RESEARCH ARTICLE

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Key Points:

- The excess ice boundary in the southern hemisphere of Mars is poorly constrained due to direct observational limits
- The distribution of sublimation thermokarst (expanded craters and scalloped depressions) is used to infer the presence of excess ice
- We find evidence for abundant ice up to ~45 degrees south and lower-latitude localized deposits, consistent with a higher relative humidity

Supporting Information:

- Supporting Information S1

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Geomorphological Evidence for Shallow Ice in the Southern Hemisphere of Mars

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Abstract The localized loss of near-surface excess ice on Mars by sublimation (and perhaps melting) can produce thermokarstic collapse features such as expanded craters and scalloped depressions, which can be indicators of the preservation of shallow ice. We demonstrate this by identifying High Resolution Imaging Science Experiment images containing expanded craters south of Arcadia Planitia (25–40°N) and observe a spatial correlation between regions with thermokarst and the lowest-latitude ice-exposing impact craters identified to date. In addition to widespread thermokarst north of ~35°N, we observe localized thermokarst features that we interpret as patchy ice as far south as 25°N. Few ice-exposing craters have been identified in the southern hemisphere of Mars since they are easier to find in dusty, high-albedo regions, but the relationship among expanded craters, ice-exposing impacts, and the predicted ice table boundary in Arcadia Planitia allows us to extend this thermokarst survey into the southern midlatitudes (30–60°S) to infer the presence of ice today. Our observations suggest that the southern hemisphere excess ice boundary lies at ~45°S regionally. At lower latitudes, some isolated terrains (e.g., crater fill and pole-facing slopes) also contain thermokarst, suggesting local ice preservation. We look for spatial relationships between our results and surface properties (e.g., slope and neutron spectrometer water ice concentration) and ice table models to understand the observed ice distribution. Our results show trends with thermal inertia and dust cover and are broadly consistent with ice deposition during a period with a higher relative humidity than today. Shallow, lower-latitude ice deposits are of interest for future exploration.

1. Introduction

Widespread ice is present in the subsurface of the Martian middle to high latitudes. While some is restricted to the available pore space within the regolith (termed “pore-filling ice”), excess ice exceeds that pore volume and is often remarkably clean, with a small fraction (<1%) of lithics (Dundas & Byrne, 2010). This clean ice is most directly explained by atmospheric deposition in the form of snowfall (Head et al., 2003), although other hypotheses include ice lenses (Sizemore et al., 2015) and thermal crack-driven diffusive water migration (Fisher, 2005). Understanding the distribution of excess water ice is valuable for its implications on the past climate history of Mars and for in situ resource utilization (ISRU) in future human exploration. However, the southern hemisphere ice boundary is poorly constrained due to resolution limits and observational biases.

Some of the earliest indications of geologically recent Martian ground ice come from Viking orbiter observations, including geomorphic features such as lobate debris aprons (LDAs) and concentric crater fill (CCF) (Squyres & Carr, 1986). LDAs are accumulations at the base of steep slopes with rounded edges and lineations that suggest flowing material (e.g., Squyres, 1978). CCF, confined to crater interiors, shows lineations similar to LDAs and likely forms by a similar process (Squyres & Carr, 1986). Lineated valley fill (LVF) is a similar feature found in valleys (Squyres, 1979). The geographic distribution of these features, concentrated between 30 and 55° in both hemispheres (Squyres & Carr, 1986), has been well documented (e.g., Souness et al., 2012; Squyres, 1979), although present-day ice persistence and depth were not determined by these studies.

The Mars Odyssey Gamma Ray (GRS) and Neutron Spectrometer (MONS) revealed high hydrogen content in the uppermost meter of the Martian regolith at high latitudes (Boynton et al., 2002; Feldman et al., 2004). While this signature could be related to the presence of hydrated minerals, hydrogen at high latitudes is more likely in the form of water ice poleward of ±60° (Feldman et al., 2004) and perhaps at lower latitudes (Feldman et al., 2011). MONS data are very low resolution, with measurements spanning hundreds of kilometers, so it only captures broad trends in hydrogen content. Recent work states that this resolution can be improved ~2

times via data reprocessing (Wilson et al., 2018). The Shallow Radar (SHARAD) instrument on the Mars Reconnaissance Orbiter (MRO) has detected reflections consistent with the base of excess ice in broad regions of the northern plains at depths of approximately tens of meters (Bramson et al., 2015; Stuurman et al., 2016) and associated with LDAs in both hemispheres (Holt et al., 2008; Plaut et al., 2009). However, SHARAD cannot resolve ice that is shallower than ~10 m and topography can produce clutter in radar data (Seu et al., 2007), which may obscure deeper subsurface reflections in the rugged Southern Highlands terrain.

Polygonal patterned ground, commonly observed at middle to high latitudes on Mars (e.g., Malin & Edgett, 2001; Mangold, 2005), is thought to result from seasonal thermal contraction processes. Levy et al. (2009) found that polygon morphologies appear to be latitude dependent, and most are consistent with thermal contraction and differential sublimation. The distribution of polygonal patterned ground generally coincides with the MONS detections of shallow ice (Mangold, 2005) and is commonly found (Levy et al., 2009) within the latitude-dependent mantle deposits that are thought to have been deposited during high obliquity climate cycles on Mars (Mustard et al., 2001).

