost" tool (see Figure 22) and begin clicking points on the image to define the outline. Clicking on the first point will close the polygon. In the simplest cases, the scene will be uniform and a single polygon encompassing the entire subframe will suffice. In this case, you can click outside the boundaries of the subframe and the polygon vertices will be projected back into the subframe. If you need to pan (slide) the image while drawing a polygon, you can hold down the spacebar and click/drag to move the image.

For each polygon, draw as closely as possible around each region of interest, with a resolution of at least approximately 50 m. A 50 m grid can be displayed using the asset description menu (see Figure 18). Any region smaller than 50 m can be ignored.

After drawing each region, proceed to select indicators as described in Section 4.4.

4.4 Select frost indicators and context

For each polygon, you will be asked to select relevant indicators and context (see Figure 23), as described in Section 2 and Section 3. Each region could have multiple indicators, but should have only a single geologic context.

As outlined in Section 2, frost marker options (choose one or more) are: uniform and bright albedo, halos, polygonal cracks or slab ice cracks, and defrosting marks. Should frost be observed but not under any of those options, please select "other."

As outlined in Section 3, geologic context options (choose one) are: dunes, gullies, and crater rim/wall. For the last category, the main focus is on the crater rim, as this is more easily identified, with the wall extending down from it, into the crater. If a gully occurs on top of a crater wall, the more specific feature (the gully) should be selected and a separate region created for the remainder of the wall. For gullies, please include the apron within the labeled region (if observed). Dunes can include the inter-dune area if it also appears to be covered in sand (e.g., if smaller ripples are visible). Should none of these options apply, select the "none" geologic context.

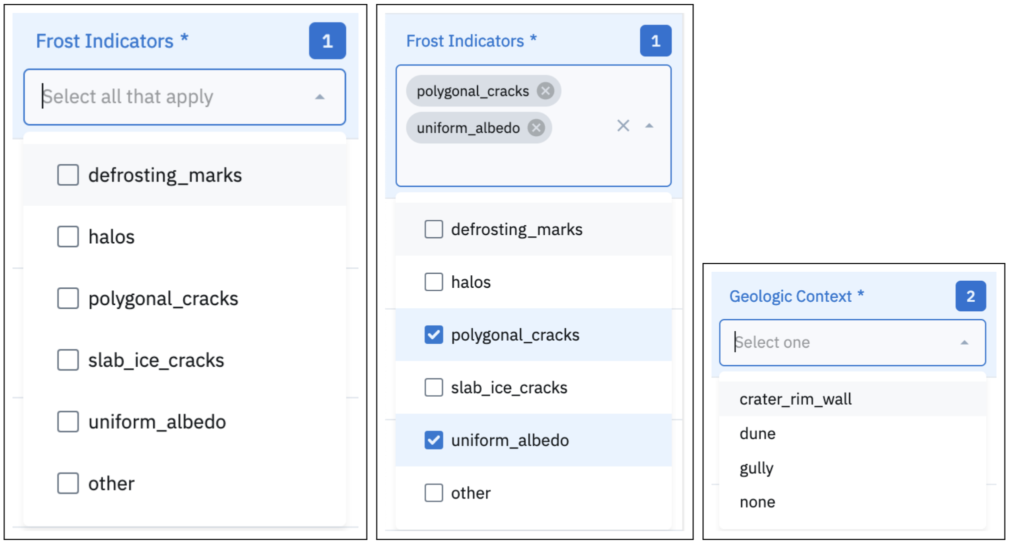

Figure 23: Selecting a frost indicators and geologic context for a polygon.

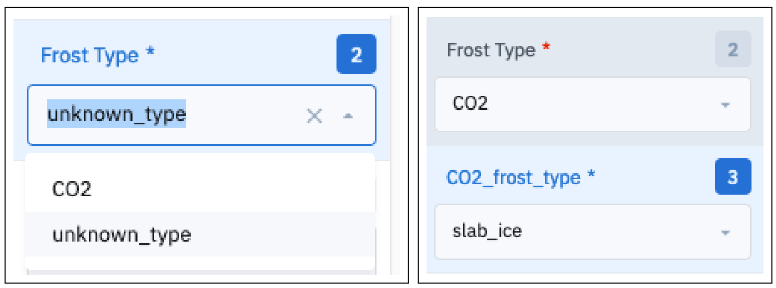

Figure 24: Selecting a frost type (unknown versus CO_2 slab ice).

