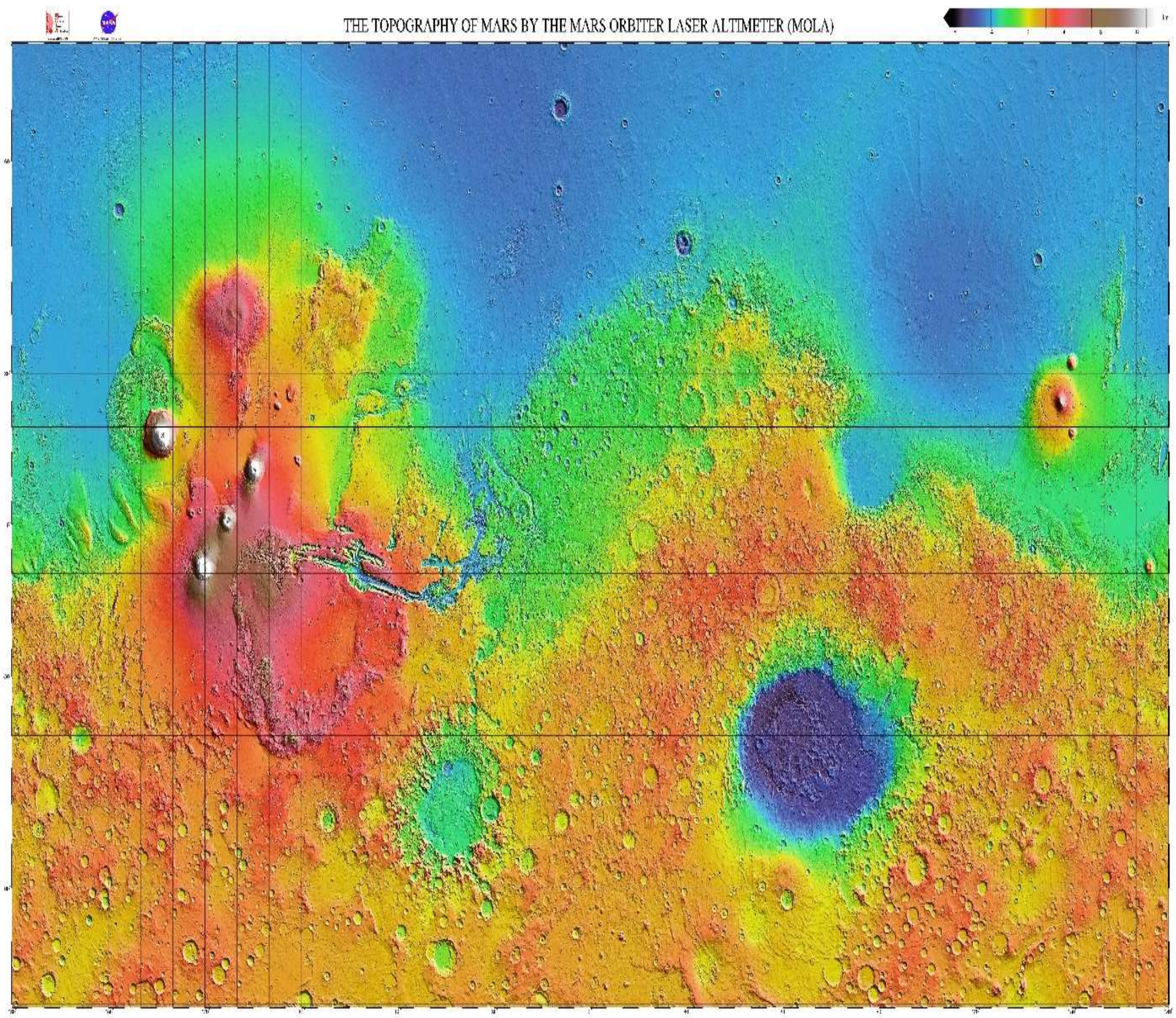
Alluvial Fans as Potential Sites for Preservation of Biosignatures on Mars



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I. <u>Introduction</u>

Understanding the origin of life

Life on Earth began 3.5 million years ago as the temperatures in the atmosphere were cool enough for molten rocks to solidify (Mojzsis et al 1996). Water was then able to condense and fall to the Earth's surface from the water vapor that collected in the atmosphere from volcanoes. Additionally, atmospheric gases from the volcanoes supplied Earth with carbon, hydrogen, nitrogen, and oxygen. Even though the oxygen was not free oxygen, it was possible for life to begin from the primordial ooze. The environment was ripe for life to begin, but how would it begin? This question has intrigued humanity since the dawn of civilization.

Why search for life on Mars

There are several different scientific ways to answer the question of how life began. Some scientists believe that life started out here on Earth, evolving from a single celled organism called Archaea. Archaea are a likely choice because they presently live in harsh environments similar to the early Earth environment such as hot springs, deep sea vents, and saline water (Wachtershauser 2006). Another possibility for the beginning of evolution is that life traveled to Earth on a meteorite from Mars (Whitted 1997). Even though Mars is anaerobic, carbonate-poor and sulfur rich, it was warm and wet when Earth first had organisms evolving (Lui et al. 2011). The solar system, Mercury, Mars, Venus, and the Moon, all show evidence of bombardments from comets and meteorites. Many meteorites discovered on Earth originated on Mars as evidenced by their mineralogy and composition (Whitted 1997). Regardless of whether life on Earth originated on Mars or evolved independently on the two planets, we can learn about the origin of life by studying the possibility for life on mars.

Where to Look

Knowing how life evolved elsewhere in the universe will help enhance our knowledge of how life formed on Earth. Throughout Mars's geologic history, there have been periods of warm wet environment that would have been capable of hosting life before the habitat turned cold. It is possible that life began during a warm period on Mars and was transferred to Earth via meteorites. To pinpoint exactly when in Mars' history that life may have begun, scientists use markers such as geology, sedimentology, and mineralogy to discover where, when and how the conditions for life may have occurred. The fact that life has not been discovered beyond our own planet does not mean it does not exist. A more strategic approach to searching for life is needed. Searching for past life on Mars is key. In this thesis, I outline such an approach and evaluate the prospects for success at several proposed locations for future exploration.

II. Background Information

Mars Geologic History

Three major time periods characterize Mars geologic history: the Noachian, the Hesperian, and the Amazonian (Figure 1). The pre-Noachian period began 4.5 Gyr ago and is characterized by Mars crustal formation and differentiation into mantle and core (Carr and Head 2002). The Noachian period began approximately 4.1 to 3.8 Gyr ago and is distinguished by the formation of the Hellas Plantia impact structure. The Tharis volcanic plateau also formed during this time. The Noachian period had heavy erosion, cratering from impacts, and valley formation. This is also the time when there was extensive weathering taking place creating phyllosilicates (Carr and Head 2002). The Valley formation during the Noachian is of particular interest. There had to have been rapidly moving water and incisions coupled with erosion to create the valleys. Water conditions in addition to warmer climate makes the Noachian a viable candidate for habitability. Sediments and bedrock exposed during the Noachian would be a good location to begin looking for life. As we continue in our discussion, it will become clear why later periods in Mars geologic history most likely did not support life.

The next period is the Hesperian period. This period, 3.7 Gyr to 3 Gyr ago, coincides with the Archean period on Earth. It occurred at the end of the heavy meteor and asteroid bombardment period and it is characterized by extensive volcanism, formation of canyons, and a decrease in the rates of erosion. The Valles Marineris is the most notable formation that developed during the Hesperian because of its puzzling origin. Scientist are not sure how it formed, if it contained a lake, and if so how the lake formed. Sulfates appeared in this time period, potentially due to weathering or erosion. The temperature also began to decrease (Carr and Head 2002).

The present period, the Amazonian period, began 3 Gyr ago and is the longest period in Mars geologic history. In addition to extensive volcanism smoothing over the heavily cratered terrain, ice began to alter the surface. Ice has been present at the poles since the Hesperian period, but the Amazonian is the first period when the ice has been conjectured to have moved. In so doing, ice has altered the surface. Temperatures have now settled at 220-230K. Liquid water cannot exist during this period because pressure and temperature at the surface are below the triple point of water (Carr and Head 2002). The cold temperature and lack of liquid water make life on Mars unlikely, but there is still hope that traces of life from an earlier era can be found.

