

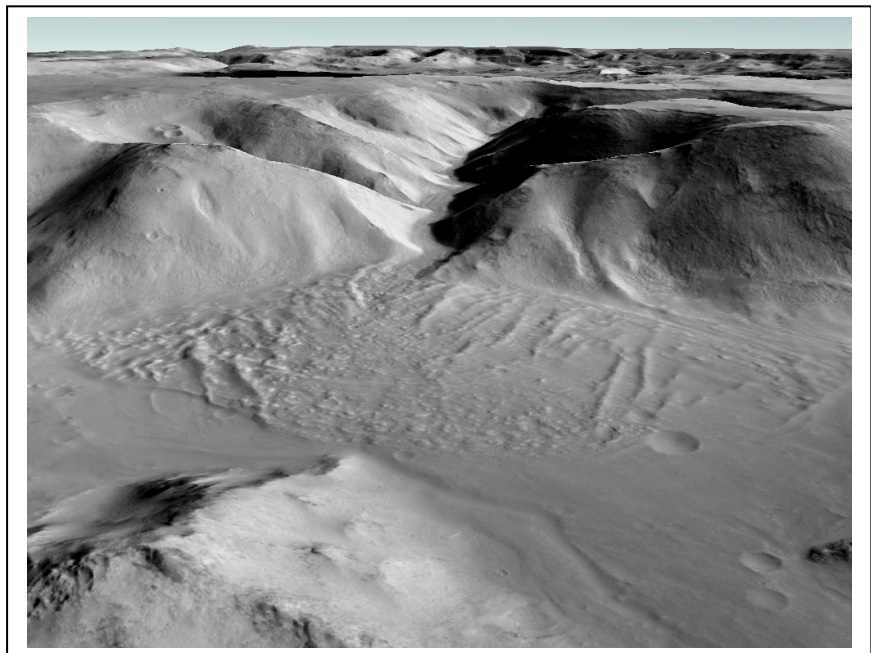


UNIVERSITY OF  
GOTHENBURG

DEPARTMENT OF EARTH SCIENCES

# Past glacial extents in Nilosyrtis Mensae, Mars

*Insights from successive moraine-like ridges and crater chronology*



**Richard Marozsan**

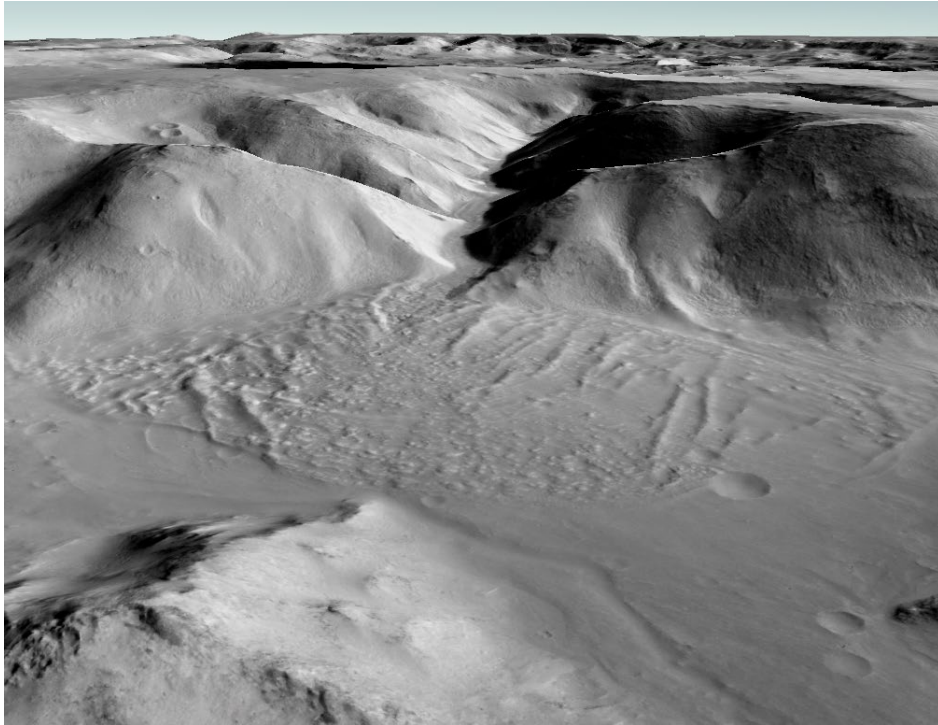
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# Past glacial extents in Nilosyrtis Mensae, Mars

*Insights from successive moraine-like ridges and crater chronology*



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## Abstract

Recent technological advancements have put Mars in the forefront of planetary interest, with several new missions planned. The Martian climate differs from Earth's, lower surface gravity gives rise to steeper mountains and features, difference in sediment transport and different erosional patterns. There is also a clear dichotomy which divides the flat plane northern hemisphere from the rugged, crater-rich and volcano ridden southern-highlands.

This study produced a geomorphological map of a valley within the Nilosyrtris region, which is at the meeting point of the dichotomy. The purpose was to identify glacier-like landforms, get an approximate age between the dichotomy and to investigate the surroundings. By using THEMIS, CTX and HiRISE data it was possible to see the extent of the lobate structure which originated from the valley and associate it with an approximate age that fell in the late Amazonian. With information of Mars obliquity and known glaciations during this period, it is possible to link the observed lobate structure to glacial activity. The valley is made up of several tributary valleys with visible VFF, LVF and ripples. There are also remnants from possible niche and cirque glaciers which when viewed in conjunction with the lobate structure could signify a piedmont glacier which has flown out into the open planes of the lowlands. Within the lobate various ridges are visible, boulderfield-like features, ripples and pitted terrain. The distinctive patterns of the various ridges could indicate possible recessional moraine. Overall, the mapping shows that the dichotomy boundary at this specific valley in Nilosyrtris is very complex.

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## 1. Introduction

Mars, revered since antiquity as both divine and unexplored, continues to captivate humanity, beckoning us forth as the frontier of tomorrow.

It is the fourth planet in our solar system with half the radius of Earth and has a surface gravity which is only one-tenth that of our planet (Bargery et al.,2011), this in turn affects the erosion; providing a much slower erosional speed of the surface (Golombek & Bridges, 2000). The slow erosional speed creates landforms which are preserved and usually older than those found on earth.

Technological advancements and the contribution as well as interest from both international and private organizations has caused a significant increase in activity related to Martian exploration over the past few years. A huge leap forward came in 2006 when the first 'High Resolution Imaging Experiment' (HiRISE) images with sub-meter resolution and 'Context Camera' (CTX) images with meter resolution were acquired from the Mars reconnaissance orbiter (MRO). The data gathered from the orbiter has provided scientists with a more detailed image of the Martian landscape, leading to the identification of safe landing locations for rovers and landers (McEwen et al.,2023), compelling evidence of liquid at the surface (NASA, 2015) and overall, a deeper geological understanding of the surface structures and their origins.

The Martian atmosphere is primarily composed of carbon dioxide and characterized by its thinness. Due to this thinness of the atmosphere the heat retention and absorption for both incoming and outgoing radiation is very low resulting in a fluctuating range of low temperatures; 150 to 300 kelvins depending on time of day, these temperatures correspond to approximately -123°C and 26°C, respectively. This in turn also affects the stability of surface water which either sublimates or freezes (Carr, 1983; Carr, 2008, p. 5, 9-11).

The Martian landscape is complex and has been shaped over long periods of time. The geomorphology found on the surface has been described based on the analogs of Earth, long sinuous ridges that resemble Eskers, moraine ridges and many other fluvial and glacial-like landforms have been observed. By studying the Martian surface and using earth as an analog, scientists have concluded that there have been past glaciations on Mars. The earlier assumptions were that glaciers on Mars were cold-based, meaning they were frozen to the ground and were not expected to actively erode the underlying surface, thus not leaving any distinct depositional morphologies. However, recent studies have shown that there have been favorable events where warm-based glaciations have occurred. (Carr,2008, p.173; Butcher et al.,2017; Hubbard et al.,2014; Kargel et al.,1992)

By investigating areas of past glaciations on Mars and using earth as an analog one can get a better understanding of the past Martian dynamics and its origin story. This thesis will focus on a specific area of a possible past glaciation within the region of Nilosyrtis Mensae.

## 1.1 Aim and objectives

The aim of this thesis is to get an overall greater understanding of a specific valley in the Nilosyrtris Mensae region on Mars by conducting a geomorphological map and thereby taking an inventory of the various landforms present within the study area. Emphasis will be put on the glacial lobate structure that has spread out from the valley system. The surrounding area will also be considered to get a better understanding of the study area and hopefully the region.

Objectives for the thesis:

- Map and find glacier-like landforms.
- Get an approximate age dating on the highlands and the lowlands as well as the glacier.
- Investigate the surrounds for other landforms.

## 1.2 Study area

The study area is situated right where the northern lowlands border the southern highlands in the Nilosyrtris Mensae region (figure 1). The specific study area is a valley outlet which has been fed by a main valley consisting of several tributary valleys with the coordinates of 74°55'32"E 27°50'26"N. The area contains glacial-like landforms (GLF) that can be connected to either erosional or depositional events (Johnsson et al., 2019). The study area is overall very complex and there are hints of an ancient landscape that has been overlaid by perhaps countless events which have given rise to the shape seen today. This study area shows that Mars has had a complex and dynamic past.

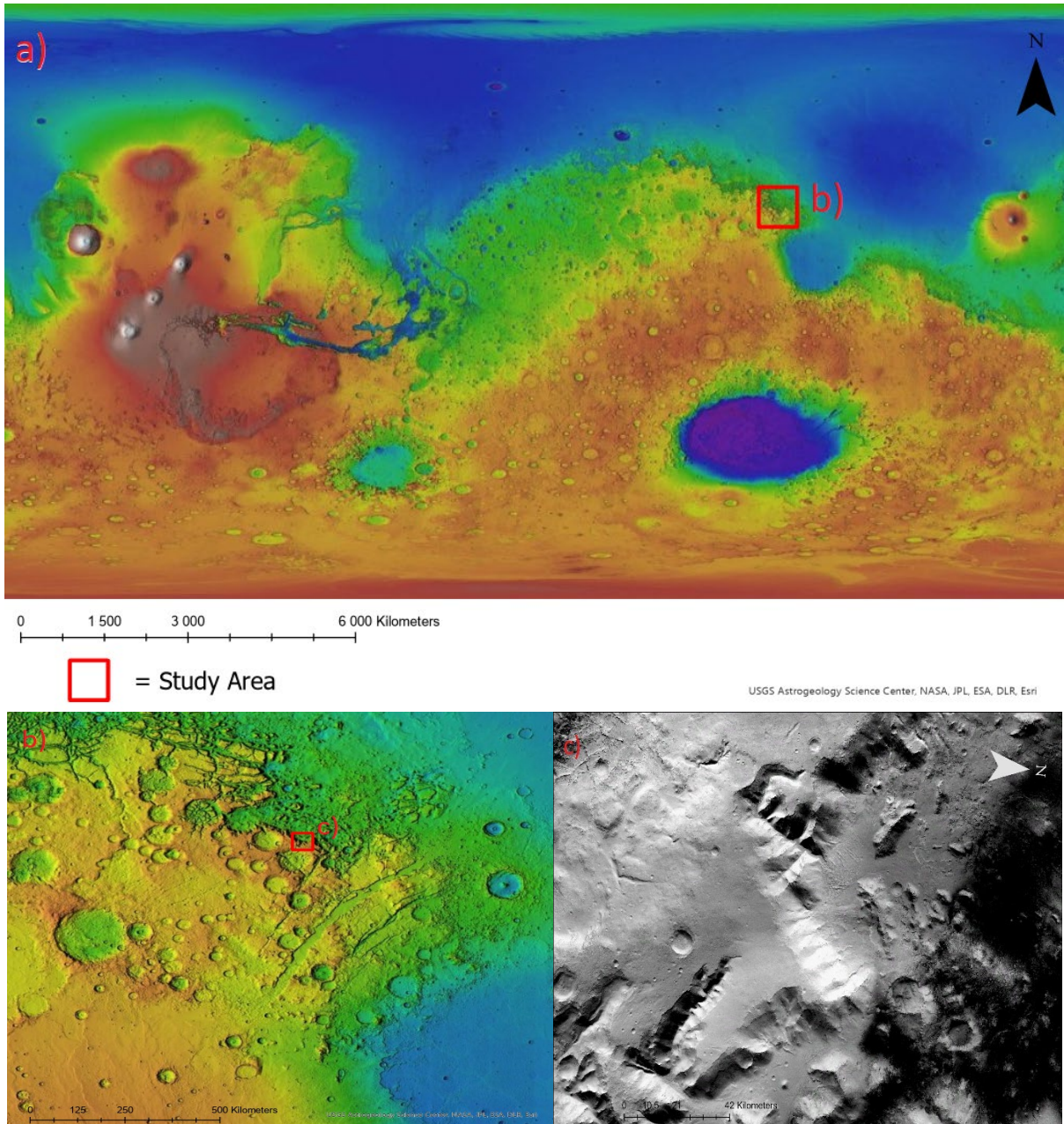


Figure 1. a) Global MOLA map of Mars together with a red square marking the study area of Nilosyrtris. b) Mola Map zoomed in for a closer view together with a square of the study area. c) CTX mosaic map of the marked study area represented in b).

The highlands tower roughly 1300m above the Martian datum (equivalent to terrestrial sea level). The elevation changes down into the valley outlet and into the lowlands is approximately 2800 meters, or 1200 meters below the Martian datum. This means that by standing at the valley outlet the height up to the plateau would be greater than the height of the tallest mountain in Sweden, Kebnekaise, at 2096 meters.

## 2. Background

The red planet has fascinated humanity since ancient times, but little was known about Mars up until recently, with the start of the space-age and its technological advancements.