Some recent middle- to high-latitude impact craters have exposed shallow, bright material that fades over timescales consistent with the sublimation of water ice, and the largest bright areas contain clear H₂O ice spectra (Byrne et al., 2009; Dundas et al., 2014) in data from the Compact Reconnaissance Imaging Spectrometer for Mars (Murchie et al., 2007). Many ice-exposing impacts have been found in the northern hemisphere at latitudes as low as 39°N (Dundas et al., 2014), extending farther equatorward than the limits of high water-equivalent hydrogen (Feldman et al., 2004). However, due to an observational bias where new impact events are more easily discovered in dustier, high-albedo regions (Daubar et al., 2013), few ice-exposing impacts have been identified in the southern hemisphere of Mars; in addition to the two reported in Dundas et al. (2014), four more icy craters have been observed (65°S, 329.8°E; 62.5°S, 76°E; 58.5°S, 207.3°E; and 57.4°S, 125.2°E), all poleward of 55°S. However, it is plausible that the southern hemisphere ice table boundary lies closer to the equator than suggested by these impacts, as predicted by several models (e.g., Chamberlain & Boynton, 2007; Mellon et al., 2004). Locating the ice table boundary provides a test of these different model results. Here we will infer the southern hemisphere ice table boundary by mapping the distribution of thermokarst as a geomorphic indicator of present-day excess ice.

Terrestrial thermokarst is associated with melting of water ice to produce surface collapse features. Some studies have suggested that localized, transient melting may occur on Mars (Chevrier & Rivera-Valentin, 2012; Hecht, 2002; Richardsom & Mlschna, 2005; Stillman et al., 2014). However, it has been difficult to model such melting during Amazonian climates (Mellon & Phillips, 2001), largely dominated by cold, hyperarid conditions (Marchant & Head, 2007). Small amounts of episodic subsurface melt and drainage may contribute to thermokarst formation, where Costard et al. (2016) argue that melt is plausible at depths of ≤150 m. Alternatively, similar features can be produced when excess ice that is exposed or destabilized near the surface sublimates, leading to the collapse of the overlying dry regolith (Dundas et al., 2015). Regardless of whether sublimation or melting was involved, thermokarstic features require the loss of excess ice (Dundas et al., 2015); the removal of pore-filling ice would leave behind regolith grains and maintain the original surface. Two examples of Martian thermokarst are expanded craters (Figure 1a) (Viola, McEwen, Dundas, & Byrne, 2015) and scalloped depressions (Figure 1d) (Costard & Kargel, 1995; Lefort et al., 2009; Sejourne et al., 2011). A key advantage of these features is that their presence indicates not only that excess ice was there at the time of formation but also that ice must remain preserved today in order to maintain the terrain immediately surrounding them, as the widespread loss of this near-surface excess ice layer would destroy thermokarstic morphologies (Dundas et al., 2015). Since thermokarst features tend to be small, we use images from MRO's High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007) to identify their locations and infer the presence of modern excess ice. We also explore spatial relationships between thermokarst and small pedestal craters, whose ejecta is thought to protect underlying ice from subliming (Kadish et al., 2008; Nunes et al., 2011).

1.1. Expanded Craters

"Expanded" craters are impact features that show evidence for thermokarstic diameter expansion, lacking distinct crater rims/ejecta with a central bowl surrounded by a shallow extension to the surface (Figure 1a). These craters have been observed extensively in/around Arcadia Planitia, where they are thought to be mostly secondary craters by origin and tend to be <500 m in diameter, with depth-to-diameter ratios of

Figure 1. Examples of thermokarst features. (a) Expanded craters in HiRISE image ESP_041304_1320. (b) Slope-isolated expanded craters in ESP_027189_1320 (located on a pole-facing 6.7° slope, estimated from MOLA data, where the top of the image is upslope). (c) Infilling material of a 5.7 km diameter crater containing expanded craters in PSP_003939_1429. (d) Scalped depressions from the Amphitrites Patera region, ESP_041973_1220. (e) Pedestal crater, ESP_024290_1215. (f) Scallop at the edge of the pedestal (inset) in Figure 1e.

~0.035 (Viola, McEwen, Dundas, & Byrne, 2015). Thermal and landscape evolution models have demonstrated that impacts into a relatively pure ice layer evolve via sublimation, becoming wider and shallower, with elevation profiles consistent with Martian expanded craters (models of impacts into pore-filling ice do not show this evolution) (Dundas et al., 2015).