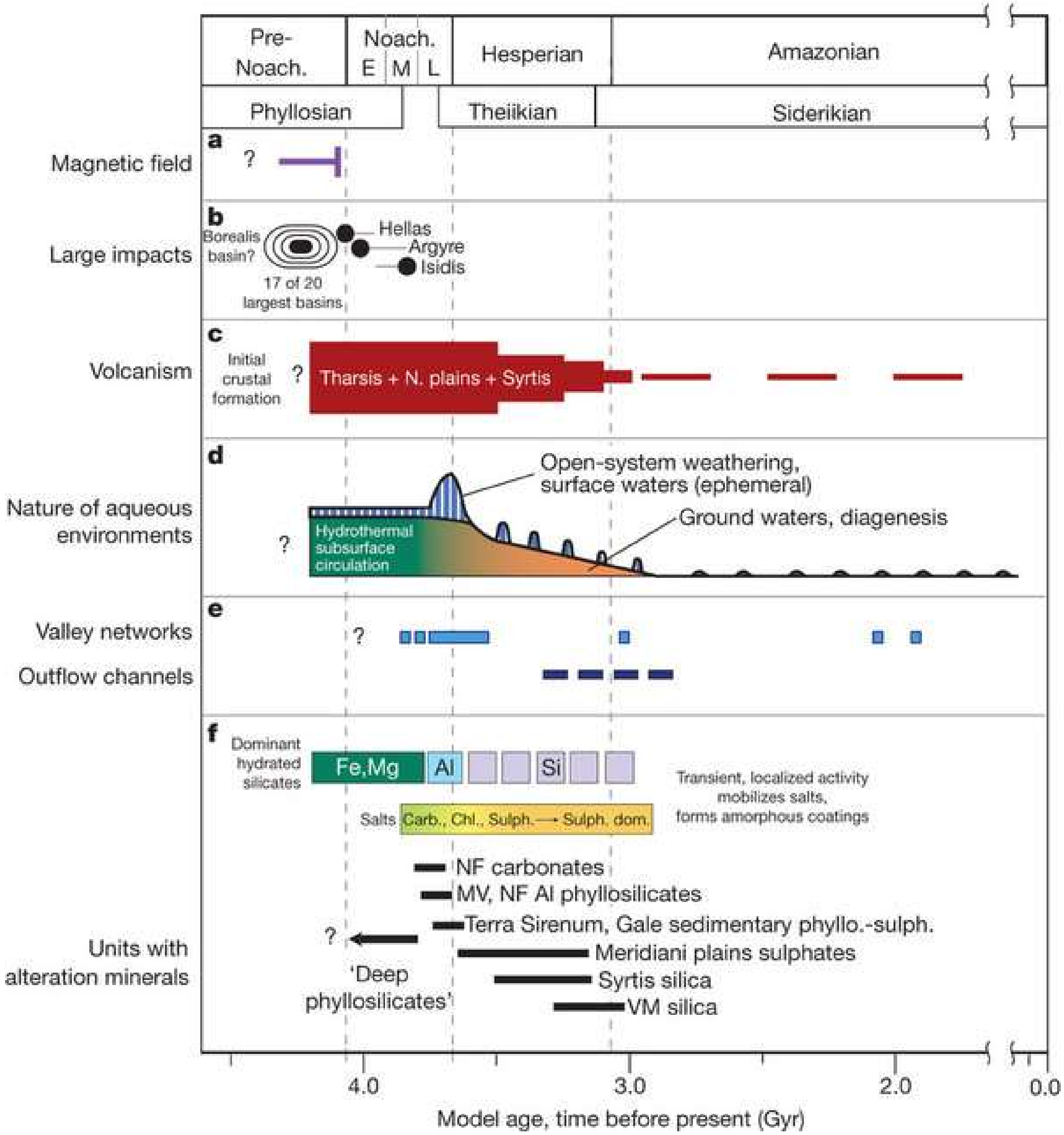

Figure 1. Mars geologic history with important events in Mars' history (Ehlmann et al. 2011).

Mineralogy and sedimentology

Another important conversation surrounding Mars is the sedimentology of the planet. The OMEGA IR Mineralogical Mapping Spectrometer was launched aboard the European Space Agency Mars Express Mission in 2003. OMEGA is an instrument that gives spectral data from the surface and the atmosphere of Mars. This data allows for studying the mineral composition on the surface and exploring the geologic details on Mars. The goal of the researchers is to build a map to gain a better understanding of the iron content, rocks, clays, and other minerals. The spectrometer uses visible and infrared light to detect wavelengths from 0.5 to 5.2 microns (Gendrin et al. 2005).

Results from Bibring et al.'s study of OMEGA data show that the most widely distributed mineral on Mars is the mafic mineral, Fe – bearing pyroxene (Bibring et al 2006). The crust is comprised of low calcium pyroxene and the lava flows show more high calcium pyroxene. Olivine and pyroxene are the most abundant minerals in the older terrains but the younger terrains are overwhelmingly made up not of mafic minerals, but of a mineral that has undergone extensive weathering (Bibring et al 2006). OMEGA spectral images also show signatures of Fe^{3+} that has been oxidized, but the oxidation is not due to water presence. Hydrated minerals are not found near the ferrous oxides, however, several minerals that do require the presence of water.

OMEGA detected two specific types of hydrated minerals, phyllosilicates, which are clay minerals, and sulfates (Bibring et al 2006). The first type of hydrated minerals are phyllosilicates. The phyllosilicates are either iron or aluminum rich and are the most widely distributed mineral on Mars. They can be seen in light toned outcrops and scarps, in volcanic plateaus, and in valley regions. They are associated with Noachian aged surfaces. Presumably, there are more phyllosilicates buried in rocks beneath the regolith found currently found at the surface. The second major class of hydrated minerals found on Mars are magnesium and calcium sulfates (Bibring et al 2006) (discussed below).

Clay minerals were most likely formed in the subsurface. Three processes could have formed these hydrated minerals. The three proposed processes are hydrothermal activity, cratering (meteors or asteroids could have created the hydrated minerals by supplying the impacted minerals with subsurface water from Mars excavated during impact), and mantle cooling (Bibring et al 2006). In each of these scenarios, Mars is not required to be warm and each of these processes require formation over an extended period of time independent of Mars' atmosphere. Clay minerals will be important in the future discussion of preservation methods, so it is important to get a full understanding of the locations of the phyllosilicates on Mars. Figure 2 comes from Bibring's research and shows the global map of hydrated minerals plotted over a Mars Orbital Laser Altimeter (MOLA) map of Mars (Bibring et al 2006).

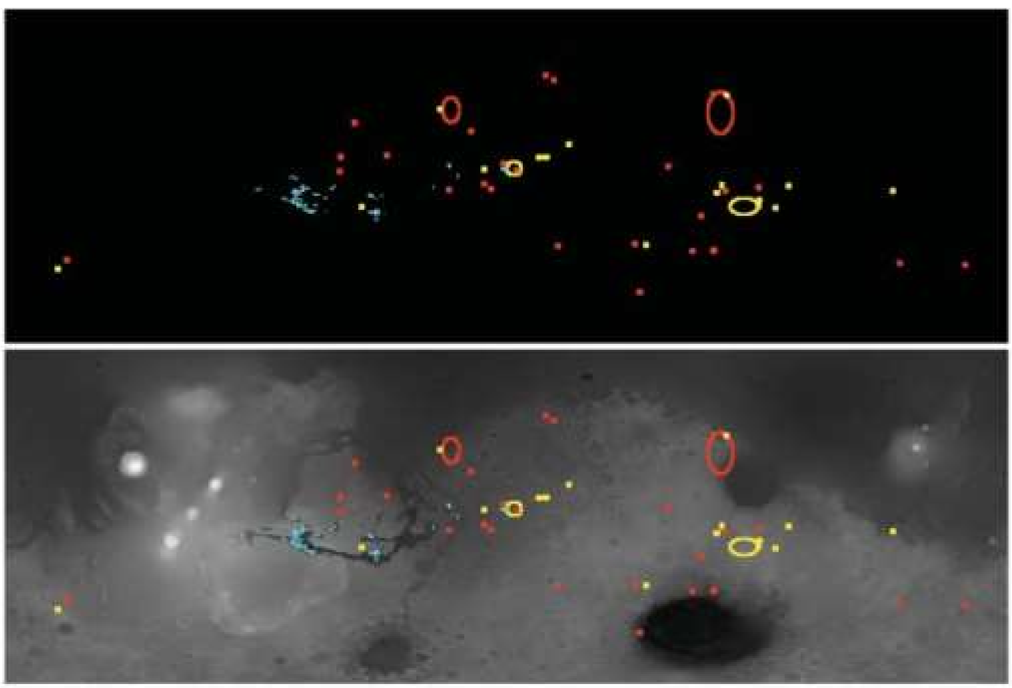

Figure 2 at the top shows the global locations of hydrated minerals and the bottom shows the hydrated minerals mapped in reference to altitude. Phyllosilicates are shown in red, sulfates in blue, and yellow references other hydrated minerals (Bibring et al 2006). Global map of Mars, 100s of km across.

Sulfates are the second major class of hydrated minerals found on Mars surface. There are three types of hydrated sulfate deposits: layered deposits, extended deposits, and dark dunes (Bibring et al 2006). Sulfates are formed through evaporation of seawater. On Mars, their presence leads to speculation that lakes and lagunas existed at the time of formation. Sulfates can also be formed at depth such as in sulfur – rich hydrothermal vents. The main sulfates found on Mars are kieserite, gypsum, and polyhydrated sulfates. Sulfates are found are at the Valles Marineris, Margaritifer Terra, and Terra Meridiani. The sulfates exhibit less of an organized distribution and tend to be scattered throughout the terrains where they are found. They can also be seen in OMEGA pictures as light toned terrains, but they have a different spectral signature than phyllosilicates. Due to the presence of brines on Mars, it is believed that there is more iron and magnesium present which explains the greater abundance of iron rich and magnesium rich sulfates on the surface (Gendrin et al. 2005). Figure 3 shows the distribution of sulfates within the Valles Marineris.

