NORTHERN MIDLATITUDE ICE EXPOSED IN CRATERS ON MARS

An Undergraduate Research Scholars Thesis

by

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RESEARCH COMPLIANCE CERTIFICATION

Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

I, Lucas Stanley, certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with my Research Faculty Advisors prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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Northern Midlatitude Ice Exposed in Craters on Mars

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Mars potentially contains a vast reservoir of buried water ice resources. Understanding the distribution and origins of these resources has become increasingly important due to the plans for a future manned mission to Mars. The northern mid latitude region of Mars is a prime candidate for future landing sites and has a widespread presence of ice. In this study, two northern mid latitude craters are analyzed; one of the craters has a confirmed ice exposing scarp, while the other does not. Analysis of temperature, thermal inertia, multispectral imaging, and geologic features have led to the conclusion that the non-confirmed crater does have ice exposing scarps. In depth multispectral imaging from the Compact Reconnaissance Imaging Spectrometer provides data for analysis that reveals exposed nearly pure water ice in Crater 1, and a mixture of water and carbon dioxide ice in Crater 2. Crater Size Frequency Distribution plots suggest that Crater 1 is about 100 million years old. This crater is interpreted to be much older due to active

resurfacing from sublimation thermokarst features. The subsurface ice layer is believed to be much older than the craters exposing it. It is likely that the ice sheets were initially deposited from ancient snow that compacted to form glaciers. Recent Mars axis changes in obliquity have led to modifications of the ice sheets both laterally and horizontally.

DEDICATION

To my professors who gave me unconditional help on this project

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NOMENCLATURE

BTR	Brightness Temperature Record
CO_2	Carbon Dioxide
CRISM	Compact Reconnaissance Imaging Spectrometer
CSFD	Crater Size Frequency Distribution
CTX	Context Camera
DLE	Double Layer Ejecta
HiRISE	High Resolution Imaging Science Experiment
ISRU	In-Situ Resource Utilization
JP2	JPEG2000
LDM	Latitude Dependent Mantle
MCS	Mars Climate Sounder
MOLA	Mars Orbital Laser Altimeter
MONS	Mars Odyssey Neutron Spectrometer
MRO	Mars Reconnaissance Orbiter
RDR	Reduced Data Records
RGB	Red Green Blue
TES	Thermal Emission Spectrometer
TUI	Thermal Inertia Unit
THEMIS	Thermal Emission Imaging System
WEH	Water Equivalent Hydrogen

1. INTRODUCTION

In the solar system, Mars is the fourth planet from the sun. Today it is characterized as a cold, dry planet that is tectonically inactive, although this has not always been the case. The surface of Mars hosts a variety of geologic features including mountains, volcanos, valleys, and even fluvial landforms. Mars' geologic history is described by three periods: the Noachian, Hesperian, and Amazonian. The Noachian Period exhibited valley formation, high cratering rates, and erosion from liquid water. At the end of this period, during the Hesperian, the rate of valley formations and impacts from craters were greatly reduced, yet active volcanism continued. At the end of the Hesperian Period and beginning of the Amazonian Period, Mars transitioned into the cold dry planet that is seen today (Carr & Head III, 2010). The most notable aspect of the Amazonian is the presence of ice. The movement of water and CO_2 ice has created many landforms during the Amazonian, including polar layered deposits, glacial deposits on volcanoes, ice rich veneers at high latitudes and many more. The exact processes and timing of the ice's deposition are still debated.

Contrary to the southern hemisphere, the northern plains of Mars are characterized by a low topography with smooth terrain. Data from the Mars Reconnaissance Orbiter Mission (MRO), Mars Odyssey Neutron Spectrometer (MONS) and the Phoenix mission have all identified the presence of water ice in the northern mid latitudes (Mellon et al., 2009; Sejourne et al., 2019; Wilson et al., 2018). The water ice in this region is typically buried in the subsurface. Its depth can range from a few centimeters to tens of meters (Piqueux et al., 2019). Water ice on Mars in the mid latitudes is likely synonymous to the water table of Earth, because it is distributed relatively evenly below the surface. As one gets closer to the equator, the top of the water ice table will become deeper and vis versa. This is because closer to the equator atmospheric conditions are less favorable for stable ice, therefore ice in lower latitudes is only present at greater depths.

The origins of the water ice is still under debate. Most research suggests that the initial ice deposition occurred due to snow precipitation, accumulation, and compaction; but the timing of this process is heavily debated. It is known that during periods of high obliquity snow fall accumulates in the mid latitudes and forms surface ice sheets (Madeleine et al., 2014). Crater observations in northern mid latitudes led by Fassett et al. (2014) conclude the water ice deposition occurred during an ice age in the middle to late Amazonian, caused by a period of increased obliquity. Mars' obliquity cycles are difficult to predict, making it hard to determine the timing of ice ages and origins of mid latitude ice. The recent ice age hypothesis is supported by data showing that mid latitude ice is not in equilibrium with the atmosphere (Head et al., 2003). The ice is actively retreating from mid latitudes and accumulating in the poles (Smith et al., 2016). However, Bramson et al. (2017) found that mid latitude ice sheets can be significantly older than the obliquity cycles that were anticipated to have led to the deposition of the ice sheets, even if the ice is actively retreating.

One way to understand the distribution and origins of the mid latitude water ice on Mars is through the analysis of craters that expose buried ice. Water ice in the northern mid latitudes is likely to stabilize in scarp associated polar and equatorial wall deposits within craters (Harish et al., 2020). Although equatorial facing scarps have been observed, most of the time they are polar facing and retreat towards the equator because of ice sublimation. They also have a slope greater than 40°, a distinct erosional pit, and are adjacent to Latitude Dependent Mantle (LDM) (Dundas et al., 2018). Erosional scarps exposing ice can be found between 50° and 61° latitude in both hemispheres and impact craters exposing subsurface ice have been found as low as 39° north (Dundas et al., 2021).

This paper analyzes ice exposing scarps in two craters of the northern mid latitudes of Mars. Physical and geologic properties of the ice exposing sites are recognized and could help aid in any future searches for ice exposing scarps. This paper also confirms (1) that an icy crater, located by Dundas et al. (2021), is exposing water ice, and (2) it recognizes a new ice exposing crater.

2. METHODS

Dozens of craters were analyzed over the course of this study with the JMars and HiView software. The craters were selected from recent publications or through manual searches (Dundas et al., 2014; Dundas et al., 2021; Harish et al., 2020). For this study, only two craters were focused on. Crater 1 was confirmed by Dundas et al. (2021) as ice exposing. Crater 2 was discovered through manual searches nearby Crater 1. These craters were selected for analysis because of their mid latitude location and scarp features.

The craters were first viewed by the Context Camera (CTX), which is a powerful camera located on the MRO. CTX views geologic features present in a given location. Data from the Mars Orbital Laser Spectrometer (MOLA) was used to create a broad overview of crater topography. To make more in depth observations, images from the High-Resolution Imaging Science Experiment (HiRISE) instrument were utilized. The HiRISE instrument operates in visible and near infrared wavelengths, allowing one to make observations about the minerals present. These images use a false coloring to depict the infrared wavelengths which are not visible to human eyes. The images are downloaded as Reduced Data Records (RDR), which compresses the image files that would normally be larger than a gigabyte into much smaller files that are much easier to work with. The RDR files come in a JPEG2000(JP2) format, which can be viewed at the full spatial scale using the HiView software. The RDR files come in several different formats. In this study the most useful format is Red Blue Green (RGB). Near infrared data is presented as red, red filter data is presented as green, and blue-green filtered data is presented as green. Each color band in the image is individually stretched to increase the contrast, which will change the image based on the colors and brightness of it. Generally, in the

RGB images, dust will be displayed as the reddest color, sand and rocks will have a dark blue color, and frost and ice will have a bright blue or white color. The most useful HiRISE images for this study are the ones taken in late Spring or Summer because they lack seasonal frost.

