Stratigraphy of Mount Sharp and Gale Crater: Implications for Martian Paleoenvironment

By

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A thesis submitted in partial fulfillment of the requirements of the degree of
Bachelor of Arts
(Geology)
at
Gustavus Adolphus College
2015

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ABSTRACT

As Curiosity continues to traverse the surface of Mars, we are presented with a unique opportunity to decipher the processes that formed the sedimentary rocks of both Mount Sharp and the surrounding Gale Crater, the region that Curiosity now explores. Prior to rover exploration, several hypotheses had been advanced to explain the horizontal layers seen in the lower portions of Gale crater, the slightly dipping layers, whose composition varies between phyllosilicates and sulfates, of the lower portion of Mount Sharp, the slightly steeper dipping beds of the upper portion of Mount Sharp, and the unconformity between the two portions of Mount Sharp. These hypotheses vary widely – invoking ancient geologic processes as disparate as lake deposition, hot springs, glaciers, and wind transport. Each of these hypotheses makes a distinct set of predictions about the rocks in Gale crater; therefore, Curiosity's data can be used to test hypotheses about ancient and ongoing geologic processes on Mars. This project examines several hypotheses and links each to a set of expected geological features, which are then tested against orbiter and rover data. Based on these data, the sedimentary rocks of Mount Sharp are best interpreted to have formed by wind transport and deposition in the complex impact structure of Gale crater.

ACKNOWLEDGEMENTS

I would like to acknowledge my advisor Julie Bartley for all of the help she gave me as I worked on this thesis and Dr. Linda Kah for the indirect help she gave me in supplying Julie with information to pass on to me. I would also like to thank Laura Triplett for giving me the opportunity to research with her and for giving me an introduction to the world of scientific research. Also, I want to thank Jim Welsh for his help revising my thesis. Lastly, I want to thank the Folke Bernadotte Memorial Library of Gustavus Adolphus College for promptly helping me with the numerous inter library loan requests I sent to them.

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INTRODUCTION

In our search for extraterrestrial life, humanity's eyes are currently fixated on Mars, and now, thanks to the Curiosity rover, on the geology of Mount Sharp and Gale crater. Mount Sharp is a mountain of sedimentary rock in Gale crater, which is also lined with sedimentary rock. The curious thing about Mount Sharp is that, despite being made of sedimentary rock, its peak is actually slightly higher than Gale crater's rim. This unusual geology, along with the fact that sedimentary rocks harbor the clues as to whether Mars was habitable (having liquid water, a favorable pH, and available nutrients) was the reason we sent the Curiosity rover to this particular area. Currently, Curiosity is traversing Mount Sharp and it is imperative we take this opportunity to understand the presently available data relevant to the processes that formed the sedimentary rocks of both Mount Sharp and Gale crater. In order to effectively evaluate the data collected by Curiosity, we must have a set of multiple working hypotheses that can be critically evaluated in light of the observations Curiosity is making. However, such a collection of data and explanations does not exist. In this thesis I created just such a collection. To do this I examined existing, published literature for hypotheses on the formation of the sedimentary rocks of Mount Sharp and Gale crater. Once my collecting was complete, I evaluated the strength of the hypotheses using additional literature and data from Curiosity in order to organize the list. Also, in ranking the hypotheses by strength, I provide an order of importance for the hypotheses to be tested as time is of the essence when working with a rover with a limited life span. It is only once we fully understand the geologic history of the area that we will be able to confidently say if life was possible in the Mount Sharp and Gale crater area.