1.2. Scalloped Depressions

Scalloped depressions, or scallops, are rimless, ovoid depressions with shallow equator-facing slopes and steeper pole-facing scarps, ranging in diameter from a few hundred meters to ~3 km (Figure 1d; Lefort et al., 2009; Morgenstern et al., 2007; Sejourne et al., 2011). Formation mechanisms involving meltwater have been proposed, including alas-type lakes (Costard & Kargel, 1995; Soare et al., 2008) and subsurface melt/drainage (Costard et al., 2016). Asymmetric sublimation driven by local heterogeneities has also been argued as a formation mechanism (Lefort et al., 2009; Sejourne et al., 2011), demonstrated by models showing scallop growth through sublimation processes alone (Dundas et al., 2015). Previous studies found scalloped terrains in Utopia Planitia (Lefort et al., 2009), south of Hellas Basin (Malea Planum, Amphitrites, and Peneus Paterae) (Lefort et al., 2010; Zanetti et al., 2010), near Argyre Basin (Soare et al., 2017; Zanetti et al., 2010), and in Acidalia Planitia (Ramsdale et al., 2017).

1.3. Pedestal Craters

Some craters at middle to high latitudes have a sharp scarp at the edge of their ejecta and are called “pedestal” craters (Figure 1e). Although eolian erosion has been proposed for their formation (Arvidson et al., 1976), the recently favored hypothesis is that pedestal craters result from an impact into an ice-rich material in a region that subsequently experiences a climate shift. The crater ejecta helps to protect the ice beneath it, slowing sublimation, while ice loss deflates the surroundings and leaves the crater and ejecta elevated above the adjacent plains. Some pedestals are associated with marginal sublimation pits (Kadish et al., 2008), supporting the hypothesis that they represent local regions of ice preservation and can act as indicators of past ice-rich layers (Nunes et al., 2011). Previous studies have found that pedestal craters ($D > 0.7$ km) are concentrated poleward of both 33°N and 40°S with some equatorial exceptions (Kadish et al., 2009). Crater retention ages suggest that frequent ice accumulations have occurred over the past 200 Myr (Kadish & Head, 2014).

2. Methods

In order to understand the modern distribution of excess ice in the Martian subsurface, we surveyed HiRISE images that were classified as “complete” (without gaps from data loss during telemetry) to look for expanded craters, scallops, and pedestal craters. All images containing one or more suspected instances of thermokarst were flagged during analysis. A classification scheme was devised over the course of image analysis when it was noted that certain terrains (crater floors/infill, mantled material/elevated mesas, low-lying smooth terrains, and glacial-like forms) tended to contain expanded craters, particularly in lower-latitude regions and in images containing more geologic diversity. It was also noted that pole-facing slopes (as identified from visual interpretation due to the lack of high-resolution topography data) also tended to preserve expanded craters. Scalloped depressions are also occasionally limited to particular terrains, such as pole-facing scarps and the margins of pedestal craters (Figure 1f). A second pass was performed for flagged images, where ambiguous detections were removed from the data set and thermokarst classifications were assigned as “widespread” (found throughout the image), terrain isolated, or slope isolated.

The identification of images containing thermokarstic features will allow for a potentially more accurate quantification of the latitudinal limits and longitudinal variations of the southern hemisphere ice boundary. Although HiRISE images only cover a small, nonrandom fraction of the planet’s total surface area (e.g., Figure 2), this data set has several advantages. Since thermokarstic features are relatively small, high resolution (< 1 m/pixel for HiRISE) is ideal for identifying them. Furthermore, $> 50,000$ HiRISE images have been collected and sample a wide variety of terrains. This survey is also sensitive to smaller pedestal craters than previous studies (Kadish et al., 2009; Robbins & Hynek, 2012), and although it lacks the spatial coverage to provide a comprehensive distribution map of small pedestals, we document trends between the presence of pedestal craters and thermokarst.

We surveyed images in two geographic regions: (1) south of Arcadia Planitia (section 3), where expanded craters and the lowest-latitude ice-exposing impact craters have been observed, and (2) the southern midlatitude band of Mars, in order to place observational constraints on the distribution of excess ice in the southern hemisphere today (section 4). Throughout this study, an image’s lack of thermokarstic features is not conclusively indicative of a lack of excess ice, since it may reflect the absence of an appropriate

Figure 2. Hot spot analysis of all HiRISE images surveyed in (a) Arcadia Planitia and (b) the southern midlatitudes with grid areas of $\sim 10^4$ km² using a fixed distance band of 260 km in Figure 2a and 780 km in Figure 2b. The basemap for each subfigure is the Mars Orbiter Laser Altimeter (MOLA) shaded relief map (Smith et al., 2003). Inset at top left shows the geographic locations of Figures 2a and 2b.

initiating mechanism for ablation to take place. Nevertheless, since thermokarst requires excess ice at the time of formation that persists over time to preserve these morphologies, their present-day distribution should provide an approximation of the modern-day excess ice boundary.

