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Analysis of Ancient Fluvial Patterns on the Surface of Mars
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Abstract

This project involves the study of ancient fluvial patterns on the surface of Mars, including raised curvilinear features (RCFs) and negative relief channels. It requires the use of geological images provided by the Mars Reconnaissance Orbiter to determine how water shaped the surface of Mars in the form of rivers, lakes and/or oceans approximately 3.5 billion years ago, during the Noachian period. The role of the intern is to examine the images and record the corresponding measurements of ancient river systems in an Excel spreadsheet to assist in determining the Noachian water cycle on Mars.

Resources used to make these measurements include the Arena software, hand-drawn sketch maps, Microsoft Word, Microsoft Excel and the images provided by the Mars Reconnaissance Orbiter. The Context Imager (CTX) returns black and white images at a resolution of six meters per pixel. The camera can take images with a width of 30 km and a length of 160 km. Seventeen images were observed in total. Images are analyzed and notes are taken concerning their terminal deposits, stream ordering and drainage pattern. The Arena software is utilized to make the images more visible by allowing control of contrast and magnification. Once the image is adjusted, measurements: length, average width, drainage basin area, sinuous ridge area are recorded, at a magnification of one, through using the line segment and polygon tools. After an image has been analyzed and measured, a sketch map is drawn in order to clearly identify the various segments, basins and terminal deposits the intern observed.

Observations are used to further classify the fluvial patterns; their drainage pattern is defined as dendritic, parallel, trellis, rectangular, radial, centripetal, deranged or discordant. Once observational notes are completed, mathematical relations are used to determine drainage density, stream frequency, theoretic basin area and sinuosity index. These data will be added to a larger data set that will yield a comprehensive view of early Mars drainage systems.

The data obtained from the work conducted will be used to characterize the nature and behavior of water on the surface of Mars. Thorough understanding of the Martian water cycle will serve as biologically significant information. Through working on this project, I acquired insight into the study of planet Mars, and skills in the Arena software as well as the organization of a vast amount of data.

The mentors who have contributed to the Analysis of Ancient Fluvial Patterns on the Surface of Mars project include Dr. Robert Haberle and Dr. Rebecca M.E. Williams.

Introduction

Images transmitted by the Viking and Mariner Orbiter Missions during the 1970s revealed meandering river beds on the Martian surface, thus providing strong evidence that water once existed on the face of the planet billions of years ago (Williams, n.d.). The fluvial patterns indicate that a large amount of water was required to carve out the features. The current atmosphere is too thin and the surface pressure is too low for the planet to sustain flowing water on it's surface. The images show numerous long, deep channels that required rainfall. For the planet to have supported rainfall, the atmosphere would have had to be thick and the surface pressure would have had to be higher. The history of the 4.6 billion year old planet’s atmosphere and water cycle remains unknown due to its low gravity and unknown history of tectonic activity(Forget, Costard, Lognonne, 2006). The celestial body may have harbored a moist atmosphere sustaining large bodies of water that were lost as the atmosphere thinned. Currently, missions are underway to address whether water existed on the planet’s surface long enough to sustain a habitable climate teeming with microscopic life. Mars missions are collecting data reconstruct the planet's history, characterize the climate and geology of the planet, determine if subsurface water is present on the planet today and prepare for future human exploration of the planet. Establishing early hydrological cycles on Mars will serve as significant information when considering the possibility of Mars sustaining a biosphere in the past. The fluvial networks currently under observation date back to the Noachian Epoch; a period that scarred the Martian surface with impact craters 4.6 to ~3.5 billion years ago. During the Noachian epoch, Mars held favorable conditions for sustaining water on its surface.

In 1972, Mariner 9 discovered Martian valleys that closely resembled river beds; in 1975, the Viking Missions provided a complete view of the surface, which includes lava plains, numerous crater impacts, wind created landforms, and indication of the planet once holding surface water. The Mars Reconnaissance Orbiter (MRO) launched from Cape Canaveral in 2005 in a pursuit to retrieve information about the 3.5 billion year old fluvial networks now preserved as exhumed paleochannels, raised curvilinear features (RCFs), and negative relief channels. The MRO is currently orbiting Mars in a sun synchronous orbit which allows the scientific instruments aboard the spacecraft to capture quality images with the aid of shadows at 3 p.m. Mars time. Its payload consists of numerous scientific instruments including HiRISE (High Resolution Imaging Science Experiment), CTX (Context Imager Camera), MARCI (Mars Color Imager) that map topography and capture images of the landscape at a global level.