Mars orbits the sun in an ellipse, and it takes roughly 687 earth days to complete a full revolution, the planet rotational speed is like Earth's, taking 24.6 hours to complete. The axial tilt is also similar with 25° but has seasons with varied lengths due to the elliptical orbit. The thin Martian atmosphere is constituted of carbon dioxide, nitrogen, and argon gas as well as water vapor from sublimation. The thinness of the atmosphere does not only give Mars a lower surface temperature but also results in more meteor strikes (NASA, n.d.).

The Martian surface is divided into a clear dichotomy, with the Northern hemisphere of flat plains and the rugged southern highlands with its distinct crater and volcanic filled surface (Bargery et al., 2011), a good representation of the topography can be seen in figure 1 a). Since Mars has no sea level there is nothing to compare the elevation to, hence, a surface reference had to be established, the Martian datum, compared to this surface reference the lowest point can be found in the Hellas Basin, which is 8km below the reference point, and the highest can be found at the summit of the solar system largest volcano, Olympus Mons, towering 21km above the reference point.

By contrast to earth, Mars has a lower surface gravity which has a significant impact on geomorphological structures. This means that slopes can become steeper before submitting to gravitational collapse, sediment transportation will differ from that on earth which also results in a different sedimental sorting, overall, this difference in gravity could lead to different erosional patterns and morphologies (Baat et al., 2024).

The Martian geologic time is divided into 3 distinct eons. The oldest geological surface found on Mars dates back 4.5Ga (billion years) and is the pre-Noachian eon, based on orbital mineralogical mapping this eon's climate is believed to have generated clay rich layers because of abundance in neutral water. It is also believed that during this eon the distinct dichotomy was created. These ancient geological surfaces have been preserved because of several various geological reasons, some of which are the thin atmosphere which reduces erosion and lack of metamorphic effects due to an absence of plate tectonics, to name a few. The Noachian eon lasted between 4.1 to 3.7Ga and was followed by the Hesperian that ended at roughly 3.0Ga. This eon is believed to have produced sulfate rich sediments due to a rich acidic environment. Towards the end of this period water was locked away as ice within the regolith and this brings forth the Amazonian eon, an eon which Mars is still in today. It is during this period that Mars gets its distinct rust-red color by the formation of anhydrous ferric oxides. The locked-up water created polar icecaps and glaciation in the mid-latitudes. An overview of the eons can be seen in figure 2. These geological boundaries between the eons are however not certain as they derive mostly from measurements of crater counting and orbital data in comparison to the terrestrial timeline that is based on fossil recordings as well as clearly defined rock dating (Bargery et al., 2011; Grotzinger et al., 2011; Ehlmann et al., 2011)).

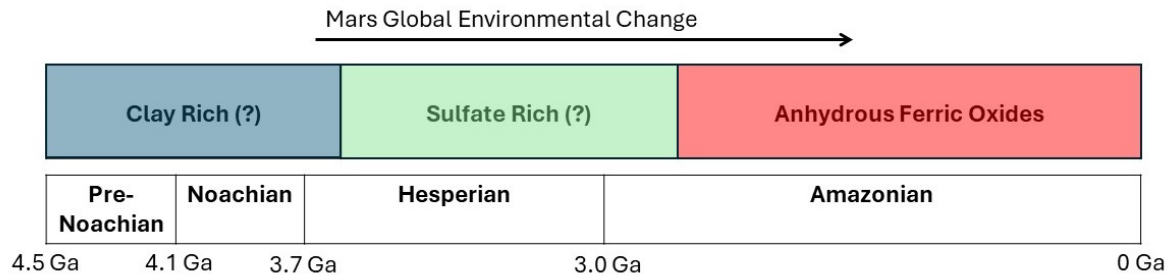
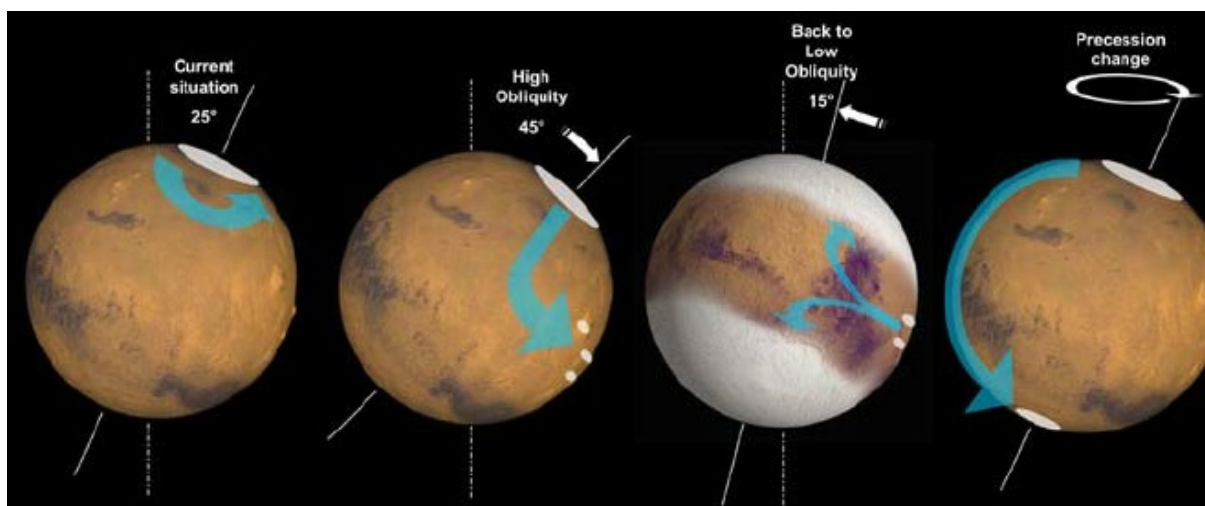


Figure 2. The Martian geological time periods from pre-Noachian (4.5 to 4.1 Ga), Noachian (4.1 to 3.7 Ga), Hesperian (3.7 to 3.0 Ga) to Amazonian (3.0 Ga to today), together with assumed stratigraphic records. Re-created and modified from: Grotzinger et al, (2011). Mars Sedimentary Geology: Key Concepts and Outstanding Questions.

### 2.1 Glaciations on Mars

Currently most of the visible ice is located at the northern and the southern poles of Mars. It is also believed that there is a vast amount of ice buried underneath the ground and bonded to the regolith (Picardi et al., 2006). There is evidence that shows past glaciers as well as vast frozen planes which can be attributed to the change in Martian obliquity. It is believed that the obliquity may have reached as high as 70° and as low as 0°. During episodes of high obliquity, the solar insolation on the icecaps is increased while it is lowered across the equator. This results in a drop of temperature around the equator as well as a wetter and warmer climate as water/ice is driven from the caps and up into the atmosphere to later condense around the equator. While during the low obliquity the insolation was increased across the equator and the opposite of what was just described occurs on the poles (Carr, 2008, p.173-174; Hauber et al., 2011).

During the late Amazonian period the Martian obliquity had exceeded the mean value of 45° which would be recognized as high obliquity, causing the solar insolation to increase at the poles and causing widespread glaciation across the Martian mid-latitudes (Head et al., 2006; Jawin et al., 2011). Figure 3 is a representation of how changes in Martian obliquity affect the distribution of liquid/ice across the landscape.



*Figure 3: Shows the effects of change in obliquity on the distribution of Martian ice. From left to right: first scenario shows how water is sublimated and put back into the poles. The second scenario shows how a higher obliquity changes the accumulation of ice into migration towards the equator. The arrows show where the ice/water is being redirected because of the corresponding differences. From: Montmessin (2006) "The Orbital Forcing of Climate Change on Mars".*

During this period a vast number of glaciers were formed in the mid-latitudes and many different forms of glaciers were created which helped further form the landscape. As there are no glaciers on the mid-latitudes a paraglacial period had to occur where deglaciation took place, causing a retreat and loss of ice which leaves distinct morphologies associated with such events. In Jarwin et al (2011) they discuss the evidence and findings of some of these periglacial features found within craters on the mid-latitudes, some of which are 'Washboard terrain' a feature characterized by parallel ridges and troughs which in their study signifies recent ice movement on the crater slope, and 'Polygonal terrain' which is assumed to have been formed by a constant change in temperature.

## 2.2 Cirque

Cirques are geological formations that are characterized by deep amphitheater like depressions that have steep walls. They are typically situated at the top of mountain valleys. It can be thought of as someone scooping out the upper part of a mountain, leaving a semicircular basin at the bottom, also known as the cirque floor. Glaciers within this formation move by rotational sliding, away from the headwall (Ritter et al., 1994, p. 299, 325-326; Marshak, 2019, p. 837).

## 2.3 Niche Glaciers

Niche glaciers can be related to cirques. Niche glaciers form in small depressions by the accumulation of ice and snow which over time erodes the landscape and contributes to the formation of cirque glaciers, however, niche glaciers have less erosional impact compared to cirques. Niche glaciers generally occupy smaller depressions and confined areas (Groom, 1959).

## 2.4 Piedmont Glaciers

Piedmont glaciers are formed when confined glaciers such as valley glaciers move from confined areas and out by the base of mountains onto open plains. As they are being fed by the glaciers from higher areas and lose their confinement they tend to spread out into lobes (Marshak, 2019, p. 837; Russel 1893). As these glaciers spill out into the lowland, they leave behind distinctive geological features after recession.

## 2.5 Marginal ice contact features

Moraines are debris rich ridges found at the edges of a glacier which has been pushed or laid out, there are many various types of moraines which causes different types of landforms. Some of which will be explained here.

End Moraines are geomorphological features that are produced at the terminus of the glacier, they can be subcategorized into three other distinct moraines. Recessional moraines is a moraine feature

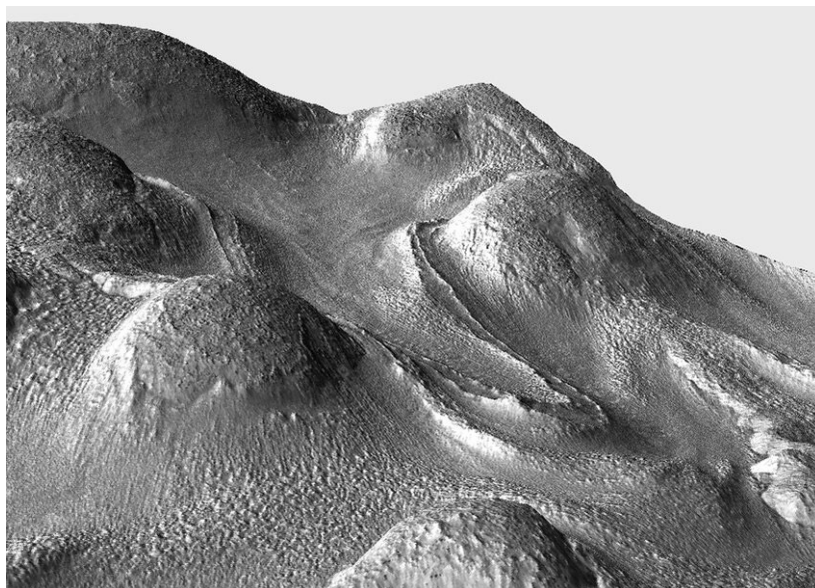
which is created during pauses in the glaciers retreat and is accompanied by slight back and forth movement. During these pauses material is being deposited which creates ridges. Overall, this feature shows interrupted glacial retreat patterns. Another one is Lateral moraines, these features are created by the deposition of material towards the side margin of the glacier. The last subcategory is the Terminal moraines, these are features produced at the forefront of the glacier which marks the maximal extent of the glacier (Ritter et al., 1994, p.340-341; Marshak, 2019, p. 854)

Ground moraine is a combination of different processes. It is created mainly by till that has been released from a flowing glacier which then remains as the glacier recessed, this is called lodgment and ablation till. The till that is left behind rapid recessions creates a hummocky, irregular pattern. These two are the backbone for ground moraine (Marshak, 2019, p. 854).

## 2.6 Flow related features

Viscous flow features (VFF) is an umbrella term used for landforms which show surface morphologies corresponding with various viscous flows. VFF includes subcategories linked to surface lineation, downslope movements, ridges and other features where material moves around or over obstacles. Simply put, these features are elongated, giving the impression of viscous flow and are composed of H<sub>2</sub>O ice rather than the commonly thought of CO<sub>2</sub> ice (Hargitai, 2014; Hubbard et al., 2014). Some of these subcategories are Glacier-Like Form (GLF) and Lineated Valley Fill (LVF).

GLF are elongated features which are of similar morphology to valley glaciers found on earth, where material is flowing downslope (figure 4). These features can 'evolve' into lobate debris aprons (LDA) if they form an apron around an elevated plain, such as a mesa or a plateau where the material flows outward from the main feature (Hubbard et al., 2014).



*Figure 4: Showing a classic example of a GLF on Mars where clear downslope flow is visible. From: Hubbard (2014) "Glacier-Like form on Mars".*

LVF is another form of VFF. These features are predominant in valley systems where they appear as lineations stretching across the valley floor. LDA from two different valley walls will converge and form LVF. The lineations of the LVF typically consist of pits and mounds that have been stretched and re-arranged by viscous flow. These features can sometimes be confused with medial moraine (Carr, 2008, p. 184-185).

### 3. Method

#### 3.1 Data collection

There are several various orbiters with different instruments monitoring Mars as of right now. From the seven currently active ones, data from the MRO and Odyssey orbiter has been gathered. There has also been a retrieval of data from the Mars Global Surveyor (MGS) which ended its mission in 2006.