2.1. Spatial Statistics

For each region of interest, spatial statistics are calculated using several ArcGIS tools (the full sequence is shown in Figure S1 in the supporting information, and more details can be found in Bennet et al., 2015). This survey treats HiRISE image data as incident points, where each feature is either present or absent. Since the distribution of HiRISE images is nonrandom, incident image data were aggregated into grid polygons and normalized relative to the number of images per grid square. To minimize distortion errors, we used a cylindrical equal area projection centered at the middle latitude of each region of interest (45°S for the southern midlatitudes) such that each grid space covers the same spatial area. The spatial join and summarize functions were used to collect the total number of images (and the total number of images with each class of features) for each grid polygon. The incremental spatial autocorrelation function, which determines the distances at which spatial clustering is the most prominent, was used to identify appropriate fixed distance band lengths for use in statistical analyses. Fixed distance bands create a sphere of influence around each grid space and analyze the features within the context of their neighbors. These distances were used as input for the hot spot analysis function for both aggregated incident data (number of images with features of interest per grid square) and normalized data (the number of images with features of interest divided by the total number of images found in each grid square). We also conducted a hot spot analysis on the total number of HiRISE images within each grid space in each region of interest to demonstrate the heterogeneity of this data set (Figure 2). Hot spot analysis uses the Getis-Ord local statistic (G_i^*) to produce a gridded heat map showing confidence ranges for both hot and cold spots within the aggregated data. The G_i^* statistic, discussed in more detail in the supporting information and Hepple (1996), returns a z-score (standard deviation) and a p value (probability) for each grid square based on the clustering of high or low values. Statistically significant hot spots are grid spaces with high values (larger numbers of images with each feature of interest) that are surrounded by grid spaces with high values. Cold spots represent clusters of low-value grid spaces, containing fewer features of interest than expected. Grid spaces that are not statistically significant represent regions where the number of features of interest is consistent with a random distribution.

Figure 3. HiRISE images containing thermokarstic features south of Arcadia Planitia, overlain on the Skinner et al. (2006) geologic map. Points represent HiRISE images with widespread expanded craters (white), terrain-isolated expanded craters (blue), and without thermokarst (black). Stars = ice-exposing recent impact craters; X = pedestal crater. Larger geologic units are defined as follows (Skinner et al., 2006): Aa1–5 = Arcadia Formation members; Hal = Alba Patera Formation, lower member; Aoa1–4 = Olympus Mons Formation, aureole members; Nf = highly deformed/older fractured material; Hr = ridged plains material; Npl2 = plateau sequence, subdued crater unit; HNu = undivided material.

2.2. Comparison to Surface Properties

For the southern midlatitudes, we compared our results to a range of surface properties to establish whether there are relationships between the presence of expanded craters and Mars Orbiter Laser Altimeter (MOLA) slope, Thermal Emission Spectrometer (TES) day and night thermal inertia (Putzig & Mellon, 2007), dust cover index (DCI; Ruff & Christensen, 2002), and GRS water concentration (Feldman et al., 2004) (section 4.4). MOLA slopes were calculated using the ArcGIS slope function, using gridded elevation data with a cylindrical equal area projection centered at 45°S to minimize distortions. Mean values for each property of interest were extracted over the area of each HiRISE footprint using the ArcGIS zonal statistics function. After correcting for null values where these data sets do not intersect with HiRISE images, we collected statistics on the distribution of each property and conducted a Kolmogorov-Smirnov two-sample test (Massey, 1951) to determine whether the value distributions for each category of expanded craters differ from the overall value distribution for both all HiRISE images surveyed and HiRISE images without expanded craters. The advantage of using this Kolmogorov-Smirnov (K-S) test is that it allows for the direct comparison between sample distributions without assuming a normal distribution. Finally, we compared our results to a range of ice table models to understand the modern distribution of ice that we observe (section 4.5).

3. South of Arcadia Planitia: Results and Discussion

The lowest-latitude ice-exposing impact crater identified on Mars is at ~39°N in Arcadia Planitia, a region that is of potential interest for human exploration (Viola, McEwen, & Dundas, 2015). In order to demonstrate the viability of a thermokarst survey to infer the presence of ice, we first analyzed HiRISE images between 25–40°N and 180–240°E, including the southernmost part of Arcadia Planitia, Amazonis Planitia, and several volcanic units north of Olympus Mons and west of Alba Patera, to determine whether the presence of thermokarst is correlated to ice-exposing impact craters. There were ~500 complete HiRISE images within this range, although ~200 were eliminated as redundant due to overlaps (including stereo and seasonal observations) and geographic similarities. Figure 3 shows the results of this survey, where 87 images contained expanded craters, one contained a small pedestal crater, and no scalloped depressions were observed. Although low-latitude expanded craters were identified, we noted that those equatorward of ~35°N were generally isolated to crater infill material and smooth terrains adjacent to mesas and are largely found in locally elevated units in Acheron Fossae and Lycus Sulci. Although the lack of expanded craters is not necessarily indicative of a lack of excess ice, the consistent isolation of thermokarst to specific geologic settings

Figure 4. Hot spot analysis of HiRISE images containing expanded craters for (a) the overall data set using a fixed distance band of 340 km and (b) normalized to the number of HiRISE images per grid space using a fixed distance band of 365 km (empty grids contain no HiRISE images). Figure 4b also contains boundaries around statistically significant thermokarst hot spot regions (teal, with 90% confidence, and purple, with 99% confidence). Grid spaces cover an area of $9,810 \pm 16 \text{ km}^2$. Basemap is the MOLA shaded relief map.

across many HiRISE images suggests the presence of patchy ice. These locations may have experienced depositional or modification histories that are conducive to longer-term ice preservation and/or represent regions where snow can accumulate during high obliquity climate cycles (e.g., Forget et al., 2006; Schorghofer, 2007). Above $\sim 37^\circ\text{N}$, expanded craters tend to be more ubiquitous, suggesting that the continuous ice table boundary is near this latitude. There is also some apparent geologic control over the presence of excess ice: abundant expanded craters are largely concentrated in low-lying Arcadia Units 4–5 (interpreted as Amazonian-aged lava flows) from the Skinner et al. (2006) geologic map (Figure 3).

