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Mathematical Data Sciences Senior Capstone Project

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New estimates of Martian erosion rates from crater obliteration statistics

Abstract

Geologists and planetary scientists have discovered and confirmed the existence of water on Mars over the past 50 years, which is arguably one of the most consequential planetary discoveries in the last century. Water vitally supports all life on Earth. Any possibility of life existing previously, presently, or subsequently on Mars also depends on the water we only recently found on the hyperarid planet. Naturally, the next question we have is: just how much water has existed on Mars throughout its history? We can begin to answer this question by zooming in on Mars's glacial and fluvial histories, and use erosion rates and latitude as a proxy for extent of hydrologic activity. With GIS databases of Martian craters and geologic unit boundaries, I will extract crater-frequency distributions for each unit to determine the age of the unit and its long-term erosion rate. From this, I will compare erosion rates across latitudes, which, like Earth, can be used to infer whether long-term erosion was more likely due to glacial or fluvial processes.

Introduction

In 1971, Mariner 9 became the first spacecraft to orbit another planet, and revealed much more clear and detailed pictures of the Martian surface than ever seen before (Hammond, 1973). By capturing over 7,000 images of the Red Planet, Mariner 9 enabled the discovery of both sinuous and dendritic channels, polar water and carbon dioxide ice, and many other Earth-like geological features in Mars' surface. Many of these channel systems contain islands and channel

bars, and resemble braided, ephemeral channels on Earth, shaped by episodic floods and a strongly varying flow regime (McCauley et al., 1972). The source of such a large amount of water needed to carve these Martian channels was not immediately evident – theories included release from the atmosphere, polar caps, and ground ice. Some believe that flares of volcanic activity (or thermal anomalies from impacts) caused ground ice to melt and release a lot of water at once. These catastrophic floods would then carve channels quickly (Plescia, 1990; Salese, 2016). Geologists have been able to answer questions and posit new ones from the results of several more space missions since Mariner 9, which includes more evidence of water on Mars (Nikiforov et al., 2020). In order to understand Martian geologic and climatic history more deeply, we need to constrain the ages of its geologic features, just as we have done to unravel Earth's history. Without rock samples, we must rely on dating methods using imagery, like crater counting (Hartmann and Neukum). Geologists have developed models called isochrons that relate impact crater densities (frequencies, along a surface) and sizes (diameters) to age the underlying surface. This research has led to the creation of geologic maps of Mars, like Figure 1, colored by geologic units and their age groups (Tanaka et al., 2014). A geologic unit represents a layer or grouping of layers of rock categorized by the rock's age and lithology – its characteristic mineral composition and structural features. With such maps and information available, we can start to outline the geologic events and processes that occurred in each time period. Smith et al. (2008) argue that Martian crater counting models must be adjusted for crater obliteration, as "low to moderate long-term rates of erosion and crater infilling can mask an ancient age and result in small-crater populations similar to those offered as evidence for young and geologically significant surface activity" (Smith et al., 2008). Martian craters erode over time, much faster than lunar craters (Figure 2). Smith et al. came up with a formula (Figure 3) relating abundance

of measured craters (N) at a time (t), crater production rate (p), crater loss rate (λ), crater diameter (d), and erosion rate (β). Now, with a database of craters falling within aged geologic units, we can fit said craters to these updated isochrons, and determine the erosion rates of each geologic period, and therefore, each geographical area of the planet. The most powerful erosive forces on Earth are ice (glaciers) and water (rivers), and thanks to Mariner 9 and subsequent orbital missions, we know these forces are at play in Mars's geologic history (Wilner et al., 2024). Combining our new erosion rates with previously published geomorphic maps, we can determine the relative importance of glacial vs fluvial processes on shaping the Red planet.

Methods

There are two main databases I will utilize for this project, the first is the Robbins Crater Database, which is a global catalog of over 380,000 Martian craters with diameters greater than 1 km (Robbins and Hynek 2012). The second database is a Martian Global Geology, Contacts, and Structures map in a digital, GIS format (Tanaka 2014). My first few steps will be conducted in ArcGIS Pro and ArcPy, a python package that enables users to perform geographic data analysis and map automation in Python. First, I will select the areas of a specific geological unit and select the craters that fall within these shapes, and loop over each unit. Then, I will update the attribute table of the crater database with a field corresponding to each crater's unit. Next, I will group the craters by their unit. Transferring to Julia code created by Palucis et al. based on the Smith et al. paper, I will then plot the craters on isochrons, comparing overall area of the geological unit to its crater-frequency distribution. The code takes an estimated age of the craters as an input, and outputs a refined age estimate and erosion rate. Once I have average erosion rates for each unit, I will create a raster layer back in ArcPro to show the variation of erosion rates across space and time. Finally, I will group units by latitude bands and observe the

relationship between erosion rates and latitude, as glacial erosion is thought to be the dominant erosional force at the poles of Mars, whereas fluvial erosion is more likely to exist closer to the tropics, the region around the equator.