##### 3.1.1 CTX and HiRISE Data

MRO has been in service since 2005 and has been used to find evidence for water on the Martian surface. The orbiter carries six different instruments with the most relevant for this project being the CTX and HiRISE instruments. The larger swath range of 30km provides a big-picture view of the Martian terrain when compared to the HiRISE images of 6km widths. The CTX is used to provide a bigger picture and is meant to supplement the other various instruments, such as HiRISE which is used to get a more detailed image (NASA, n.d.). The spatial resolution is 5-by-5 meters while the spatial resolution for the HiRISE images is 1-by-1 meters. Two different TIFF files were merged into a single mosaic which was then used for the geomorphological mapping within the study area.

##### 3.1.2 MOLA Data

MGS was launched in 1996 and has provided a host of scientific information until its failure in 2006. It was equipped with six different instruments that gathered information about the atmosphere, the interior as well as the overall Martian surface which later helped provide landing sites for landers and rovers. One of the six instruments is the Mars Orbiter Laser Altimeter, MOLA. This instrument gathered data which was used to determine the elevation changes on Mars, it has an accuracy which is less than 1meter vertically (NASA, n.d.). The MOLA data was used to create a 3D image of the surface to ease the visualization and provide more information about the study area.

##### 3.1.3 THEMIS Data

The mineral and chemical mapping orbiter, Mars odyssey, was launched in 2001 and has greatly increased the scientific and overall geologic understanding of the Martian surface with its 3 instruments: Spectrometer, Radiation detector and the Thermal Emission Imaging System (THEMIS). THEMIS is used to view the infrared and visible reflections and can thus be used to distinguish between various minerals (NASA, n.d.). There are variations between the day and night datasets due to the temporal variations, in the context of this thesis the THEMIS dataset 'Night' will be used to get an understanding of the glacial extent.

### 3.2 Data availability

The study used CTX data provided by The Bruce Murray Laboratory for Planetary Visualization from the Californian Institute of Technology, HiRISE data from NASA(JPL-Caltech/UArizona). And MOLA as well as THEMIS data from the USGS astrogeology division. A summary of all data used in the study is provided in table 1, together with the specific filenames.

*Table 1. Summary information of the various datasets used in this study.*

Datasets	Resolution & File type	Satellite/instrument	Source
MurrayLab_GlobalCTXMosaic_V01_E072_N24	5m/pixel TIFF	MRO CTX	Murray-Lab Caltech
ESP_081666_2080	1m/pixel TIFF	MRO HiRISE	NASA/JPL- Caltech/UArizona
MurrayLab_GlobalCTXMosaic_V01_E072_N28	5m/pixel TIFF	MRO CTX	Murray-Lab Caltech
Mars MGS MOLA – MEX HRSC Blended DEM Global 200m V2	200m/pixel TIFF	MGS MOLA	USGS Astrogeology
Mars Odyssey THEMIS-IR Night 60N60S Mosaic 100m V14	100m/pixel TIFF	Odyssey Orbiter THEMIS	USGS Astrogeology

### 3.3 Age dating of plateau

An estimated age calculation will be conducted between the northern lowlands and the southern highlands (plateau) to provide valuable insight into the geological surface evolution within the region. Crater Size-Frequency Distribution (CSFD) is a tool used to gather data for either relative or absolute age analysis on planetary bodies within our solar system. This is done by measuring the amount of crater impacts on the surface; an area of older age would exhibit both more as well as larger craters in comparison to a younger surface which hasn't been around long enough to have been bombarded by meteors (Oetting et al., 2023). By using the CSFD one measures across the rim of an impact crater and gathers the data, it works regardless of map projection, but a specific procedure is recommended to reduce distortion (Kneissl et al. 2011). The gathered data is then used in a mathematical function where the frequency of the craters and their relative sizes are compared, this will in turn output an age estimation (Oetting et al., 2023). It is important to note that the age is only a relative age date and not an absolute. Not all craters are equal and therefore some need to be excluded from this method (Platz et al., 2013), craters with no clear border and secondary impacts craters. Secondary impact craters are produced by the ejecta from the primary impact crater. Since it's difficult to separate secondary and primary impacts a method of consistency was used, if a clear rim was seen then the crater would be counted, if the rim had any other geometry than a circle it was excluded due to impact craters creating circular craters. The included craters might have had some faded/eroded rims, but this was kept constant throughout the data gathering; meaning that similar craters were recorded on all areas as long as they looked the same. Craters that were too eroded were excluded from the crater counting. Since its difficult to distinguish between the two types of craters, most effort was put into keeping the data gathering consistent throughout the three areas.

### 3.4 Software

The bulk of the geomorphological mapping has been carried out within ArcGIS PRO due to ease of use when creating a 3D-modell of the study area. The MOLA data was used as a base map to create spatial depth, this was then draped by the two CTX images which were combined by the tool 'Mosaic To New Raster' to create a seamless mosaic. The THEMIS data was used as an additional layer which could be toggled to gain a better understanding of the glacier extent within the study area. All the rasters were then clipped to fit into the study area to reduce the amount of data needing to be loaded.

The addon Crater-Tools were used with ArcMap and together with CTX data to identify and measure impact craters within the study area, both size and frequency of various impacts are recorded. Polylines are drawn for the highland, lowland and the glacial extent, within these three polygons, crater counting will occur. In order to create a CSFD the use of Crater-Stats was used, this program analyzes the statistical properties of the gathered data from Crater-Tools mathematically and estimates the surface age based on the gathered data.

### 3.5 Geomorphological analysis

Different geomorphological features that have different geological origins are sighted within the study area. Some of the structures and features can be connected to ones found here on earth, these terrestrial analogs can be used in conjunction with scientific knowledge of Mars to gain an insight into the landforms and the processes which have created them. The various landforms within the study area will be compared to known morphologies explained throughout the literature.

#### 4. Results

The Geomorphological mapping has yielded an insight into the Martian landscape of the Nilosyrtis area, showing a complex terrain with a long history of many various geological activities. The final map is shown in figure 5. The following sections will go into more detail about the various features found within this area.

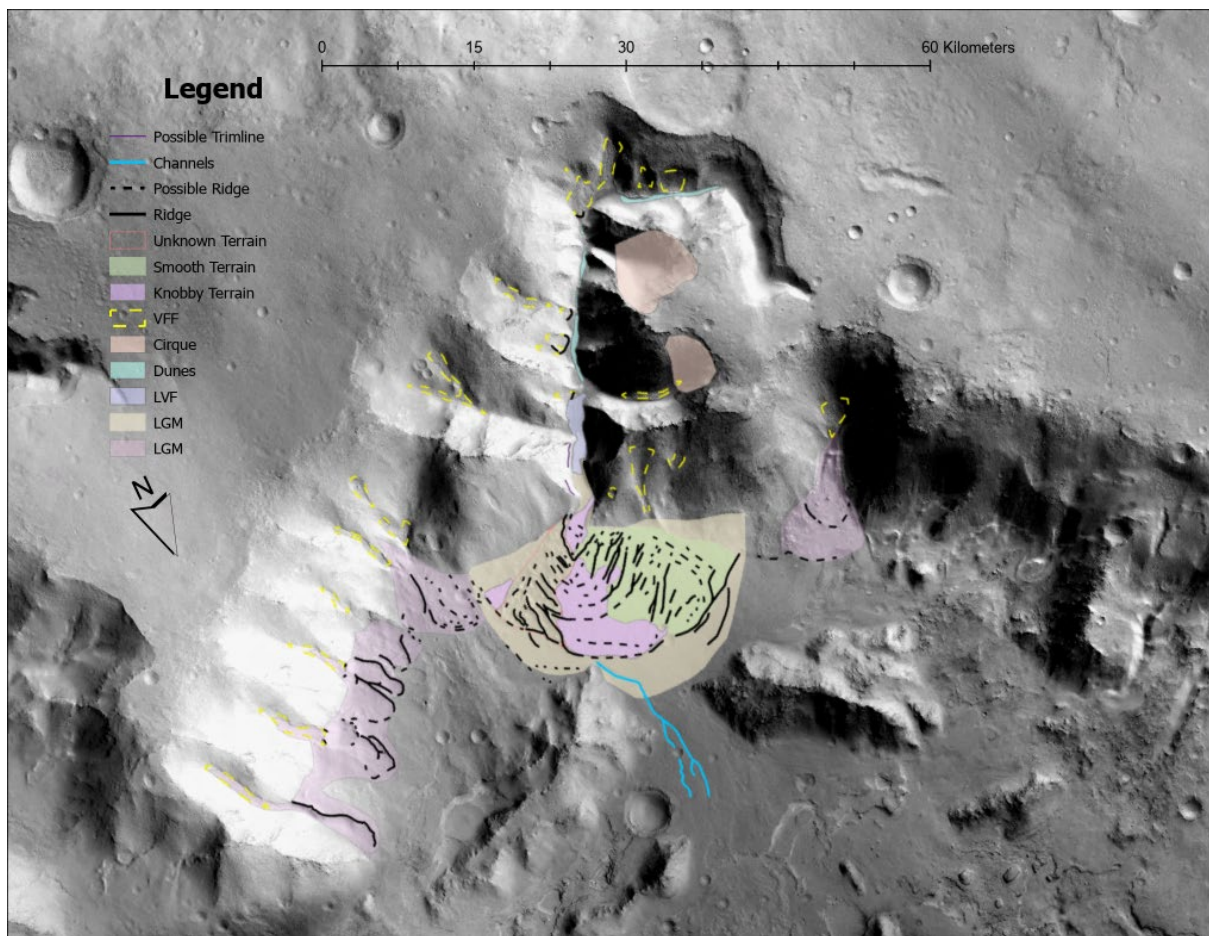


Figure 5: Showing the study area together with various different mapped landforms and terrain.

##### 4.1 Glacier extent

THEMIS night provides a good insight into the potential extent of the VFF which seems to be pointing towards a last glacial maxima (LGM) (on Mars) by comparing grainsize distribution (figure 6). By using the data provided from THEMIS in conjunction with mapped ridges as well as proposed ridges a map of the LGM can be created as seen in figure 6b.

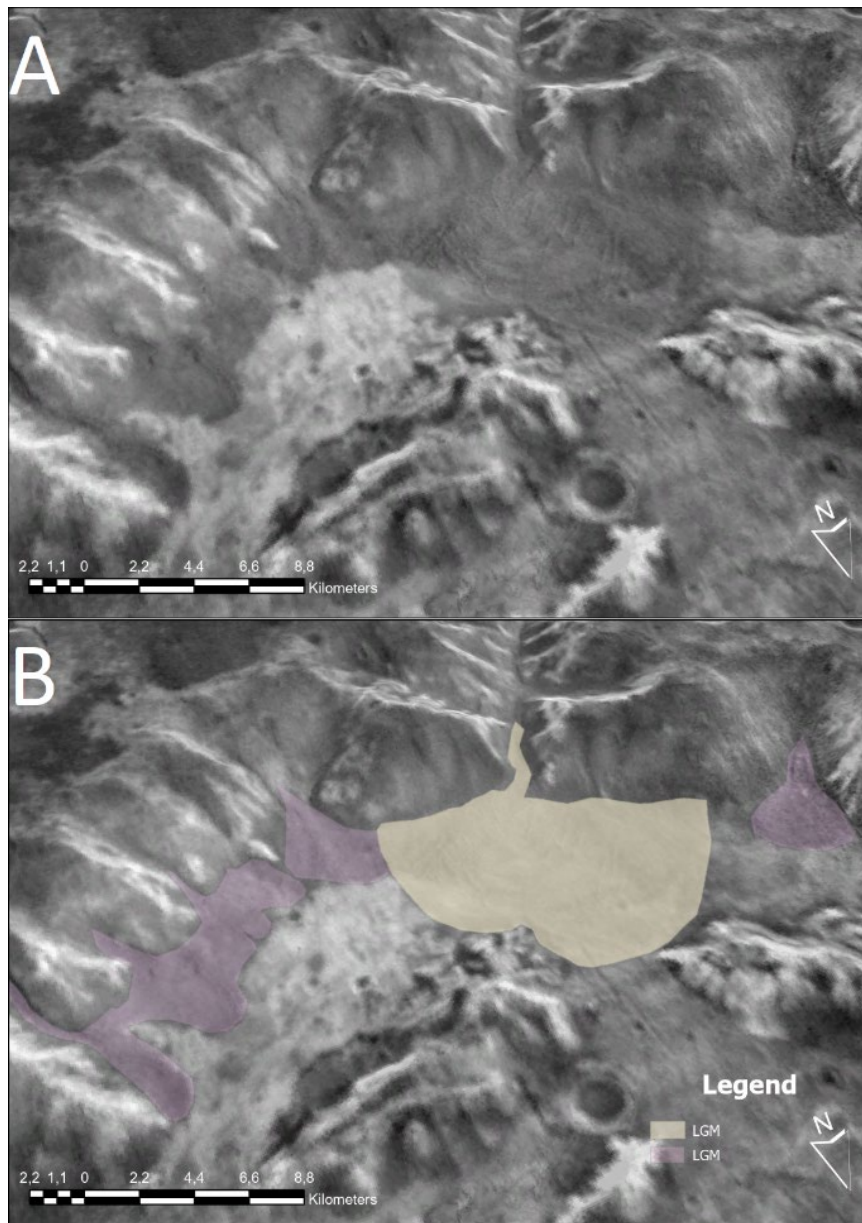
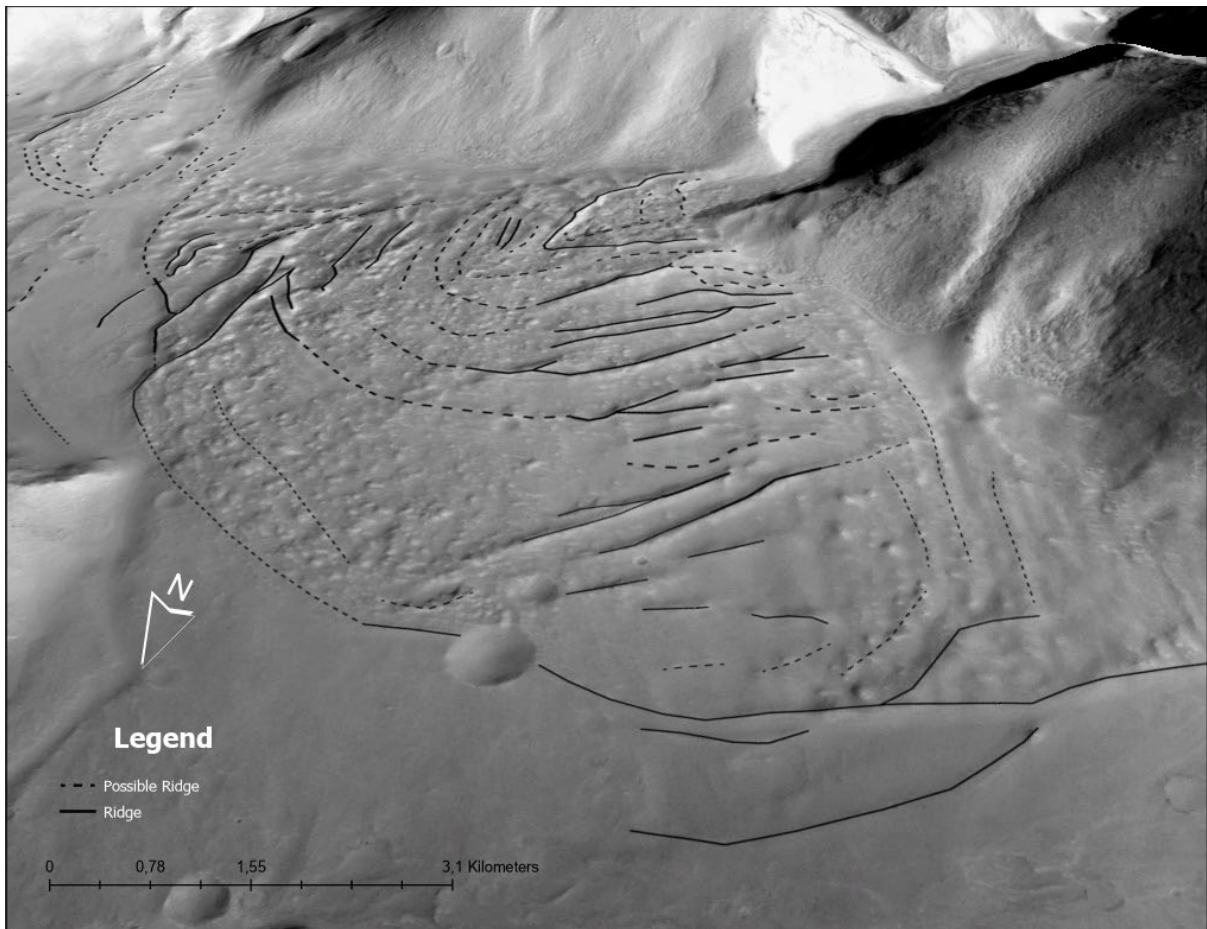