When available, Compact Reconnaissance Imaging Spectrometer (CRISM) data was utilized to interpret the composition of the ice. CRISM operates in visible and near infrared wavelengths. It can also provide greater observations of the mineral groups present in a scene than HiRISE. However, in depth CRISM observations were not available for the selected craters so revised spectral observations created by Viviano et al. (2014) were utilized. Thermal Emission Imaging System (THEMIS) Brightness Temperature Records (BTR) were observed in the late afternoon for Craters 1 and 2 to determine if seasonal frost is likely to accumulate on their surfaces. The Mars Global Surveyor Thermal Emission Spectrometer (TES) was utilized for thermal inertia analysis to further confirm the presence of ice.

With the crater counting feature from JMars, all craters superposing the ejecta of Crater 1 were measured and recorded. This data was later imported into the Craterstats 2.0 software to get an estimate of Crater 1's age using CSFD analysis.

3. RESULTS

3.1 Crater 1

Crater 1 is located 58.7° latitude and 244.5° longitude: it is a decent sized crater with a diameter of 19.3 Km (Figure 1.1). HiRISE images present two polar facing scarps on the Southern edge of the crater with coloration indicative of ice. There are several other scarps that can be seen in the RGB HiRISE image, although only two have the distinct blue coloration indicating exposed ice (Figure 1.2). BTR results show scarp temperatures well above the likely atmospheric frost point. CRISM analysis of this crater reveals a likely presence of water ice exposed by the scarps, rather than CO_2 ice (graph A1 and A2). The average thermal inertia values are above 200 TIU, yet there are three locations across Crater 1 with values of 170 TIU.

Several geologic features can be observed on and around this crater. The most important features are scalloped depressions, polygons, and scarp associated pits. In Figure A6 scalloped depressions located in the lowest elevation of Crater 1 can easily be seen. Directly in front of the two ice exposing scarps in Figure 1.2, polygonal features can be seen (Figure A7). The polygonal cracks are present in the scarp associated pits, but they are faint and cannot be found anywhere else on Crater 1. An example of an inactive scarp associated pit can be seen in Figure A8. It is a prime example because one can easily see how the scarp started off small and widened as it sublimated towards the equator.

Crater size frequency distribution plots were made based on the craters that superposed the ejecta of Crater 1 (Figure A9). This method predicts the crater is about 100 million years old (Figure 1.3).

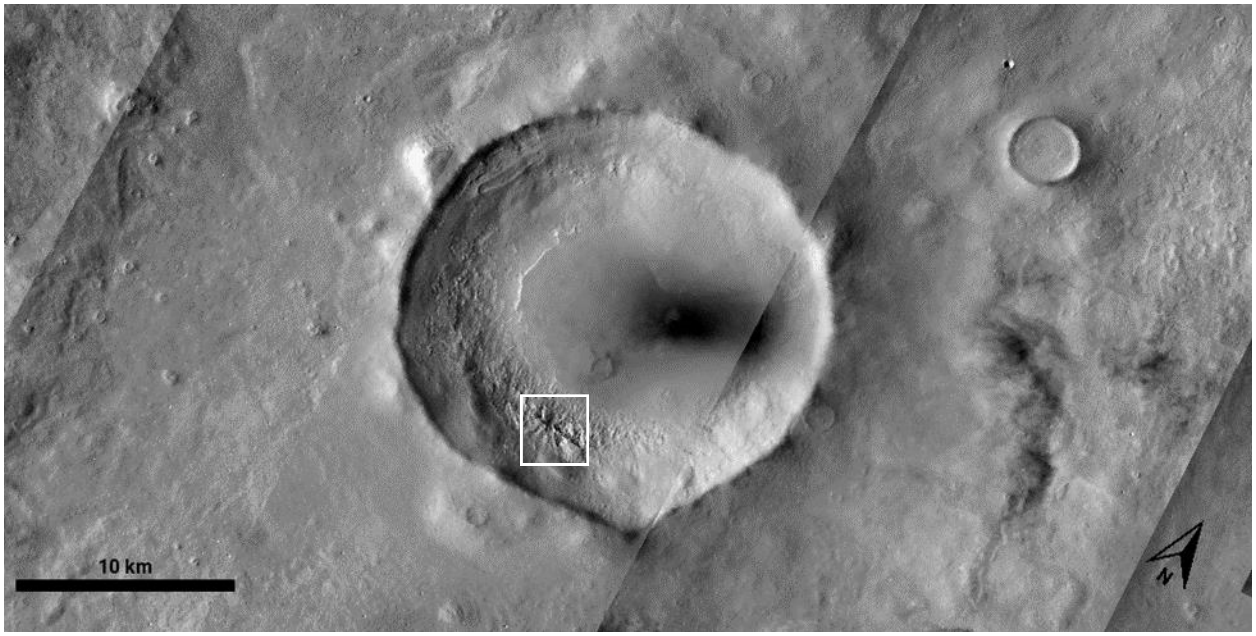

Figure 1.1: multiple CTX images are combined to depict the size and shape of crater 1. The white arrow indicates the ice exposing scarp.

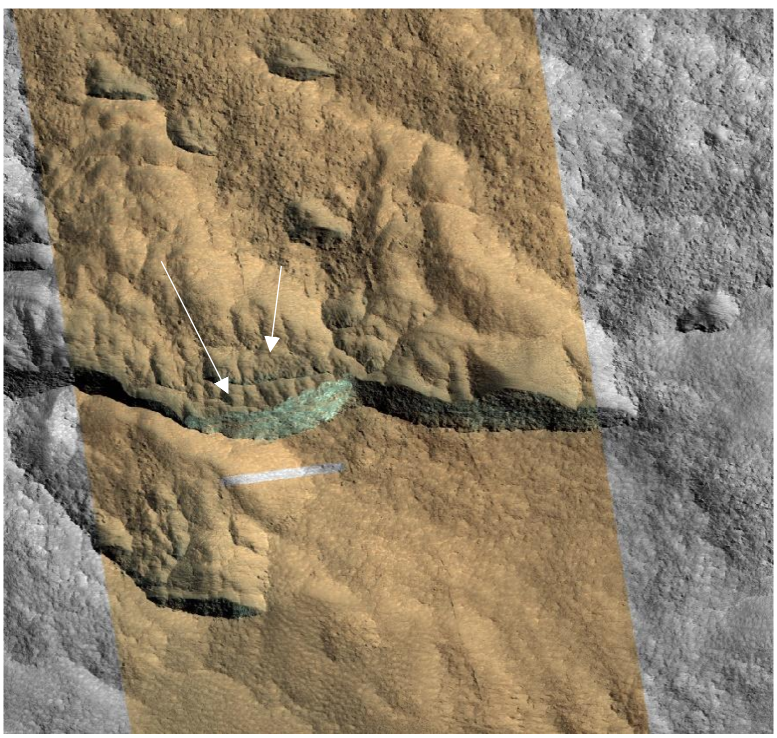

Figure 1.2: HiRISE images of ice exposing scarps on crater 1. The white arrows point to the ice exposing scarps. NASA/JPL/University of Arizona

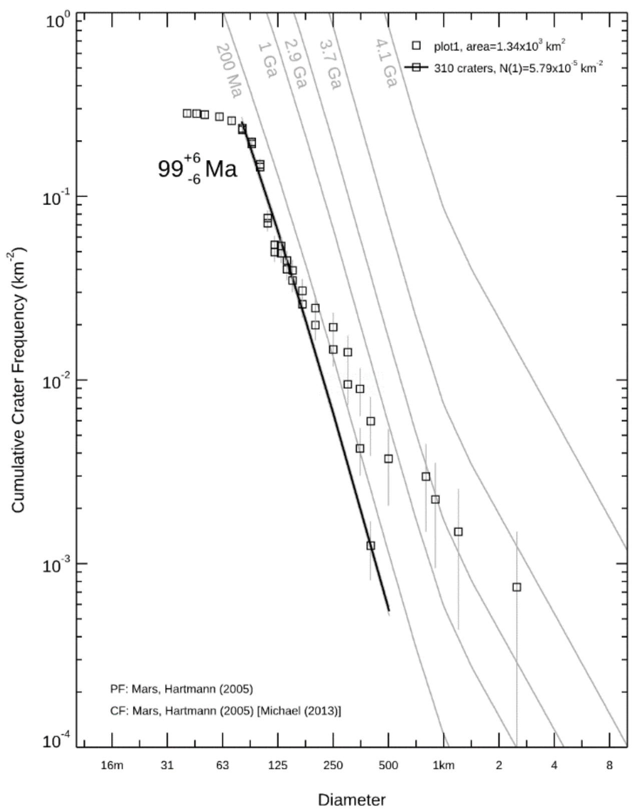

Figure 1.3: CSFD plot dates crater one to be about 100 million years old.
Plot created by Andrew Britton.