Images of the Martian landscape reveal the various preservation states of valley networks on Mars; they include inverted paleochannels, negative relief channels and raised curvilinear features (RCFs). Inverted paleochannels went through the process of induration, when the valley bed is covered by coarse grains, cemented by silcrete, ferricrete, calcrete or gypcrete and enforced by an impermeable material, such as lava, which makes the valley bed more resistant to erosion than the valley slopes(Williams, 2009). Eventually, as processes of erosion take over the planet, the valley slopes dissipate revealing the valley floor at topographic elevation. These raised meandering features are referred to as inverted paleochannels and RCFs. These features have been observed all over Earth; paleochannels in east-central Utah resemble the Martian RCFs in morphology and in scale. The longest paleochannel observed in the Utah paleochannel study exists on the Colorado Plateau; at Emery County Utah, this paleochannel started off as a fluvial channel in the Early Cretaceous, by late Cretaceous it was buried by a sea because water levels rose due to global warming. By late Quaternary, erosion stripped away at the network and showed the surface deposits. Due to constant erosion, the once fluvial channel is now preserved as a ridge. The arid climate of the plateau prevented the formation of soil, thus leaving terminal deposits undisturbed and ideal for research (Chidsey, Eby, Williams, n.d.).

Documenting the fluvial networks on Mars will assist in characterizing the fluvial sedimentary processes that took place on the planet. The purpose of the project is to document and classify the fluvial features and gather corresponding quantitative data that will be used to determine the amount of water flow and sediment as well as the length of time the water flowed in the system.

Goals and Purpose

The purpose of the project is to create a database of quantitative measures that will allow us to

1) Document and categorize each network.
2) Construct a range for the active water flow in the system , an amount of sediment involved in erosion and the length of time the water flowed in the network.
3) Characterize the diversity of erosion processes that caused the morphology of these landforms.

Completing the aforementioned objectives with the provided images will be used as a foundation for comparison as more images are discovered and documented. In entirety, the collection of data and observations of Martian fluvial networks will enable the characterization of the Noachian water cycle. Knowledge of the water cycle will serve as a piece in the goal of reconstructing an all encompassing history of the Martian atmosphere, climate, topography and resolving the question of the planet sustaining a biosphere in the past. Understanding of the past will allow better preparation for future human exploration of the planet and scientific experiments to be conducted on the planet.

Methods and Procedures

The Context Camera on the MRO provided the 17 images that were analyzed during the course of this project. The camera captured grayscale images, at a resolution of 6 meters per pixel, with dimensions of 30 km width and up to 160 km in length. CTX images can be assembled images into mosaics which are calibrated, processed and map projected by scientists. This process allows images to be measured in Arena. Arena is a software program specifically designed to be used to make measurements of the CTX images. Arena also permits manipulation of images with contrast and magnification tools so they are better visually represented and calculated. For accuracy, a magnification of positive one is used.

Observational data is documented for each image. This data includes stream ordering, drainage pattern, notes on terminal deposits and preservation style. Stream ordering involves numbering the segments like the nodes of a tree. (see FIGURE 1) The segments combine to form a parent stream. Two or more first order streams join to form a second order stream, second order streams combine to form a third order stream, etc. If one first order stream merges into a second order stream, the stream remains in the second order.