Figure 6. A) Showing THEMIS Night imagery of the study area together with a scalebar and north arrow. B) Showing THEMIS Night imagery together with the potential LGM based of THEMIS data, legend showing the various glaciers. Note that the scalebar is not accurate as this is not a top-down view.

#### 4.2 Ridges and potential ridges

Within the lobate structure there are ridges and what seem to be potential ridges, see figure 7. These ridges are possibly of glacial origin, meaning that they are some sort of moraine or eskers.

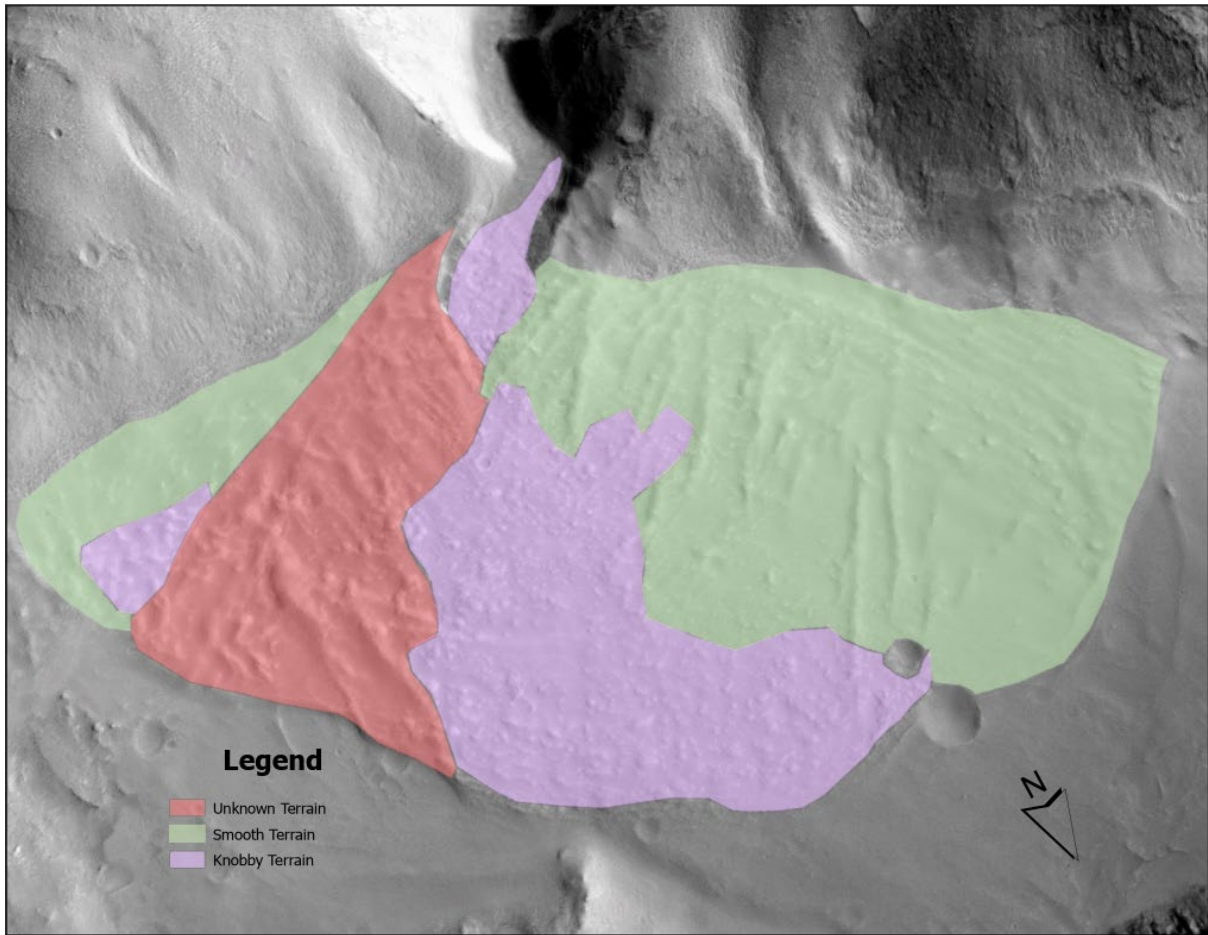
The Terminal moraine is the moraine we see furthest out on the lobate structure. It is possible to see that the glacier has retreated laterally as there are ridges connecting and entwining each other as seen in the figure.



*Figure 7: Ridges and potential ridges seen within the glacial area.*

#### 4.3 Terrain

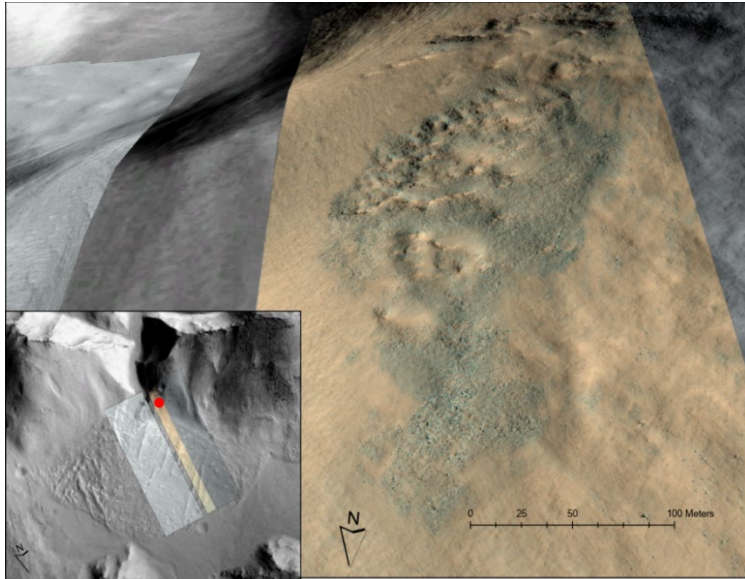
The lobate structure can be categorized into various different terrains based on surface 'texture' as can be seen in figure 8. The western side is dominated by a smoother surface texture with few knobs and mounds between the ridges. The 'middle' part of the lobate structure can be classified as knobby or hummocky terrain with its distinct mounds protruding and giving a distinct texture to the surface. The last area is the eastern part of the lobate structure. This area has a complex terrain that is difficult to describe due to the lack of tectonic activity, ridges are cross cutting one another in various, and perhaps somewhat organized, orientation with the exception of a few that borders the eastern smooth zone. These zones could show proof of overprinting as there seems to be a specific order to the zones.



*Figure 8: Showing 3 distinct terrains within the lobate area by the valley outlet. Green represents smooth terrain, purple represents knobby terrain and red represents a complex terrain which is unknown.*

#### 4.4 HiRISE

The spatial resolution of HiRISE data gives greater detail which provides a more detailed analysis of the area. Smaller aeolian ripples can be seen throughout the area, towards the valley entrance they have a cusp-to-cusp distance of roughly 5 meters. Boulders of various sizes are seen spread out across the lobe. One potential boulderfield-like terrain can be seen in figure 9. The sharp contrast between the boulderfield-like terrain and the smoother terrain is clearly visible. Towards the West within the smooth terrain section features similar to pitted terrains are noticed, the image in figure 10 has been modified by the change of gamma, contrast and brightness in order to bring forth the sharpness of these structures within the image.



*Figure 9: Showing boulderfield-like terrain on HiRISE data together with an overview of HiRISE area and area of interest.*



*Figure 10: Showing possible pitted terrain within the HiRISE data. Gamma, contrast and brightness has been modified to 'sharpen' and bring out the features better.*

#### 4.5 Glacier Retreat

As there is no visible ice within the study area and only GLF which could pose as possible glacial remnants, a suggested glacial retreat can be estimated based of observed ridges and potential ridges. An assumed map of the possible glacial retreat is presented in figure 11.

The Glacial retreat of the main body, including its valley outlet and tributaries, has been prone to a more lateral retreat as can be seen by the ridges which are connected to the northern tip of the glacial terminus of the glacial expanse. Several smaller ridges connected to a larger ridge suggest that there has been a retreat by lateral shrinkage.

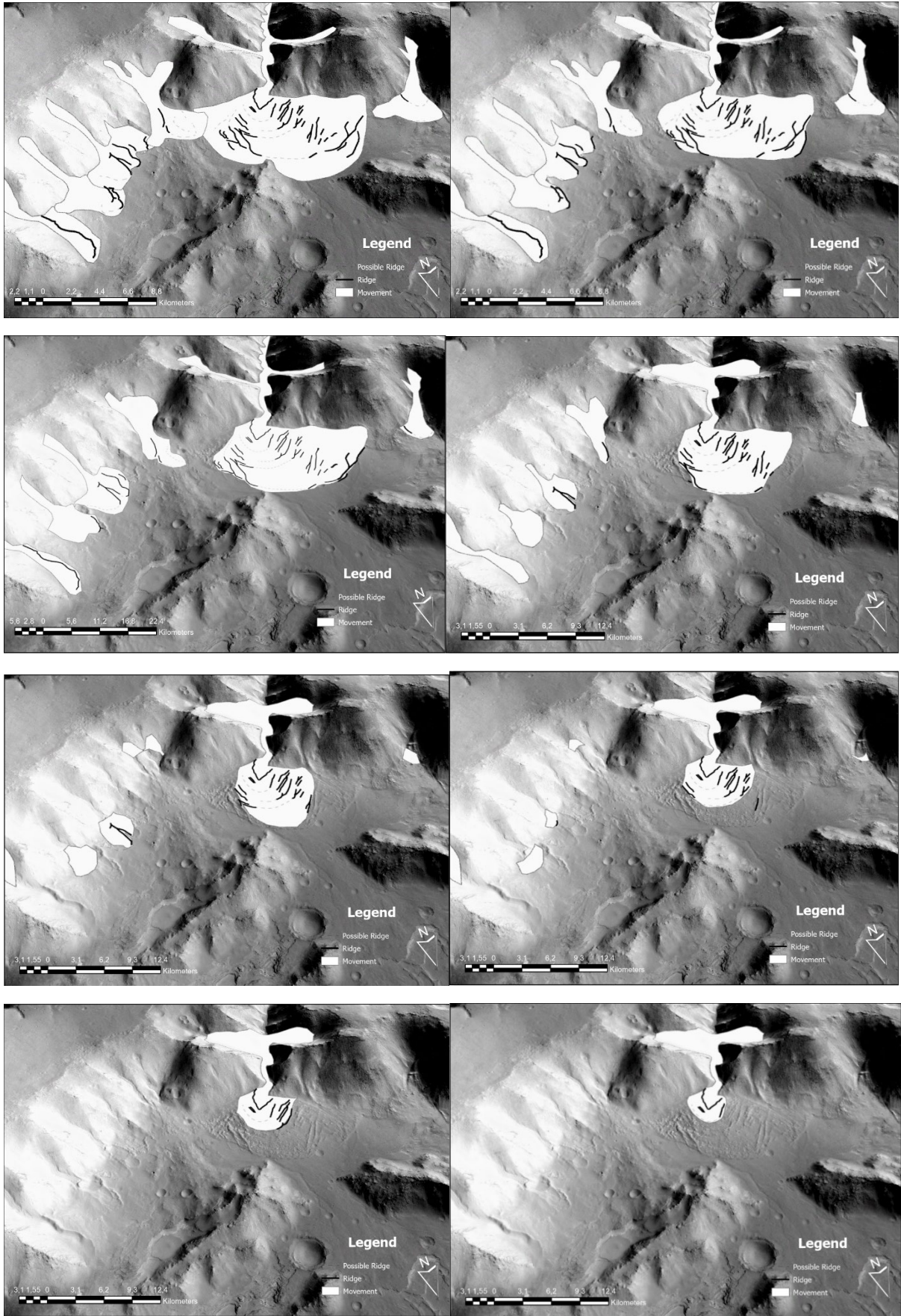


Figure 11: From Top Left to Bottom right (1-8) figures showing an assumed glacier retreat based on ridges and potential ridges which has been observed within the study area as well as through THEMIS. Note that the scalebar is not accurate as this is not a top-down view.