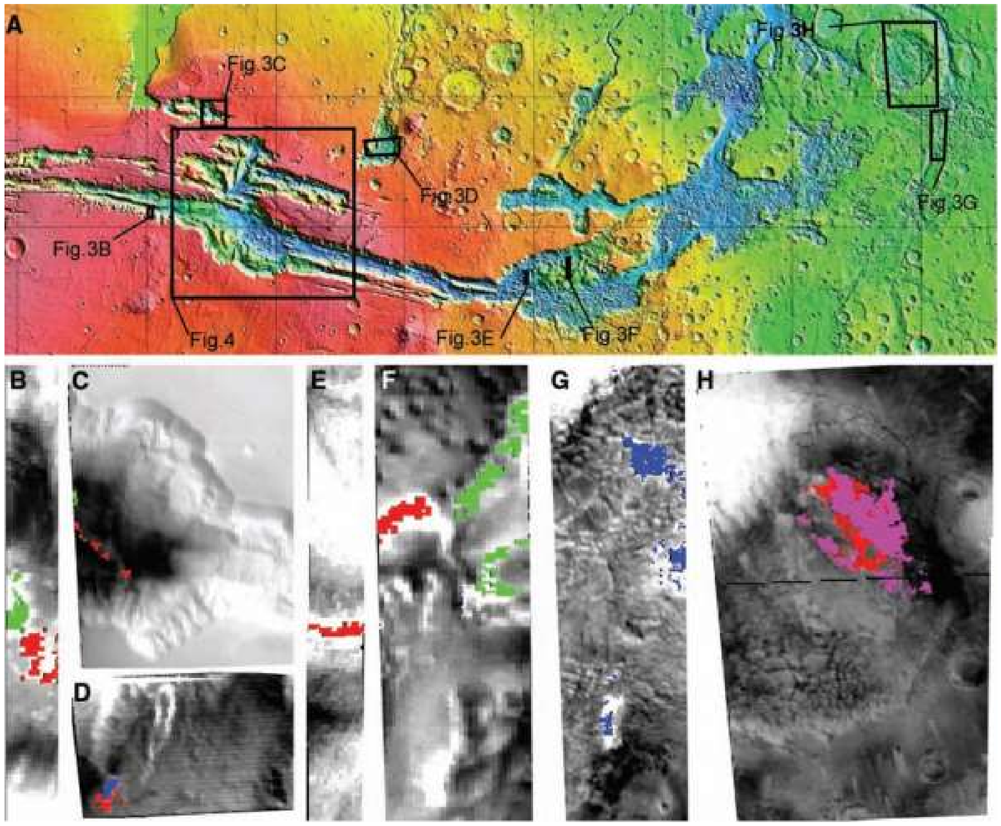

Figure 3 shows the location of sulfates in Valles Marineris. (A) displays Vallers Marineris plotted with altitude. Red indicates kieserite. Green indicates polyhydrated sulfates. Blue indicates gypsum. Pink indicates other hydrated minerals. (B-F) represent different locations within the Valles Marineris: Lus Chasma floor, East Hebes Chasma interior, Juvente Chasma interior, Capri Chasma, (crater flank, interior butts), Iani Chaos and Aram Chaos Interiors, respectfully (Gendrin et al. 2005). Top map, global map of Mars, 100s of km across. Bottom pictures are local and are 10s of km across.

Rocks as a record of climate and planetary evolution

Sedimentary rocks on Mars are just as important as clays. These rocks hold the history of planetary evolution. The Mars Reconnaissance Orbiter was the first spacecraft to detect and confirm the presence of sedimentary rocks (Grotzinger et al 2011). The Mars Reconnaissance Orbiter was launched in 2005 and carried several different instruments, three cameras and two spectrometers, to collect data (Mustard et al 2008). Finding the sedimentary rocks on Mars was important because they hold the history of the climatic evolution on Mars. The Noachian period consisted of lots of weathering coupled with a neutral pH that created lots of clays minerals. In the Hesperian period, a significant amount of sulfates formed due to acid in the environment. The current Amazonian period is characterized by having an abundance of anhydrous ferric oxides.

Scientists have proposed that, currently, a slow weathering process is happening on the surface of Mars without liquid water being present (Grotzinger et al 2011), quite a contrast to the world of rushing water indicated by formations from the Noachian. Sedimentary rocks on Mars hold the key to answering the question of whether or not the regional/global change from water-rich to water-poor conditions happened on Mars. While scientists speculate that water once existed on the planet, the only way to know for sure is to study the rocks. To answer this question appropriately, rocks of different ages would have to be gathered to see the transitions of chemistry within the rock stratigraphy. This has been done to some extent based on collections of rocks/spectra from various missions. The way the rocks are sequenced, it appears that clay rich strata formed prior to the sufate-rich strata (Grotzinger et al 2011).

How sediment production occurred on Mars is still a major area of research that needs to be addressed. Images show that physical weathering is taking place. Grotzinger (2011), reviewing this imager, proposes that processes such as eolian abrasion, thermal stress, and permafrost processes have taken place on the surface. The other major cause of weathering on Mars is impact cratering. On impact, meteorites and asteroids shatter the bedrock causing physical weathering on the surface. This shows that there is a balance of chemical and physical weathering taking place on Mars (Grotzinger et al 2011). Large sediment deposits related to the physical processes described above have been observed across the southern hemisphere and near the equator on Mars (Grotzinger et al 2011). Clay sediments are also widespread and contain the history of fluid chemistry on Mars. Life on Mars, if it existed, was in the microbial state and would thus have been closely tied to the fluid history on Mars. Understanding the fluids on Mars will give us a greater understanding of the microbial past on Mars.

The history of water on Mars

When Viking made first contact with Mars in the 1970s, it discovered evidence of water. The spacecraft saw incised channels, outflow channels, and valley networks (Levy 2015). Since then, scientists have proposed six potential sources of water on Mars. They include polar ice caps, hydrous minerals, ground water, permafrost and ground ice, atmospheric water vapor, and recurring slope linea. Ice caps can be found at both the north and South Pole of Mars. They are permanent water ice and are covered by frozen CO_2. The North Pole is covered with CO_2 ice during its winter season and the South Pole is covered with CO_2 ice during its winter season. The CO_2 at the Martian North Pole fully sublimes during summer, but the sublimation is never complete at the South Pole. The water found at the poles in their respective summers is not necessarily useable by microbial lifeforms. Water occurs only as ice, and it is constantly forming and disappearing due to sublimation (Cockell 2013).

Hydrous minerals are minerals that have water in their structure, such as the phyllosilicates – clay minerals, chlorites, and sulfates – found on Mars (Carter et al. 2013). When they were formed, presumably water existed on Mars. These minerals cover approximately 3% of the surface in the southern highlands and are potentially older than 4Gyrs (Carter et al 2013). Finding the exact locations of these minerals on Mars will help to constrain the locations of potential water sources. Investigating these locations will also lead to a better understanding of the environment in which they were formed, including clues about the amount and form of water present.

Of all the water present on Mars today, one of the two main sources is ground water. This water is locked up deep within the crust of Mars (Clifford et al. 2010). The cryosphere traps water and when the amount of trapped water exceeds the pore space of the cryosphere, it gets stored as ground water (Clifford et al. 2010). The other main source is ground ice. Ground ice, or permafrost, refers to water in the form of ice under the surface of Mars. There are many features on Mars that support the idea that permafrost exists. Channels on the surface that appear to be carved by water, valley networks on older terrains, and ejecta flow features from craters all support the idea that permafrost exists beneath the Martian surface (Jakosky and Mellon 2004).

Ground ice near the surface is important because it seasonally exchanges water with the atmosphere in the form of water vapor (Jakosky and Mellon 2004). Atmospheric water vapor is another potential source of water on Mars. Stable liquid water does not exist on Mars because the temperature on the surface is well below the freezing point of water, but water vapor and ice clouds are trapped in the atmosphere (Jakosky and Mellon 2004).

The humidity in the atmosphere is usually high and near saturation, leading to the formation of recurring slope linea (McEwen et al 2011). Recurring slope linea are proposed to be a current source of water on Mars. These features are narrow, dark markings that are found on steep slopes (McEwen et al 2011). They are considered recurring because they lengthen in warm seasons and then fade in cold seasons. Mass wasting would produce a consistent trend of loss over time. However, recurring slope linea appear in some seasons and disappear in other seasons (McEwen et al 2011). At this exact moment, the origin of water within the recurring slope linea is unknown. It is speculated that volatiles are the source of the recurring slope linea. McEwen argues that a volatile phase change creates dry flows (McEwen et al 2014). Another hypothesis of the source of the water for recurring slope linea is brines. Brines are the only volatile that can link the temperatures where recurring slope linea form with the locations where they form (McEwen et al 2011). Further investigating recurring slope linea will give us clues about how they formed. If liquid water is present, this would be of great importance to the field of astrobiology. When looking for life on other planets, you have to follow the water.

III. How to find life on Mars

Biosignatures

A habitable environment on Mars was not continuous throughout its history, it was sporadic. Westall et al (2015) have determined that if life existed, it was most likely constrained to the pre-Noachian or Noachian time period. During this period, liquid water might have been present in stand-alone bodies of water, such as a lake or an ocean. Westall et al. (2015) suggest that another potential time period for life is the Hesperian- Amazonian time period when cells could have been safeguarded from radiation in the subsurface. Astrobiologists look for morphological structures, organic molecules, and metabolic signatures to indicate the potential for life on Mars. These are the three types of biosignatures that could be found on Mars.

Morphological structures that would indicate life include cells, cellular products, and associations of cells (Westall et al. 2015). Cells can be preserved in fine grained sediments or entombed in minerals. Organic molecules are the organic components that make up the cells, such as extracellular polymeric substances, that can become degraded and trapped in minerals and thus become preserved (Westall et al. 2015). Metabolic structures refer to the class of biosignatures that are the result of metabolic activity. The most common is isotopic fractionation (Westall et al. 2015). All of these types of biosignatures must be preserved against further decay by the environment to be observed by astrobiologists and to be useful in determining if and how life evolved on Mars.

Preservation of biosignatures

Smith and Jakosky (2004) define two processes, entombment or enrichment, which can lead to the preservation of biosignatures on Mars. Entombment refers to the process of preserving microorganisms and organic molecules from degradation by rapid mineralization. Entombment mostly occurs in situations with highly oxidizing environments. The processes involved in entombment include evaporation, freezing, temperature and phase changes, and diffusion-driven reactions. During evaporation, mineralization happens when solute concentrations increase as water is removed. A precipitate is rapidly created and particles can be trapped in a mineral matrix. Evaporate salt formation and particle entombment happens during the process of freezing. Another process leading to precipitation is supersaturation due to cooling during temperature and phase changes. Finally, diffusion-driven reactions can lead to precipitations from concretions that happen in response to varying concentrations of solutes. One way or another, biosignatures can end up encased in minerals, where they may be discovered and observed as evidence of life.