We conduct a statistical analysis on the distribution of all expanded craters and terrain-isolated expanded craters. Using gridded polygons with an area of $9,810 \pm 16 \text{ km}^2$, we find that each grid space contains 0–7 HiRISE images. Images in this area have a more uniform distribution than in the southern midlatitudes (Figure 2), with only a moderately sized hot spot in the northwestern corner. Figure 4 shows the results of the hot spot analysis for abundant expanded craters using a fixed distance band length of 340 km and a normalization using a fixed band length of 365 km. There is a significant hot spot between ~ 190 and 210°E , extending down to a latitude near the 35°N grid space, as well as a significant cold spot along the southernmost latitudes of the study area and including the edge of the Olympus Mons/Alba Patera volcanic units in the normalized data set. Although terrain-isolated expanded craters are present in this region, incremental spatial autocorrelation failed to identify any statistically significant clustering length scale. It is notable that the hot spot in Figure 4 includes the locations of the two lowest-latitude icy craters and is comparable in extent to the lowest latitude SHARAD reflectors identified by Bramson et al. (2015) (which reach as far south as 38°N between 190 and 210°E). These spatial correlations further support our argument that thermokarstic features are a viable indicator of shallow excess ice.

Scalloped depressions were not found in this study area, agreeing with previous studies in the northern hemisphere of Mars which only identified scallops at higher latitudes, largely in Utopia Planitia (centered at $\sim 47^\circ\text{N}$, 118°E) (e.g., Costard & Kargel, 1995; Morgenstern et al., 2007), although some were observed in Arcadia Planitia at $\sim 50^\circ\text{N}$ (Ramsdale et al., 2017). Since thermokarstically expanded and ice-exposing craters both indicate the presence of excess ice, the lack of scallops could be due to differences in the mechanisms and conditions required for their formation. If small topographic disturbances drive scallop growth via asymmetric sublimation, differences in the initial topography between Arcadia Planitia and Utopia Planitia may explain the lack of scallops in the former. There are also many boulders in Utopia Planitia ($\leq 4 \text{ m}$ in size; Lefort et al., 2009), and it is possible that preferential warming of surface boulders could play a role in the local destabilization of shallow ice, initiating scallop formation. Differences in ice characteristics could also plausibly drive variations in the regions where different thermokarst features form, although the dielectric constants of the Arcadia and Utopia Planitiae ice deposits are roughly similar (2.5 and 2.8, respectively), indicating reasonably pure ice with some degree of porosity (Bramson et al., 2015; Stuurman et al., 2016).

Figure 5. Southern midlatitudes of Mars. Panels show the geographic distribution of (a) all surveyed HiRISE images and ice-exposing impact craters; (b) images with expanded craters (white points), including examples of slope-isolated (light blue points) and terrain-isolated (dark blue points) settings; (c) images containing scalloped depressions (white points), including those that are isolated to particular terrains (blue points), overlain on the results of Zanetti et al. (2010), where gray represents HRSC regions that they surveyed and black regions are those that contained scalloped depressions; and (d) pedestal craters identified in this survey (dark blue points) and in Robbins and Hynek (2012) (light blue points). All parts are displayed using a polar stereographic projection (centered on the south pole), overlain on the MOLA shaded relief map.

Only a single, small pedestal crater ($D \sim 170$ m, near 39°N) was identified in this region (Figure 3), within the Aa2 geologic unit that lacks thermokarst features. Although HiRISE is not the ideal data set for identifying pedestal craters, this observation agrees with previous work showing that this area is devoid of pedestal craters (Kadish et al., 2009). A lack of pedestal craters is consistent with the tens of millions of years minimum age estimates of the Arcadia Planitia excess ice deposit (Viola, McEwen, Dundas, & Byrne, 2015), where regions containing expanded craters should not have experienced the widespread ice loss required for pedestal crater formation.

We use the results of our statistical analysis to approximate the ice table boundary in Arcadia Planitia (Figure 4) and compare it to different ice table models in section 4.5. The spatial correspondence between the distributions of expanded craters, ice-exposing impacts, and SHARAD reflections thought to result from excess ice supports our hypothesis that the presence of thermokarst landforms can provide a

Figure 6. Hot spot analysis of expanded craters (where each grid space has an area of $9,660 \pm 30 \text{ km}^2$, using a fixed band length of 590 km), overlain on the MOLA hillshade. The same overall trends are apparent in both (a) the incident analysis and (b) after normalizing for the total number of images per grid space. Boundaries are traced around hot spots of 90% (teal) and 99% (purple) confidence, where dashed lines represent equatorial limits in longitude ranges that did not contain statistically significant hot spots.

reasonable estimate of the modern-day ice table boundary on Mars. Therefore, we extend this survey into the southern midlatitudes.