#### 4.6 Potential connection and outflow channel

At the terminus of the glacier, it is possible to deduce a form of VFF or channel running downslope and further into the lowlands. This channel is most likely related to the movement of liquids and might even give insight into the history of the area. The channel is shown in figure 12. This type of erosion might have been caused by liquid from the glacial retreat or perhaps by the creation of this valley.

Figure 12 also shows the valley ridge that serves as a boundary between the higher elevated highlands and the lower lowlands. It is easy to assume that this ridge was once flat and that there was no valley or channel cutting through the highlands and down into the lowlands. A closer image can be seen in figure 13, where 'A' can be connected to 'B'. Even though there is erosion on both sides they are nearly the same height at roughly 430 meters above the Martian datum.

In these figures we also observe what seems to be truncated spurs, which might have been formed by either glacial or fluvial processes. These landforms indicate that the area has undergone substantial erosion. When a glacier moves through a valley it erodes the valley sides, or spurs, and truncates them, creating steep and abrupt triangle-shaped walls as seen in the figures.

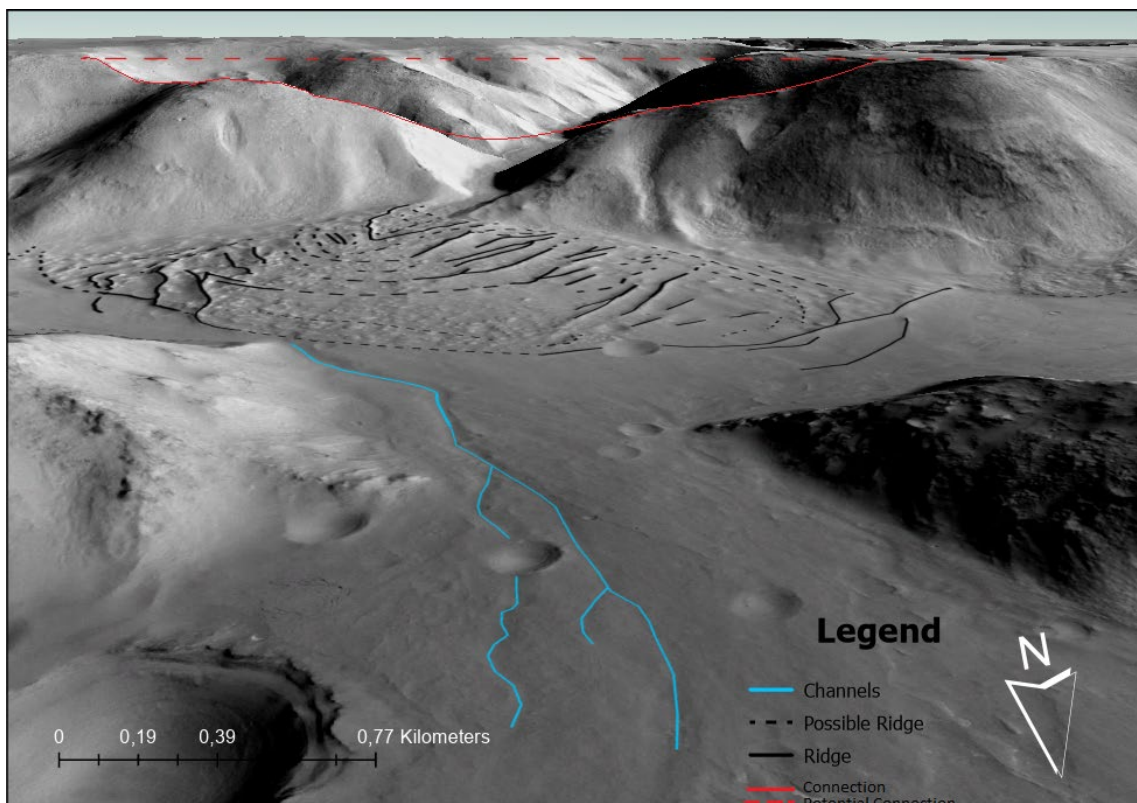


Figure 12: Showing how a possible channel has eroded the lowlands together with the glacial extent denoted by the ridges/potential ridges as well as a possible connection between the two truncated spurs. Note that the scalebar is not accurate as this is not a top-down view.

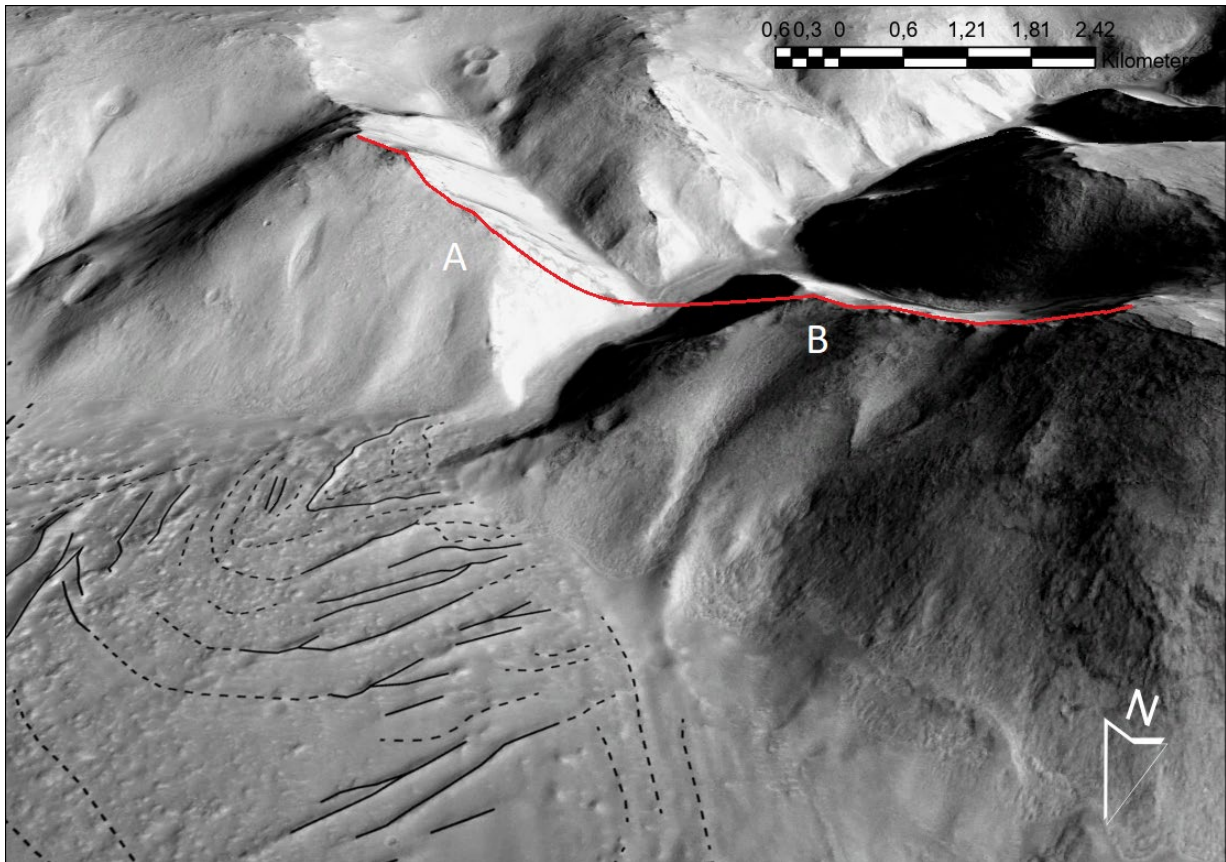


Figure 13: Showing the outlet valley together with a north arrow, scale and ridges/potential ridges. The red markings show how the valley might have been connected between point A and point B. Note that the scalebar is not accurate as this is not a top-down view.

#### 4.7 Valley

The valley is built up by tributary valleys that feed a main channel that leads out into a lobate structure on the lowlands. Within the valley many various structures can be found. Structures that seem like terrestrial dunes can be seen by following the valley-floor towards the south (figure 14). These dunes have an east-west orientation with a spacing of roughly 120-meters apart and seem like transverse dunes. These dune-like structures are perpendicular to the valley system and can also be seen further down the valley, towards the valley outlet.

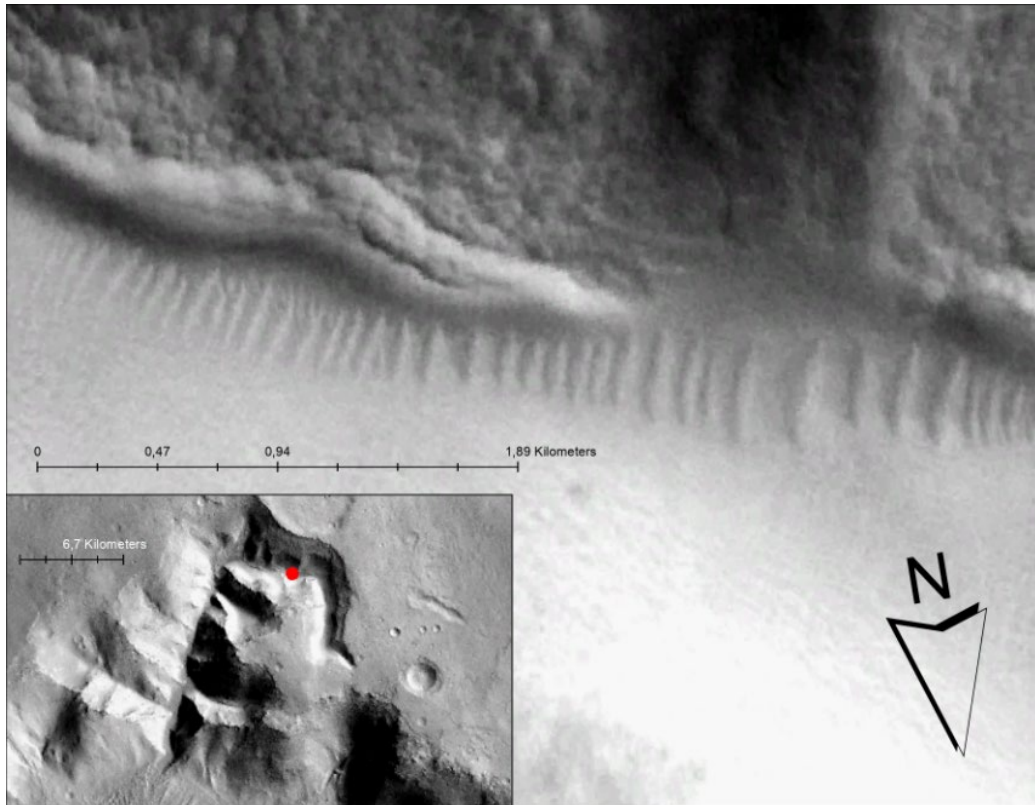


Figure 14: Showing dune-like structures within the valley floor with a rough spacing of 120-meters apart from one another. A red dot is shown in an overview map to clarify the location of the shown dunes.

In figure 15 we can see the remaining dunes mentioned earlier, the spacing between crests are decreasing as we move towards the valley entrance, it drops down to roughly 110m and then the last section becomes 80m apart. All the dunes seem to follow the previously mentioned formula of staying perpendicular to the valley walls. In this figure one can also see LVF, though not as prominent as other examples from Mars, they are still visible as streaks running parallel with the valley, these viscous flow features can only be observed near the valley entrance. Next to the entrance, on the sidewalls of the truncated spurs we might get a hint of something resembling trimlines, however these lines are very thin and with no trimzone visible. Ridges are found on the valley walls signifying past movement and might be associated with the glacial retreat.

Figure 16 shows the previous ridge lines and two distinct features, VFF and possible cirque glaciers remnant. The VFF which are found within the tributary valleys could signify areas where niche glaciers have occurred as these tributaries lack the geomorphology to be categorized as cirques. There are also two tributaries which can be classified as cirques due to the distinct geomorphology visible.