Expected Results

Once I fit the craters to the isochrons, I will have a visualization of the erosional variation across the whole globe. We expect older units to have undergone more erosion, as they have been exposed for longer, but when normalizing for time exposed (age of the unit), units should have similar erosion rates. However, erosion rates might have quickened in time periods and locations with more water available. In a GIS study of specific types of glacial landforms observed on Mars, Levy et al. found that erosion rates in the Amazonian epoch (the last 3 Gyr) have been slow, from 5–10 m/Myr, but glacial landforms show erosion rates 4–7 orders of magnitude higher than average Amazonian rates in non-glaciated regions. The Amazonian glacial erosion rates are similar to terrestrial cold-based glacier erosion and entrainment rates. Noachian erosion rates were orders of magnitude higher than Amazonian rates due to increased fluvial activity (Levy et al. 2016). During the Noachian epoch, Mars's climate was relatively warm and wet, whereas today it is extremely cold and hyperarid. However, there are highland paleodrainage systems that indicate hydrological activity during the Amazonian epoch (Salese et al., 2016). I expect to observe significant variations in erosion rates across time periods (Noachian, Hesperian, Amazonian) and latitudes. Because of Earth's positive correlation between latitude and glacial activity, its negative correlation between latitude and fluvial activity,, I expect to see higher erosion rates at the poles and tropics on Mars.

Conclusion

After 50 years of innovation in Martian orbital imagery, we are answering vital questions

about the early climate of Mars in impressive detail without having ever sent a manned mission. For example, two different models of Mars's past climate have been proposed and debated. The first is akin to "Snowball Earth", where the globe would have been covered in carbon dioxide ice, extremely cold and hyperarid. The second is more like the terrestrial Arctic, covered in water ice and flowing streams, which would be warmer and wetter than the former model (Ramirez and Craddock, 2018). If we can determine how much glacial and fluvial activity there was across the planet, using erosion as a proxy, we can get a better picture of how wet the climate was. The implications of water and ice on Mars are massive, particularly when considering the prior, present, or future habitability of Mars for water-based life. These different ice ages meant different thresholds existed for habitability. Geologists have found evidence of ice driven processes and subsurface ice in younger terrains and climates, implicating both the existence of water more recent than the Noachian epoch, and potentially microbial life in the subsurface. In the perspective of sending manned missions to Mars, or even, though seemingly far-fetched, starting colonies on Mars, it is important to know where water could be, to recycle and drink. Finally, in the perspective of comparative planetology, expanding our understanding of Martian climate and geologic surfaces can aid in our understanding of Earth's history. We don't have access to very much ancient rock or original landforms on Earth because of tectonic plate recycling. Mars doesn't have tectonic plates – its entire record is still etched in its surface (barring erosion). We can study Martian systems, including the relationship between geology and climate, and compare them to terrestrial patterns. We have so much more to learn about both planets, and determining global erosion rates and the processes causing erosion is a step forward along this path.