3.2 Crater 2

Crater 2 is located very close to Crater 1 at 59.4° latitude and 245° longitude. This crater is a bit smaller than the first, with a diameter of 3.62 Km. In the center and along the southern wall of the crater are several scarp-like features that can easily be seen with HiRISE imagery (Figures 2.1 and 2.2). According to the BTR from a THEMIS stamp taken at hour 15.9 (late afternoon) the lowest temperature found in the crater was 227° K, which is well above the likely atmospheric CO_2 frost point. TES thermal inertia analysis of the crater resulted in most values above 200 TIU, but there were several values within the crater at about 197 TIU. CRISM observations from ICER1 indicate the presence of water ice at the scarp defined in Figure 2.1; however, observations from ICER2_2 strongly suggest that this scarp hosts CO_2 ice.

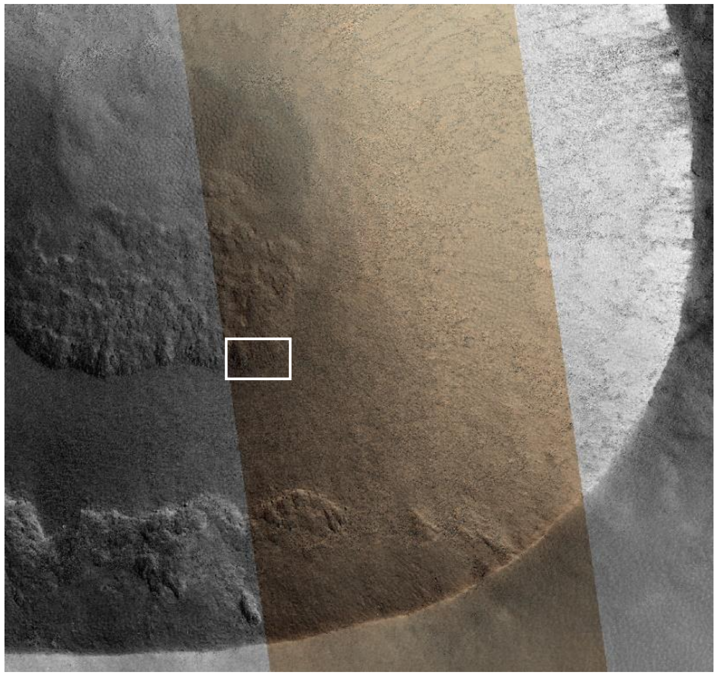

Figure 2.1: HiRISE image of Crater 2. A scarp formation can be seen in the center crater facing the poles.
NASA/JPL/University of Arizona

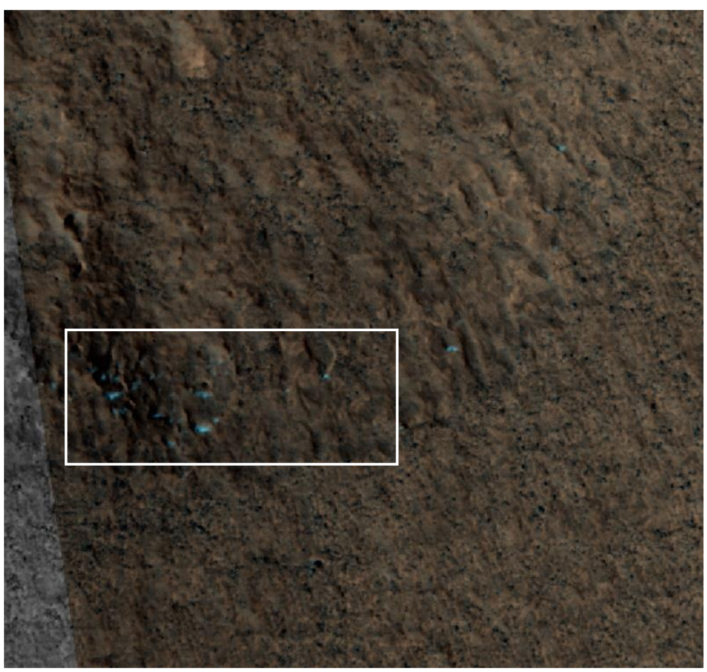

Figure 2.2: Zoomed in HiRISE image of Crater 2. Small scarps with ice exposing color indications can be seen within the white box.
NASA/JPL/University of Arizona

4. DISCUSSION

4.1 Confirming the Presence of Ice

Scarps within Craters 1 and 2 both have properties that can be interpreted as ice exposing. Crater 1 had been confirmed as ice exposing by Dundas et al. (2021); therefore, it will occasionally serve as the control group for identifying features that expose ice in Crater 2. Scarps in each of the craters all possess a blueish white color in the RGB HiRISE images, which is a very strong indication that exposed ice is present. The HiRISE images for Crater 1 were taken at a solar longitude of 140.5° which is Summer in the northern hemisphere and for Crater 2 the images were taken at a solar longitude of 65.4° or Spring. The timing of these images suggests little possibility of seasonal frost being present at the scarp locations. To further rule out the possibility of seasonal frost, late afternoon scarp temperatures were observed using BTR data from THEMIS. The Phoenix lander never observed a frost point above 209° K, although its landing site was at located at 68 °N (Zent et al., 2016). Even though Phoenix landed at a higher latitude, the frost point measurements can still be of use when ruling out the presence of frost (Dundas et al., 2018). BTR from both scarp sites indicate that frost is very unlikely to be present in the HiRISE images (Figure A5 and B5).

As discussed in Dundas et al. (2018), thermal inertia values less than 200 TIU is indicative of subsurface ice. TES observations of Craters 1 and 2 present few instances where the thermal inertia drops below 200 TIU, although the few drops in thermal inertia were not too far from the scarp features (Figure A4 and B4). The high thermal inertia could be the result of using profiles drawn in JMars for analysis.

CRISM observations were made at the scarp sites of both craters. The two ice exposing scarps in Crater 1 are most likely made of water ice, based on the results from Graphs A1 and A2. For scarps within Crater 2, Graph B1 indicates that water ice is likely exposed. However, Graph B2 strongly suggests that CO_2 is present here. When looking at Graph B2 the data seems unreasonable, which could be due to atmospheric interference. Clouds of CO_2 and water ice exist on Mars, the exchange of ice through the atmosphere is responsible for the increase and decrease of polar ice caps during the changing seasons (Smith et al., 2016). A patch of CO_2 ice in the atmosphere could account for the results in Graph B2 appearing to be unreasonable and conflicting with the results from Graph B1. The scarps in Crater 2 are thus interpreted to likely contain a mixture of water and CO_2 ice.

4.2 Geologic Analysis

Scarps in both craters are adjacent to a smooth LDM unit hosting scalloped depressions (Figures A6 and B7). Some polygons can also be found in the scarp associated pits in Crater 1 (Figure A7). Both features are hypothesized to form from the sublimation of ice rich terrain and are known as sublimation thermokarst features. Scalloped depressions are likely to be active features of the Martian surface (Dundas, 2017). These depressions further conclude that Craters 1 and 2 are located in a region where subsurface ice is widespread.