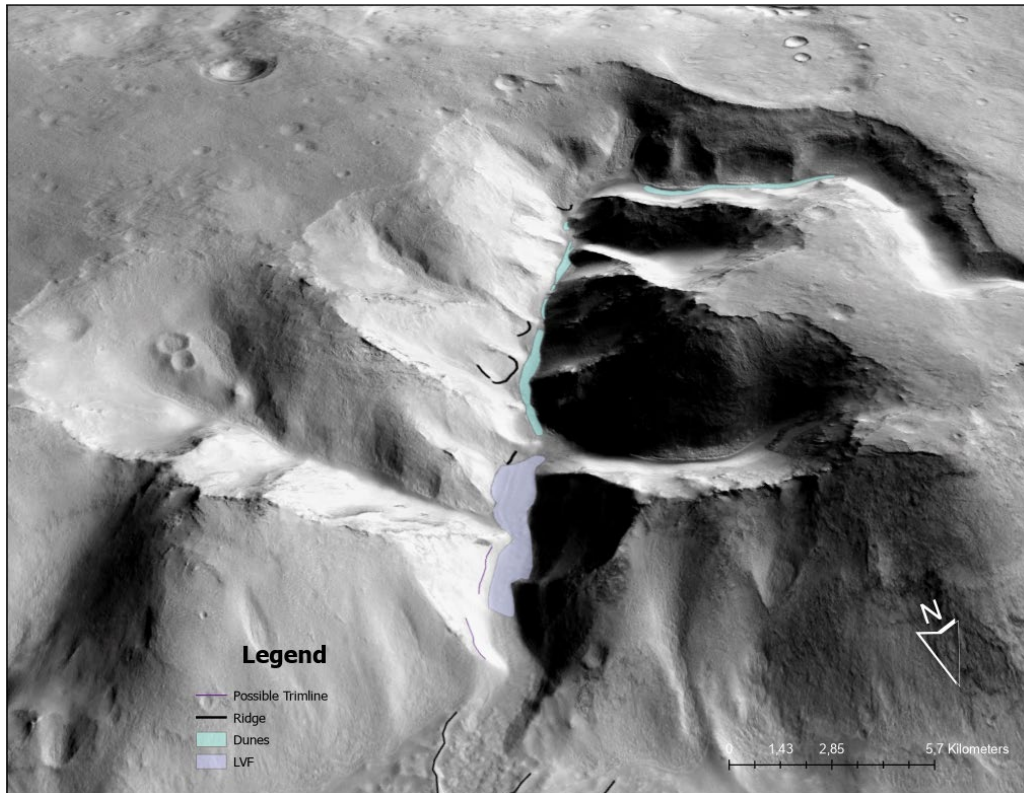


Figure 15: Showing locations with ridges together with areas of dunes, LVF and possible trimlines within the valley.

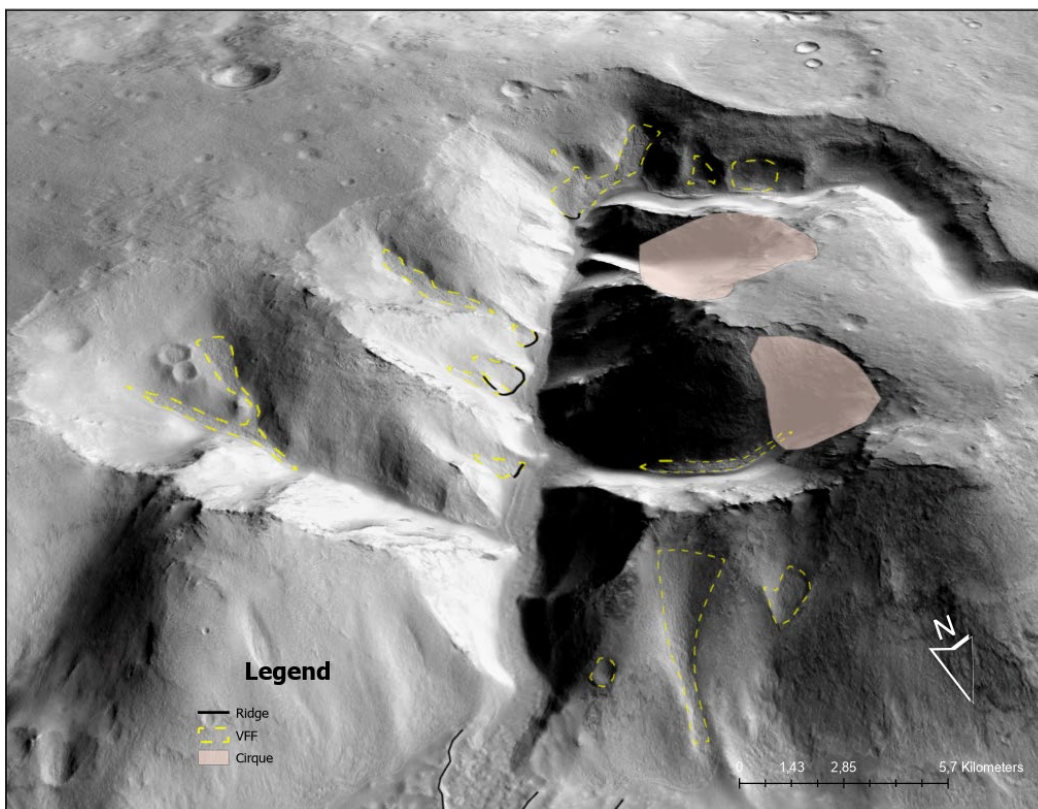
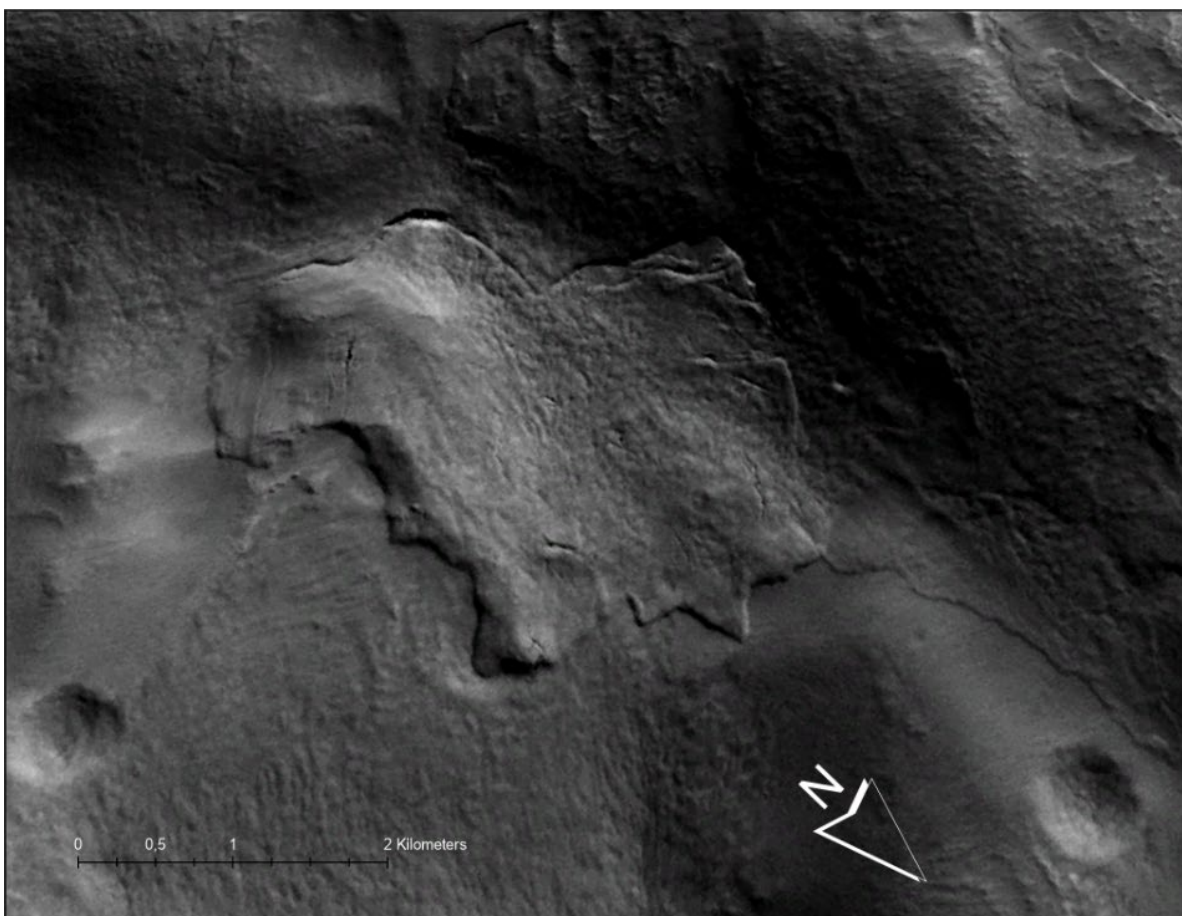


Figure 16: Showing previously shown ridges in conjunction with possible areas of past cirque glaciers as well as VFF connected to the tributary valleys and on the valley outside.

#### 4.8 Features in close proximity

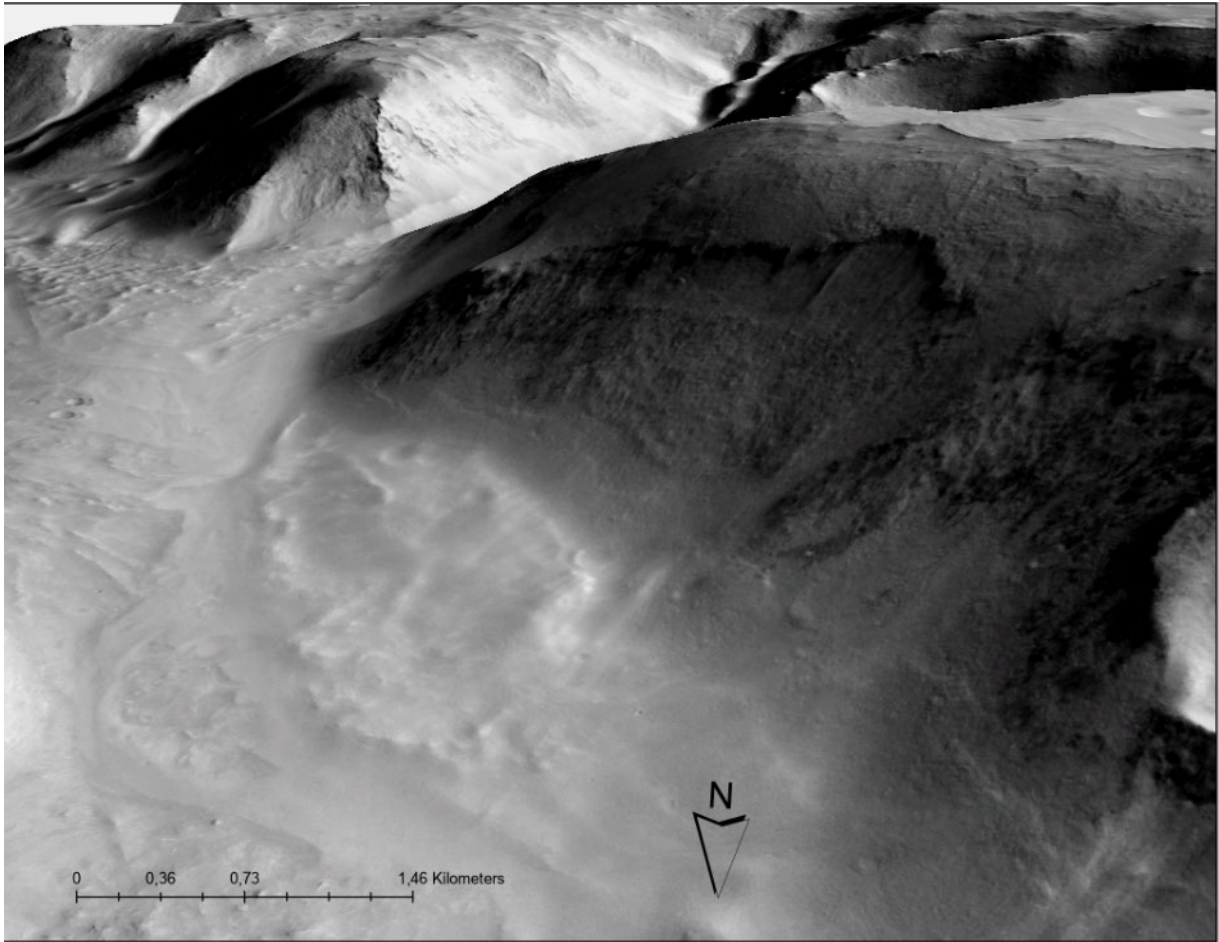
There are many various geological features in close proximity to the study area, many of these structures found throughout the landscape have been discussed or mentioned previously, some more varied and interesting features will be shown in this section. Overall, there are many VFF that indicate some type of flow throughout the area and on the slopes of the dichotomy, however no larger LVF have been observed across the lowlands. There are also no significant findings that would suggest signs of tectonic activity within the area.

In figure 17 we can see a large coherent mass which has been shifted down-slope. This mass seems to be a sort of slide block where the mass moves as a single unit. The unit seems to have shifted roughly 100 meters from its original point and encompasses an area of roughly 10 kilometers.