Enrichment processes refer to processes that enhance concentrations of particles and compounds. On Earth, biosignatures may be enriched in sedimentary rocks or in iron oxides and clays. Sedimentary rocks lead to enrichment of biosignatures by providing an environment where biomass can gather and be buried, thus preserving morphological biosignatures. Iron oxides enrich specific organic molecules further enriching organic acids on the surface of the molecules. Clays also adsorb organic molecules. Where clays are present, such as many places on Mars, enrichment may occur, followed by burial and preservation.

Working with preserved biosignatures

Where to look

Many astrobiologists believe finding DNA would clearly substantiate the existence of life on Mars. Unfortunately, no biosignatures have been discovered, much less DNA. For a better chance at success, exploration for life on other planets has to center around looking for places where biosignatures could be found. One of the best prospects is within alluvial fans. Craters that hold alluvial fans are important sources for the sediments containing entombed biosignatures and alluvial fans themselves are important environments for enriching biosignatures. Alluvial fans are sources for sedimentary rocks that include iron oxides, and clays. When water sources were abundant on Mars, deposits of sediments could have occurred and biomolecule enrichment could have occurred along with deposition (Smith et al. 2007). Clays are abundant within alluvial fans. The structural make-up of clays allow them to enhance adsorption of organic matter allowing clays to concentrate biomolecules from the solution in which they were formed (Smith et al. 2007).

What to look for

Glass impactites are formed on Mars as asteroids hit the surface melting rocks creating silicate liquids that mix with the un-melted rocks and cools to create impact glass (Cannon and Mustard 2015). The glass is preserved due to the cold atmosphere that was likely present in the Amazonian age. The cold atmosphere mixed with the glass to create an environment capable of preserving signs of ancient life on Mars (Cannon and Mustard 2015). Cannon and Mustard confirm that the products if found on Mars would have to have been formed between 4.5 and 3.0 Ga and would be of mafic to ultramafic in composition (2015). The time constraint leads to questions about radiation exposure damaging the impact glass. Scientists speculate that the Martian atmosphere existed prior to 4.0 Ga yet the oldest craters found to date are not older than

4.0 Ga (Cannon and Mustard 2015). Thus, the impact glass impactites are not old enough to have been formed in the time when Mars had a magnetic field that would have shielded them from radiation (Cannon and Mustard 2015). Without being protected from harmful radiation, any preserved biosignatures would not be as valuable because they would be damaged. Clay sediments are a more stable preservation method of biosignatures and provide a preferable environment when searching for biosignatures directly.

Clays provide a confining environment in which it is hypothesized that early life may have developed (Yang et al. 2013). For life to evolve, it was necessary to have biomolecules and biochemical reactions be confined within cell membranes (Yang et al. 2013). Questions arrive about early life evolution on Earth and Mars because it is unclear how life could have evolved without the confinement of cell membranes. One method of confinement proposed is clay hydrogels. Clays not only provide a way to achieve confinement, but they also enhance and increase several biological functions that would have taken place within the cell membrane (Yang et al. 2013). Yang et al postulate that clay minerals are an excellent medium for evolution because they are widely distributed, historically prevalent, and their relationship with organic molecules (2013).

Translation and transcription are important biochemical reactions that occur within cell membranes. Zhou and Minton (2008) describe how the cell membrane allows the concentration to become localized while protecting the nucleic acids, amino acids, and other important biomolecules. Positive charges on the rim of clay structures help create the clay hydrogel as it mixes with ocean water (Yang et al. 2013). As mentioned previously, it is possible that ocean water was present on Mars. In the presence of the water a hydrogel, or polymer chain, is created as the clays link up (Yang et al. 2013). The clay hydrogel thus creates a protective environment for the processes that should take place within the cell membrane. The research of Yang et al shows that not only can the hydrogels create an environment for protection of nucleic acids, the hydrogels can protect DNA and RNA from digestion by DNase and RNase as well as other molecules associated with RNA and protein synthesis (2013). This research is compelling even considering that ancient seawater could have been drastically different from current seawater on Earth. Their theory was tested experimentally under differing Fe concentrations, pHs, temperatures, and CO_2 concentrations (Yang et al. 2013).

Given the evidence about the most likely preservation methods that would have been available during the time when life may have originated on Mars, the most likely place to find well preserved biosignatures is within its alluvial fans.

IV. **Alluvial fans: a place where life may be found**

Definition, formation, and characteristics

Alluvial fans are characterized as landforms that make a semi conical shape out of sediment deposits forming as water carries the sediment from a steep slope upstream to an unconfined drainage outlet downstream, often in flatter terrain (Morgan et al. 2014). Alluvial fans on Earth can be found in dry dessert locations such as Death Valley California, Chile, Peru, India, and China. Alluvial fans have been discovered on the surface of Mars as well. Figure 4 shows several fans within the large Crater L (Moore and Howard 2005).

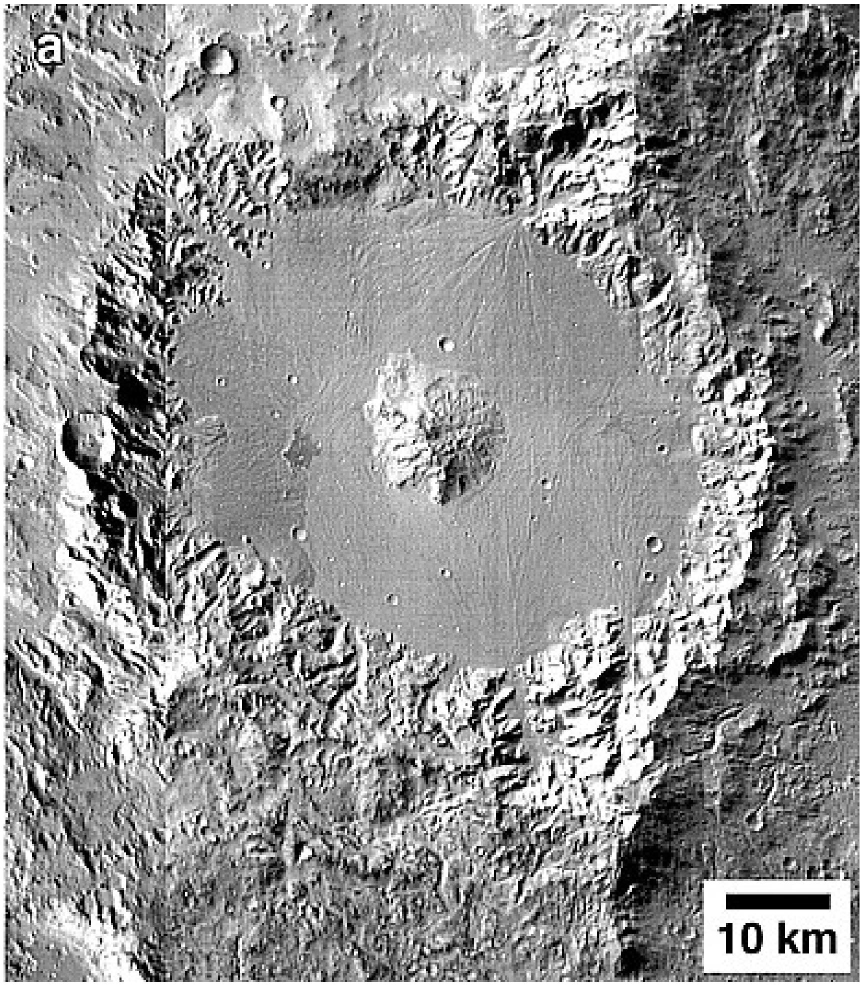

Figure 4 . Alluvial fans within Crater L. The crater is 66km in diameter and the floor is covered with alluvial fans. Taken from Moore and Howard 2005.

Fans are formed as coarse sediment is fluvially transported from high above due to steep slopes. The flow comes out from its source, becoming unconfined, depositing sediment in and around the distributary network on the fan’s surface (Williams and Malin 2008). The flow could be a result of several different water sources one of which is snowmelt. If it were a flashflood scenario, the material would come to rest near the drainage outlet (Moore and Howard 2005). At any given moment, only one part of the fan might be active because the distributary channels become abandoned. Specific features about how fans are formed help to differentiate them from deltas and debris flows. A channel entering a standing body of water forms a delta, whereas alluvial fans are formed subaerially. Debris flows also are different from alluvial fans because they are formed from a muddy matrix that is gravity driven (Kraal et al. 2008).

An alluvial fan has several distinct parts. The basin, or alcove, source the sediment and water. As the flow moves from the source in the alcove to the apron stream, it loses some of its power and the sediment being transported gets deposited in the alluvial apron. The characteristic cone shape of the fan is formed as the apron stream flows down the steep slope and creates a profile that is concave. The sediment gets transported as bed load in the stream (Kraal et al. 2008). Williams and Malin (2008) detail the conditions that are necessary for alluvial fan development. First, there must be a topographic setting where an upland is adjacent to a lowland. Second, there has to be sufficient sediment in the drainage basin. Finally, there has to enough fluid so that the sediment can be transported out of the drainage basin. Debris flows are capable of emplacing large volumes of sediment with low fluid and in a short period of time compared with alluvial fans that need large amounts of water to incrementally build fans (Williams and Malin 2008).

Major investigations into alluvial fans are made using THEMIS and MOLA data. THEMIS stands for Thermal Emission and Imaging Spectrometer. THEMIS was launched aboard the 2001 Mars Odyssey Orbiter. The instrument is a camera that combines a 5-wavelength visual imaging system with a 9 wavelength infrared imaging system to take pictures that are 18 meters per pixel for visual images and 100 meters per pixel for infrared images. It was launched in 1996 aboard the Mars Global Surveyor Spacecraft and collects altimetry data about the height of surfaces from pole to pole on Mars. THEMIS data is the limiting factor in researching alluvial fans. Most of the fans studied are larger than 50km in diameter (the smallest being discussed is 20km), because that is what is available to view in the data collected. Fans with smaller diameters may exist on Mars, but with the technology available they are hard to discern.

