MORPHOMETRIC COMPARISONS OF TERRESTRIAL ESKERS AND MARTIAN RIDGES REVEAL PATHWAYS OF PERSISTENT MELTWATER DRAINAGE

Medha Prakash[1], Marion McKenzie[1], Lauren M. Simkins[1], Jacob W. Smith[1], Ajay B. Limaye[1]
[1]University of Virginia

Abstract

Sinuous ridges on the martian surface in midlatitude and polar regions have been subject to multiple interpretations. Due to the widespread evidence of ice on Mars and ridge morphology similarities with terrestrial eskers, a leading interpretation is the ridges formed as deposits in subglacial channels (i.e. eskers). The presence of eskers would indicate there were subglacial meltwater channels on Mars capable of transporting sediment downstream. I use morphometric analysis to compare terrestrial eskers and martian sinuous ridges. The terrestrial dataset includes over 20,000 eskers from deglaciated landscapes of the Laurentide, British-Irish and Fennoscandian paleo-ice sheets, which are analyzed to determine ridge length, sinuosity, and along-esker relief. Martian sinuous ridges are analyzed for the aforementioned measurements using publicly available data and mapping. I also assess the spatial distribution of these features on both planets by determining density and occurrence associations with glacial history. I find martian ridges similar in form to terrestrial eskers but generally larger, alluding to pathways of persistent and continuous subglacial meltwater drainage formed by ice sheets on Mars. Additionally, features resembling esker beads indicate multi-seasonal retreat, but do not preclude synchronous esker formations elsewhere in other regions associated with relevant ice sheet.

1 Introduction

Glacial landforms preserve information about patterns of ice flow and retreat, glacial extent, patterns and locations of subglacial meltwater drainage, and consequently, past climates (e.g. Banks et al., 2009; Bernhardt et al., 2013; Clark et al., 2018; Greenwood et al., 2016). Eskers, a type of subglacial meltwater landform, are long, positive-relief, sinuous ridges of glaciofluvial sediment deposited in subglacial channels and found in formerly glaciated terrains where meltwater was present and the overlying ice was not frozen to the underlying bed (Aylsworth et al., 2012; C. D. Clark et al., 2018; Prest, 1968; Storrar et al., 2013). In addition to providing insight into subglacial hydrology, esker morphology and length inform us about basal conditions at the time of glaciation, stability of ice-flow, and can contribute to the reconstruction of ice-surface profiles (Arnold et al., 2020; F. E. G. Butcher et al., 2016; Shreve, 1985; Storrar et al., 2014). It is widely understood that esker formation depends on bedrock lithology, abundance of meltwater, and sediment supply (Beaud et al., 2018; Burke et al., 2015; Storrar et al., 2014). For example, crystalline bedrock is more conducive to esker formation as the ice at the base of the glacier resists meltwater flow less than crystalline bedrock, although eskers have been found on more permeable, softer sediments as well (Frydrych, 2022; Storrar et al., 2014). Eskers formed on these different lithologies are often representative of the different subglacial channel types they were formed in, where those on more crystalline bedrock were formed by channels incised upwards in to the ice base (Röthlisberger channels) and those in softer sediment formed in Nye- channels or a combination of Röthlisberger and Nye channels (Rotnicki, 1960; Michalska, 1969; Wright, 1973; Mooers, 1989; Atkinson et al., 2014; Storrar et al., 2014; Burke et al., 2015; Frydrych, 2022). Other metrics of eskers provide insight to their formation, such as their orientation, where eskers are generally oriented in the direction of former ice flow, but topographic features such as valleys and differences in slope cause eskers to branch, also suggesting thinner and sluggish ice overlaying those regions (Shreve, 1985). Additionally, the sorting of the sediment and crest morphology of eskers suggest the strength of melting, where broader crests and well-sorted debris would indicate freezing, as opposed to the sharp crests and poor sorting of eskers formed with strong melting at the base (Shreve, 1985).

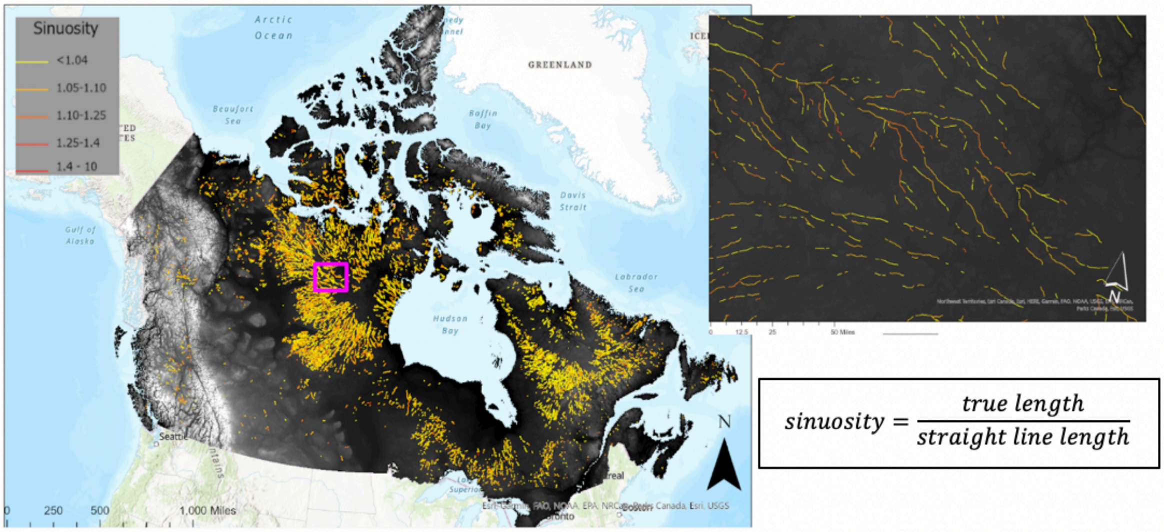


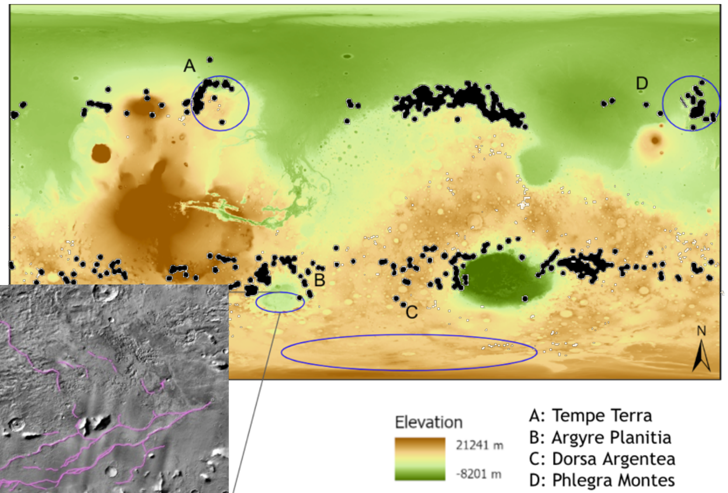
Figure 1. Canadian eskers traced by Storrar et al. with coloration depicting varying sinuosities

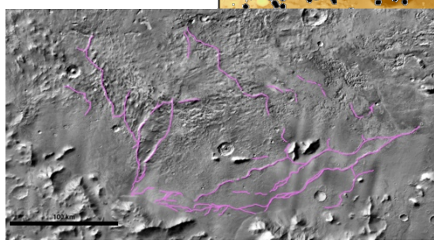
Because eskers conceptually grow in time and space, shorter eskers are thought to have formed during individual drainage events, such as glacial outburst floods, or at least during less persistent hydrologic conditions (e.g., Burke et al., 2015). Contrastingly, time-transgressive formation of longer eskers are often associated with periods of subglacial water drainage stability over hundreds to thousands of years (P. U. Clark & Walder, 1994; Kehew et al., 2012; Storrar et al., 2014). Eskers formed in outburst floods are believed to have distinct sedimentological and morphological signatures, with a wider and higher head and narrower and lower terminus (Burke et al., 2010). Outburst flood eskers are heavily controlled by conduit geometry in their formation (Burke et al., 2010).

Eskers have been widely found in deglaciated areas in the Northern Hemisphere including Canada, the United Kingdom and Ireland, Scandinavia, Mauritania (e.g., C. D. Clark et al., 2018; Mangold, n.d.; Shreve, 1985; Storrar et al., 2014); yet, there is a lack of definitive examples in Antarctica, despite the abundance of meltwater and presence of other meltwater landforms (e.g., Simkins et al., 2021). Large-scale statistical analyses of esker form and relations to topography and lithology have not yet been integrated across the aforementioned regions.