CSFD plots were made to estimate the age of the crater and gain some insight on the origins of the exposed ice. Following Harish et al (2020), craters that superpose the ejecta of Crater 1 were counted to estimate the age of the crater formation. However, the sublimation thermokarst features have deformed some of the craters making them hard to see: it is likely that many craters were not counted in the CSFD analysis due to this. Therefore, Crater 1 is likely much older than the predicted 100 million years. It is likely that Crater 1 formed after the initial ice deposition, which indicates that the ice layer could be up to billions of years old.

One of the defining characteristics of a scarp is the pit it forms. These sublimation thermokarst features likely form due to the retreat of the polar facing exposed ice layer (Dundas et al., 2018). The beginning of the pit is believed to be the initial ice exposing location. In Figure 1.2 these pits can be seen located directly in front of the ice exposing scarps and other smaller scarps. Figure A8 presents a scarp associated pit that is no longer active, likely due to ice coverage by lag deposit or dust. These pits usually have a triangular shape where the tip of the triangle is located at the initial ice exposing site. The shape indicates that the scarps widen over time (Figure A8). Similar scarp associated pits can be seen in multiple locations within Crater 2. They are much smaller than the pits in Crater 1 but still show movement towards the equator (Figures 2.2 and B6). Just outside of the northern rim of Crater 2, there appears to be another small ice exposing scarp (Figure B8). This scarp seems much younger than the rest, based on its retreat distance, and the ice exposure appears to have been initiated by a small impact crater measuring tens of meters in diameter. It also has all the important characteristics of scarp (polar facing, retreating towards the equator, and triangular shape), as do many other features around Crater 2. The presence of these pits on and around both craters further verifies that there is an ice exposure at Crater 2 and demonstrates that subsurface ice is widespread in this area.

4.3 Distribution and Origins of the Northern Mid Latitude Ice Sheet

Based on the analysis of escarpments exposing shallow ice, it is clear that thick bodies of ice exist in the subsurface of the mid latitude region on Mars (Dundas et al., 2021; Harish et al., 2020). Evidence from MONS correlates with these scarp observations. Water Equivalent Hydrogen (WEH) maps calculated from MONS data suggest that this ice is not pore filling ice, it is actually excess ice (Feldman et al., 2011). Previously ice in the mid latitude region was thought to fill the pore space of Mars' regolith, but this research suggest that the ice is a layer mixed with regolith. Water ice depths modeled with data from the Mars Climate Sounder (MCS) and THEMIS instruments show that widespread water ice can be found at latitudes as low as 35°N, ranging from less than a meter to tens of meters deep (Piqueux et al., 2019).

Double layer ejecta and ring mold craters have both been hypothesized to form when impact occurs over the presence of surface ice, these craters can be used to determine previous periods of glaciation on mars (Head & Weiss, 2014; D. K. Weiss, 2019). The double layer ejecta craters are distinguished by longitudinal ridges and a broad rampart along the inner facies (first layer of ejecta). The outer facies are depicted by a repressed rampart and a sinuous outer edge. Ring mold craters possesses an irregular morphology; they are typically rimless and present a circular moat surrounding an interior feature, plateau, or mound (Kress & Head, 2008). Crater size frequency distribution analysis of DLE craters has shown that Mars has endured a cumulative mid latitude ice age of about 600 million years (David K Weiss & Head, 2018). If this is true, it would indicate that Mars has undergone long and frequent ice ages. One thing to consider is the resurfacing due to thermokarst sublimation features. These features have resurfaced portions of the northern mid latitudes making CSFD analysis less accurate but the real question lies in the timing of the ice deposition.

Some new research has suggested that ice deposition has occurred within recent epochs (Fassett et al., 2014; Harish et al., 2020; Laskar et al., 2004; Madeleine et al., 2014). These ideas are supported by the obliquity shifts of Mars. Currently, Mars obliquity is 25° favoring ice concentrated on the polar regions. However, when the obliquity is ~30-40°, then the surface ice would become concentrated in the mid latitude regions (Weiss, 2019). The predicted mean obliquity for the Amazonian is 35-40°, which would favor ice accumulation in the mid latitudes (Head & Weiss, 2014). Although, it seems unlikely that a change in obliquity could allow snowfall to occur on Mars in recent epochs. A study conducted by Bramson et al. (2017) has shown that the subsurface ice layer could easily be billions of years old (Bramson et al., 2017). Before snow can recrystallize into a glacier, it undergoes an intermediate stage known as "firn". Due to the lack of atmospheric pressure on Mars, Martian firn could hold porosity longer than the rate of predicted retreat due to geothermal vapor migration through porous ice (Bramson et al., 2017). The geothermal vapor migration models created by Bramson et al. (2017) are consistent with the observations made from the Phoenix mission, due to the fact that the models suggest vapor migrates through a layer of porous ice where it then recondenses into a dense top layer of ice (Mellon et al., 2009). Considering this information, shifts in obliquity may have only minor impacts to the depth and latitudinal distribution of the ice table. The current ice layer exposed by scarps today is likely to have been initially deposited by an ice age two to three billion years ago, during the late Hesperian or early Amazonian Eon. Shifts in obliquity, vapor diffusion through firn, or growth of ice lenses could later modify the distribution of the ice table.

4.4 Greater Implications

Currently, there has only been one physical sample of ice tested on Mars. It was observed by the Phoenix mission at a high latitude of 68° (Mellon et al., 2009). The data received from this ice sample has allowed for major improvements in ice models and helped researchers understand the ice table in greater depth, as well as the processes that led to its original deposition. On 18 February 2021 NASA's latest Mars rover "Perseverance" landed on the western side of the Jezero Crater, which is located at about 18° latitude. Although, the main goal of perseverance is to look for signs of past microbial life on Mars, the data it will obtain could lead to far greater understanding of the water ice distribution on the northern hemisphere of Mars and Mars hydrologic cycle history. Images of Jezero Crater suggest that it was once flooded with water causing the formation of an ancient river delta to occur. The mineral samples that will be obtained from Perseverance should give researchers a major clue about the initial ice deposition that allowed for such a large ice table to be present in the northern mid latitude region.

The cumulative research on the water ice distribution of the northern mid latitude region of Mars will provide tremendous benefits to future manned missions to Mars. The local topographic low and smooth terrain that characterizes the northern mid latitude region is perfect for a future Mars landing site. By understanding the distribution of water ice in this region, future astronauts will be able to utilize these resources easily and effectively. In space, water costs $4,500 to $7,000 a pound which equates to 15.3 ounces, this is less volume than a small drink at most fast-food establishments (McCurdy, 2001). Water is expensive in space because it must be carried by spacecraft from Earth, and the more weight loaded onto a spacecraft the more propellant will be needed to get to the desired destination. Locating water ice reservoirs in space has more benefits than just drinking, which also increases its value. Water is comprised of two parts hydrogen and one-part oxygen, elements that are essential to any extraterrestrial mission since hydrogen can be used as propellant and oxygen can be used for respiration. By using water for In-Situ Resource Utilization (ISRU), astronauts can stay in space for longer, travel farther, and with less expense. Therefore, locating water ice reservoirs in the northern mid latitude region of aid human exploration of that planet.

5. CONCLUSION

Two craters in the northern mid latitude region of Mars have been studied and one new ice exposure is reported. Spectral observations form HiRISE images show presence of exposed ice signatures in scarps on each crater. Temperature analysis has supported that the ice is a subsurface ice layer rather than seasonal frost. Evidence from CRISM supports water ice exposures in Crater 1, but suggest a mixture of water and CO_2 ice for Crater 2. CSFD analysis suggests that crater one is about 100 million years old, although, it is likely far older due to resurfacing from sublimation thermokarst features.