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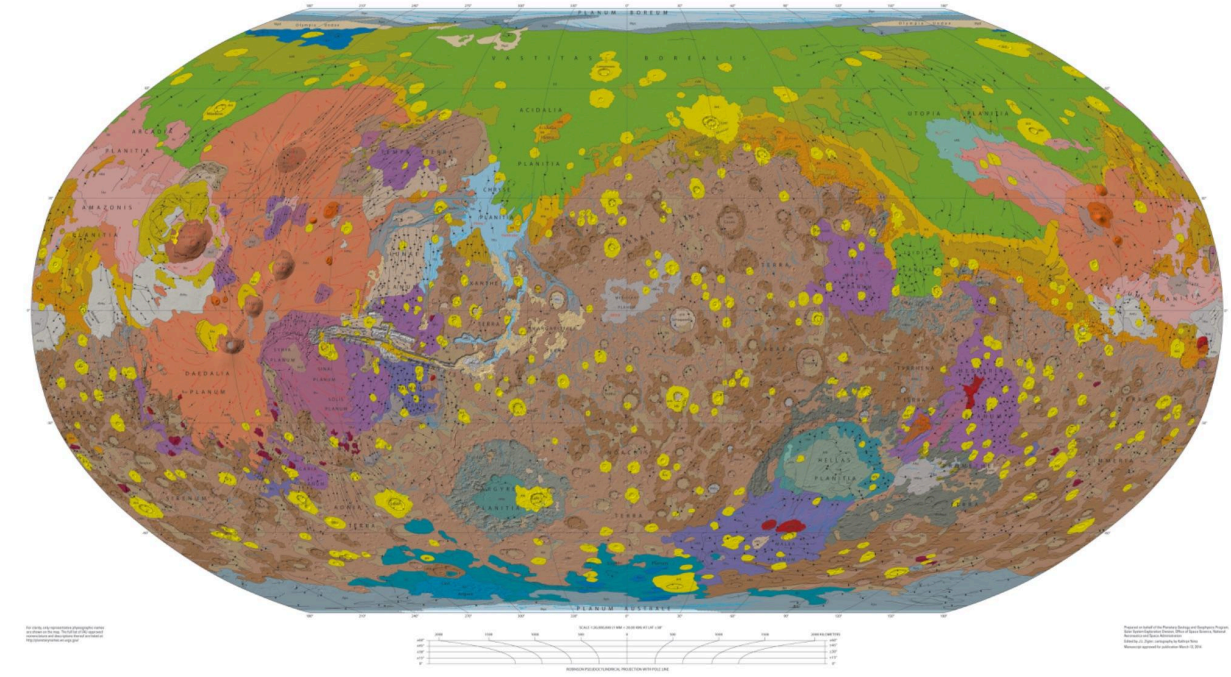
Figures



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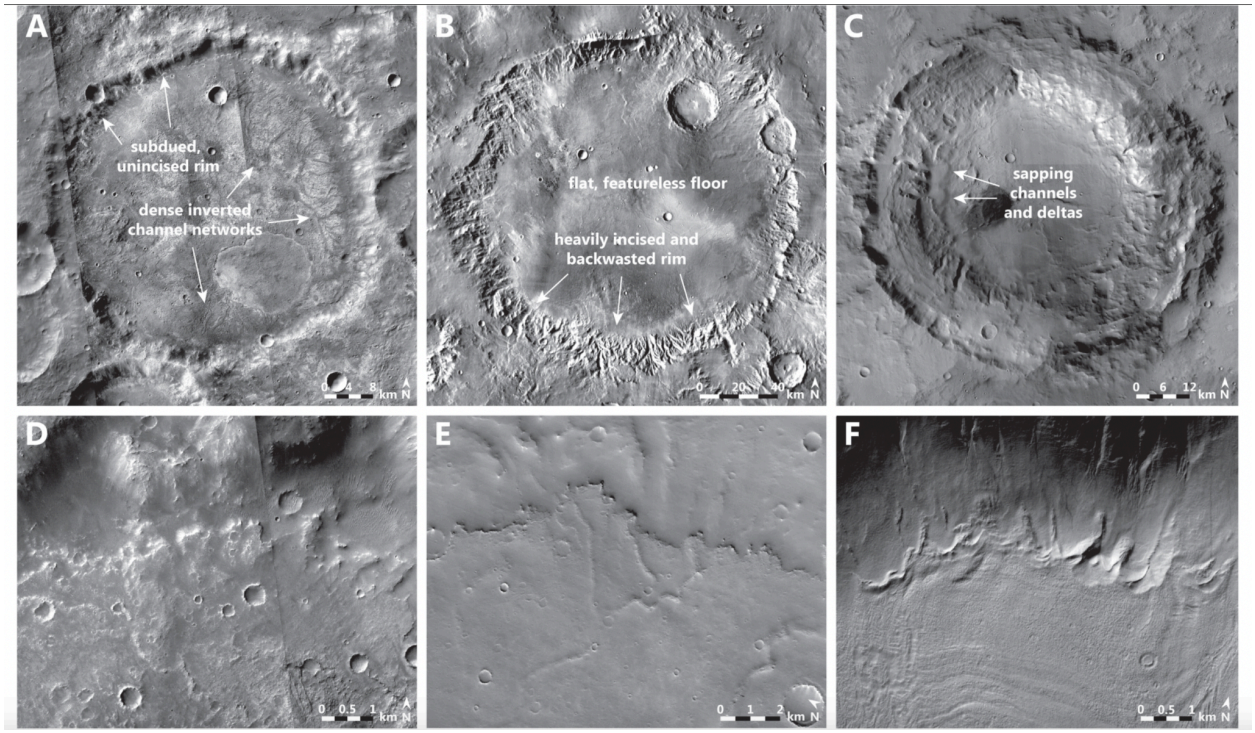