4.5 Select frost type

It is nearly impossible to conclusively determine frost type (CO_2 versus H_2O) from visible images alone. However, two visible markers indicate that enough CO_2 frost has accumulated to develop a "slab ice" layer that is brittle enough to crack or form sublimation spots. The appearance of slab ice with diagnostic cracks is shown in Figure 7, and with uneven defrosting patterns is shown in Figure 8.

Therefore, if slab ice is visible, select the CO_2 frost type and slab ice subtype (Figure 24, right). Otherwise, select the "unknown" frost type option (Figure 24, left).

4.6 Select frost confidence

As described in Section 2, specific frost indicators may be associated with frost identification in weak, medium, or strong ways. The strength of association is considered in the confidence for an assessment of frost presence. Table 1 provides a rough summary of how much each type of indicator (considered in isolation) can be treated as an indication of frost. However, this is guidance only, as a particular indicator might be more or less apparent in some situations versus others. Alternatively, additional contextual information can further inform a confidence estimation.

Indicator	Uniform Albedo	Polygonal Cracks	Halos	Slab Ice Cracks	Defrosting Marks
Strength	Weak	Weak	Medium	Medium	Strong

Table 1: Strength of the association of Visible Indicators that contribute to overall frost confidence assessment.

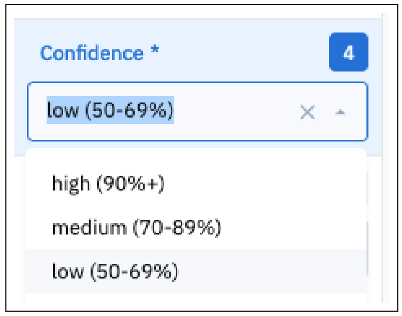

Figure 25: Selecting frost confidence

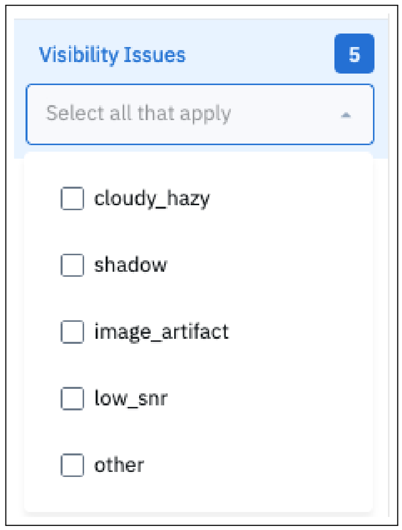

Figure 26: Selecting visibility issues (if any)

Confidence in the identification of frost is assigned to each frost polygon, as shown in Figure 25. Within the polygon, the full set of indicators should be used to determine confidence. If only a single weak indicator is present, this would correspond to a low confidence assessment. If several weak indicators or a medium indicator is present, then this would correspond to medium confidence. If a strong indicator or several medium indicators are present, then this would produce a high confidence assessment (e.g., defrosting spots in one part of a region with uniform albedo increases confidence that the whole bright area is frost). In some cases, the strength of an indicator also depends on geologic context. For example, if the geologic context is known to have varying albedo, such as in a field of dunes (which are predominantly dark basalt), then the uniform albedo indicator would be a medium or strong indicator.

4.7 Select visibility issues (if any)

If your confidence assessment is Medium or Low (not High) due to difficulty in confidently assessing the frost indicators, please select any relevant visibility issues (see Figure 26):

- **cloudy_hazy**: surface details are blurry and could be caused by intervening cloud or dust
- **shadow**: surface details are hard to determine because the polygon region is shadowed
- **image_artifact**: image quality is low due to an artifact that extends across the polygon region, such as striping, stippling, or missing data; if a small artifact may be present within a larger region, it is fine to mark the entire region

- **low_snr**: image quality is low due to lack of instrument sensitivity, which could manifest as an artificial lack of contrast with highly pixelated areas
- **other**: surface visibility is low due to another cause not captured in the options above

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