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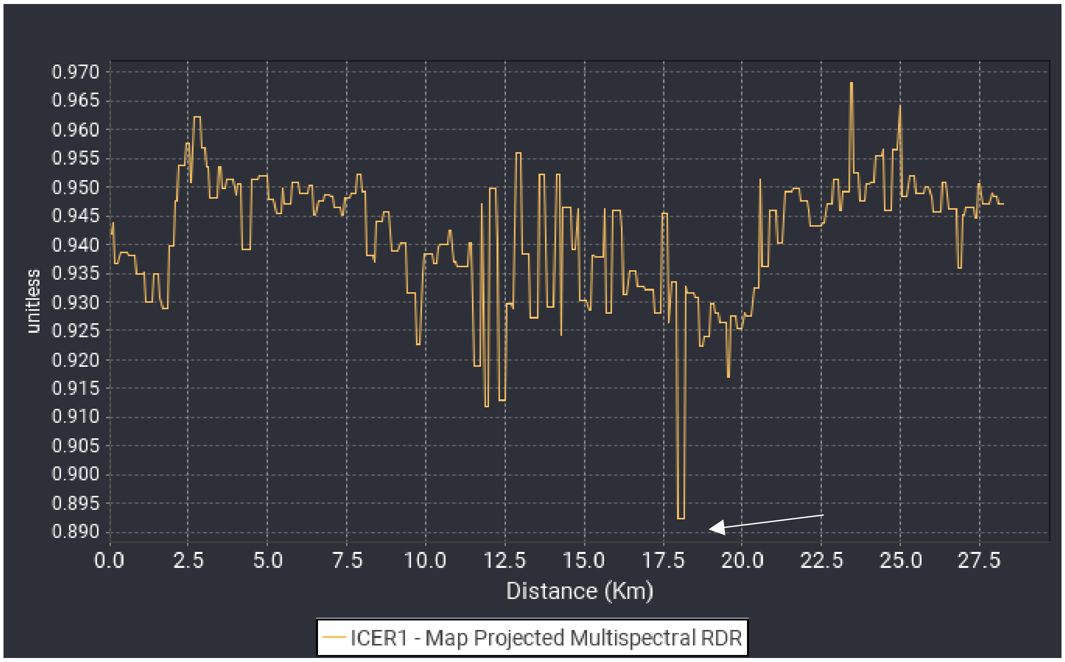
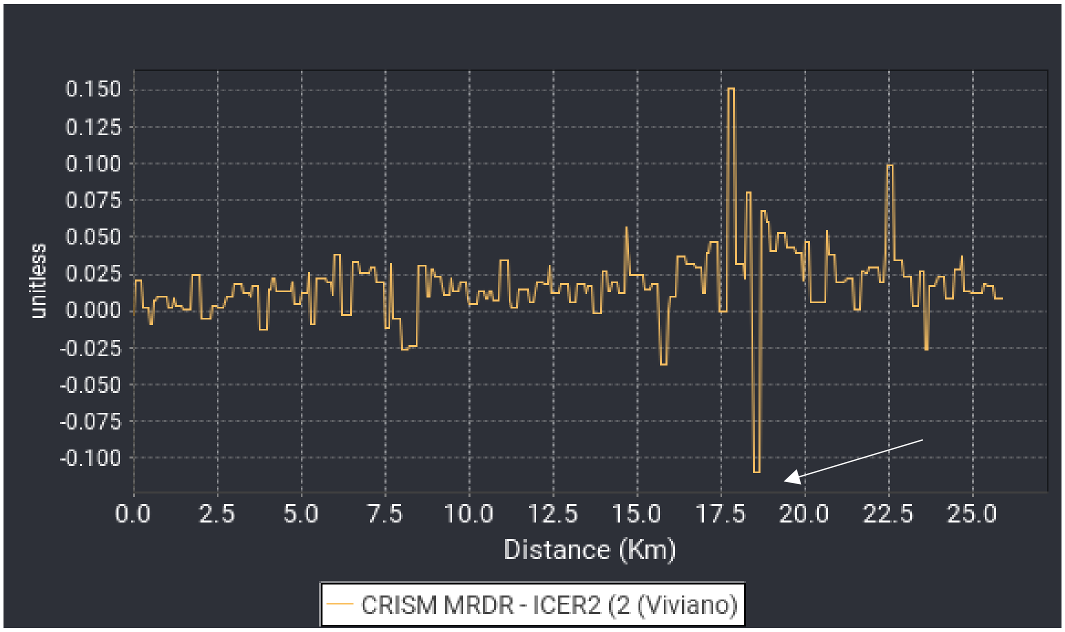
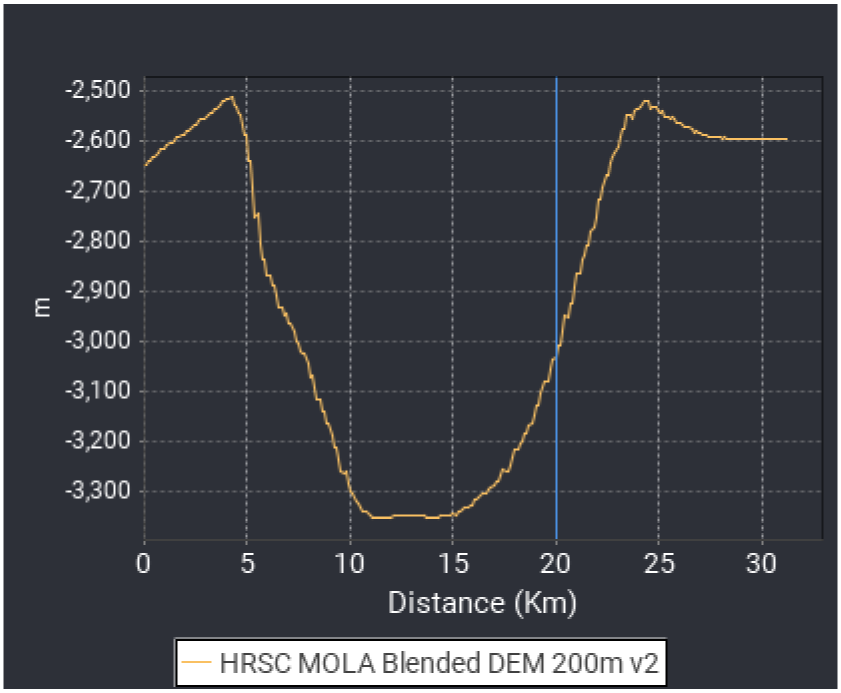
APPENDIX A: CRATER 1



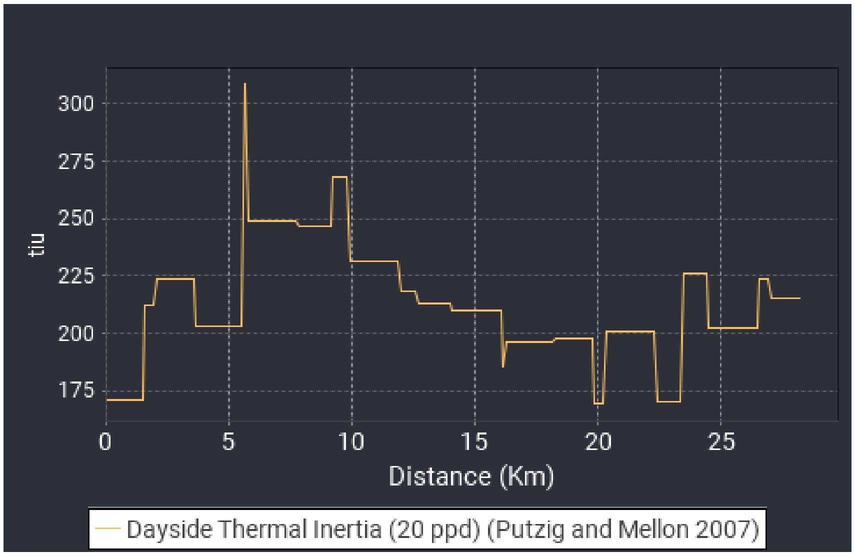
Graph A1: Shows data from Icer1 layer in JMars across crater 1. Along the Y-axis values greater than 1 indicate CO_2 ice and values less than 1 indicate H_2O ice. The arrow points to the location of the ice exposing scarp in crater 1. Created in JMars