Before Curiosity reached Mount Sharp, the area has been studied using satellite imagery Mars orbiters. These data allowed for the creation of several hypotheses for the origin of the sedimentary rocks of the area and established this region as a suitable landing and exploration site for the Curiosity rover. In brief, the hypotheses for the origin of the sedimentary rocks of Mount Sharp and Gale crater are a lacustrine environment (Grotzinger et al., 2014, Grant et al., 2014, Schwenzer et al., 2012, Milliken, R. E., Grotzinger, J. P., and Thomson, B. J., 2010), ice weathering (Niles et al., 2014, Niles, P.B., and Michalski, J., 2012,), seasonal melting (Kite et al, 2013a), spring environment (Rossi et al., 2008), Slope Wind Enhanced Erosion and Transport (SWEET) (Kite et al., 2013b), and rapid dune cementation (Milliken et al., 2014). All of these hypotheses will be described in detail, as well as have their predictions for what Curiosity will see in the future as it keeps climbing Mount Sharp documented.

GEOLOGY OF GALE CRATER AND MOUNT SHARP

Gale crater and Mount sharp are located 4.55° south of the Martian equator at latitude 137.5° east; this area is near the boundary between the older, heavily cratered southern highlands and the younger, smoother northern lowlands (Milliken et al., 2010). According to the crater impact aging method, Gale crater formed 4.1 to 3.5 Ga, and at least some of the sediments in the crater formed 3.5 to 2.9 Ga (also Milliken et al?). According to the most recent data from the Curiosity rover, the particles that make up the rocks of the crater floor are 4.2 ± 0.35 Ga (Farley et al., 2014). Gale crater is roughly 150 km across and 5 km deep. Mount Sharp is a stratified sequence of rocks which rises about 5 km high; this is close to the same height as the southern crater rim, but is up to several kilometers higher than the degraded northern crater rim. Besides the sedimentary rocks of Mount Sharp, Gale crater is lined with its own sedimentary rocks, making the area an ideal for study of the martian paleoenvironment. Sedimentary rocks of on the bottom of the crater are anywhere from 3.5 billion years old (Grotzinger et al. *Yellowknife,* 2014) to 4.21 billion years old. A recent Ar-Ar analysis suggests that the rocks of the crater floor were buried and only recently exposed (78 million years ago, Farley et al., 2014); however, this exposure date relies on assumptions that are difficult to test on Mars, and the date and could represent an exposure age of up to 1 billion years ago (Farley et. al, 2014). Water activity at this location has been inferred, based on the presence of conglomerates towards the edges of the crater, and the presence ofphyllosilicates and Ca-Mg sulfates on the crater floor (Milliken et al., 2010).

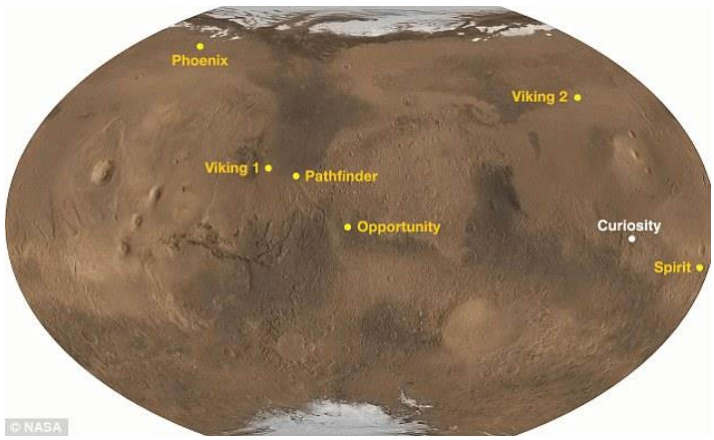

Figure 1. A global picture of Mars with the locations of various missions shown as well as the location of Gale Crater and Mount Sharp. (NASA)