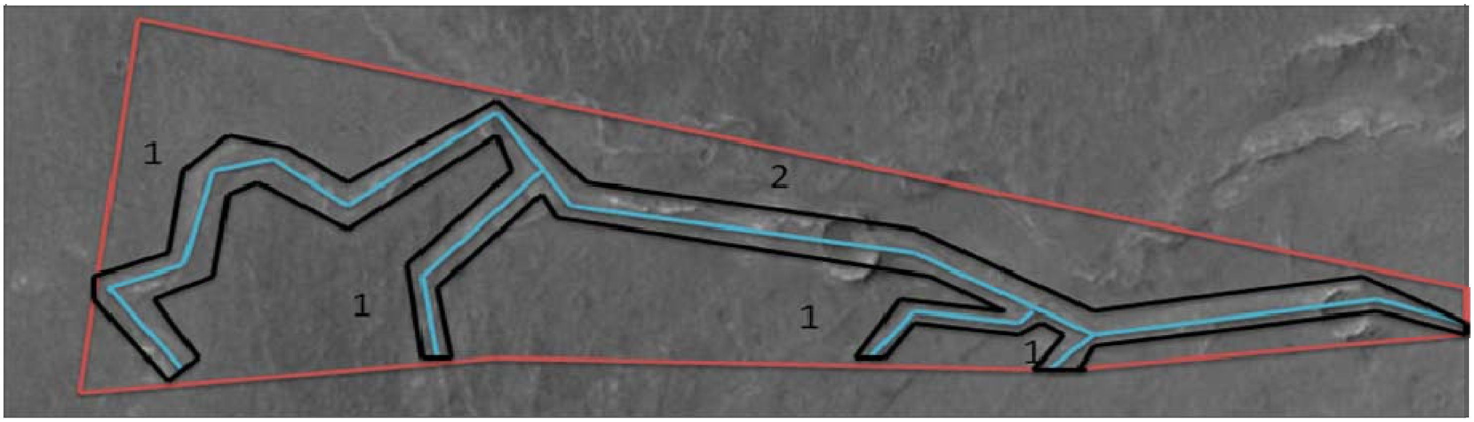

Figure 1. Image MC 18-11. The stream ordering of the Martian fluvial network is indicated by numbers and the sinuous ridge area is enclosed by the red border.

Just like mathematical trees, a tributary with an order of n must be a combination of at least 2^{n-1} streams of index 1. In the database, the number of observed segments, the highest order present in the network and the number of first order segments are recorded. The highest order channel is the main trunk; it's the channel that all of the tributaries feed into.

The dendritic drainage pattern was observed in thirteen of fluvial networks; dendritic follows the branching of tributaries off the main fluvial trunk similar to a tree. This pattern is common in areas of homogenous materials; the material doesn't control the direction of the segments. The parallel pattern was observed in three images; it's characterized by the branching following the slope of the ground. The pattern can also indicate the presence of a fault through steep bedrock.

If positive relief remnants of a stream are clumped and spread out at the end of a stream, the network has terminal deposits. Terminal deposits indicate water forced sediments to mass together at the end of the stream.

Documenting preservation style involves identifying the positive and negative relief portions of each fluvial network. Using the shadows of the images, the preserved networks are categorized as valleys or ridges. If a network has multiple style of preservation, then the order of preservation is recorded from the tributaries to the main trunk, from upstream to downstream.

Since images are manipulated in Arena, sketch maps are traced of the fluvial networks in order to elucidate the identified tributaries (see to Figure 2). For each sketch map, an 8in. by 11in. key is drawn in order to indicate the location of the fluvial network in the entire image.