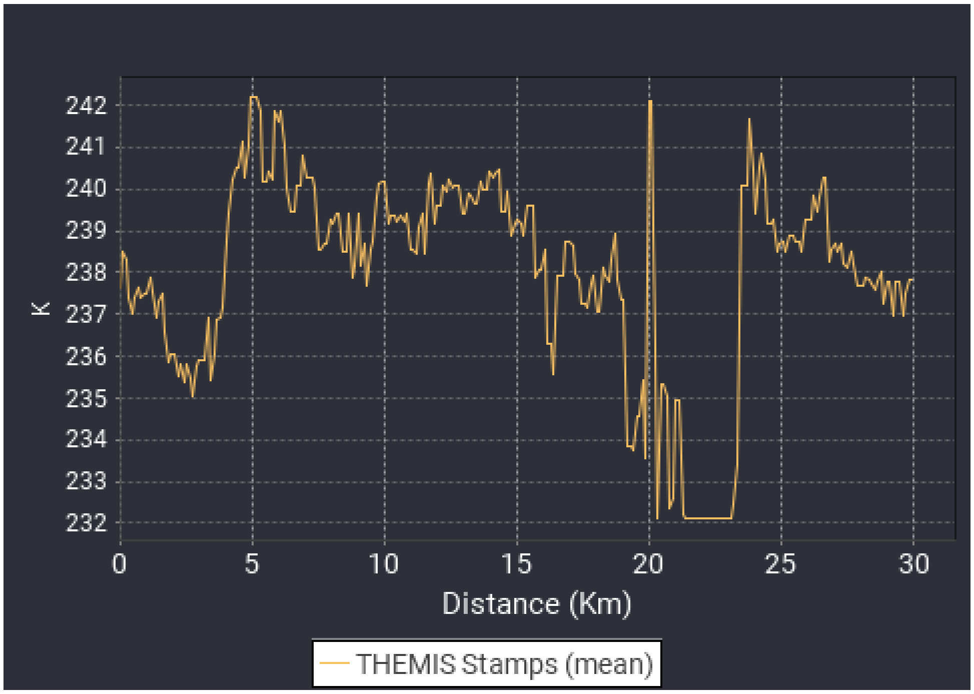
Graph A2: Using the same trend line from Graph 1, this graph represents another CRISM analysis of crater 1. CO_2 ice is strongly greater than zero H_2O ice is less than zero along the Y-axis. The arrow points to the location of the ice exposing scarp in crater 1. Created in JMars



Graph A3: Using HRSC and MOLA blended data, this graph represents the topographic cross section of crater 1. The blue line is the location of the ice exposing scarp. Created in JMars



Graph A4: TES thermal inertia graph of crater 1. Units on y axis are thermal inertia unit (J $m^{-2}K^{-1}s^{-1/2}$) and the X axis represents distance across the crater. Created in JMars



Graph A5: X axis shows distance and the Y axis shows temperature in Kelvin. Temperature is BTR from THEMIS. The stamp was taken in the late afternoon at hour 16.2. Created in JMars


Figure A6: Scalloped depressions on the floor of Crater 1. NASA/JPL/University of Arizona

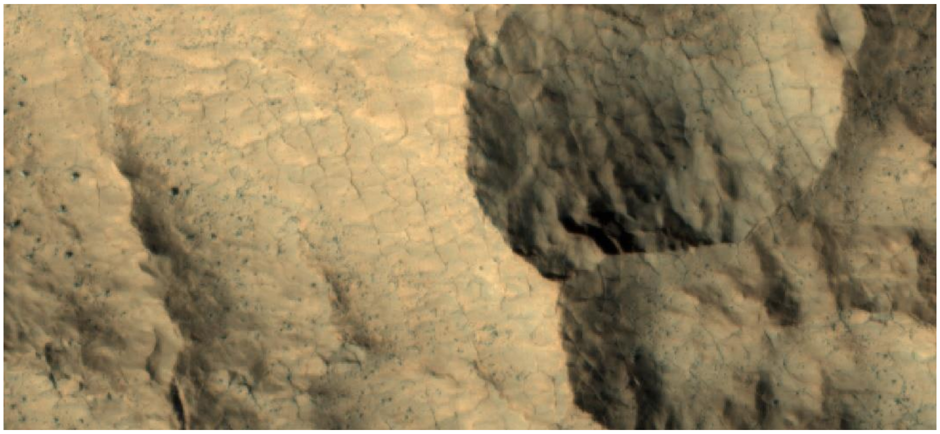


Figure A7: polygons located in scarp associated pits of Crater 1.
NASA/JPL/University of Arizona

Figure A8: scarp associated pit on the outside of Crater 1. Equatorward migration of the scarp can easily be seen in this image.
NASA/JPL/University of Arizona

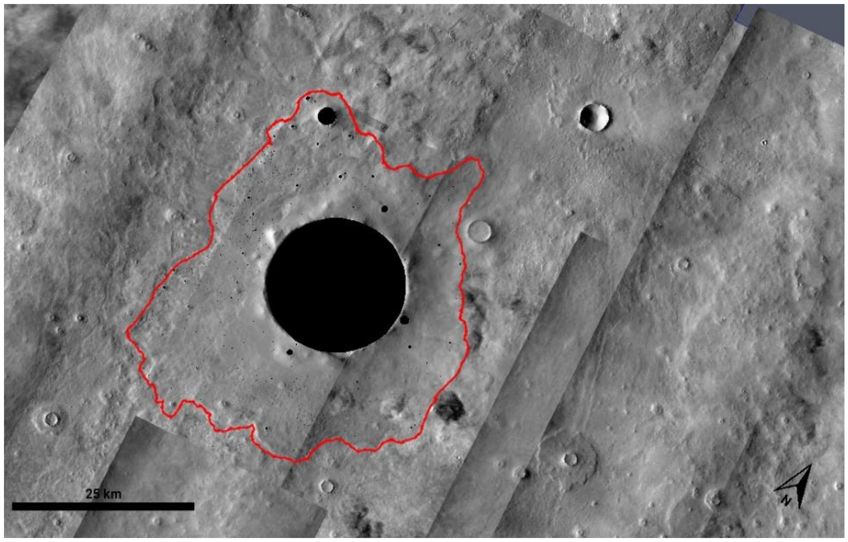
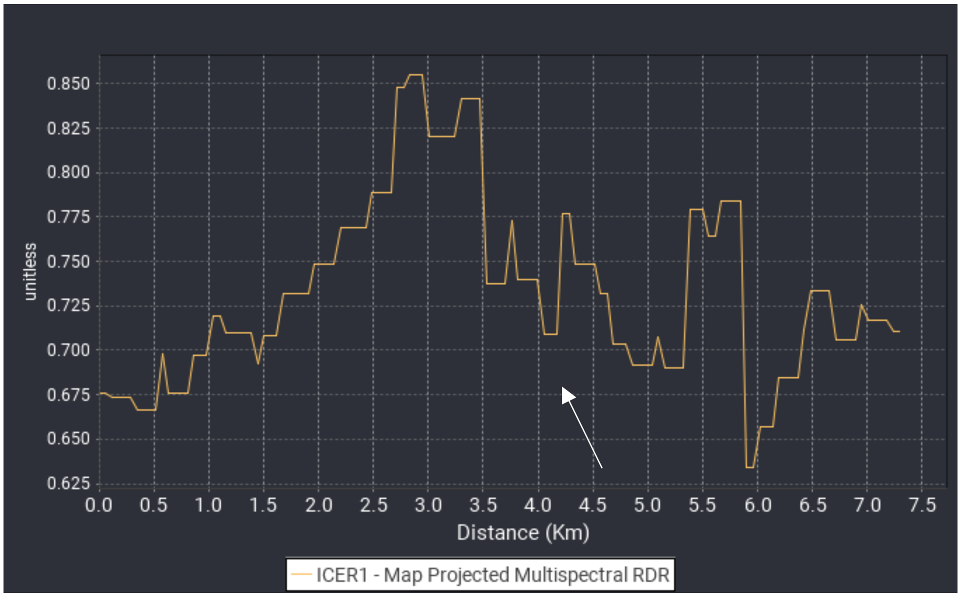
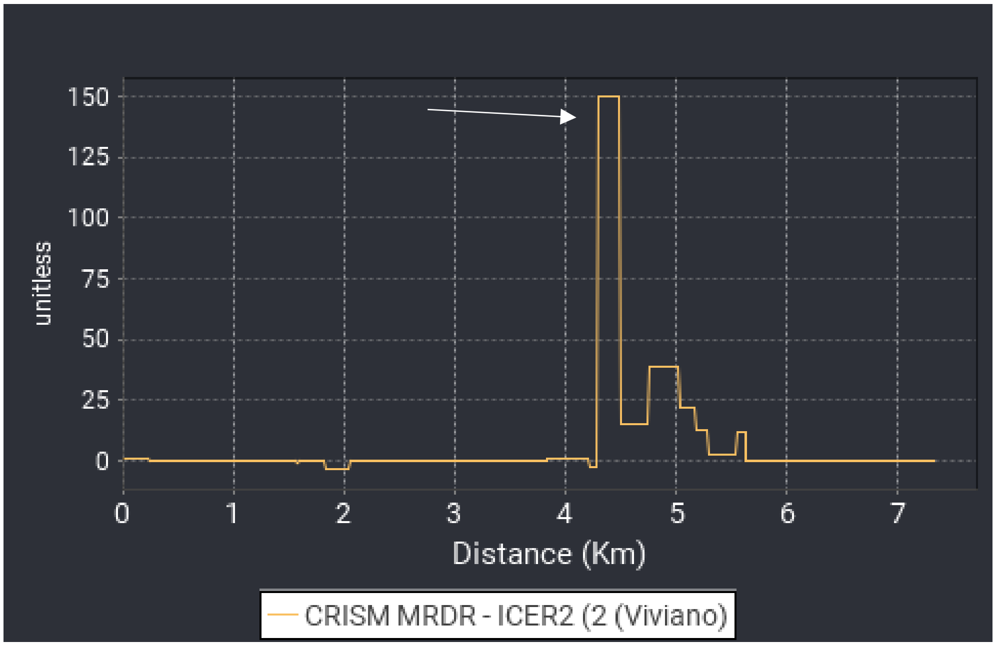