Elsewhere in our solar system, certain sinuous ridges (positive-relief features) near polar ice caps on Mars as well as mid-latitude regions such as Tempe-Terra and Phlegra Montes have been hypothesized to be glaciofluvial in origin. However, current interpretations do not necessarily preclude other formative processes such as eolian or volcanic in origin. If these ridges are determined to be eskers, the presence of these features may validate previous interpretations constraining the occurrence and duration of past meltwater flows on Mars and consider the atmospheric conditions and thermal conditions that would allow warm-based glaciation (e.g., Banks et al., 2009; Gallagher et al., 2021; Gallagher & Balme, 2015). Many of the interpretations of formative processes of these ridges are based on qualitative observations or morphometric assessments (e.g., Banks et al., 2009; Butcher et al., 2016; Gallagher & Balme, 2015). The ridges on Dorsa Argentea have been studied morphometrically and compared to the Canadian eskers (Storrar et al., 2013), with measurements of length, sinuosity, spatial characteristics such as density and branching counts statistically compared (F. E. G. Butcher et al., 2016). However, ridges in Argyre Planitia and elsewhere around the south polar ice sheet have not been compared with a terrestrial analog morphometrically although the features have been interpreted to be formed by ice sheets (Banks et al., 2009; F. E. G. Butcher et al., 2020; Gallagher et al., 2021; Gallagher & Balme, 2015). Additionally, eskers SW Finland has recently been used as an analog for candidate eskers associated with debris-covered mid-latitude glaciers in Tempe Terra and Phlegra Montes, but for graphic

Figure 2. Candidate eskers in Argyre Planitia in the broader context of areas of previous study on Mars as depicted by an elevation map, in addition to showing identified recessional Glacier Like Forms (GLFs) by Brough et al. 2015.





comparisons of height, width, length, and sinuosity, and cross-sectional slope (G. Butcher et al., 2019). Comparative studies of landforms on Earth and Mars enhance knowledge on landscape evolution, especially when examining the formation of features on a world substantially less manipulated by humans. Quantitative parameters from terrestrial examples can be extrapolated to other planetary surfaces to determine the influence of similar processes. On Earth, due to modern analogs and accessibility, we are able to infer many aspects of ice sheet behavior using esker geometry. Further, extending ideas about terrestrial esker formation to Mars has the potential to inform interpretations of past martian glaciers. While previous work has compared terrestrial and martian eskers in order to develop working theories on glacial flow velocities and esker formation on Mars (Arnold et al., 2020; Pelletier et al., 2010), a spatially expansive analysis of eskers on Earth and Mars can reveal new and quantitative insights to the defining properties of terrestrial eskers while inferring stability of martian meltwater conduits in previously subglacial environments. I used quantitative and spatial analyses of terrestrial and martian ridges to test whether martian eskers have geomorphic semblances to terrestrial eskers, and test controls on esker form including regional geology and topography.

2 Literature Review

2.1 Defining properties of terrestrial eskers

Terrestrial eskers range in size from 10s to 100s of meters wide, 10s of meters in amplitude, and 10s of kilometers in length (Storrar et al., 2014). Eskers vary in cross-sectional shapes including single- to multiple-peaked triangular, semi-circular, and flat-topped crests (e.g., Perkins et al., 2016). In contrast to river channels, eskers are thought to be less sinuous and the pressurized water in eskers can flow from downhill to uphill, such that eskers can cut across topography (e.g., Limaye et al., 2021; Storrar et al., 2014).

Eskers are commonly associated with other subglacial landforms such as glacial lineations and are found in ice-marginal environments near the paleo-glacier termini, and their density (number per unit area) has been observed to increase towards final termini positions of glaciers (Aylsworth & Shilts, 1989; P. U. Clark & Walder, 1994; Hebrand & Åmark, 1989; Huddart et al., 1999; Storrar et al., 2014). Bed lithology is thought to impact the number, continuity, and organization of eskers, with softer rock favoring less organized and irregularly spaced eskers (P. U. Clark & Walder, 1994; Grasby & Chen, 2005; Storrar et al., 2014). Previous research suggests that longer and less fragmented eskers imply stable ice margins and meltwater pathways, an interpretation that may apply to some of the ridge systems on Mars (Banks et al., 2009; F. E. G. Butcher et al., 2016). Whereas large-scale morphometric analyses have been carried out for the eskers produced under the Cordilleran and Laurentide Ice Sheets, there are no similar studies for eskers produced under the Fennoscandian or British-Irish Ice sheets (Storrar et al., 2014).

2.2 Work on martian ridges

The hypothesized glacial features on Mars in Dorsa Argentea, Argyre Planitia, Tempe Terra, and Phlegra Montes have been examined through modeling, remote sensing, and in some cases, terrestrial analog studies (Figure 2).

Mars has extensive ice caps with thicknesses exceeding 1 km, at both the north and south poles. Additionally, glacier-like forms have been hypothesized to speckle the midlatitude ranges, showing that Mars is potentially still glacially active (Arnold et al., 2023; Brough et al., 2016).

While the exact nature of the epochs of martian geologic history are debated upon, some hypothesized glacial features on Mars have been interpreted to have formed in the Late-Noachian/Early Hesperian epochs (around 3.5 Ga) and while others in the Amazonian epoch (between 3-2.5 Ga until now). The late-Noachian/early-Hesperian time period has been discussed to have a climate conducive to liquid water able to form valley-networks, and thus poses a possibility for warm-based glaciation and surface melt (Fassett & Head, 2008; Kress & Head, 2015). Smaller late-Amazonian, mid-latitude candidate eskers are becoming increasingly prolific, often alluding to regional or localized geothermal heating to cause enough basal melting at a period where mid-latitude glaciers were more prevalent, followed by glacial retreat via sublimation (Arnold et al., 2023; F. E. G. Butcher et al., 2016; Gallagher & Balme, 2015; Kress & Head, 2015).

Large morphometric analysis of the Dorsa Argentea ridge system (Figure 2), compared to Canadian eskers, may indicate extensive glacial flow of the southern polar ice cap, as they are hypothesized to be eskers (F. E. G. Butcher et al., 2016; Storrar et al., 2014). There were similarities between both populations for the statistical distributions of length and sinuosity, and the variations in ridge-crest morphology aligned with observations of terrestrial eskers (F. E. G. Butcher et al., 2016). Metrics measured included width, amplitude, length, sinuosity, continuity, nodes, density, and relations to topographic slope, and were summarized in terms of moments (e.g. mean) of the metrics' distributions (F. E. G. Butcher et al., 2016). While this paper addressed the ridges in this specific region, there are a multitude of other ridge systems surrounding the southern polar ice cap in Planum Australe that have not been morphometrically analyzed (F. E. G. Butcher et al., 2016; Kress & Head, 2015). These ridges have been hypothesized to form in two stages of glaciation in the late Noachian-Hesperian boundary (Kress & Head, 2015). Through crater counting, they determined ridges between 270 degrees and 0 degrees E around the South pole formed in the Early Hesperian. East of this, Promethei Planum and Chasmata ridge systems were dated to the Late Noachian.

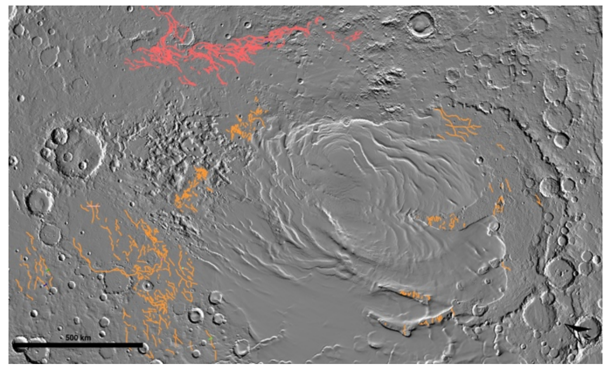


Figure 3. Traced ridges around the south polar ice cap remnants in areas demarcated by previous studies (F. E. G. Butcher et al., 2016; Kress & Head, 2015). The red ridges correspond to Dorsa Argentea, an area which has been compared to terrestrial analogs (F. E. G. Butcher et al., 2016). The orange ridges have not been morphometrically