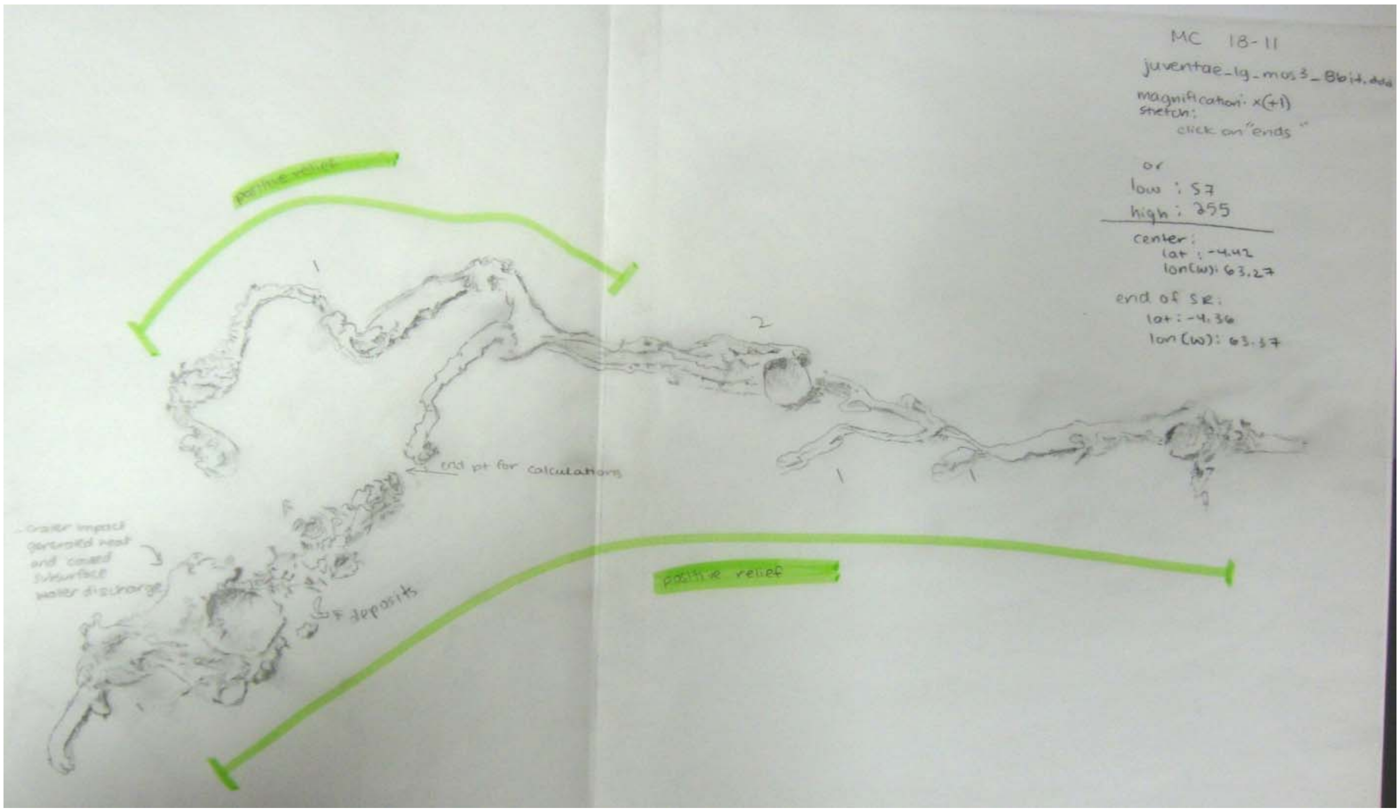

Figure 2. A sketch map of image MC 18-11. Green indicates positive relief preservation style.

Mathematical observations and analysis were made as well. Through using the line segment tool in Arena, the length of the main trunk and the total length of the network are recorded in kilometers. The total length is the sum of the length of the main trunk and the lengths of the multiple tributaries. The minimum width and maximum width are taken using the line segment tool and stretching the produced line across the width. Minimum width is the shortest width observed along the main trunk; the maximum width is the longest width observed along the main trunk. Using the same method, and measurements eight other random widths are recorded all along the main trunk; the total ten widths are used to calculate the average width and the standard deviation. The standard deviation shows how much the widths vary from the average width. A high degree of variance can indicate erosion or modification of the RCF. With the polygon tool, the endpoints of the sinuous ridge are connected and the corresponding RCF area (SR) the network resides over is recorded. Another measurement of area, precise area, is taken by laying the polygon tool's lines along the outline of the network. The aforesaid mathematical measurements are used to determine drainage density, stream frequency, theoretic basin area and sinuosity index, which are defined as follows:

Drainage Density = $L(A)^{-1}$

Stream Frequency=$N(A)^{-1}$

Theoretic Basin Area= $(X/ 1.4)^{5/3}$

Sinuosity Index=SI=actual sinuous ridge length / shortest possible sinuous ridge length

where

L= total length of network, includes length of the main trunk and individual tributaries in km.

A= basin area in km^2

N= total number of segments

X=length of the main trunk in miles

The drainage density is a measure of the amount of stream length per kilometer squared. The stream frequency is a measure of the number of segments per kilometer squared. The amount of basin area that should be taken up by a stream, according to the length of its main trunk,is defined by the empirical equation of theoretic basin area. The calculated basin area was compared to the actual basin area; such comparison demonstrates the amount of basin preservation. Sinuosity index is a ratio between the actual length of the main trunk to the shortest length possible of the main trunk. A sinuosity index greater than one indicates a meandering stream.