Kraal and Asphaug (2006) conducted a global study and discovered that an overwhelming majority of alluvial fans are located in three distinct regions in the southern hemisphere. Additionally, impact craters hold 98% of the fans they discovered. This shows a strong correlation between impact craters and alluvial fans. Researchers believe that the process of forming an impact crater creates an environment that is conducive to alluvial fan formation (Kraal and Asphaug 2006). This idea still needs further research. Scientists are trying to understand why some craters have fans while other craters, identical in every way, do not have fans. Figure 5 shows the global locations of alluvial fans and impact craters. The majority of the fans they found originated from the same direction, but panels 5b and c show several fans in Porter Crater and an unnamed crater, respectively, that are originating from different directions. Panel d shows the only fan that did not originate within the impact crater (Kraal et al.2008). Kraal et al (2008) define fan orientation as the location on the rim where the fan originates. They show that it has a broad spread as far as the direction the fan travels and there is not one preferred orientation.

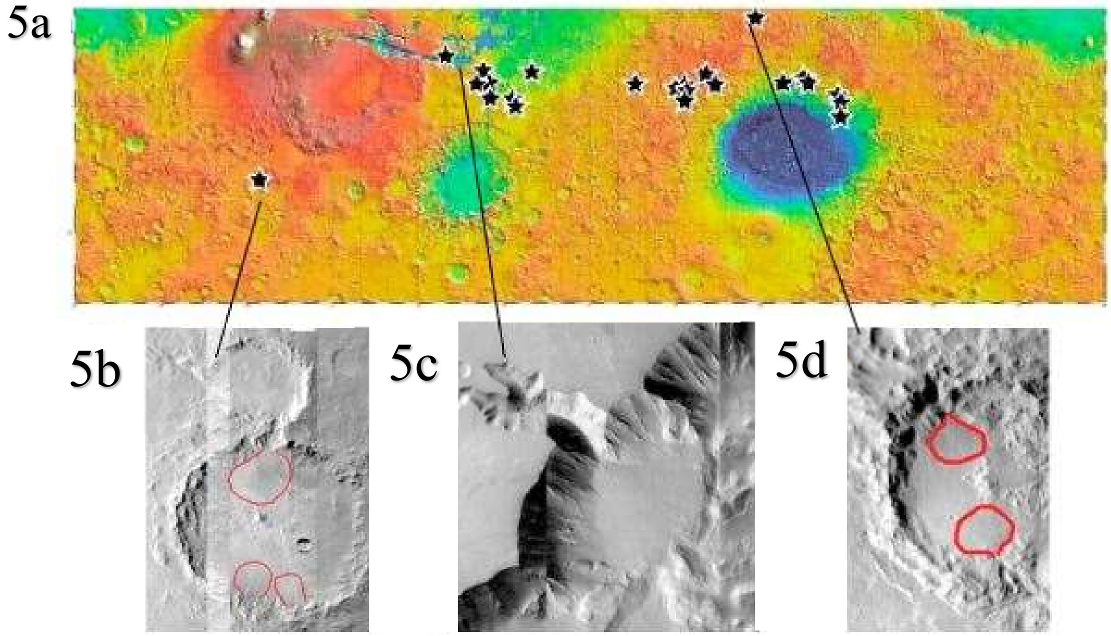

Figure 5. Distribution of alluvial fans in the southern hemisphere on Mars (5). Panels 5b, 5c, and 5d show different orientations of fans. From Kraal et al 2008. Top map is a global map, 100s of km across. Bottom inserts are 10s of km across.

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Water in Fans

Noting the amount of water necessary to form fans and the fact that fans develop incrementally, alluvial fans are thought to develop over an extended period of time. A single event that created the fan (Moore and Howard 2005). Fans, on Mars and on Earth, especially large fans, are formed over hundreds of flow events that take placed over tens of thousands of years (Morgan et al. 2014). There are several constraints to formation of alluvial fans. At the head, fans are constrained by the need to erode sediment then transport it. At the end, fans are constrained by absence of deep lakes that reside within the larger craters (Morgan et al. 2014). Fans can form inside of crater basins because they can source material from the crater rim that is deeply incised within the alcove basin (Morgan et al. 2014). The incised alcove basins add another layer of constraints on the hydrological and sedimentary environment.

Alluvial fans on Mars expose rocks of different ages. The sediments record only the final stage of development of the fans. Several techniques are used to constrain the ages of the fans. One of the most popular ways is to use crater counting, because the number of craters on a surface is related to the passage of time (Grant and Wilson 2011). From the crater statistics, Grant and Wilson (2012) propose that most fans formed in the Amazonian or close to the Hesperian – Amazonian boundary. Another important issue when discussing the age of fans is to determine which landform was first, the fan or the crater. In general, the crater forms first, allowing the fans features to be visible. If the fans were formed before the crater, the crater would cover up the fan deposits.

Grant and Wilson's data is consistent with the age of the fans studied by Moore and Howard in 2005. Moore and Howard concluded that the large fans they studied were formed in the Noachian-Hesperian boundary into the mid Amazonian period (Grant and Wilson 2011). There is some disagreement when it comes to the eastern fan on Harris Crater. Grant and Wilson (2011) believe that that fan is younger than the others in its area. Young fans are an exciting discovery because their existence means that the time when water could have occurred on Mars can be elongated. Instead of formation of alluvial fans only happening in the Noachian fans could have formed in the Amazonian. Younger fans, implying more recent formation, will create a greater window of potential habitability on Mars by proposing that the water on Mars flowed beyond early Mars history and even perhaps into present day. This leads to the question of how alluvial fans can be formed and the differing sources of water available for formation.

Sediments and sedimentary rocks on Mars are studied to give us clues about the environment in which they are formed. Studying alluvial deposits gives us more information about the style and type of runoff possible for their formation also allowing us to better constrain when they were formed (Grant and Wilson 2012). Grant and Wilson were able to add to the existing body of knowledge about alluvial fan water sources by using updated data sources. The previous work, done by Howard and Moore (2005), was based on THEMIS infrared and visible images. Grant and Wilson (2012) used CTX and HiRISE images which have more images available. They found a strong connection between craters and alluvial fans. Of the 22 craters that were studied (all being 50km or greater in diameter), 7 of them contained alluvial fans (Wilson and Grant 2012). Again, craters that were much smaller than the 50km diameter were excluded from the data. This is partially because the images are hard to decipher, but also because the smaller features had heavy mantling which may have buried older alluvial deposits (Grant and Wilson 2012).

To answer the question of how the fans could have been formed and under what environmental context, investigators examine the fan morphometry. The possible sources of water for fan formation are local/regional or global scale and the two generate different signatures in the land surface. Local precipitation could be related to the impact – induced release of volatiles. The runoff would result in valley incisions creating fluvial features inside the newly formed crater (Grant and Wilson 2012). The impact event is responsible for melting and excavating the subsurface creating water- driven activity on the crater. This process of melting and excavating can last up to a period of 1,000 years (Grant and Wilson 2012). The topography of Mars as well as its orbital variation may also contribute local sources of precipitation. There are a few powerful arguments against the idea of a local source of water, such as the broad distribution of fans on the surface of Mars and the common ages of the fans.

The most widely accepted model for the source of water responsible for fan formation is a late driven water model with synoptic sources of water such as precipitation in the form of rain or snow. The evidence that synoptic precipitation occurred on Mars comes from studying the time delay in the formation of the Hale crater verses the Holden crater. Additional evidence for synoptic late water erosion are valley incisions on volcanoes, putative supraglacial and proglacial valleys, and an overlap in fan activity and valley incisions (Grant and Wilson 2012).

Grant and Wilson also propose that late water-driven activity on the fans could be a result of debouched water pouring into the northern lowlands (2012). This second proposed source of water for alluvial fans represents global as opposed to regional or local sourcing. Global sourcing involves re-starting the global hydrologic cycle. Initially, the local or regional sources of water get stored as groundwater. With outflow activity, the ground water is released, and the hydrologic cycle becomes active again. When the global hydrologic cycle is jumpstarted in the northern lowlands, it would cause precipitation to be distributed in the southern highlands. This process would continue until there was no water left in the northern lowlands (Grant and Wilson 2012). This mechanism is the best proposed because the global runoff that would result corresponds perfectly with the models explaining fan formation.

The late water activity fan formation model described by Grant and Wilson proposes limited amounts but repeated events of snow fall as the source of water. When the snow fell, it was concentrated into alcove depressions that already existed. These alcove depressions would trap snow, and over time, erosion ensued. Rock present in the impact crater would be exposed to snow in the pre-existing depressions. Repeated freeze thaw cycles facilitate physical weathering of this rock which produces the finer grained sediment that is found within the fans and craters. While this is all happening on the crater rim, the accumulation of the melted snow would be gradual enough to produce the run off that is responsible for bringing the sediment down the fan surface to be distributed on the bottom surface of the fan (Grant and Wilson 2012). This argument is strengthened by the fact that fans do not form on the rims and central peaks of craters, only on the crater floors.

V. Particular sites for astrobiological exploration

The majority of alluvial fans, particularly the large alluvial fans, are all found in one central location. The overwhelming majority of craters with alluvial fans are found in the southern hemisphere in the southern Margaritifer Terra, the southwestern Terra Sabaea, and the southwestern Tyrrhena Terra. A few special places have fans that occur outside of this zone. Most research is conducted within 30°S and the equator because that band excludes the heavily cratered Northern Hemisphere. The heavily cratered Northern Hemisphere might have alluvial fans but they might not be seen due to the heavy bombardment covering the surface. Fans could form, but they may be too small to investigate or may not be present at all.

Ausonia Cavus, Gale Crater, Zunil Crater, Valles Marineris, and Hale Crater are the sites most likely to reveal evidence of life on Mars. They are all currently being considered by NASA. The Evolvable Mars Campaign Program is tasked with site selection for the human manned mission to Mars. A host of criteria, both scientific and engineering related, go into rating each site. A rubric was created as a tool for gathering and displaying information for the landing site, not necessarily as a qualitative tool for ranking. The scientific rubric includes criteria such as potential for past habitability, evidence of aqueous processes, and potential for interpreting relative ages.