4. Southern Midlatitudes: Results and Discussion

Over 6,000 complete HiRISE images were identified between 30 and 60°S, and ~4,000 were analyzed for thermokarst after accounting for overlapping observations. Figure 5a shows the overall distribution of images analyzed and the locations of ice-exposing impact craters, and Figures 5b–5d show the locations of images that contain thermokarstic features and pedestal craters. We identify nearly 700 images containing expanded craters (267 where they are abundant, 187 limited to pole-facing slopes, and 228 in localized settings within images). Not all HiRISE images target terrains that are conducive to the presence of shallow ice and therefore thermokarst landforms (e.g., large dune fields or bedrock exposures). While those images were still analyzed in this survey, the complex geologic history of the southern midlatitudes leads to small-scale variations in surface morphologies and, probably, in shallow ice content. It is therefore plausible that there are ice-free regions poleward (and/or ice-rich regions equatorward) of the estimated excess ice boundary discussed here, so we offer these latitudinal limits and longitudinal variations of shallow excess ice as estimates alone.

4.1. Distribution of Expanded Craters

Expanded craters can be found over a range of latitudes (Figure 5b). Similar to south of Arcadia Planitia, they tend to be isolated to particular terrains in the more equatorward images, including crater infill, glacial-like features, and remnant smooth mantle material, suggesting the possibility of patchy excess ice at latitudes approaching 30°S. Poleward of ~50°S, expanded crater-bearing terrains become more common (white points in Figure 5b), often associated with polygonal patterned ground. We also observe images containing expanded craters isolated to pole-facing slopes, a pattern that was not evident in southern Arcadia Planitia, which has less topographic variation overall. Figure 5b shows that images containing slope-isolated expanded craters extend close to 40°S, ~10° more equatorward than those with abundant expanded craters (which are found on a range of slope aspects). This observation is unsurprising since pole-facing slopes are colder (Malin & Edgett, 2000) and therefore may be able to prolong the preservation of ice at lower latitudes.

Spatial statistics were calculated for the distribution of images containing expanded craters and slope- and terrain-isolated expanded craters. Figure 6 shows the heat map for all images containing expanded craters

Figure 7. Heat map for slope-isolated expanded craters for (a) the overall data set (fixed band length = 300 km) and (b) normalized over the number of images per grid (fixed band length = 495 km). Basemap is the MOLA hillshade.

and a normalization over all images found in each grid space using a fixed band length of 590 km. Similar trends are observed in both heat maps. Expanded crater “hot spots” are largely concentrated poleward of 45–50°S, with some longitudinal variations, suggesting the presence of excess ice in southern Hellas, Eridania, and Argyre Planitiae.

Figure 7 shows the hot spot analysis results for the distribution of slope-isolated expanded craters, using fixed distance band lengths of 300 km for the incident analysis (Figure 7a) and 495 km for the normalization (Figure 7b). Two hot spots emerge in the overall data (near Terra Sirenum and Eridania Planitia, Figure 7a), but since this trend disappears in the normalized data, we do not attribute any statistical significance to this observation.

Figure 8. Heat map of terrain-isolated expanded craters using a fixed band length of 495 km for (a) the overall data set and (b) normalized over the number of images per grid. Boundaries have been traced around statistically significant hot spots (as described in Figures 4 and 6) in Terra Sirenum and Cimberia. Basemap is the MOLA hillshade.

Terrain-isolated expanded craters also reveal a hot spot near eastern Terra Cimmeria and west-central Terra Sirenum in the overall data set at a fixed band length of 495 km (Figure 8a). These are regions with large concentrations of HiRISE images, and the hot spots shrink in the normalized data but remain statistically significant (Figure 8b).

The delineation of the excess ice boundary was inferred from the distribution of statistically significant regions of nonisolated expanded craters (derived from Figure 6), which extends equatorward to latitudes of 45°S in Hellas and Eridania Planitia and 47°S in Argyre Planitia. Trends for slope-isolated expanded craters appear to have less spatial significance (Figure 7), but a spatially significant hot spot for terrain-isolated expanded craters is noted in part of Terra Cimmeria and Terra Sirenum (Figure 8), where ~50 out of 290 images contained expanded craters (largely restricted to smooth/mantled regions).

4.2. Distribution of Scalloped Depressions

We identified 66 HiRISE images containing scalloped depressions, 42 where they are abundant and 24 where they are isolated to particular terrains (e.g., crater walls/rims, edges of mesas, and pedestal craters). The southern hemisphere distribution of scalloped depressions is largely consistent with previous observations using High Resolution Stereo Camera images (HRSC; Zanetti et al., 2010; Figure 5c), where they are ubiquitous south of Hellas Planitia. Our results show that scallops extend more equatorward along the western edge of Hellas Planitia and can be found in isolated terrains south of Argyre Basin and near Aonia Terra. While not all images with expanded craters contain scallops, most of the images containing scalloped depressions include expanded craters. However, there were too few images with scalloped depressions to provide statistically meaningful results using the methods described in section 2.1.