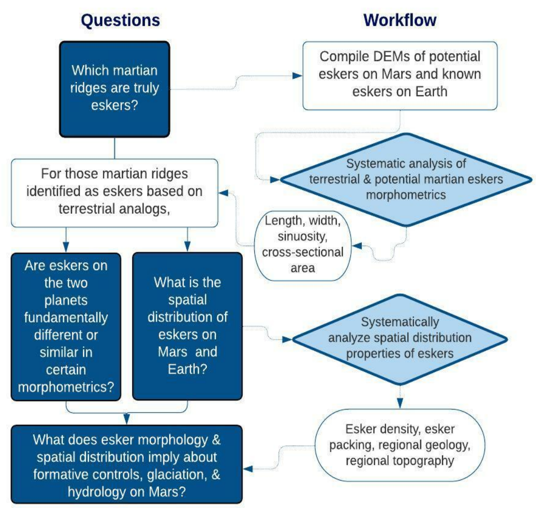
Ridges in Argyre Planitia, the second largest impact basin on the planet, have been hypothesized to be formed by a thick, stagnating ice deposit, due to the length and 97% continuity of the eskers (Banks et al., 2009). Additionally, studies have alluded to other glacial depositional and erosional features in proximity to these hypothesized eskers such as lobate debris aprons (LDA), kettles, cirques, and drumlins (Banks et al., 2009; Bernhardt et al., 2013). Modeling has also supported to the viability of large esker formation on Mars due to larger subglacial tunnels allowing sediment deposition over longer lengths and greater depths (Arnold et al., 2020). Additionally, smaller-scale features including ridges found at Tempe Terra and Phlegra Montes, mid-latitude regions on Mars have been interpreted as eskers due to the their proximity to LDAs as well as viscous-flow features (VFF) (Bernhardt et al., 2013; F. E. G. Butcher et al., 2020; Gallagher et al., 2021; Gallagher & Balme, 2015). Their smaller size is associated with the size of midlatitude glaciers as opposed to the ice sheets hypothesized to form the ridges in Argyre Planitia and Dorsa Argentea. No terrestrial analog has been posed for Argyre Planitia, although Tempe Terra and Phlegra Montes have had crest shape, slope, amplitude, and width calculated for them as well as analog eskers in SW Finland (F. E. G. Butcher et al., 2020; G. Butcher et al., 2019).

3 Research Hypotheses

As a metric, I hypothesize that lower reliefs will be an indicator of maturity of an esker system. I hypothesize that if the features on Mars are indeed eskers, they will have similar sinuosity (true length/straight line length) and morphometric distributions (Banks et al., 2009; F. E. G. Butcher et al., 2016; Komar, 1979; Miller & Komar, 1977). **S**econdly, I hypothesize that alongside the similarities in dataset distributions and ratios, if created by an ice sheet, the features on Mars will be larger than ones seen on Earth (i.e., longer length and larger cross-sectional area). Finally, while esker density will vary based on differential styles of retreat and elevated geothermal heat in some areas, I hypothesize there will be a general increase in the number and size of eskers towards the center of ice flow, which may provide information on organization of subglacial meltwater and the origins of the glacial bodies that form these eskers (F. E. G. Butcher et al., 2016). I hypothesize that the aforementioned terrestrial esker properties support the interpretation of martian sinuous ridges as eskers formed by persistent subglacial water flow. If this hypothesis is indeed supported, this would imply that there was liquid meltwater on Mars present for an extensive period of time. Comparisons in metrics between terrestrial analogs and potential martian eskers, the subsequent analyses, and the results of previous research will provide a better understanding of glacial processes on Mars and their role in the evolution of the solar system.

To test these hypotheses, I utilized terrestrial esker length, sinuosity, along-crest relief, and density derived from previously existing datasets across Canada, Finland, Ireland, and the UK. These data will then be compared to martian ridge data with the same metrics in Argyre Planitia, Dorsa Argentea, Planum Australe, and Cavi Angusti. (Figure 3).

Figure 4. Research questions and workflow regarding martian and terrestrial eskers



4 Data

4.1 Terrestrial Data

The curated terrestrial dataset for this project includes eskers from the deglaciated regions in Canada, Finland, United Kingdom and Ireland (Table 1). The Canadian eskers are a shapefile of 20,186 eskers compiled by Storrar et al. 2013., projected in the Canada Lambert Conic Projection. The geographic coordinate system of this file is NAD 1983. The topographic data is a Digital Elevation Model (DEM) obtained from the Government of Canada, with 16 m in Spatial resolution, referenced to the UTM NAD83 (CSRS) coordinate system. It is projected in the NAD 1983 Canada Atlas Lambert projection. To minimize area distortion and the distortion of raster data, the esker shapefile is projected into the coordinate system of the raster data set.

The UK eskers are derived from the BRITICE Map by the University of Sheffield, an initiative devoted to mapping glacial landforms formed by the British-Irish Ice Sheet. They are derived from over 1800 publications, British Geological Survey, and Irish Geological Survey mapping. The eskers in the currently recognized UK are available as polylines, however the Irish eskers are available as polygons. These eskers are projected in the British_National_Grid

Region (Planet)	Ave. Width of feature (m)	Spatial Resolution of DEM	Vertical Resolution of DEM
Canada (Earth)	100	16 meters	---
UK/Ireland (Earth)	100	90 meters	5-16 meters
Finland (Earth)	100	32 meters	~1 meter
Argyre Planitia (Mars)	3000	200 meters	~1 meter
South Pole regions	1000-1500	256 ppd (pixels per degree)	~1 meter

Table 1. Regions of interest along with the average widths of relevant features (eskers or ridges) noted by previous research papers. In addition, the spatial resolution and vertical resolution of the current DEMs are being used.

coordinate system. The elevation data is created by merging 6 tiles, with the "Mosaic" tool on ArcGIS, of the World DEM based on Shuttle Radar Topography Mission (SRTM) in 2000.

The Finnish eskers are derived from the Geological Survey of Finland (GTK), as well as the bedrock lithology maps. The glacial features dataset includes various glaciofluvial features, but I specifically subset those that correspond to eskers and esker sands. The dataset was produced in 2015 and is continually updated. The projected coordinate system is EPSG-3067.

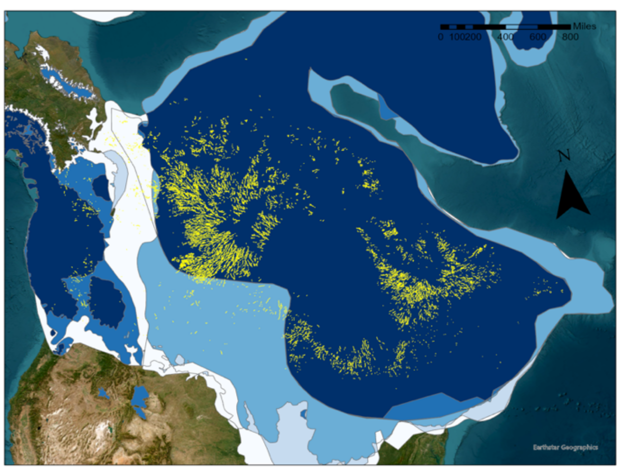


Figure 5. Canadian eskers from Storrar et al. mapped over a map of glaciation cycle counts where darker colors indicate more glaciations have occurred (Batchelor et al., 2019).

Additionally, polygon shapefile layers depicting the configuration of northern hemisphere ice sheets through the quaternary were downloaded and overlaid using the "Count Overlapping Features" in ArcGIS (Batchelor et al. 2019). This creates a polygon feature class differentiating regions of Canada based on the amount of glaciation cycles the region experienced (Figure 5). These files are originally projected in the North Pole Lambert Azimuthal Equal Area projection.

4.2 Martian Esker data

Although no publicly available shapefiles of martian eskers exist, Java Mission-planning and Analysis for Remote Sensing (JMARS) is a geospatial information system that aggregates mission data to create an interactive map of Mars. I utilize traced ridges in Argyre Planitia and South Pole, Mars, as these have been hypothesized to be formed by ice sheets rather than mid-latitude glaciers in contrast to areas such as Tempe Terra and Phlegra Montes. To obtain martian ridge polylines, using a combination of HiRISE, CTX, and HRSC imaging in JMARS, I manually trace the ridges, and export it as a shapefile. Specifically, for Dorsa Argentea, I use the ridges Dr. Frances Butcher traced from her work in 2016 (Butcher et al. 2016, Butcher pers. comm.), that were originally projected in MARS_Stereographic_Polar coordinate system while referenced to the GCS_Mars coordinate system. For the regions of Argyre Planitia, Planum Australe, and Cavi Angusti, the ridges are traced manually in JMARS in Argyre Planitia, demarcated by previous research (Banks et al., 2009; F. E. G. Butcher et al., 2016; Kress & Head, 2015). They will be identified from previous image mosaics and the overlaid 512 ppd and 256 ppd MOLA Hillshades, CTX and HRSC imagery. The elevation data is a 256 ppd MOLA DEM below 59 degrees S with a vertical precision of ~1 meter.