On Earth, the typical width of a system is approximately ten times its depth, thus dividing the average width by ten gives the depth of the main trunk. If a fluvial system has multiple preservation styles, then the average of the average positive relief width and average negative relief width is calculated if the system's width can be better represented by this method. The depth, width and length of the main trunk are multiplied to find the minimum volume of the channel. The total length is multiplied with the depth and average width in order to solve for the maximum volume of the channel. The volume of the channel represents the amount of sediment involved in the erosion of the network.

The ratio of sediment to the amount of water involved in the active network is 40 percent to 60 percent, thus the range of the volume of water l involved in the active fluvial system is defined as follows:

Minimum volume of water = (6s)/4

Maximum volume of water = (6S)/4

where

s= the minimum channel volume

S= the maximum channel volume

Precipitation levels are calculated by dividing the minimum water volume by the theoretic basin area, when the theoretic basin area is larger than the sinuous ridge area. Theoretic basin area is used in this formula because the water that fell onto the surface the network was active over would drain into the tributaries. The formula gives the volume of water per kilometer squared over the fluvial network region. If the sinuous ridge area is larger than the theoretic basin area, than the fluvial network must carefully analyzed to evaluate the area that most appropriately represents the network.

Findings

ID	Main Trunk Length (km)	Total Length (km)	Highest Order	Sinuous Ridge Area (km^2)	Stream Frequency (km^2)	Density (km)	Theoretic Basin Area (km^2)	Sinuousity Index	Average Width-Pos. Relief (km)	Average Width-Neg. Relief(km)	Minimum Vol. of Water (km^3)	Maximum Vol. of Water (km^3)	Precipi-tation(km)
MC 5-1	161.2	222.3	2	1474.7	0	.15	3193.58	1.22	.860	1.080	22.75	31.37	.0071
MC 19-3	44	46.1	2	140.2	.02	.33	366.79	1.62	.430	.480	1.22	1.28	.0033
MC 18-1	34.8	39.7	1	125.5	.01	.32	248.1	1.14	.760		3.02	3.44	.0122
MC 21-12	64.4	146.7	2	420.4	.02	.35	692.06	1.14	.410		1.65	3.76	.0024
MC 13-1	9.5	28.8	3	40.2	.2	.72	91.28	1.37	.130		.02	.07	.0003
MC 21-7													
Network 1	1.5	2.61	1	.00035	5768.68	7529.28	1.31	1.15	.050		.0005	.0009	.0004
Network 2	1.5	1.5	N/A	.00008	N/A	18115.94	1.31	1	.040		.0004	.0004	.0003
Network 3	.71	1.9	1	.00058	3445.31	3273.04	.38	1.08	.050		.0002	.0007	.0006
Network 4	1	2.2	1	.00028	7027.00	7730.15	.67	1	.050		.0004	.0008	.0006
Network 5	1	2.68	3	.00064	12470.77	4179.27	.67	1.05	.060		.0006	.0016	.0009
Network 6	1.8	1.8	N/A	.00021	N/A	8551.07	1.78	1.06	.040		.0005	.0005	.0003
Network 7	3.6	3.6	N/A	.00061	N/A	5877.07	5.66	1		.140	.0101	.0101	.0018
Network 8	1.9	1.9	N/A	.00037	N/A	5144.87	1.95	1.06		.130	.0046	.0046	.0023
MC 21-9	38.8	38.8	1	249.8	N/A	0.16	297.43	1.14		1.340	10.39	10.39	.0349
MC 11-20	49.3	107.01	3	490.9	.03	0.22	443.36	1.15	.300	.110	.3	.64	.0006
MC 11-21	11.1	39.41	3	91.9	.14	0.43	36.94	1.23	.100	.100	.02	.07	.0002
MC 11-1	11.9	50.28	3	97.3	.11	0.52	41.48	1.12	.200	.130	.05	.22	.0005
MC 25-1													
Network 1	17.5	24.2	2	.08	.08	0.48	78.9	1.09		.34814	.32	.44	.0040
Network 2	5.7	27.7	2	.03	.03	0.44	12.17	1.02		.40362	.14	.68	.0022
MC 16-2	106.5	106.5	N/A			0.31	1600.49	1.2	.180	1.670	13.82	13.82	.0086
MC 18-7	5	18.18	33	2.32	2.32	2.63	9.78	1	.200		.03	.1	.0029
MC 18-9	12.8	31.5	3	.59	.59	0.92	46.85	1.14	.160		.05	.12	.0015
MC 18-10	5.5	21.57	3	1.7	1.7	1.93	11.47	1.12	.05		.02	.01	.0002
MC 18-11	5	12.15	2	.77	.77	1.87	9.78	1.02	.140		.01	.03	.0014
MC 18-12	8.8	82.48	4	.35	.35	0.88	25.09	1.33	.270		.09	.87	.0010
Averages	24.19	42.46		149.44	1511.5	2416.53	288.77	1.14	.22	.54	2.16	2.69	.0036