4.3. Distribution of Pedestal Craters

Many pedestal craters (>1.5 km) are included in Robbins and Hynek (2012) and have been mapped in other works (Kadish et al., 2008; >0.7 km). Figure 5d shows the distribution of HiRISE images containing pedestal craters ($N = 37$) identified in this survey, with diameters ranging from 0.2 to 4.1 km. The locations of pedestal craters from Robbins and Hynek (2012) are also shown in Figure 5d, which range in diameter from 1.65 to 23.8 km. Due to the lack of high-resolution topography, there is some uncertainty in the vertical dimensions of these features. However, most of the HiRISE images containing potential pedestal craters lack thermokarst (33 instances), with the exception of three with thermokarst features confined to the pedestal ejecta/margins and one with expanded craters both on the pedestal and in the surroundings, in a high-latitude location (58°S) where widespread ice is likely present. The presence of thermokarst on some pedestals and pedestal margins confirms that these features can preserve excess ice (Kadish et al., 2008). Furthermore, the overall lack of thermokarst features in the regions surrounding pedestal craters is consistent with, although not definitive proof of, a lack of excess ice, in accordance with the expectation that these regions have experienced widespread ice loss. Regions at similar latitudes with indications of modern ice must have retained the excess ice into which the thermokarst features formed.

4.4. Trends With Surface Properties

We looked for relationships between expanded craters and several surface properties: thermal inertia (TI) from the Thermal Emission Spectrometer (TES) (Putzig & Mellon, 2007), dust cover index (DCI) (Ruff & Christensen, 2002), GRS water concentration (Feldman et al., 2004), and slopes derived from MOLA elevation, using a Kolmogorov-Smirnov test. This test returns the K-S statistic and p values for each comparison analyzed, where p is the probability that the null hypothesis (the two distributions being compared are the same) is true. The results of this analysis are shown in Table S1, where boxes highlighted in green have $p < 0.01$, interpreted as statistically significant distribution differences.

While there is no significant difference between the values for all HiRISE images surveyed and those images that lack expanded craters (gray column in Table S1), some statistically significant trends emerged for comparisons to images containing expanded craters (Table S1). Slope-isolated expanded craters tend to be found in images with greater overall MOLA slopes averaged over the image area (Figure 9a), with a mean slope of 5.7° (median = 5.3°) compared to a mean slope of 3.8° (median = 2.7°) for images without expanded craters. Images with expanded craters tend to have slightly lower thermal inertia values than all images surveyed in both day and night TI. Figure 9b compares the distribution of mean TES night TI for images with expanded craters (mean = 237 and median = 232) and all images surveyed (mean = 250 and median = 242).

Figure 9. Histograms showing the value distributions of (a) mean MOLA slopes, (b) TES night TI, (c) DCI, and (d) GRS water concentration, comparing the distribution of all images surveyed (red) with images containing slope-isolated expanded craters (Figure 9a) and abundant expanded craters (blue) (Figures 9b–9d). Purple represents distribution overlap.

Consistent with lower TI values, images containing expanded craters have DCI values that are statistically significantly lower (mean = 0.9664 and median = 0.9668) than all HiRISE images surveyed (mean = 0.9683 and median = 0.9697). The distribution of DCI values for all images has a more prominent peak near 0.97, whereas the values for images with expanded craters have a broader distribution (Figure 9c). Lower DCI values represent more dust cover, although this region is still less dusty than the northern plains (values in Arcadia Planitia are typically between 0.92 and 0.94; Ruff & Christensen, 2002). More than half of the higher-latitude images containing expanded craters did not intersect with the water concentration data from Feldman et al. (2004). However, the H₂O concentration distribution for those that did intersect has slightly higher values (mean = 3.42 and median = 3.41) than the distribution for all HiRISE images surveyed (mean = 3.21 and median = 3.24) (Figure 9d).

4.5. Comparison to Ice Table Models

We also compared our results to several ice table models. Figure 10 shows comparisons with Mellon et al. (2004), Schorghofer and Aharonson (2005), and Aharonson and Schorghofer (2006). Figure 11 shows comparisons with Chamberlain and Boynton (2007).

Figure 10. Ice boundaries inferred from the normalized heat maps shown in Figures 4, 6, and 8 (dashed lines represent longitude ranges without statistically significant hotspots) superposed on the model results of (a) Mellon et al. (2004), with an atmospheric water vapor pressure of 20 pr μm , including the Feldman et al. (2004) MONS ice boundary (black line); (b) the modern equilibrium depth to ice from Schorghofer and Aharonson (2005), where ice was predicted to be unstable in white regions; and (c) Aharonson and Schorghofer (2006), accounting for MOLA slopes.