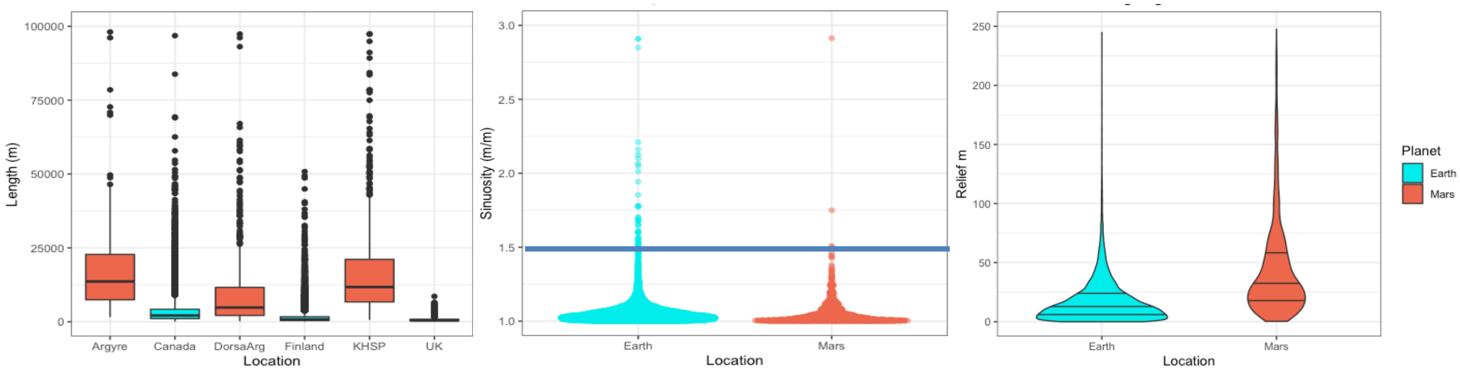


Figure 6. Mosaic of plots depicting distributions of length, sinuosity, and relief of each planet from left to right respectively. Turquoise depicts terrestrial esker data sets. Red depicts martian ridge data sets. Note: Martian ridges had lengths above 100 km, up until 250 km. KHSP refers to Planum Australe and Cavi Angusti. The blue line displays a cut off at which subaerial river sinuosity tends to cluster (Limaye et al., 2021)

This spatial resolution is adequate for resolving martian eskers. This data is also referenced to GCS_Mars. Lengths and sinuosity for the shapefiles arre calculated in the MARS_Stereographic_Polar projection to preserve distance and area, while 3D-metrics were calculated in the projection of the raster data.

5 Methods

For mid-latitude tracing of martian ridges, I use the default cylindrical projection on JMARS centered at 0 degrees North and 0 degrees E. For tracing Planum Australe and Cavi Angusti ridges, I center the projection at -90 degrees N and 0 degrees E to create a stereographic projection at the South Pole. I import the JMARS Mars Projection file into ArcGIS as well as the martian ridge shapefile. After ensuring the projections align for the data, I calculate 2D properties for all terrestrial eskers and martian ridges (length, sinuosity etc.) using the "Calculate Geometry Attributes" tool, and 3D properties (mean, minimum and maximum elevation) after interpolating the features using the "Interpolate Shape," then "Add Z Information" tool, which will be used to calculate along-ridge relief for each esker.

Each terrestrial esker is given a centroid point with all attributes pertaining to the esker. Using the "Spatial Join" tool, I assign each esker centroid the number of glaciations the underlying terrain had experienced (Batchelor et al. 2019). A 1-degree fishnet is created over the landmasses of Canada and UK/Ireland (Figure 9). Using the "Spatial Join" tool in ArcGIS, the amount of these centroids per unit area is used to calculate the density of eskers for a given area. Within each cell of the fishnet in Canada and the UK, the length, relief, and sinuosity of terrestrial eskers were aggregated via averaging each of the metrics respectfully for all eskers within the cell. The same process was repeated for their standard deviations.

In order to statistically compare the ridges in Argyre Planitia to terrestrial eskers, I bootstrap the Argyre Planitia esker population in order to make its size comparable to that of the terrestrial eskers. After randomly sampling 100 eskers from each dataset, I use a Levene's test to determine if the variance was the same between both populations. After determining the variances to be different, I use a Welch T-test to compare the distributions of length, sinuosity, and relief.

6 Results:

Individual metric distributions:

The martian ridges studied are broadly longer and visibly more continuous than terrestrial eskers. The median length of martian ridges was around 8282 meters (Standard Deviation = 3.71 km) while the median terrestrial esker length was around 1220 meters (Standard Deviation = 18.73 km).

As seen in Figure 6, sinuosity distributions of both planet's populations are positively skewed and clustered around one. Martian ridges had a lower median sinuosity of 1.02 than terrestrial eskers, which had a median sinuosity of 1.04 (Table 1A).

Despite having similar relief ranges, a much smaller proportion of martian ridges were low relief (relief between 0 and 15 meters) as compared to terrestrial eskers. Of the martian ridges, 20.7% had low along-esker reliefs as opposed to the 57.6% of terrestrial eskers. The terrestrial median along-esker relief was 12.6 m as opposed to 31.7 m of martian ridges studied (Table 1A).

Additionally, the distributions of all the metrics for the eskers and ridges are positively skewed and leptokurtic.

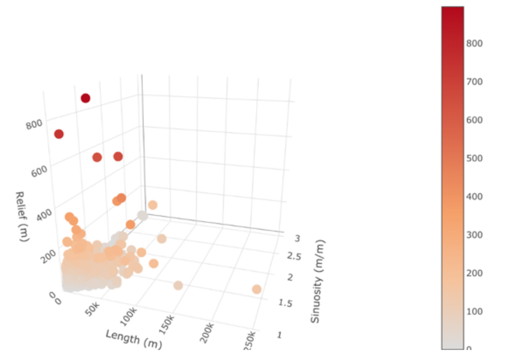


Figure 7. 3D scatterplot depicting relationship between along-esker relief, length, and sinuosity of terrestrial eskers. Darker shades of red correspond to higher reliefs while lighter colors correspond to low relief.

Relations between metrics

Terrestrial eskers with shorter lengths tend to have higher sinuosities and higher along-esker reliefs. Alternatively, sinuosities closer to one (straighter eskers) and low esker reliefs (low variability in crest elevation) correspond to longer eskers (Figure 7).

Martian ridges conform to the negative correlation between length and sinuosity seen in terrestrial eskers (Figure 8). Additionally, there is a negative correlation between sinuosity and along-esker relief, showing that higher reliefs occur with shorter eskers, a trend which martian ridges also display (Figure 8). When examining the relationship between length and relief, there is a negative correlation where higher reliefs are mainly possible at lower lengths, however, there is a threshold minimum along-esker relief which gradually increases as the length of the ridge increases in both planet's ridge populations. Martian ridges are a subset of terrestrial eskers when plotted together.

Terrestrial spatial relations of metrics

When examining these metrics related to the esker density (number of eskers per unit area), shorter mean lengths, lower mean sinuosities, and lower mean reliefs are seen in areas with higher