Figure A9: Crater counting for CSFD plot. Base map consists of CTX images rendered through JMars.

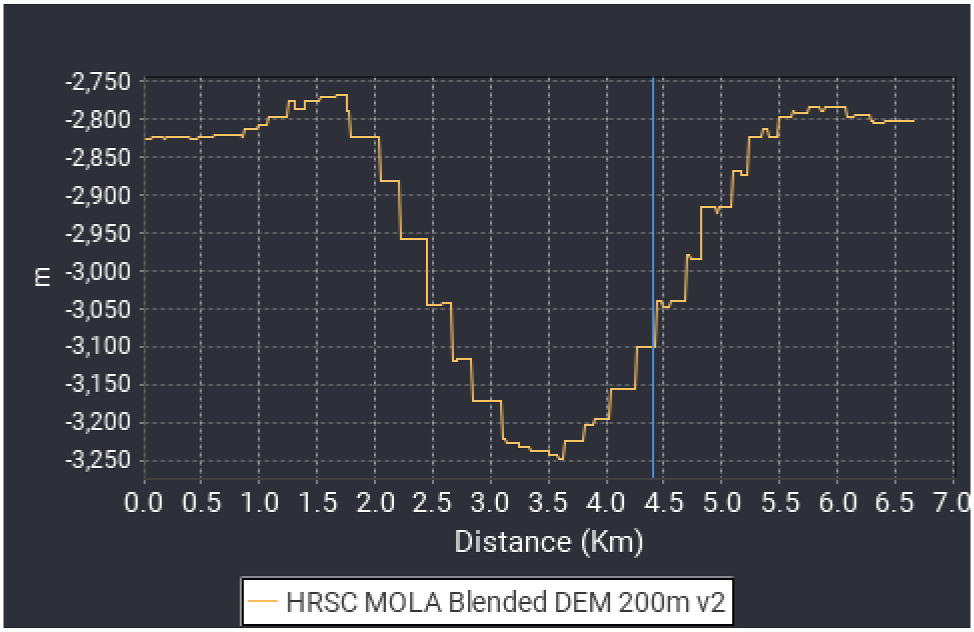
APPENDIX B: CRATER 2



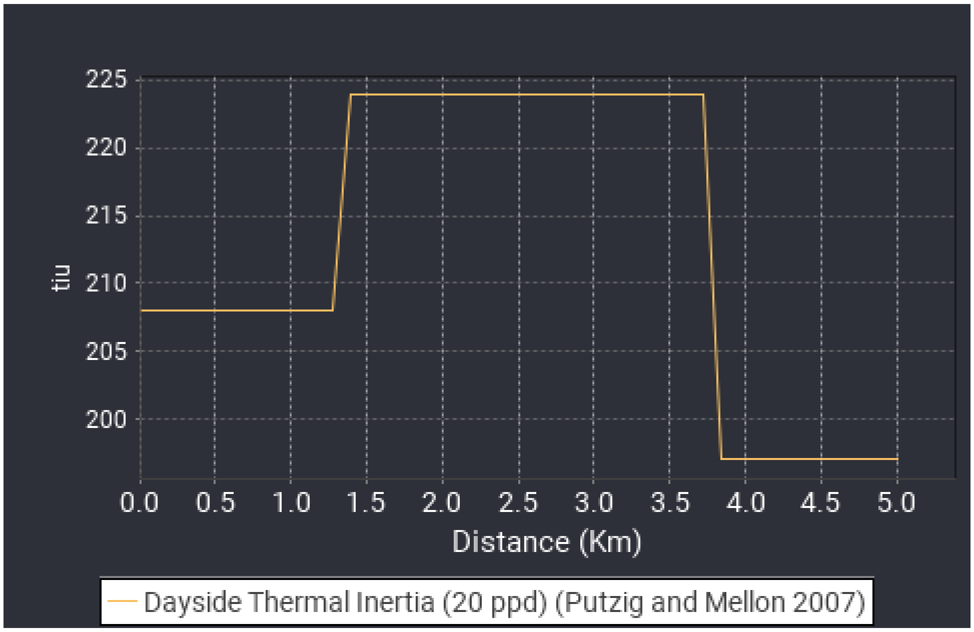
Graph B1: The location is directly through the center of crater 2, parallel to the colorized HiRISE image. The data is adjusted CRISM data (ICER1) that shows differences in H_2O and CO_2 ice (Viviano-Beck et al., 2014). Y-axis values greater than 1 indicate CO_2 ice and values less than 1 indicate H_2O ice. The arrow points to the possible ice exposing scarp in crater 2. Created in JMars



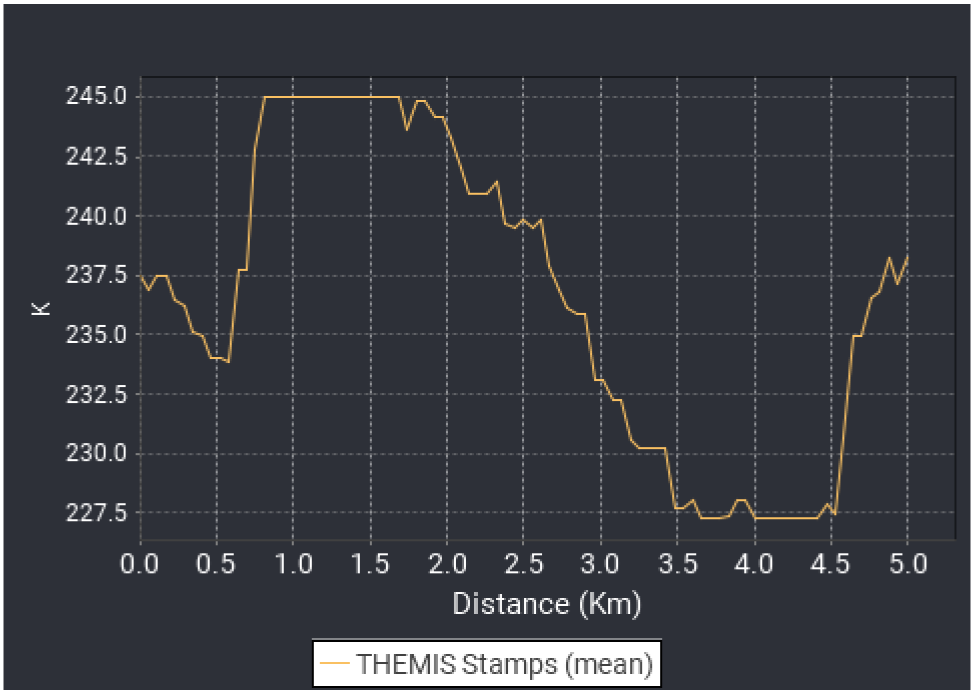
Graph B2: The location is directly through the center of crater 2, parallel to the colorized HiRISE image. The data is adjusted CRISM data (ICER2) that shows differences in H_2O and CO_2 ice (Viviano-Beck et al., 2014). CO_2 ice is strongly greater than zero H_2O ice is less than zero for Y-axis values. White arrow indicates the probable ice exposed scarp in crater 2. Created in JMars