The Ausonia Cavus lies near a drainage basin in the Dao and Niger Valles on Mars just downslope of the volcano Tyrrhenus Mons (see Figure 6). Hadriacus Mons is another volcano nearby that is thought to have formed in the Hesperian era that has ancient lava flows and glacial deposits. Paelolakes from the Hesperian are also present at this site. Imagery gathered from

CRISM reveals interesting site features such as fan shaped deposits. Technically, this site is not ideal for astrobiological exploration because fans have not been confirmed in the area. However, the presence of fan shaped deposits, ice rich lobate debris features, and other debris aprons in this area indicate that alluvial fans could be present at this site (Williams and Malin 2004). A crater is present, and as discussed above, craters are often associated with fans. This crater is, however, filled with new debris. The presence of debris suggests activity, most likely Aeolian, and it also hides the evidence that there may have been at one time a fan present. This area has geological features that may have been present in an earlier geological eras as well. Large outcrops of phyllosilicates are found in this area (Williams and Malin 2004). As noted above, phyllosilicates are clay minerals and clay minerals mixed with water could potentially form clay hydrogels that would be able to preserve biosignatures for life. The water that was potentially nearby in the form of the paleolakes coupled with the existence of clay minerals make this a good site for exploration for evidence of Martian life.

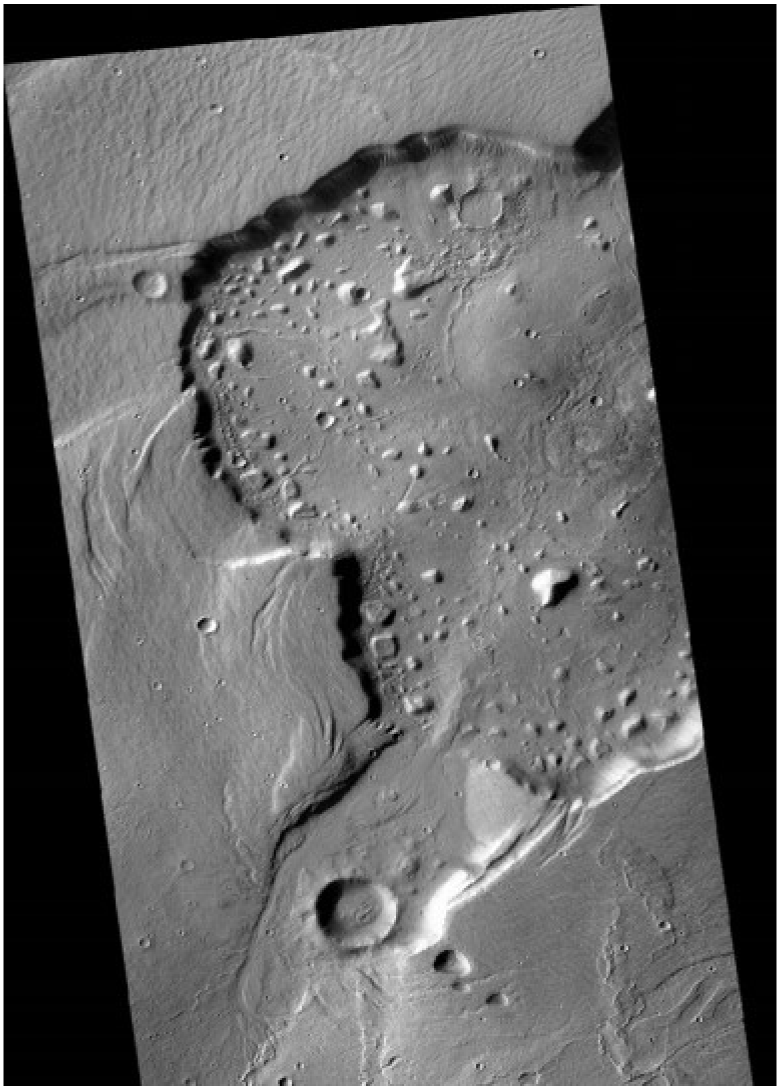


Figure 6 Ausonia Caves: 10s of km across.
https://www.nasa.gov/sites/default/files/atoms/files/1045_uhhilo_hamilton.pdf

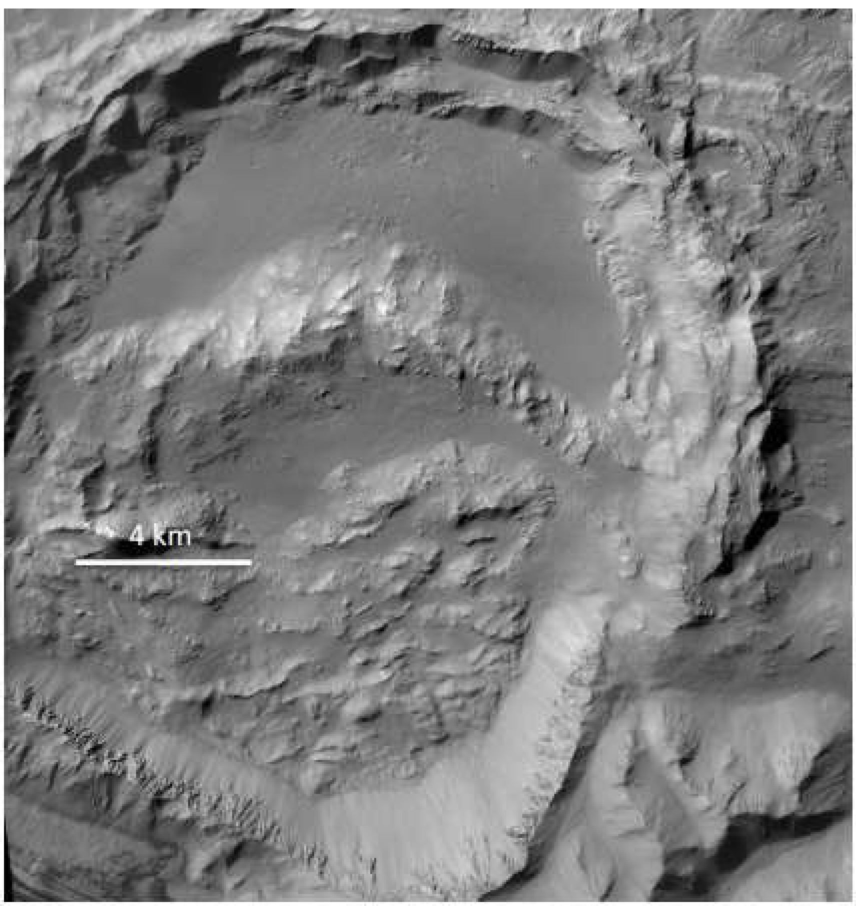
A site with an alluvial fan that would make a great site for exploration is the Gale Crater (Figure 7). The Gale crater was covered extensively in previous missions carried out by the Mars Science Laboratory (MSL). The most geologically interesting regions of the crater are near Mount Sharp. An alluvial fan is found within the Gale crater as well as dunes, lake sediment deposits, and exposed outcrops (Williams et al 2013). Because the MSL has been gathering data from the Gale Crater since 2012, the chemistry, morphology, and environment have been well characterized. So much data is available because Gale crater is easily accessible. In-situ exploration through mining is a possibility and may even expose hydrated minerals in the soils, minerals such as Si and Fe (Williams et al 2013). These minerals in conjunction with a source of water would build a strong case for the presence of clay hydrogels which in turn would create the potential for the preservation of biosignatures.

Figure 7 Gale Crater (150km across), taken from http://www.planetary.org/multimedia/space-images/mars/gale-crater.html.

The Zunil crater hosts the Cerebus zone (Figure 8). This crater has older flows that mostly come from the Hesperian or Noachin age. Basaltic flows of lava and faults can help constrain the geologic era during which the crater was formed (Callahan et al 2013). Of primary interest are a variety of rocks and other geologic features including igneous rocks, Aeolian sediments, and crater ejecta. This area is also interesting because it is located in an area where Mars' magnetic field may have been present (Boynton et al 2002). Investigating soils in this area gives us greater information about magnetization on Mars. This site is also home to three recurring slope linea, currently widely accepted as sources of water on Mars presently (Boynton et al 2002). Water in addition to clay minerals being found in the area give this site the credibility it needs to be on the astrobiological exploration list.

Figure 8 Zunil Crater (whole image 10s of km across) taken from http://hirise.lpl.arizona.edu/geographikos.php?q1=&q2=73&q3=139&q4=169&order=release_date&page=10

Valles Marineris (Figure 9) is Mars' Grand Canyon. It is situated within the western Coprates Chasma. It has a significant amount of geologic features that make it a candidate for preserving evidence of life. There are cross cutting alluvial fan deposits, impact craters (which we would expect from the alluvial fans), clay mineral deposits, and olivine deposits. The source of water proposed for this site is recurring slope linea (Martin-Torres 2015). There is a definitive zone of habitability that has a significant amount of recurring slope linea present. These and other features provide a strong argument for finding life at Valless Marineris. The alluvial fans that cross through the Ophir Labes and Coprates Labes create locations that could have preserved organics and microfossils (Senthil Kumar 2013). The presumed source of water for these fans is groundwater discharge. In addition to clays being found and the potential for clay hydrogels, there also has been impact glass in the area allowing for a second source of preserved bio-signatures (McEwan 2014).