The Mellon et al. (2004) model does not explain the boundaries defined in Arcadia Planitia or Terra Cimmeria/Terra Sirenum (Figure 10a) from our data. However, our results for Arcadia Planitia are consistent with excess ice that was deposited during a climate period with ~ 50 pr μm atmospheric water abundance and/or an obliquity near $25\text{--}30^\circ$ (Figures 11b and 11d). For Terra Cimmeria and Sirenum, our observations are consistent with ice deposited when the planet's obliquity was $\sim 30^\circ$ (Figure 11d) and/or the regions have a low fraction of slope-stable ice ($\leq 1\%$, Figure 10c). It is plausible that ice in these areas was deposited at higher obliquity and only remains preserved in small regions where slopes support longer-term stability. Our results are inconsistent with the equilibrium ice table depth derived from Schorghofer and Aharonson (2005) (Figure 10b) and the modern ice table depth predicted by Chamberlain and Boynton (2007) (Figure 11a), which fail to explain the boundaries in Arcadia Planitia and Terra Cimmeria/Terra Sirenum. Schorghofer and Aharonson (2005) also have notable deviations from our results near Hellas and Eridania

Mellon et al. (2004) modeled the presence of ground ice under several atmospheric water vapor pressure conditions (1–100 precipitable micrometers (pr μm)) to explain the MONS data from Feldman et al. (2004) and predicted an atmospheric water column abundance of 10–20 pr μm . Figure 10a compares our results to their model at 20 pr μm , including the epithermal neutron boundary of 6 cm s^{-1} (black line), where ground ice is likely too deep for MONS to detect. We find that it is roughly consistent with the southern hemisphere boundaries from Figure 6, with some exceptions: (1) expanded craters in Argire Basin extend up to $\sim 47^\circ\text{S}$, approximately 10° equatorward from the MONS observations; (2) southeast of Hellas Basin, the ice boundary inferred from the neutron spectrometer is near 47°S , whereas expanded craters are $5\text{--}10^\circ$ further poleward, (although the absence of expanded craters does not necessarily indicate a lack of ice); and (3) smaller deviations ($\sim 3\text{--}5^\circ$ equatorward) from the MONS boundary between $185\text{--}216^\circ\text{E}$ and $148\text{--}176^\circ\text{E}$. Since the MONS data have a large geographic footprint, some of these variations can likely be explained by resolution differences. Schorghofer and Aharonson (2005) similarly model the distribution of ground ice expected to be in equilibrium under modern atmospheric conditions, reporting the depth to stable ice in g/cm^2 . Our results suggest ice at lower latitudes, where Schorghofer and Aharonson (2005) predicted ice to be unstable (Figure 10b).

Aharonson and Schorghofer (2006) modeled the effect of topography on ice stability, combining MOLA surface roughness with a slope-dependent model to predict the fraction of ice within the uppermost meter (“top meter filling fraction”). Figure 10c compares our data to their results. Our southern hemisphere boundary lies near the region where the model predicts that the top meter filling fraction transitions to values ≥ 0.2 (Aharonson & Schorghofer, 2006). This is consistent with the presence of excess ice (covered by some dry material), conducive to the formation and preservation of thermokarstic features.

Chamberlain and Boynton (2007) varied several parameters to determine their effect on ice table stability: (1) atmospheric water vapor, (2) perihelion position, and (3) obliquity (Figure 11). Our southern hemisphere ice table boundary is consistent with formation under conditions with a water column abundance of 10 pr μm (Figure 11b) or an obliquity of $\sim 20\text{--}25^\circ$ (Figure 11d) (Chamberlain & Boynton, 2007). Model predictions of the ice table boundary when Mars is at different perihelion positions ($L_s = 0^\circ, 90^\circ, 180^\circ$, and 270°) (Chamberlain & Boynton, 2007) generally lie nearer the equator than the boundary we observe, although the models do not reproduce the small-scale variations that are seen in our data (Figure 11d).

Figure 11. Ice table model results from Chamberlain and Boynton (2007) varying a range of atmospheric and orbital conditions, compared to the ice table boundaries we infer in Figures 4, 6, and 8. (a) Present-day ice stability depths and ice (b) table variations with different atmospheric water vapor from 1 to 100 pr μm . (c) Perihelion positions of L_s 0°, 90°, 180°, and 270° and (d) obliquity, from 10 to 40°. Colors in Figures 11a, 11b, and 11d represent the equatorward extent of ice stability under the conditions found in the associated color bars.

Planitia. Varying the perihelion position fails to describe Terrae Cimmeria and Sirenum, although a perihelion position between L_s 0 and 180° may help account for ice in Arcadia Planitia (Figure 11c).

5. Conclusions

As demonstrated in section 3, the presence of thermokarstic features can be correlated with the presence of clean subsurface ice as indicated by ice-exposing impacts in the northern hemisphere, with abundant features that indicate the presence of ice in Arcadia Planitia as far south as ~37°N. Therefore, we extend this survey into the southern midlatitudes to use the presence of thermokarst to infer subsurface ice where new impacts are not as easily observed. We find the presence of abundant thermokarst up to latitudes of ~45°S in some regions, roughly consistent with the MONS boundary defined by Feldman et al. (2004) and with the slope-derived ice stability model of Aharonson and Schorghofer (2006). Lower-latitude ice deposits, of interest for future human exploration, may be present in localized regions approaching 25°N and 30°S, likely containing less extensive excess ice than higher-latitude regions. However, due to the complex geologic history of the Southern Highlands, where not all terrains are conducive to the presence and preservation of ice, these observations only offer constraints on the distribution of excess ice. Therefore, particularly in regard to potential in situ resource utilization (ISRU), we recommend case-by-case, high-resolution studies of regions of interest using thermokarst as one indicator of the presence of excess ice.

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