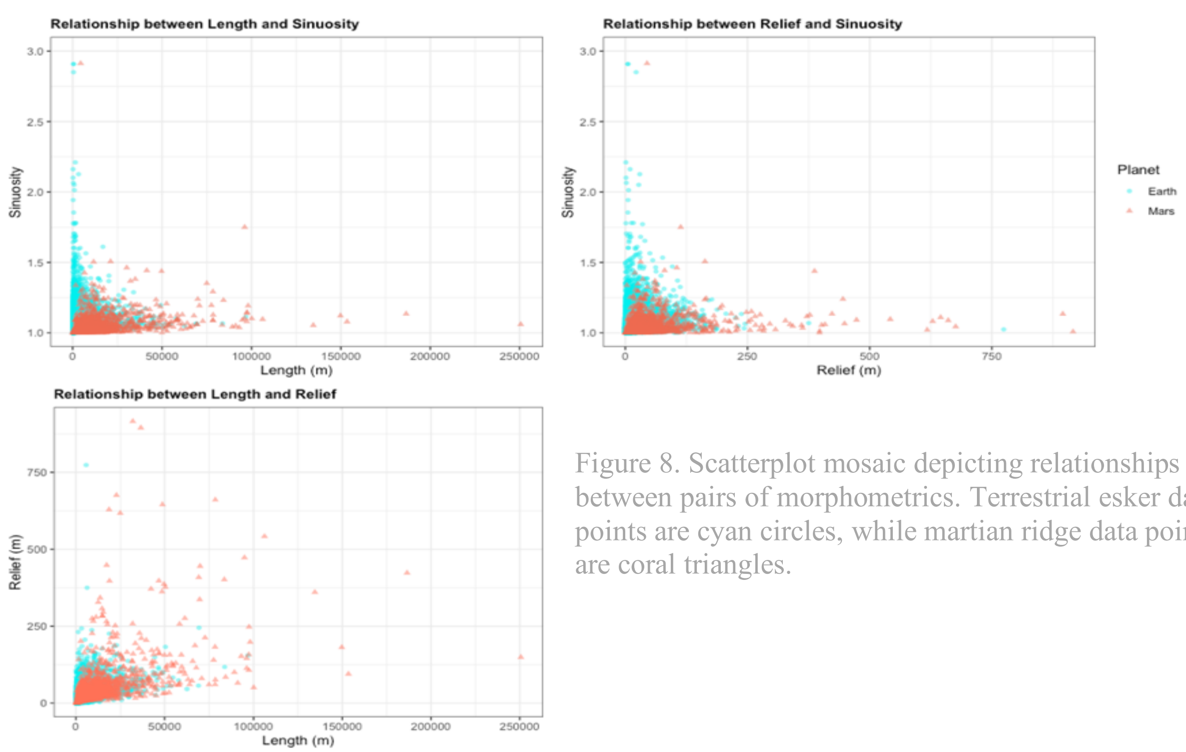


Figure 8. Scatterplot mosaic depicting relationships between pairs of morphometrics. Terrestrial esker data points are cyan circles, while martian ridge data points are coral triangles.

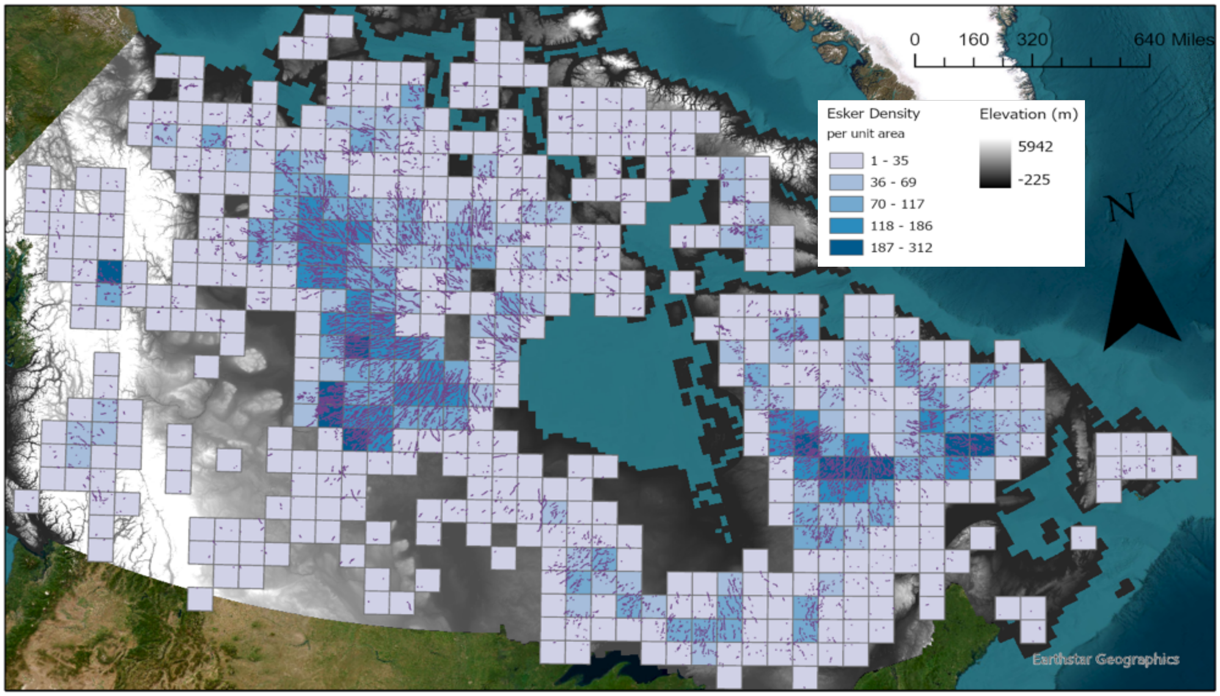


Figure 9. Fishnet depicting density of eskers per unit area in Canada, where darker colors correspond to more dense esker areas.

densities of eskers occur in areas with higher densities of eskers (Figure 10). Additionally, there are negative correlations between the standard deviations of these metrics and esker density, indicating less variability length, relief, and sinuosity in areas with a higher density of eskers (Figure 10). Certain outliers that further support this trend were excluded due to the anomalous nature of the fishnet cells with one or two esker centroids inside of them.

7 Discussion

Metrics on Earth

A negative correlation was observed between length and sinuosity for terrestrial eskers, suggesting persistent and efficient meltwater transport for longer eskers. Lower sinuosity is typically associated with time transgressive formation, in R-channels while higher sinuosity is associated with softer sediment and synchronous formation (Frydrych, 2022; Livingstone et al., 2020; Storrar et al., 2014). Observed relations between length, sinuosity, and relief also support this association.

Higher relief was shown to generally occur for shorter eskers, indicating that relief is minimized with flow persistence and esker maturity (Figure 4). The minimum possible relief threshold keeps increasing as esker size lengthens. There would be more space available for inconsistencies in sediment transport and water flow in longer channels. The interpretation of relief reflecting more mature eskers and persistent flow aligns with initial studies performed with outburst flood eskers in Iceland, Alaska and Nepal (Burke et al., 2010; Frydrych, 2022). Outburst flood eskers are formed over short time periods. Initial conduits may begin as severely nonuniform, changing from constricted to enlarged conduits within 10s of meters along an esker (Burke et al., 2010, 2015). Structural weaknesses in ice would also have a greater impact on the formation of these eskers, thus varying their geometries (Burke et al., 2010, 2015). Width and height are strongly correlated in these systems (Storrar et al., 2015). Thus, with these considerable variations in width, it is to be expected to have variable crest elevations with less mature esker systems.

In areas of higher density of eskers, shorter eskers generally occur, indicating that spatial footprint increases in areas of high density of eskers (Figure 10). The amount of space water flows through increases, and the number of