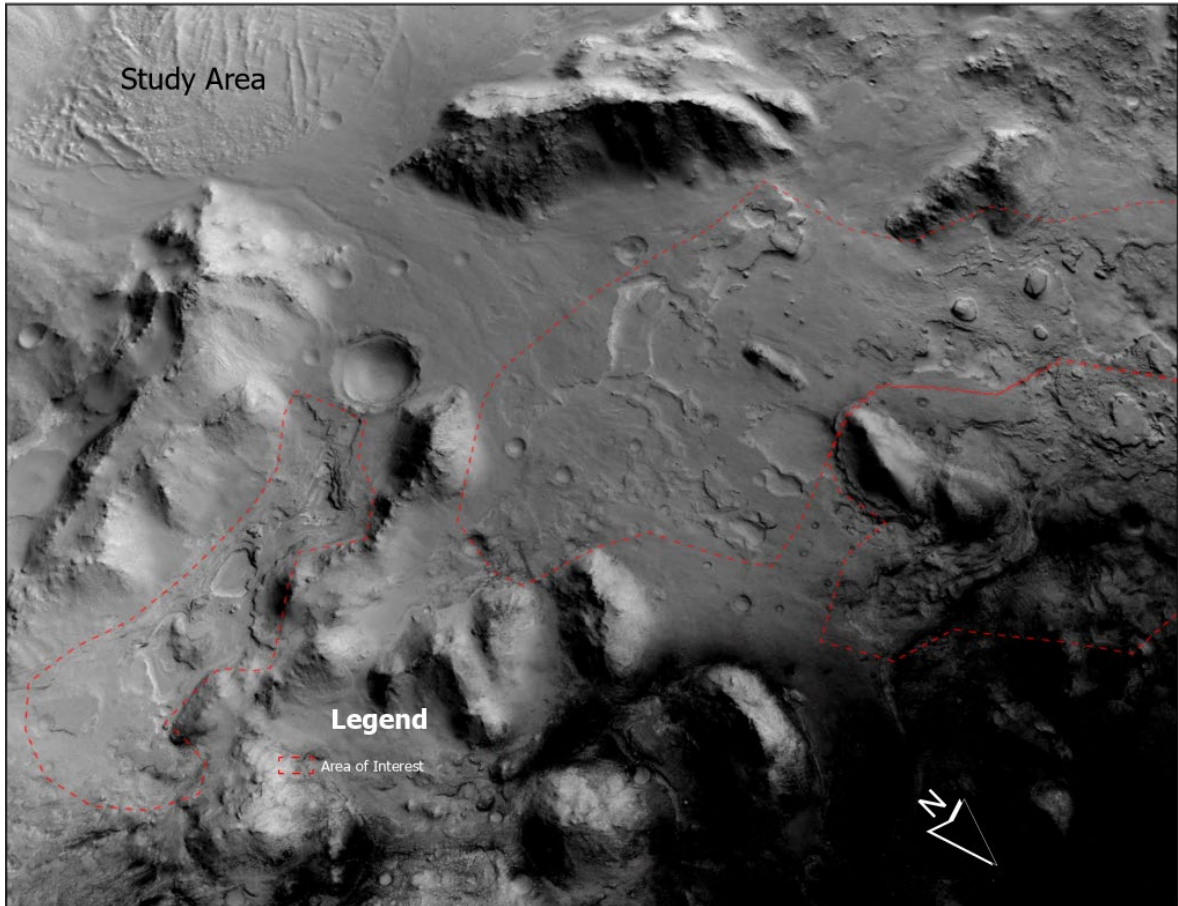
*Figure 17: Showing slide block. Mass movement down-slope, west from study area.*

Displaced material, or landslides have also been recorded within the study area. Figure 18 is located towards the east of the study area, when following the distinct dichotomy. In this figure it is possible to see the main crown where material is still in place. Towards the bottom we can see debris that has accumulated from past events with the material fanning out across the lower plain in three distinct sections.



*Figure 18: Showing a landslide east from the study area.*

Figure 19 gives insight into the complexities of the area. Situated north, roughly 20 kilometers from the terminus we find layered step-like features that look like terraces. This area might give insight into some complex sedimentation process where the various different terraces could represent different depositional periods. Some of the terraces create pits where eolian ripples can be seen. Within the image there are also several eroded craters.



*Figure 19: Showing landscape with various surface layers, showing that the area is very complex. Can also find several eroded craters*

#### 4.9 Age determination

Age dating was carried out on three areas, highland, lowland, and the outflow area (glacier). Figure 20 shows the three different areas together with all the craters counted. In the lowlands 198 craters were counted, the glacier had 16 craters and the highland a total of 492 craters within the pre-determined area of crater counting.

It is important to note that large impacts can remove previous impact craters, especially if it is in an area of higher age that has been susceptible to many impacts of various sizes. The crater counting by the glacier might also have had fewer impacts due to shielding of the plateau that towers roughly 2.8 kilometers above, this gives rise to fewer impacts which can land in this specific area. Overall, it is important to not take the following age estimations as an absolute date but more like something in between with relative age dating and possible large uncertainties. However, this method goes beyond the scope of this thesis.

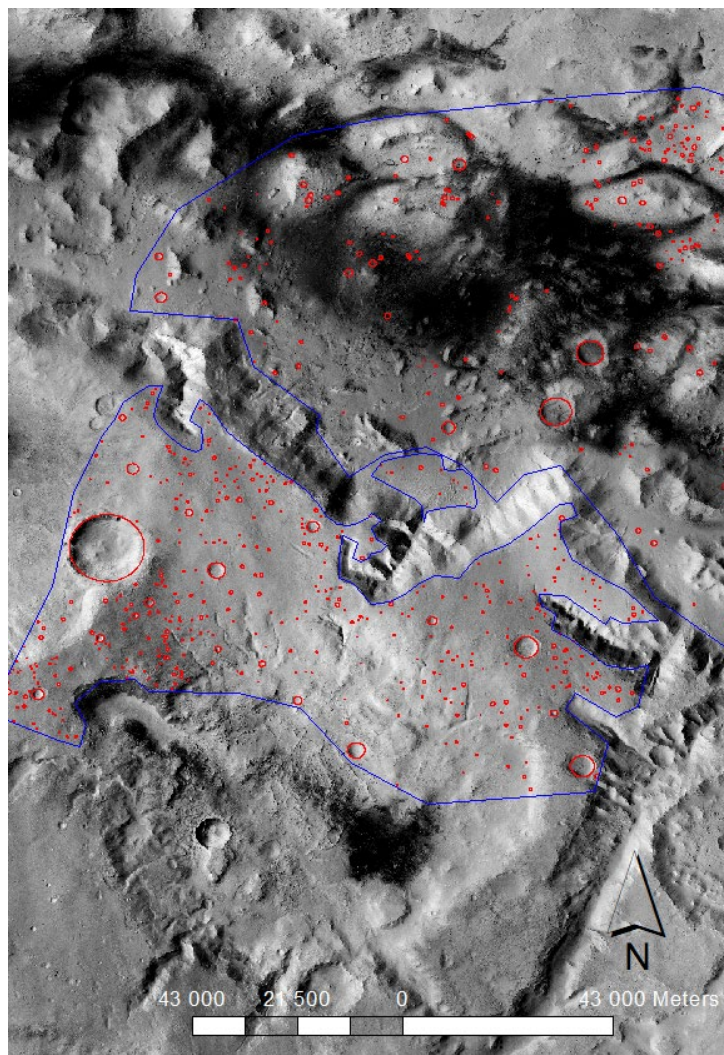
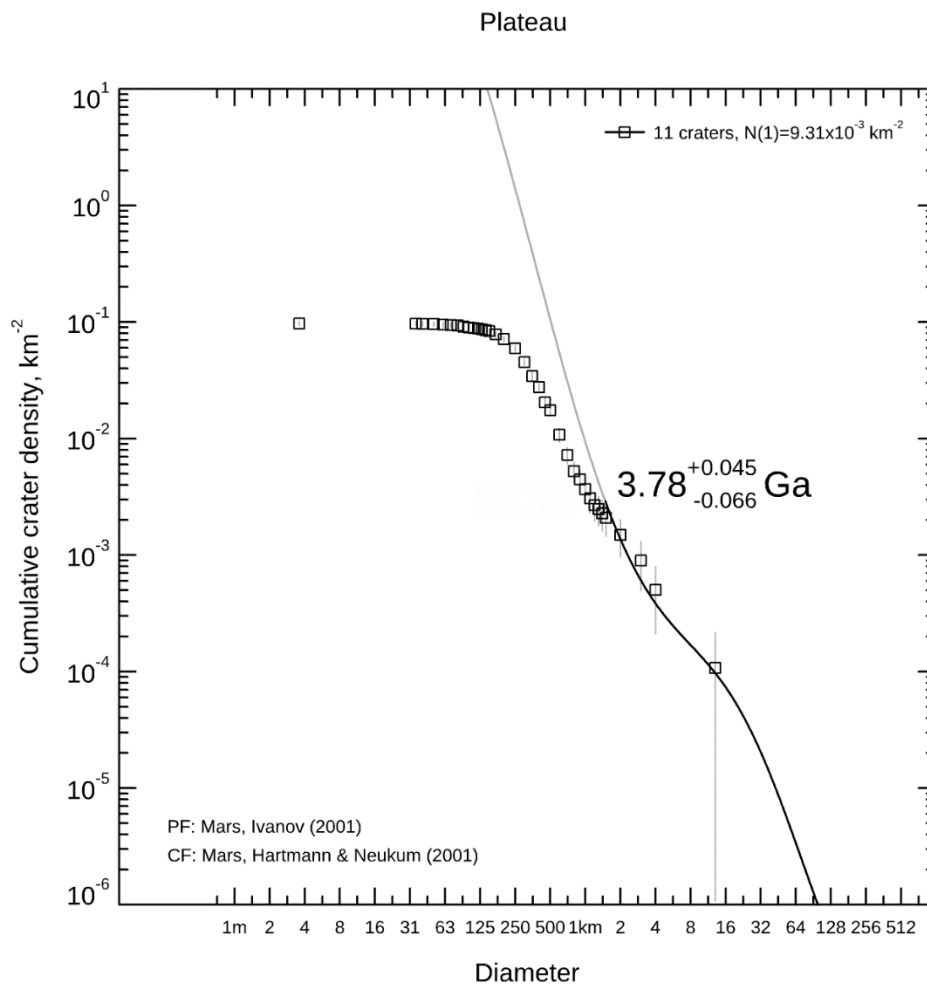


Figure 20: Showing the 3 areas surrounded by blue polyline, the highland (south), Outflow area (middle) and the lowlands (north). Also showing all the measured craters in the color red. The total crater count accumulated to 706.

#### 4.9.1 Age determination of highland

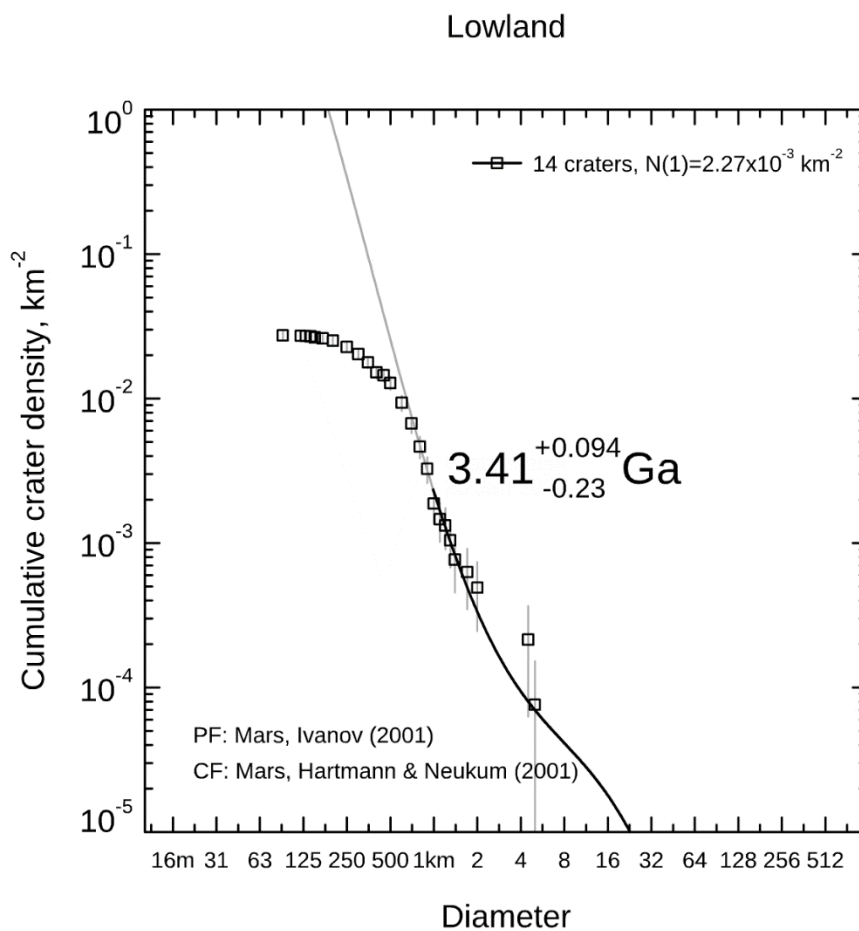
The highland shows a high age of approximately 3.78 billion years which can be seen in graph 1. By looking at Martian eons in figure 2, it is possible to place the highland to be of the Nochian eon. When looking from further away one can see that there are massive impact craters that seem to have been eroded, one of which the polylines run through. These massive craters seem to span over 100km in diameter, and if included might change the approximate date of the highland and even put the plateau into the pre-Nochian eon.



Graph 1: Showing an estimated age date of the Highlands/plateau together with diameter of the craters and the density of the respective diameters. The age is estimated to be 3.78 billion years.