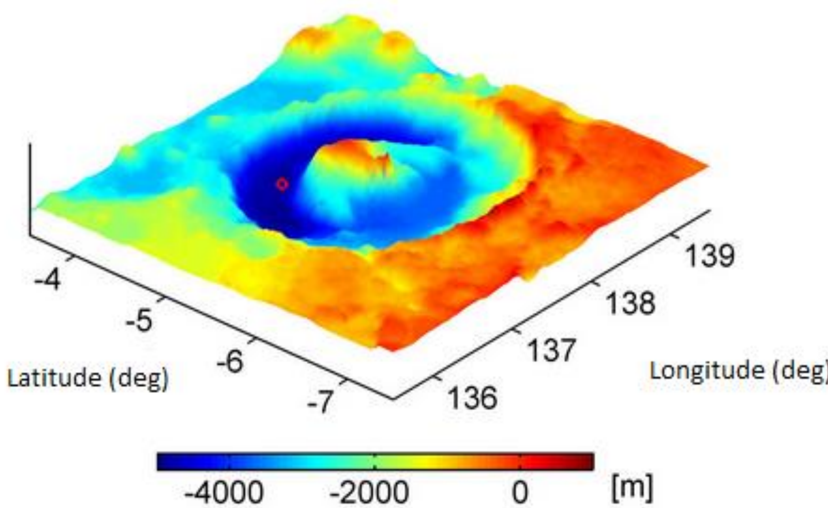

Figure 2. Topography of Gale Crater and Mount Sharp. Hot colors represent high elevations and cool colors represent low elevations (Kite et al., 2013a).