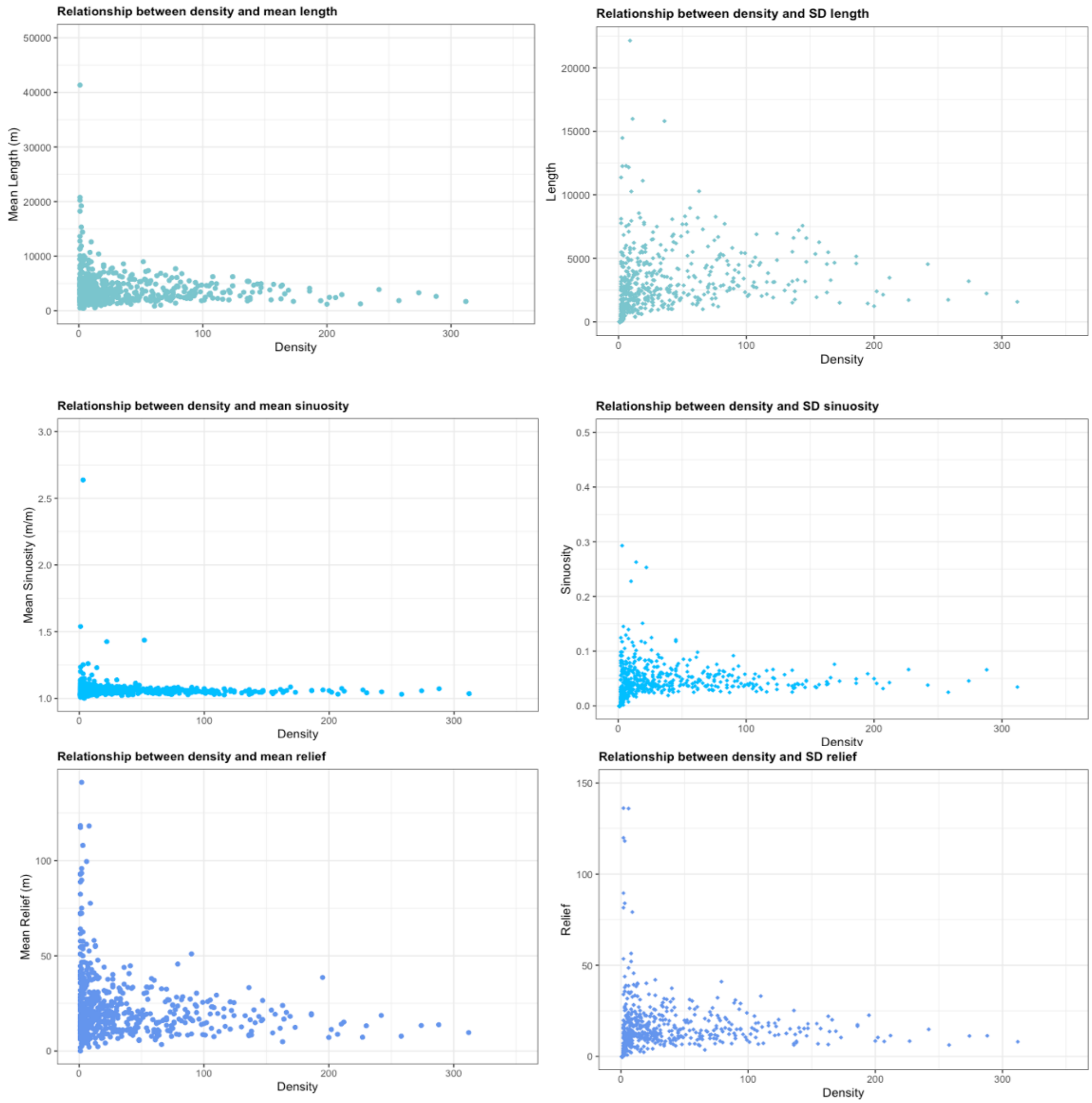


Figure 10. Scatterplot mosaic depicting the means and standard deviations within each fishnet cell of various metrics taken of terrestrial eskers. Each metric is differentiated with color and the means are larger round points while the standard deviations are depicted with smaller diamonds. **these plots don't include outliers or instances of extremely low-density esker areas with 1-2 really long, sinuous, or high relief eskers that distorts the rest of the data.

available pathways increase, but eskers are still short.

Previous research shows that during increased availability and flow of meltwater, eskers formed in R-channels are more closely spaced but are smaller in size (Hewitt & Creyts, 2019). This could represent transient water flow pathways, where eskers are not developing into longer coherent pathways.

It is also possible that if these eskers were from older glaciations, while eskers in the higher density areas were from recent glaciations, because of their size they had better preservation potential away from the ice margin as opposed to those affected by more glaciations, in elevated areas.

Additionally, eskers tend to have lower reliefs in areas of high density of eskers. The number of eskers per unit area could be an indicator of how temporally extensive was the glacial influence on the landscape. In addition to showing lower reliefs, eskers tend to be straighter (have lower sinuosities) in areas of high density. Spaces of higher esker density can occur when subglacial channels more efficiently occupy space and are better organized. Higher density of subglacial channels may warrant more channelized, homogenized drainage. It is important to note that points of higher relief or sinuosity do not necessarily correspond to the longer length eskers seen in the scatter plots. These observations align with the trends in variability of these metrics. The standard deviations of relief and sinuosity decreased as esker density per unit area increased. These could be attributed to bed substrate, where softer sediments are less conducive to esker formation, but also promote more ephemeral configurations of subglacial channels.

What does this mean for Mars?

Argyre Planitia:

The Welch-T test showed the median length and relief of the esker to be significantly different, but the sinuosities to be much more variable for terrestrial eskers than those of martian esker in this region, despite the center of distribution being extremely similar. Based on these findings, I interpret Argyre Planitia eskers as more spatially, possibly temporally, stable pathways of meltwater flow, which align with other hypotheses of a thick, stagnating ice body previously posed for this region (Banks et al., 2009; Bernhardt et al., 2013).

Dorsa Argentea and Planum Australe

Creating eskers of the magnitude of these ridges seen on Mars (3 km in width and 10s of meters in height) would require an immense amount of supraglacial meltwater (Butcher et al. 2016, Storrar et al. 2020). Smaller candidate eskers in Phlegra Montes and Tempe Terra are formed by mid-latitude glaciers, thus the meltwater supply is limited in contrast to the ice sheets potentially responsible for these ridges.

The terrestrial examples examined in Finland and UK/Ireland were formed in deglaciation, where subglacial meltwater was inadequate to form eskers of those sizes (1 km or less in width and 10s of m in height) (G. Butcher et al., 2019; C. D. Clark et al., 2018). Channelized drainage becomes increasingly important during deglaciation. A possible source of the large amount of meltwater could be a glacial outburst flood, an instantaneous, outflux of water from the base of a glacier that has the ability to deposit sediment large amounts of sediment. However, there are extensive networks of ridges around the southern polar ice cap. Single glacial events often lead to single eskers as opposed to ridge networks. Additionally, features resembling esker beads are seen in regions around the polar ice sheet, indicating melt occurring over multiple seasons (Livingstone et al., 2020).

I interpret the ridges as eskers formed over the course of multiple seasons through persistent meltwater flow. I also interpret them to be eskers formed in R channels due to seeing dendritic patterns and low sinuosities in various study regions in addition to their dense organization, akin to those seen in Canada on the Canadian shield, where there are more dense eskers (Livingstone et al., 2020; Storrar et al., 2014).

Additionally, examples in Iceland (with presumably similar substrate assuming a basaltic composition), show that long continuous eskers

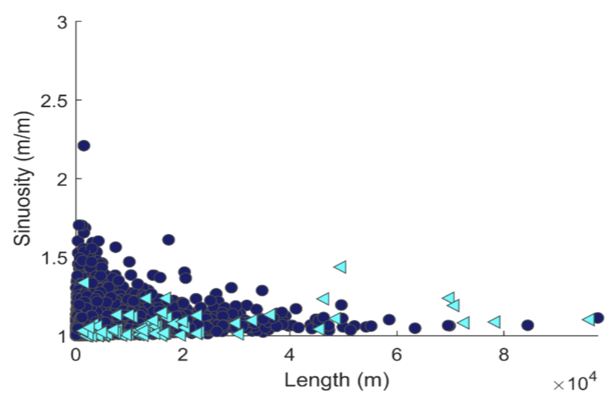
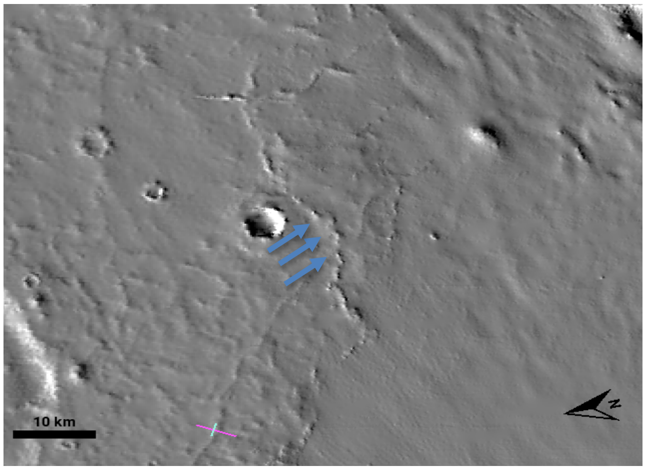


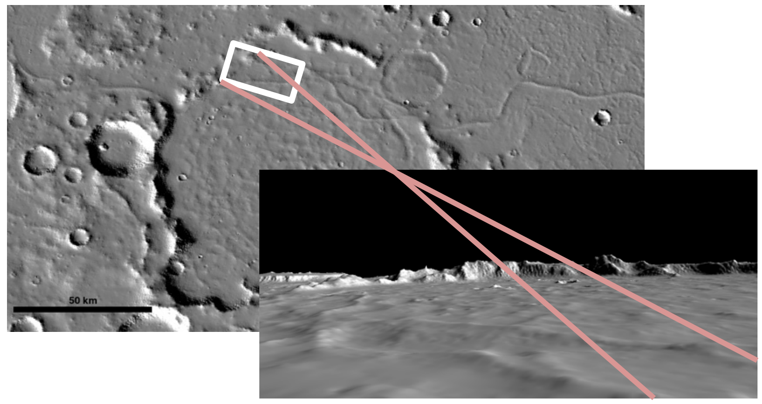
Figure 10. Graph depicting the negative correlation between sinuosity and length, with dark blue circles representing values from the Canadian esker data set and light blue triangles representing values from the Argyre Planitia esker data set.

are possible in time-transgressive manners. This doesn't preclude unique examples of subglacial conduit collapse or outburst floods within these ridge systems. There were specific eskers with



An esker moving up and down an impact crater in Planum Australe. The 3D figure has a vertical exaggeration with a scale of 15:1.