#### 4.9.2 Age determination of lowland

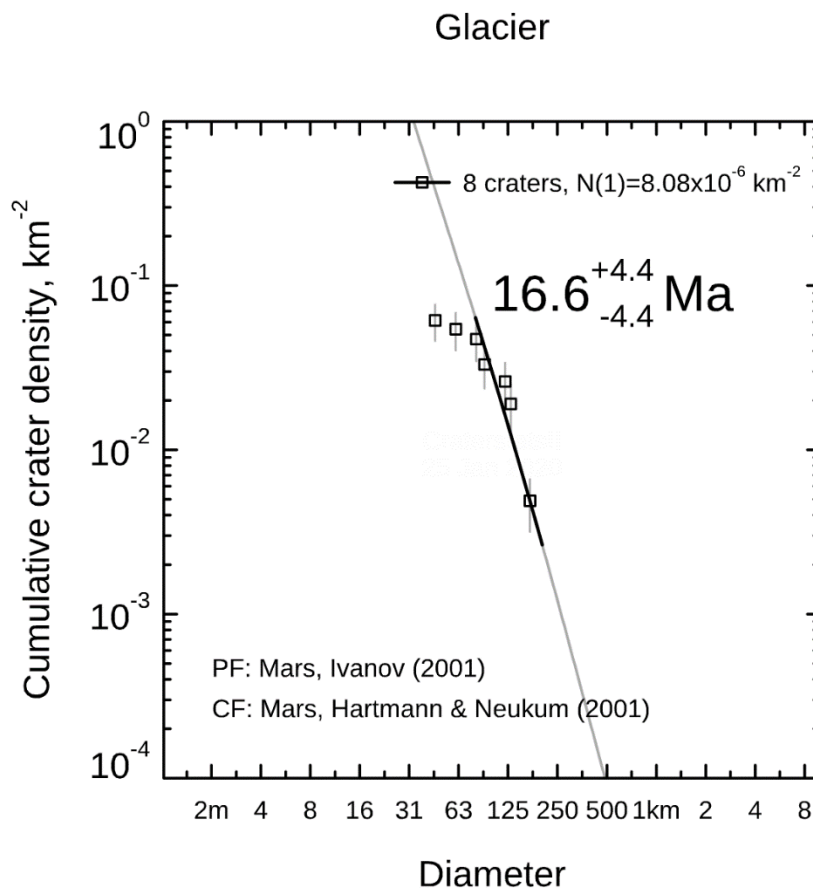
By analyzing 198 craters within the polyline of the lowlands an age estimation of 3.41 billion years was formed, as can be seen in graph 2. This puts the lowland in a younger eon compared to the highland as it falls into the Hesperian eon. The area does not boast larger crater sizes in conjunction as well as in proximity of the polyline which signifies that the lowlands are younger than the highlands. The data used shows a blanket of dark shadow that covers quite a large area within our polyline, as seen in figure 20, these are areas where more craters can exist and be used for a better dating.



Graph 2: Showing an estimated age date of the lowlands together with diameter of the craters and the density of the respective diameters. The age is estimated to be 3.41 billion years.

#### 4.9.3 Age determination of glacial remnant

The age of the glacial remnant is approximately 16.6 million years old, as seen in graph 3. This age should represent the age when the glacial retreat occurred and happened in the late Amazonian. It is important to remember that there are few craters within this polyline and therefore the result will be less accurate. However, the difference between the ages of both the highland and lowland in comparison to the glacial area is so great that there is no contest as to which order they fall into.



Graph 3: Showing an estimated age date of the glacier together with diameter of the craters and the density of the respective diameters. The age is estimated to be 16.6 million years.

## 5. Discussion

### 5.1 Study area

THEMIS night has been an important addition to better understand the study area and the presence of glacial activity. By using THEMIS the potential glacial extent has been verified. The THEMIS night image (figure 6) does however not show consistent results with ridges observed in figure 7. There are no ridges at the outskirts of the LGM when looking in the same orientation as the possible channel (see figure 5). Perhaps THEMIS might be showing features from an even older glaciation prior to the current one, with ridge features being eroded over time. But the more likely cause is that there have been depositional features such as shallower outwash planes (compared to the mapped channel) that have been eroded (or not visible due to the spatial resolution of the CTX data). Despite these inconsistencies it is highly certain that the data from THEMIS shows a clear boundary that can be connected to the lobate structure flowing out from the valley entrance.

The lobate structure contains various ridges. These potential ridges appear as various mounds which systematically follow a specific orientation that suggests a ridge system which might have been eroded over time. With knowledge of there being past glaciations within mid-latitudes and the observed structures it might be reasonable to hypothesize that these ridges are of glacial origin. The GLF, or moraine as we now assume, fit well with the lobate shape and supports the theory of a glacial retreat with recessional moraine, something that was already assumed by Johnsson et al., (2019). Several recessional moraines are observed on the lateral sides of the lobate structure, there are also intertwining moraine structures which could help indicate a sequence of glacial retreat. These intertwining structures might suggest a faster lateral retreat. The Terminal moraine appears to have been eroded in the area of the channel (apex of lobe). By looking at figure 7 it is possible to see that the erosion is mainly centered in the central part of the lobe, denoted by the dashed lines, following an invisible line from the channel to the valley entrance. This might provide insight into the glacial retreat since these ridges have been eroded, material and liquid might have helped to erode this specific area quicker.

The lobate structure exhibits various terrains as can be seen from figure 7 and 8. These variations in surface textures can be divided into three distinct textural categories and can give a good insight into the past dynamics of the glacier. The smooth texture appears to have few mounds when viewed through the CTX data, however when looking thorough the HiRISE data with a higher spatial resolution it is possible to see smaller blocks and mounds present, however, still smooth when compared to the knobby terrain. This smoothness may result by liquids filtering and redistribution the larger blocks towards the terminus. Since there seems to have been a significant glacial retreat on the western lateral side of the glacier as indicated by the angled ridges pointing towards the terminus, suggests that the glacier retreated faster laterally than longitudinally, causing the redistribution of material to be pushed towards the terminus. However, is an assumption based on the current data, and further investigations could clarify this smooth-like terrain. Another terrain is the knobby or hummocky terrain. This area of terrain is indicative of the recessional moraines mentioned prior, the surface texture suggesting multiple stages of glacial advancement and retreat as a cause by irregular deposition of glacial material. The third type of terrain is the “unknown terrain”, Johnsson et al., (2019) describes this area as “wrinkle terrain” which truly defines the area as it has ridges of various sizes intertwining and extending in different directions, the texture resembles a rug which has been compressed, reflecting complex depositional and erosional processes. It is possible to

assume that the different terrains, or zones could have occurred in different phases. The Green phase seems to be the underlying and perhaps even be the first terrain, the second one would be the purple terrain and thirdly the red terrain. This is assumed by noticing that the purple layers seem to have been laid out on top of the green terrain while the red terrain has been laid out on top of the purple terrain.

The HiRISE dataset shows that the terrain is knobbier than previously thought. Various aeolian ripples scattered around the mounds and moraine-like structures. Boulders of different sizes are also scattered all over with two areas of high concentration. The first area can be seen in figure 9 where boulders of various sizes are clustered together within a smoother textured area. The second is located near the valley entrance, where a boulder path stretches for approximately 2kilometers. This is of interest as the boulders are within a straight column with the heading of north-east. The surrounding area shows no sign of a similar “migration” of boulders. This boulder column also crosses over mounds and ridges while continuing their straight path further down the lowlands. This could be due to debris falling onto or carried by the glacier and during retreat and melting of the glacier the debris was laid out in this linear pattern. Another interesting feature can be found within figure 10 where pitted terrain-like features can be observed. These pitted features may result from the sublimation of subsurface ice, as the ice sublimates the overlying material collapses, creating depressions similar to the ones seen in this figure.

The Glacial retreat is an interpretation of the glacial movement during its retreat. It is based on the various moraine-like structures found within the lobate. Another assumption, which might be more plausible, would be the same type of retreat as seen within figure 11, but with less glacial loss on the eastern side. The reasoning behind this is the “unknown terrain” or as we now call it, the wrinkled terrain. Based on the accumulated masses it would be more appropriate to assume that the glaciers toe was shifted into this direction when the initial glacial retreat began, another evidence for this can be observed at the valley entrance where there is a steep ridge on the western side which gives the possibility for the interpretation that the ice moved and was retained for longer within the eastern side as this side could have been prone to higher glacial movement.

At the terminus there runs a channel which extends out and into the lowlands. There are no other channels visible within the study area which suggests that other channels have either been eroded away or are not detectable by the spatial resolution of the CTX camera. This channel may have existed prior to the glaciation event, possibly formed during a period when ice or liquid water created the valley system. Over time this system might have evolved and been modified by the channel. However it is more likely that this channel remnant is associated with past glaciation. While this valley system grew several glaciations could have taken place, eroding the valley further. As there are no channels that resemble this one on earth one could also assume that there was once a braided stream which has since been eroded. Evidence for several past glaciations may be inferred by the truncated spurs by the valley outlet, several glaciations would have been needed to create these large spurs, or a single glaciation of larger magnitude. However more information of the past glaciation is needed, information regarding its erosive prowess by gathering information regarding its accurate size, thickness, duration and the erosive properties of the bedrock.

Within the actual valley aeolian ripples can be observed, these are found further away from the valley entrance, however, based on the small aeolian dunes found in HiRISE images in the lobate structure, it can be assumed that there are smaller dunes present throughout the valley system of which the spatial resolution of the CTX camera is unable to visualize. HiRISE imaging for the valley system could show more details regarding potential trimlines that might be sighted at the valley entrance. These trimlines could provide a better understanding of the glacier height and erosive power. The valley system is a great way to get a better understanding of the type of glacier that might have been. There are two distinct valleys that have been scooped out, something that signifies that cirque geomorphology. The other tributary valleys could represent niche glaciers. These two glaciers likely combined to create a valley glacier which upon exiting the valley entrance expanded into the open plains, creating a piedmont glacier that resulted in the lobate structure seen today.

### 5.2 Close proximity

Various geological features are present close to the study area. Features such as slide block and landslides. However, something more interesting is found north from the study area which could indicate the complexities of the Nilosyrtris region. The area 20km north shows terrace like features which may represent various depositional periods and overprinting, as discussed in Levy et al., 2007 paper of Nilosyrtris Mensae. This shows how complex the area is where layers from various timeframes can be found and exposed. These terraces may be exposed due to lack of erosional strength from the overlying material and or erosional processes from liquids from past glacial retreats.

### 5.3 Age Determination

Age dating from the three areas provided coherent results with expectations and geological eons on Mars. The highlands were dated as the oldest area falling into the Nochian eon, however, it is possible that this area is of older origin as there are larger craters visible on the plateau, spanning over 100kilometers in diameter which were not included into the crater counting. To get better accuracy, the polyline would need to be extended. The lowlands fell into an eon of younger age which was expected, there might have been ice or an ocean protecting the underlying surface from registering impacts. The age dating of the lobate structure shows a stark contrast in age compared to the two other areas. It is true that due to fewer impact craters the accuracy is less reliable. A reason for less impact craters can be due to the steep wall that creates the distinct dichotomy, this might shield the area somewhat from the potential meteorites. The age of the glacial area fits well with the Amazonian eon where the obliquity exceeded the value of  $45^\circ$ , providing favorable conditions for glaciers. Moreover, the recognition of glaciations from around this timeframe is stated in Conway & Mangold., 2013, where they mention the connection between high obliquity and the deposits within craters, relating them to events of at least 5 million years ago. There might be large uncertainties, but it still provides an excellent results for showing the chronological order by very old and very young areas.

### 5.4 Conclusion

As Mars has a varied climate compared to earth, even if geomorphologies are similar to terrestrial ones, it is not possible to be perfectly certain of the origin of their creation. However, the parallels

can help provide meaningful insight into what might have happened within this specific area and further help to get a better understanding of the planet Mars.

The observed features within this study show that with great certainty has been a glaciation within the valley system as well as outside the valley system. The Valley has geomorphological features resembling cirques and niche glaciers. The LVF also shows that there has been viscous flow. Together this data proposes that the lobate structure which extends from the valley entrance is of glacial origin and could be a piedmont glacier.

THEMIS data provided insight into the size of the potential glacier and together with ridges and potential ridges by aligned mounds, helps draw parallels to the terrestrial moraine features, recessional moraine.

The area is overall very complex as shown by the various landforms and features presented throughout this study, specifically with overprinting features from the observed terraces just north of the study area.

#### 6. Uncertainties

The age dating of the various areas is a difficult thing, as it was hard to distinguish between secondary and primary impacts. The lack of craters found within the lobate structure might be too few to show statistical significance.

#### 7. Further research

The addition of HiRISE data for the valley would be significant as more features would be able to be observed, trimlines on the valley entrance walls for one.

Studying the dichotomy boundary could further help humanity understand processes which helped shape Mars.

Using data from SHARD and CRISM to investigate the subsurface as well as the mineralogy within the area could further help solidify the glacial theory of the area.

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## Appendix

### *Data*

Mars MGS MOLA – MEX HRSC Blended DEM Global 200m V2

[https://astrogeology.usgs.gov/search/map/Mars/Topography/HRSC\\_MOLA\\_Blend/Mars\\_HRSC\\_MOLA\\_BlendDEM\\_Global\\_200mp\\_v2](https://astrogeology.usgs.gov/search/map/Mars/Topography/HRSC_MOLA_Blend/Mars_HRSC_MOLA_BlendDEM_Global_200mp_v2)

Mars Odyssey THEMIS-IR Night 60N60S Mosaic 100m V14

[https://astrogeology.usgs.gov/search/map/Mars/Odyssey/THEMIS-IR-Mosaic-ASU/Mars\\_MO\\_THEMIS-IR-Night\\_mosaic\\_60N60S\\_100m\\_v14](https://astrogeology.usgs.gov/search/map/Mars/Odyssey/THEMIS-IR-Mosaic-ASU/Mars_MO_THEMIS-IR-Night_mosaic_60N60S_100m_v14)

Unusual Moraine-Like Ridges: ESP\_081666\_2080 (NASA(JPL-Caltech/UArizona)

[https://www.uahirise.org/ESP\\_081666\\_2080](https://www.uahirise.org/ESP_081666_2080)

MurrayLab\_GlobalCTXMosaic\_V01\_E072\_N24 & MurrayLab\_GlobalCTXMosaic\_V01\_E072\_N28

<https://murray-lab.caltech.edu/CTX/V01/tiles/>