CTX NASA/JPL/ASU/MSSS

Figure 9 Valles Marineris from http://mars.jpl.nasa.gov/gallery/atlas/valles-marineris.html

Hale Crater (Figure 10) is a result of an impact that occurred in the Amazonian period. The source of water for this crater is believed to be ground water released after the impact. The crater rim has been modified through impact activity, but deep within the mantle the crustal material should have been preserved (McEewan et al 2014). This means that the minerals found in this area would record activity from three different impacts. Researching this area would give great detail into the mineralogy of each impact event. Gullies on the surface of Hale Crater could be a result of sublimation of CO_2 but are most likely the result of liquid water. Studying the presumed gullies would inform us of the atmospheric environment of the area at the time of formation (Wray et al 2013). Hale Crater also has hundreds of recurring slope linea making this a great site for better understanding the environment of recurring slope linea. Current evidence suggests that recurring slope linea are so briny that life as we know it could not evolve here, but Martian life may have thrived in these features. In addition to other channels and gullies, channels with hydrothermal altered minerals are also present (Wray et al 2013). It is unclear without further investigations if these hydrothermal events linked to channels and outflow networks were formed when Mars was habitable. This site hosts fluvial ejecta and fans nearby that might have filled some of the channels but would still be interesting none the less (Cabrol et al 2001).

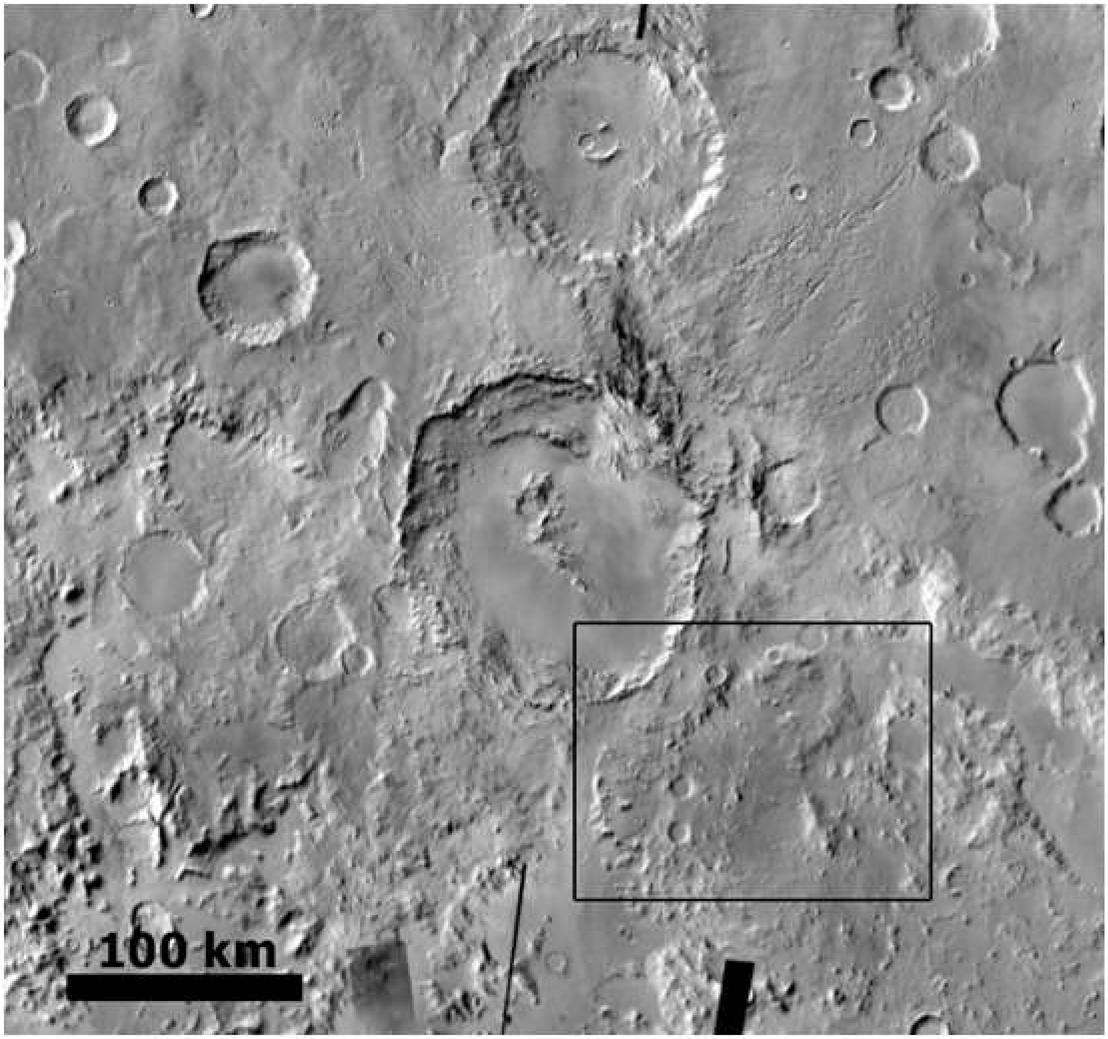


Figure 10 Hale Crater. Image taken from http://www.psi.edu/pgwg/images/jun11image.html

Recommendation for the human landing Mars

The best location to search for life on Mars is the Kasei Valles (Figure 11), formed during the Noachian period when life on Mars is most likely to have occurred. Kasei Valles is situated in the Tharis region and has bedrock exposed from both the Noachian period and the Hesperian period (Williams and Malin 2004). The extensive outflow region is indicative of subsurface ice that potentially was left behind from mudflows in a period where fluvial activity was decreasing.

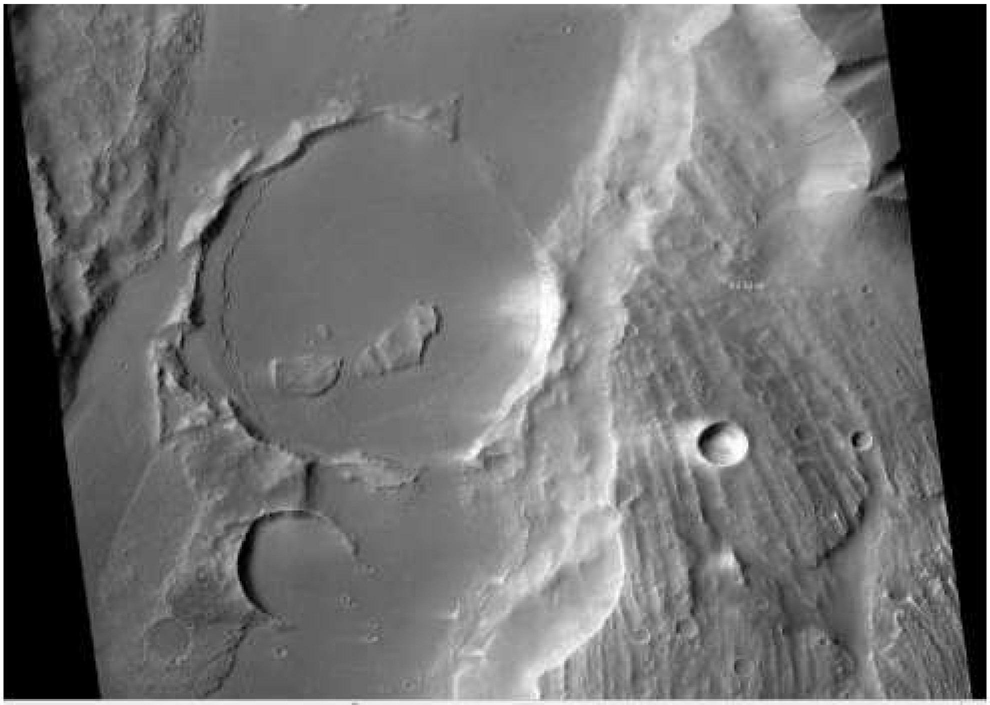


Figure 11 Shows a HiRISE image of Kasei Valles (10s of km) taken from Williams and Malin 2004.

In addition to ice being a potential source of water, MOLA profiles show several narrow outflow channels that likely were formed during several flood events (Williams and Malin 2004). Alluvial fans are also present in the Kasei Valles. Figure 12 shows a THEMIS image of Kasei Valles and Figure 13 shows a close up on the fans in the southern hemisphere of Kasei Valles. The lake presence coupled with the alluvial fans are strongly suggestive of the presence of phyllosilicates (Cabrol and Grin 2001). Clays being present with a potential water source create the perfect environment for preserving biosignatures. Investigation of this area is most likely to lead to finding remnants of past life on Mars.

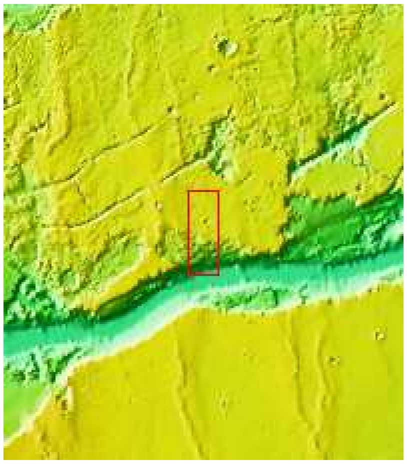


Figure 12 shows Kasei Valles (10s of km) within the red square taken from http://themis.asu.edu/zoom-20140430a