Figure 11, Esker bead resembling features in Planum Australe, Mars with a transect of a nearby esker.



higher sinuosities which could imply subaerial formation or formation through the aforementioned means (Frydrych, 2022).

The implications of martian eskers formed by persistent meltwater flow and multiple melt cycles are unconstrained. If abundant supraglacial meltwater is required to form eskers of this size, what conditions would allow for surface melt on a martian ice sheet over multiple seasons?

Possible explanations previous literature has resorted to is rapid atmospheric warming or ice-volcano interactions (Kress & Head, 2015). If there wasn't abundant surface meltwater what other conditions could create such large eskers? Previous papers have discussed how the conduits of subglacial channels in thick ice sheets don't close as quickly as ones on Earth due to martian gravity (Arnold et al., 2020). As the channels are open for longer, it allows more time for sediment to be deposited and more subglacial meltwater to flow out the channel (Hooke & Fastook, 2007; Shreve, 1985).

It is also possible that these channels terminated in a body of water, such as a proglacial lake, which would create a constant pressure against the mouth of the channel and provide an abundance of water, such as ones seen in Iceland (Storrar et al., 2015). It would not necessarily be a persistent body of water; it could be transient.

If the eskers on Mars were formed during times of high impact, as dated by the crater counting in relevant sites (Kress & Head, 2015), there may have been sources of localized geothermal heat fluxes or ice-volcano interactions also enabling the production of meltwater for synchronous events, but as these ridges are seen surrounding the polar ice cap, spatially covering a wide range of area, this seems more difficult. The size variation in eskers on Mars can be attributed to the glacial bodies creating them, where mid-latitude glaciers create smaller eskers seen in Phlegra Montes, and ice sheets likely create the ones in Argyre Planitia or Dorsa Argentea. The size difference between Canadian eskers and ones such as those seen in Iceland or Poland also shows this contrast in size. Size variation in eskers on Earth is related to sediment supply and meltwater abundance (Beaud et al., 2018; Burke et al., 2015; Simkins et al., 2021). Considering the erosive forces necessary to create an abundance of sediment supply, ice bodies on the scale of ice sheets would be necessary to generate the eskers of the size seen in Argyre Planitia and Planum Australe.

The ridges studied are mainly concentrated in topographic lows. This aligns with observations of the distribution of terrestrial eskers, where high elevation areas have low densities of eskers, and the distribution of mean crest elevation of the eskers were positively skewed.

8 Conclusions

Along-esker relief is an adequate indicator of esker system maturity. In future work, I would like to test the robustness and further expand upon along-esker relief 's utility as a metric through direct comparisons of this metric between outburst flood eskers and time-transgressive ones. The correlations between esker length, sinuosity, and relief indicate persistent and efficient meltwater transport are associated with longer and straighter eskers with minimal variability in crest elevation. Similarity in sinuosity distributions and ranges in relief, the ability to travel across topography, and the presence of additional glacial erosional and depositional features are useful in identifying martian eskers. Using these relations, I am able to see that martian eskers are a sub-population of the larger terrestrial esker data set that exhibit similar relief range, similar sinuosities, and longer lengths, corresponding to more persistent flows. These eskers were likely formed by thick ice sheets at a time period conducive to warm-based glaciation. As size of the glacial body in consideration increases, it is important to note the diversity of lithological, topographic, and subglacial conditions that can be encountered in the system. Within an esker system, route and region, there are diverse sinuosities, esker reliefs, and lengths, displaying that the morphology of eskers changes spatially. Varying widths, amplitudes, and configurations are seen between populations encountering different amounts of glaciological cycles but also while considering the implications of synchronous and time-transgressive formation, showing that eskers aren't temporally uniform either. Post depositional modifications also must be considered when analyzing these systems.

9 Future work

I would add additional comparisons between esker relief between outburst flood eskers, such as those in Iceland and those formed underneath the Cordilleran Ice Sheet (Burke et al., 2010, 2012; Storrar et al., 2015), and eskers believed to have been formed in a time transgressive manner, such as those in Finland. Additionally, I would like to incorporate LiDAR elevation data and polylines of esker crestlines traced by Dr. Robert Storrar in future morphometric analyses and comparisons.

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References

Arnold, N., Butcher, F., Gallagher, C., Balme, M., & Conway, S. (2020). *Modelling Esker Formation on Mars* [Other]. oral. https://doi.org/10.5194/egusphere-egu2020-3463

Arnold, N., Butcher, F., Gallagher, C., Balme, M., & Conway, S. (2023). *Estimating subglacial water discharges needed to form Amazonian-aged mid-latitude eskers on Mars* [Other]. display. https://doi.org/10.5194/egusphere-egu23-14816

Aylsworth, J. M., & Shilts, W. W. (1989). *Glacial features around the Keewatin ice divide: Districts of Mackenzie and Keewatin* (No. 88–24; pp. 88–24). https://doi.org/10.4095/127320

Aylsworth, J. M., Shilts, W. W., Russell, H. A. J., & Pyne, D. M. (2012). *Eskers around the Keewatin Ice Divide: Northwest Territories and Nunavut* (No. 7047; p. 7047). https://doi.org/10.4095/290075

Banks, M. E., Lang, N. P., Kargel, J. S., McEwen, A. S., Baker, V. R., Grant, J. A., Pelletier, J. D., & Strom, R. G. (2009). An analysis of sinuous ridges in the southern Argyre Planitia, Mars using HiRISE and CTX images and MOLA data. *Journal of Geophysical Research*, *114*(E9), E09003. https://doi.org/10.1029/2008JE003244

Batchelor, C. L., Margold, M., Krapp, M., Murton, D. K., Dalton, A. S., Gibbard, P. L., Stokes, C. R., Murton, J. B., & Manica, A. (2019). The configuration of Northern Hemisphere ice sheets through the Quaternary. *Nature Communications*, *10*(1), 3713. https://doi.org/10.1038/s41467-019-11601-2

Beaud, F., Flowers, G. E., & Venditti, J. G. (2018). Modeling Sediment Transport in Ice-Walled Subglacial Channels and Its Implications for Esker Formation and Proglacial Sediment Yields. *Journal of Geophysical Research: Earth Surface*, *123*(12), 3206–3227. https://doi.org/10.1029/2018JF004779

Bernhardt, H., Hiesinger, H., Reiss, D., Ivanov, M., & Erkeling, G. (2013). Putative eskers and new insights into glacio-fluvial depositional settings in southern Argyre Planitia, Mars. *Planetary and Space Science*, *85*, 261–278. https://doi.org/10.1016/j.pss.2013.06.022

Brough, S., Hubbard, B., & Hubbard, A. (2016). Former extent of glacier-like forms on Mars. *Icarus*, *274*, 37–49. https://doi.org/10.1016/j.icarus.2016.03.006

Burke, M. J., Brennand, T. A., & Perkins, A. J. (2012). Transient subglacial hydrology of a thin ice sheet: Insights from the Chasm esker, British Columbia, Canada. *Quaternary Science Reviews*, *58*, 30–55. https://doi.org/10.1016/j.quascirev.2012.09.004