The measurements corresponding to each fluvial network have been compiled over several spreadsheets. The following spreadsheet is a condensed version of the information collected. This information indicates that most sinuous ridges' average widths don't exceed 1 km. Another observation made was that eight fluvial networks have the third ordering as their highest and only one, MC 18-12 has a fourth ordering. Through comparison, it's evident that the empirical formula for theoretic basin area produces a larger number than the measured area in 13 of the images. The average main trunk length is 24.19km, average total length of the sinuous ridge is 42.46, average of the positive relief widths is .22km and of the negative relief widths is 54km. The typical amount of precipitation was about 3.6 meters, which is an immense amount of water. The data will be studied with other data collected from other fluvial images to characterize the Martian hydrological cycles of the past.

Conclusion

Of the 17 fluvial images analyzed, most streams averaged a 2nd or 3rd order. The 2nd to 3rd order indicates a semi mature network that must have required a large amount of water to carve out. One network has a fourth order stream; higher order streams are probable but cannot be observed because they have been eroded. For the majority of the networks observed, the precipitation levels average about 3.6 meters. These observations suggest that the Martian surface had to be exposed to continuous rainfall over an extensive period of time; a single event could not have caused this. Future research will indicate when the Martian surface was subjected to rainfall and what caused it.

The database of quantitative measures serves as a foundation of comparison as more images are collected by the MRO and future Martian orbiters. The data is only a portion of the entire research that has yet to be conducted. The observations and measurements gathered will help determine the diversity of processes involved in the morphology of the fluvial networks; the amount of sediment and the amount of precipitation per region would be made more accurate as more images are analyzed. The research has begun to characterize the Noachian water cycle. This information will help reconstruct an all encompassing history of Mars that includes its atmosphere, climate, and topography. This knowledge will help determine the existence of a Martian biosphere 3.5 billion years ago. Such understanding provides information for developing further experiments and preparing the next generation of human exploration of the planet.

Acknowledgements

I am grateful to the following mentors and organizations for significantly contributing to this project:

Dr. Williams for giving me the opportunity to work with images from the Mars Reconnaissance Orbiter, organizing the tasks I needed to complete for the images and inspiring me to learn more about the worlds beyond our planet.

Dr. Haberle for organizing the project with Dr. Williams, taking the time to demonstrate the steps I needed to follow for the images and inspiring me to pursue a field involving scientific research.

NASA and INSPIRE for arranging research opportunities for young students, further inspiring them to continue work in STEM fields and preparing the next generation of scientists and engineers.

Personal Impact

Through working on this project, I have gained insight into the geology of planet Mars. I have learned about the physical changes the planet went through as it progressed through the Noachian, Hesperian, and Amazonian epochs; and I discovered that despite erosion over billions of years, fluvial networks are still visible today in the forms of exhumed paleochannels and negative relief networks. The project allowed me to learn how the information retrieved by technology sent to Mars is received here on Earth. This project has taught skills in a new measurement taking software, Arena. Through telecons with geologist Dr. Williams, I have learned about the collaboration, teamwork and the division of tasks that a large scale project requires. I have gained work skills in a professional research environment; the skills include proper communication of work progression as well as organization of time for individual tasks. Being exposed to planetary systems research has also inspired me to pursue a career in astronautical engineering, a field of engineering involving the research of planetary atmosphere and geology. The skills in communication, project management, organization and research gained by working on this project will forever benefit the higher educational and professional worlds that lie ahead of me.

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