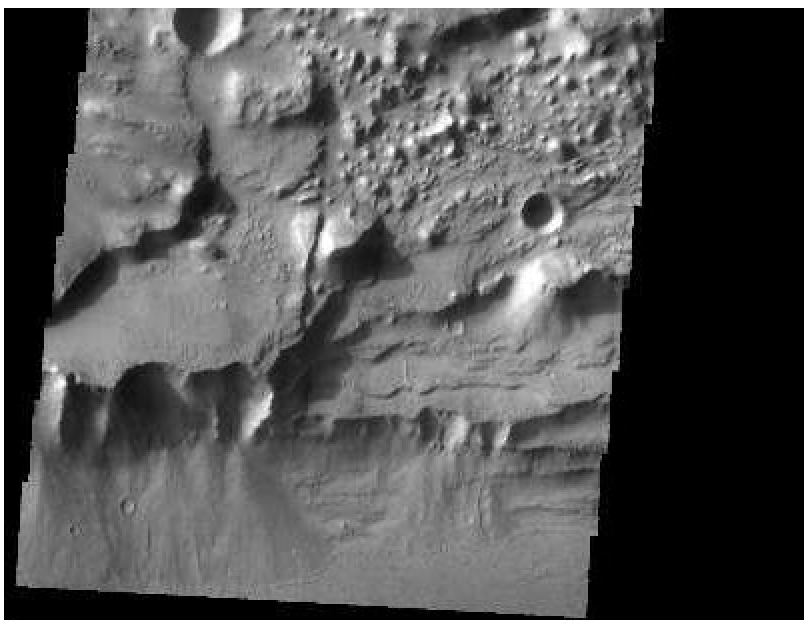


Figure 13 shows the close up image of the alluvial fans within the Kasei Valles (10s of km) taken from http://themis.asu.edu/zoom-20140430a

Ultimately Up to Engineers

Identifying the most scientifically promising location on Mars is only one part of the equation in Mars exploration. The other requirements are based on engineering constraints. One major concern is the ease of maneuvering through entry, descent, and landing. Additional requirements center around the access the site has to resources that can be used for engineering and research, such as water which can be used for radiation protection and as a power source. If present, water would be one less item to transport from Earth. Gathering information and giving the decision makers the opportunity to make the appropriate decision based on both engineering criteria and on what is geologically and biologically interesting will help NASA make the best decision in where to land on Mars for future missions.

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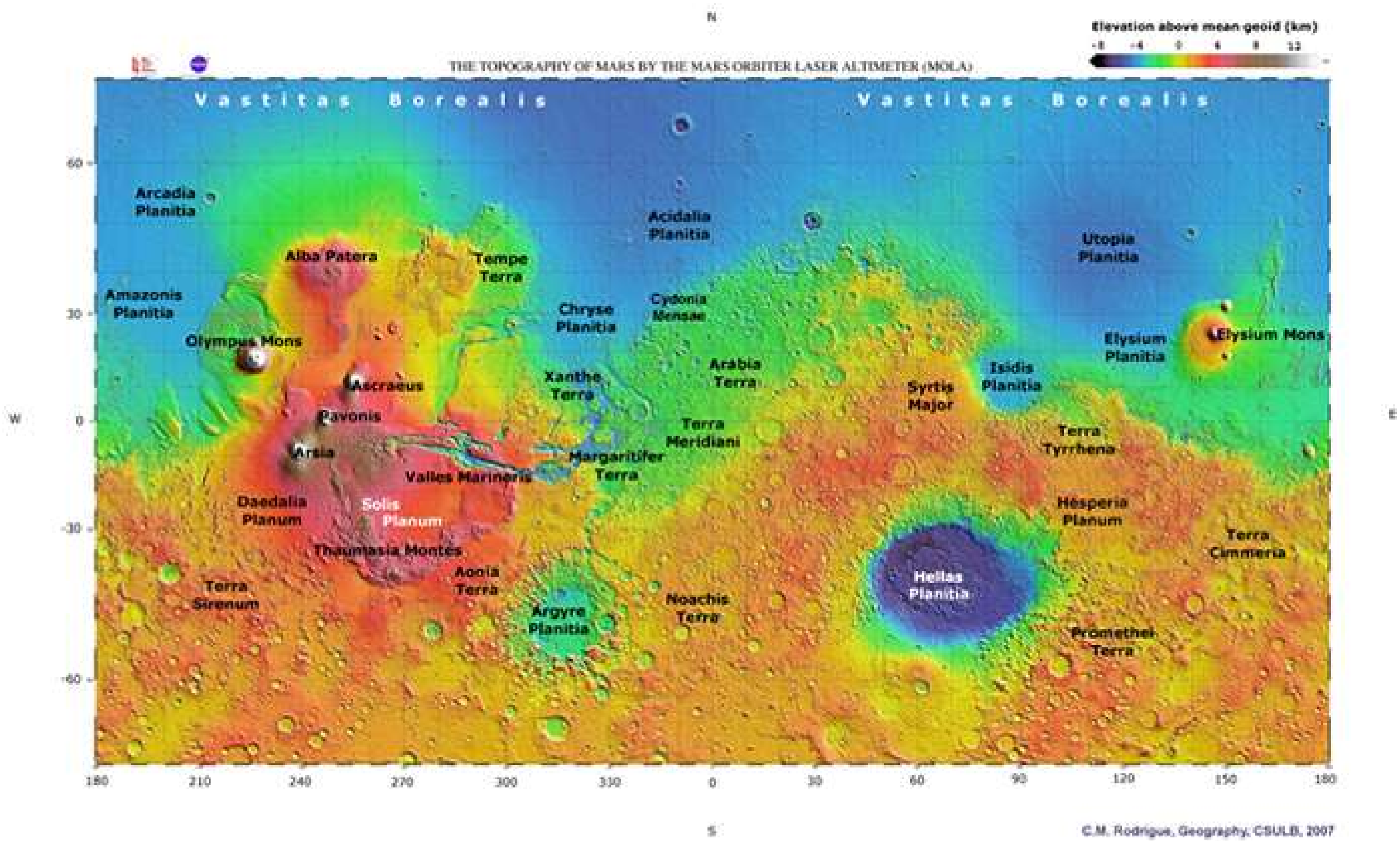
*Cover Photo Source http://mola.gsfc.nasa.gov/images/mercat.jpg *

Appendix A

Map of Mars topography taken from: http://crism.jhuapl.edu/science/geology/physiography.php



Appendix B

History of Mars Missions taken from: http://mars.nasa.gov/programmissions/missions/log/

#	Launch Date	Name	Country	Result	Reason
1	1960	Korabl 4	USSR (flyby)	Failure	Didn't reach Earth orbit
2	1960	Korabl 5	USSR (flyby)	Failure	Didn't reach Earth orbit
3	1962	Korabl 11	USSR (flyby)	Failure	Earth orbit only; spacecraft broke apart
4	1962	Mars 1	USSR (flyby)	Failure	Radio Failed
5	1962	Korabl 13	USSR (flyby)	Failure	Earth orbit only; spacecraft broke apart
6	1964	Mariner 3	US (flyby)	Failure	Shroud failed to jettison
7	1964	Mariner 4	US (flyby)	Success	Returned 21 images
8	1964	Zond 2	USSR (flyby)	Failure	Radio failed
9	1969	Mars 1969A	USSR	Failure	Launch vehicle failure
10	1969	Mars 1969B	USSR	Failure	Launch vehicle failure
11	1969	Mariner 6	US (flyby)	Success	Returned 75 images
12	1969	Mariner 7	US (flyby)	Success	Returned 126 images
13	1971	Mariner 8	US	Failure	Launch failure
14	1971	Kosmos 419	USSR	Failure	Achieved Earth orbit only
15	1971	Mars 2 Orbiter/Lander	USSR	Failure	Orbiter arrived, but no useful data and Lander destroyed
16	1971	Mars 3 Orbiter/Lander	USSR	Success	Orbiter obtained approximately 8 months of data and lander landed safely, but only 20 seconds of data
17	1971	Mariner 9	US	Success	Returned 7,329 images
18	1973	Mars 4	USSR	Failure	Flew past Mars
19	1973	Mars 5	USSR	Success	Returned 60 images; only lasted 9 days
20	1973	Mars 6 Orbiter/Lander	USSR	Success/Failure	Occultation experiment produced data and Lander failure on descent
21	1973	Mars 7 Lander	USSR	Failure	Missed planet; now in solar orbit.

22	1975	Viking 1 Orbiter/Lander	US	Success	Located landing site for Lander and first successful landing on Mars
23	1975	Viking 2 Orbiter/Lander	US	Success	Returned 16,000 images and extensive atmospheric data and soil experiments
24	1988	Phobos 1 Orbiter	USSR	Failure	Lost en route to Mars
25	1988	Phobos 2 Orbiter/Lander	USSR	Failure	Lost near Phobos
26	1992	Mars Observer	US	Failure	Lost prior to Mars arrival
27	1996	Mars Global Surveyor	US	Success	More images than all Mars Missions
28	1996	Mars 96	Russia	Failure	Launch vehicle failure
29	1996	Mars Pathfinder	US	Success	Technology experiment lasting 5 times longer than warranty
30	1998	Nozomi	Japan	Failure	No orbit insertion; fuel problems
31	1998	Mars Climate Orbiter	US	Failure	Lost on arrival
32	1999	Mars Polar Lander	US	Failure	Lost on arrival
33	1999	Deep Space 2 Probes (2)	US	Failure	Lost on arrival (carried on Mars Polar Lander)
34	2001	Mars Odyssey	US	Success	High resolution images of Mars
35	2003	Mars Express Orbiter/Beagle 2 Lander	ESA	Success/Failure	Orbiter imaging Mars in detail and lander lost on arrival
36	2003	Mars Exploration Rover - Spirit	US	Success	Operating lifetime of more than 15 times original warranty
37	2003	Mars Exploration Rover - Opportunity	US	Success	Operating lifetime of more than 15 times original warranty
38	2005	Mars Reconnaissance Orbiter	US	Success	Returned more than 26 terabits of data (more than all other Mars missions combined)
39	2007	Phoenix Mars Lander	US	Success	Returned more than 25 gigabits of data
40	2011	Mars Science Laboratory	US	Success	Exploring Mars' habitability
41	2011	Phobos-Grunt/Yinghuo-1	Russia/China	Failure	Stranded in Earth orbit
42	2013	Mars Atmosphere and Volatile Evolution	US	Success	Studying the Martian atmosphere

43	2013	Mars Orbiter Mission (MOM)	India	Success	Develop interplanetary technologies and explore Mars' surface features, mineralogy and atmosphere.