Burke, M. J., Brennand, T. A., & Sjogren, D. B. (2015). The role of sediment supply in esker formation and ice

tunnel evolution. *Quaternary Science Reviews*, *115*, 50–77. https://doi.org/10.1016/j.quascirev.2015.02.017
Burke, M. J., Woodward, J., Russell, A. J., Fleisher, P. J., & Bailey, P. K. (2010). The sedimentary architecture of outburst flood eskers: A comparison of ground-penetrating radar data from Bering Glacier, Alaska and Skeiðarárjökull, Iceland. *Geological Society of America Bulletin*.
Butcher, F. E. G., Balme, M. R., Conway, S. J., Gallagher, C., Arnold, N. S., Storrar, R. D., Lewis, S. R., & Hagermann, A. (2020). Morphometry of a glacier-linked esker in NW Tempe Terra, Mars, and implications for sediment-discharge dynamics of subglacial drainage. *Earth and Planetary Science Letters*, *542*, 116325. https://doi.org/10.1016/j.epsl.2020.116325
Butcher, F. E. G., Conway, S. J., & Arnold, N. S. (2016). Are the Dorsa Argentea on Mars eskers? *Icarus*, *275*, 65–84. https://doi.org/10.1016/j.icarus.2016.03.028
Butcher, G., Balme, M. R., Gallagher, C., Storrar, R. D., Conway, S. J., Arnold, N. S., & Lewis, S. R. (2019). *3D MORPHOMETRIES OF ESKERS ON MARS, AND COMPARISONS TO ESKERS IN FINLAND. F. E. 2132*, 2.
Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M., & Sheehy, M. (2018). BRITICE Glacial Map, version 2: A map and GIS database of glacial landforms of the last British-Irish Ice Sheet. *Boreas*, *47*(1), 11-e8. https://doi.org/10.1111/bor.12273
Clark, P. U., & Walder, J. S. (1994). Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. *Geological Society of America Bulletin*, *106*(2), 304–314. https://doi.org/10.1130/0016-7606(1994)106<0304:SDEADB>2.3.CO;2
Fassett, C. I., & Head, J. W. (2008). Valley network-fed, open-basin lakes on Mars: Distribution and implications for Noachian surface and subsurface hydrology. *Icarus*, *198*(1), 37–56. https://doi.org/10.1016/j.icarus.2008.06.016
Frydrych, M. (2022). Morphology of eskers in Poland, southward of the Last Glacial Maximum. *Geomorphology*, *415*, 108418. https://doi.org/10.1016/j.geomorph.2022.108418
Gallagher, C., & Balme, M. (2015). Eskers in a complete, wet-based glacial system in the Phlegra Montes region, Mars. *Earth and Planetary Science Letters*, *431*, 96–109. https://doi.org/10.1016/j.epsl.2015.09.023
Gallagher, C., Butcher, F. E. G., Balme, M., Smith, I., & Arnold, N. (2021). Landforms indicative of regional warm based glaciation, Phlegra Montes, Mars. *Icarus*, *355*, 114173. https://doi.org/10.1016/j.icarus.2020.114173
Grasby, S. E., & Chen, Z. (2005). Subglacial recharge into the Western Canada Sedimentary Basin—Impact of Pleistocene glaciation on basin hydrodynamics. *Geological Society of America Bulletin*, *117*(3), 500. https://doi.org/10.1130/B25571.1
Greenwood, S. L., Clason, C. C., Helanow, C., & Margold, M. (2016). Theoretical, contemporary observational and palaeo-perspectives on ice sheet hydrology: Processes and products. *Earth-Science Reviews*, *155*, 1–27. https://doi.org/10.1016/j.earscirev.2016.01.010
Hebrand, M., & Åmark, M. (1989). Esker formation and glacier dynamics in eastern Skane and adjacent areas, southern Sweden. *Boreas*, *18*(1), 67–81. https://doi.org/10.1111/j.1502-3885.1989.tb00372.x
Hewitt, I. J., & Creyts, T. T. (2019). A Model for the Formation of Eskers. *Geophysical Research Letters*, *46*(12), 6673–6680. https://doi.org/10.1029/2019GL082304
Hooke, R. LeB., & Fastook, J. (2007). Thermal conditions at the bed of the Laurentide ice sheet in Maine during deglaciation: Implications for esker formation. *Journal of Glaciology*, *53*(183), 646–658. https://doi.org/10.3189/002214307784409243
Huddart, D., Bennett, M. R., & Glasser, N. F. (1999). Morphology and sedimentology of a high-arctic esker system: Vegbreen, Svalbard. *Boreas*, *28*(2), 253–273. https://doi.org/10.1111/j.1502-3885.1999.tb00219.x
Kehew, A. E., Piotrowski, J. A., & Jørgensen, F. (2012). Tunnel valleys: Concepts and controversies — A review. *Earth-Science Reviews*, *113*(1–2), 33–58. https://doi.org/10.1016/j.earscirev.2012.02.002
Komar, P. D. (1979). Comparisons of the hydraulics of water flows in Martian outflow channels with flows of similar scale on earth. *Icarus*, *37*(1), 156–181. https://doi.org/10.1016/0019-1035(79)90123-4
Kress, A. M., & Head, J. W. (2015). Late Noachian and early Hesperian ridge systems in the south circumpolar Dorsa Argentea Formation, Mars: Evidence for two stages of melting of an extensive late Noachian ice sheet. *Planetary and Space Science*, *109–110*, 1–20. https://doi.org/10.1016/j.pss.2014.11.025
Limaye, A. B., Lazarus, E. D., Li, Y., & Schwenk, J. (2021). River sinuosity describes a continuum between randomness and ordered growth. *Geology*, *49*(12), 1506–1510. https://doi.org/10.1130/G49153.1
Livingstone, S. J., Lewington, E. L. M., Clark, C. D., Storrar, R. D., Sole, A. J., McMartin, I., Dewald, N., & Ng, F. (2020). A quasi-annual record of time-transgressive esker formation: Implications for ice-sheet reconstruction and subglacial hydrology. *The Cryosphere*, *14*(6), 1989–2004. https://doi.org/10.5194/tc-14-1989-2020
Mangold, N. (n.d.). *GIANT PALEO-ESKERS OF MAURITANIA: ANALOGS FOR MARTIAN ESKER-LIKE LANDFORMS*. 1.
Miller, M. C., & Komar, P. D. (1977). The development of sediment threshold curves for unusual environments (Mars) and for inadequately studied materials (foram sands). *Sedimentology*, *24*(5), 709–721. https://doi.org/10.1111/j.1365-3091.1977.tb00266.x
Pelletier, J. D., Comeau, D., & Kargel, J. (2010). Controls of glacial valley spacing on earth and mars.

Geomorphology, *116*(1–2), 189–201. https://doi.org/10.1016/j.geomorph.2009.10.018
Perkins, A. J., Brennand, T. A., & Burke, M. J. (2016). Towards a morphogenetic classification of eskers: Implications for modelling ice sheet hydrology. *Quaternary Science Reviews*, *134*, 19–38. https://doi.org/10.1016/j.quascirev.2015.12.015
Prest, V. K. (1968). *Nomenclature of Moraines and ice-flow features as applied to the glacial map of Canada* (No. 67–57; pp. 67–57). https://doi.org/10.4095/106451
Shreve, R. L. (1985). Esker characteristics in terms of glacier physics, Katahdin esker system, Maine. *Geological Society of America Bulletin*, *96*(5), 639. https://doi.org/10.1130/0016-7606(1985)96<639:ECITOG>2.0.CO;2
Simkins, L. M., Greenwood, S. L., Munevar Garcia, S., Eareckson, E. A., Anderson, J. B., & Prothro, L. O. (2021). Topographic Controls on Channelized Meltwater in the Subglacial Environment. *Geophysical Research Letters*, *48*(20). https://doi.org/10.1029/2021GL094678
Storrar, R. D., Evans, D. J. A., Stokes, C. R., & Ewertowski, M. (2015). Controls on the location, morphology and evolution of complex esker systems at decadal timescales, Breiðamerkurjökull, southeast Iceland: Controls on Complex Esker Systems at Breiðamerkurjökull, Iceland. *Earth Surface Processes and Landforms*, *40*(11), 1421–1438. https://doi.org/10.1002/esp.3725
Storrar, R. D., Stokes, C. R., & Evans, D. J. A. (2013). A map of large Canadian eskers from Landsat satellite imagery. *Journal of Maps*, *9*(3), 456–473. https://doi.org/10.1080/17445647.2013.815591
Storrar, R. D., Stokes, C. R., & Evans, D. J. A. (2014). Morphometry and pattern of a large sample (>20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. *Quaternary Science Reviews*, *105*, 1–25. https://doi.org/10.1016/j.quascirev.2014.09.013

Appendix

Planet	Metric	Median	Standard Deviation	Skewness	Kurtosis
Earth	**Length (m)**	1220	3711	5.501	64.95
	Sinuosity (m/m)	1.041	0.1858	64.83	5322
	Relief (m)	12.57	19.53	5.230	117.4
Mars	**Length (m)**	8282	18730	4.325	34.96
	Sinuosity (m/m)	1.025	0.08486	9.312	176.8
	Relief (m)	31.77	77.29	5.178	41.06

Table 1A. Table depicting the summary and moment statistics of the individual distributions of length, sinuosity, and relief for the conglomerate of datasets on Earth and on Mars.