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$$N = \frac{1000}{\psi\beta} p(d)\xi(1 - e^{\frac{-\psi\beta t}{1000\xi}})$$

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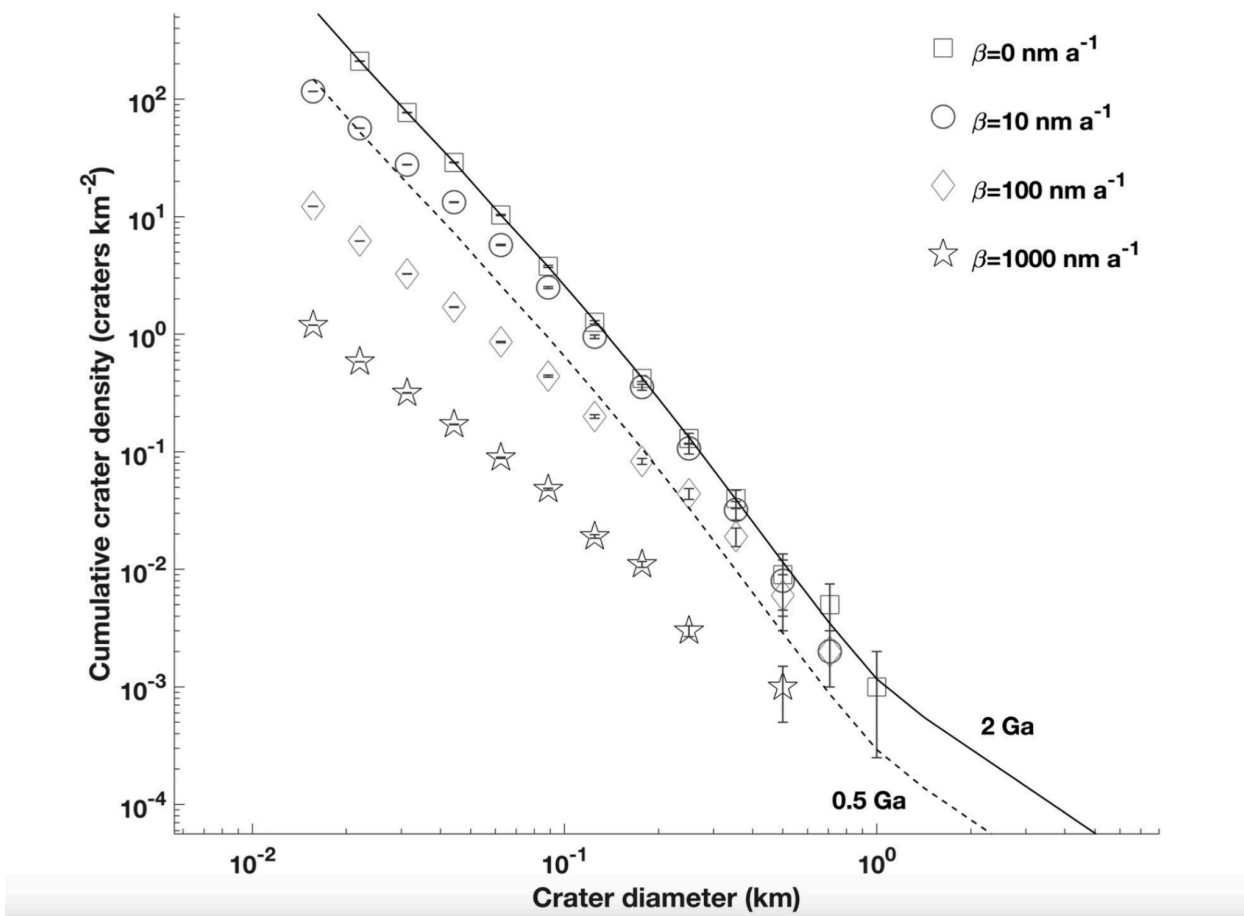

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