Graph B3: cross section of crater 2 with data from MOLA and HRSC. Blue line represents the ice exposing scarp site in figure 2.2. Created in JMars



Graph B4: TES thermal inertia graph of crater 2. Units on Y axis are thermal inertia unit (J $m^{-2}K^{-1}s^{-1/2}$) and the X axis represents distance across the crater. Created in JMars



Graph B5: X axis shows distance and the Y axis shows temperature in Kelvin. Temperature is BTR from THEMIS. The stamp was taken in the late afternoon at hour 15.9. Created in JMars

Figure B6: additional scarp site in crater 2 imaged with HiRISE. On the polar facing walls of the scarps blue white colors can be seen and are indicative of exposed ice.
NASA/JPL/University of Arizona

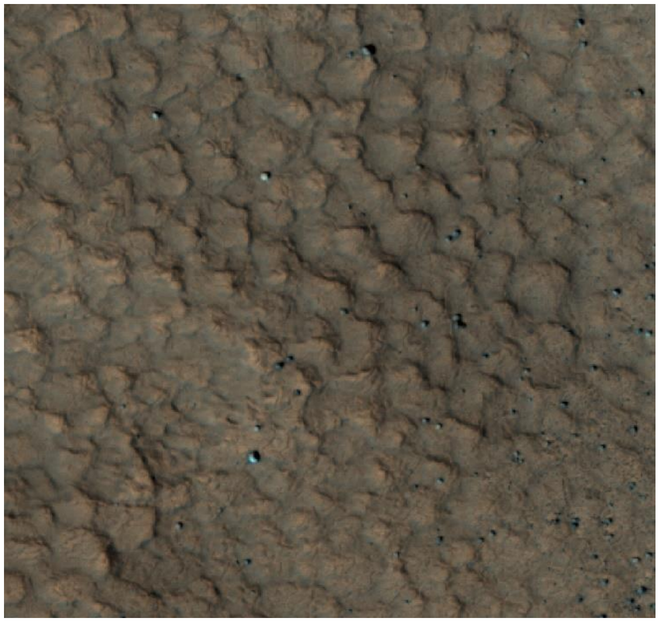


Figure B7: scalloped depressions seen on the floor of Crater 2.
NASA/JPL/University of Arizona

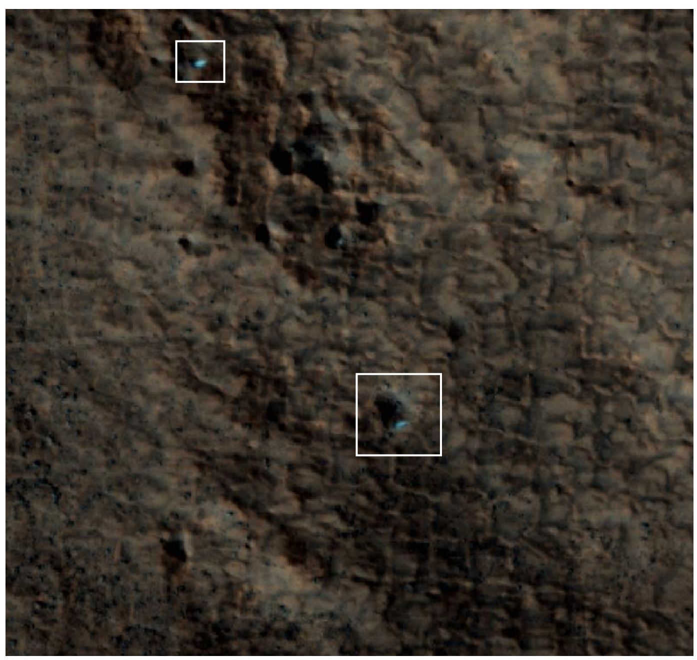


Figure B8: located outside the rim of Crater 2. Two possible ice exposing sites, lower site appears to be a scarp possibly created by a small impact.
NASA/JPL/University of Arizona

APPENDIX C: CRATER ANALYSIS TABLE

Table 1: All analyzed craters from northern midlatitudes excluding scarps at Milankovitc Crater. I=impact, E=ice exposing scarp, C=confirmed ice. All sites with letters I and E were discovered by Dundas et al., (2021)

Site	Coordinates: (latitude, longitude)	HiRISE Image ID	CRISM Observation ID	Description
Crater 1	58.6,244.5	ESP_063262_2390	X	Clear indications of exposed ice.
Crater 2	59.3,245.0	ESP_025878_2395	X	Small scarps with ice exposing signatures.
A	47.83481,3.536695	ESP_016617_2280	00016715	Patches of dark blue along rim and in center. Superposed crater also has blue patches, dark with little light blue.
B	52.705, 17.031	ESP_028326_2330	00017B2D	Patches of mostly dark blue north of the craters central peak
C	71.043,248.897	ESP_019812_2515	X	Appears to have clear water ice signatures near the western wall of crater. Could be due to frost
D	72.436,247.841	ESP_054624_2525	00024499	No visible evidence of exposed water ice
F	56.7,112.3	ESP_016969_2370	X	No traces of exposed water ice
G	68.926,26.768	PSP_008757_2490; ESP_017691_2910	X	
I1	54.753,196.851	ESP_027937_2350	00019F60	Not much to it, can hardly see an impact. Not icy
I2	54.89,254.55	ESP_062998_2350	X	Small recent impact crater slight blue rim. Regarded as not icy
I3	46.35,176.89	ESP_047533_2265	000027B2	Non distinct crater walls, some small bright blue patches near center. Ice exposure is present according to Dundas et al. (2021)

I4	39.11,190.25	ESP_029256_2195	X	Regarded as icy
I5	39.56,202.42	ESP_043853_2200; ESP_052569_2200	X	Good image, easy to see exposed water ice
I6	41.46,48.76	ESP_046707_2220	X	Good exposed ice
I7	41.91,36.42	ESP_046747_2220	X	Good ice
E1	56.9,216.9	ESP_035650_2375	X	Some brightish blue spots on or near scarps

Table 2: Scarps at Milankovitc Crater that expose subsurface ice. All craters initially found by Dundas et al., (2021)

Site	Lat,Lon	HiRISE data	CRISM data	Notes
1	54.89,212.01	ESP_045857_2350	X	Clear ice signature on scarp
2	54.2,211.89	ESP_053241_2345	x	Clear ice signature on scarp
3	54.125,212.13	ESP_061681_2345	x	Tough to make out ice, other ice related features here too
4	53.85,212.26	ESP_061048_2340	X	
5	54.836,214.507	ESP_053175_2350; ESP_061615_2350	X	
6	54.19,214.63	ESP_061127_2345	X	
7	53.7,212.77	ESP_053452_2340	X	Milankovitch crater rim. HiRISE image shows ice well