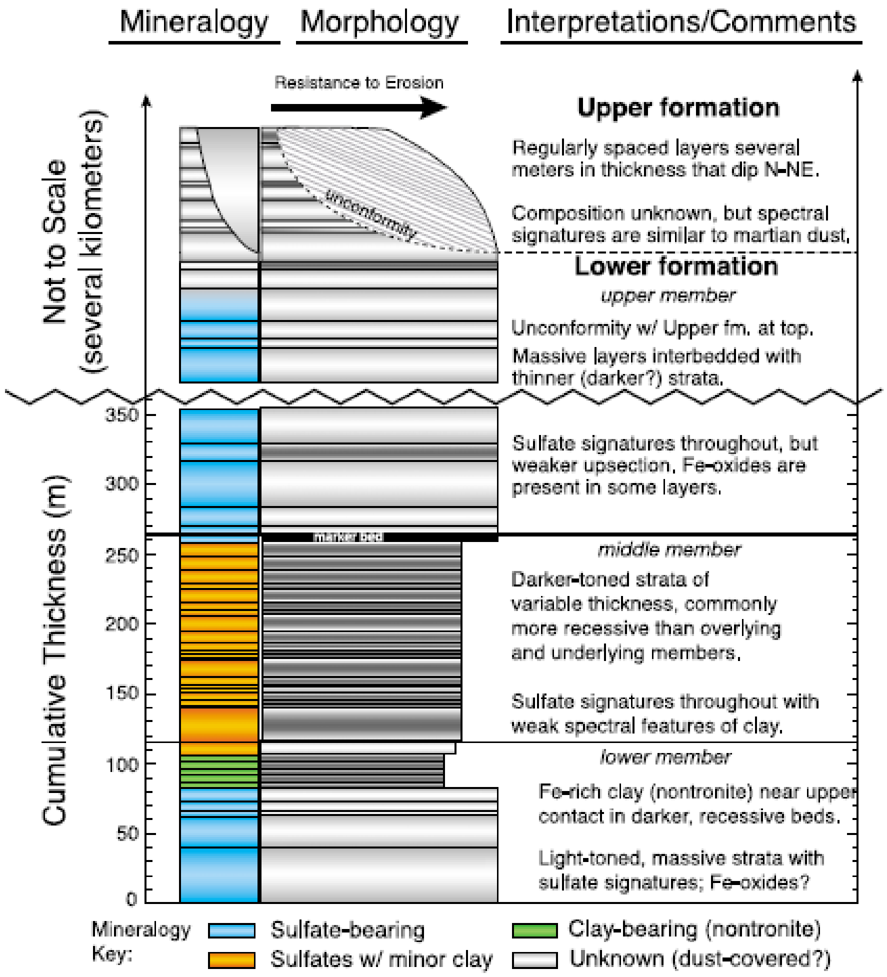

Figure 3. Interpreted stratigraphic column for a section of the Gale Crater mound. Where marked, bed thicknesses are measured from HiRISE DTMs. Mineralogical interpretations are based on CRISM data, though not all individual beds observed in HiRISE images are resolved in CRISM images. A group of thin (<7 m) recessive beds in the lower member contains clays (green), whereas the middle member exhibits sulfate and very weak clay signatures (orange). Sulfate-bearing beds (blue) are generally thicker than clay-bearing beds and are found throughout the upper member. Gray and white beds in the morphology column are qualitative indicators of general changes in albedo. (Milliken et al., 2010)

Mount Sharp is divided into an Upper and Lower formation by an unconformity. This unconformity separates the Lower formation which is composed of mainly sulfates and clays dipping at shallow angles from the rocks of the Upper formation which have a spectral signature similar to Martian dust and dip more steeply than the rocks of the Lower formation. The Lower formation is sulfate-bearing at the base, transitioning upwards to clay-bearing rock, followed by a period of sulfates with small amounts of clay, and finally sulfate-bearing rocks at the top. The unit is packaged in beds that are nearly horizontal, with a dip of 2-4 degrees. The deposits of the Lower formation also contain canyons. The deposits on the floor of Gale crater postdate the beds of the lower formation, based on observations that crater floor deposits onlap the beds of the Lower formation. The beds of the Upper formation dip more steeply than the Lower formation, exhibit a regular thickness of several meters, and have a spectral signature roughly similar to Martian dust. The Upper formation lacks the canyons seen in the Lower formation. In addition, there are rocks near the crater rim which are large grain sand to pebble in size and dip slightly towards Mount Sharp seen by Curiosity near its landing location (Millikenet al., 2010; Grotzinger et al., 2014). These are associated with the crater rim and floor, however they are not considered a part of the Lower formation.

Figure 4. A picture from Curiosity showing the crater floor, Lower, and Upper formations with the stratigraphic column superimposed over it. The inserted black line represents the unconformity. (NASA)

RESEARCH APPROACH

In this project, I used a compilation of available geologic data and observations of the sediments in Gale crater and Mount Sharp as a framework against which to test proposed hypotheses to explain its formation. Each hypothesis is summarized from the literature; I then used the authors' hypothesis to construct a predicted set of geologic features that could be compared to the geology observed thus far. Such an approach permits the strength of each hypothesis to be evaluated in terms of its ability to explain for individual geologic features and the entirety of Gale crater and Mount Sharp. Images used in this analysis came from both the JMARS and the HIiRISE databases; the chemical analyses came from the collected literature, but were sourced originally from both HiRiSE and Curiosity.

RESULTS: THE COLLECTED HYPOTHESES

Lacustrine Environment:

According to the lacustrine hypothesis, Gale crater and Mount Sharp represent an ancient fluvial system where rivers flowed into a lake situated within Gale crater. In this model, the layered surface units represent lacustrine and fluvial clastic rocks, with subsidiary chemical sedimentary rocks that formed 3.7 billion years ago (Schwenzer et al., 2012, Farley et al., 2014, Grotzinger et al., 2014, Grant et al., 2014).

The erosional unconformity between the Upper and Lower formations is explained as a transition in environment from a lacustrine to one which forms dunes. This is explained by Gale crater being completely filled with lacustrine sediments (the horizontally bedded rocks of the crater floor and Lower formation) and then being covered by dunes for a period of time which then lithified. Once the dunes were lithified, creating the more steeply dipping layers of the Upper formation, erosion created the topography we see now. This also explains why Mount Sharp is taller than Gale's crater walls. The Upper formation was eroded away from everywhere in the crater except on Mount Sharp. (Grotzinger et al., 2014, Grant et al., 2014, Schwenzer et al., 2012, Milliken, R. E., Grotzinger, J. P., and Thomson, B. J., 2010)

One of the strengths of this hypothesis lies in its explanation of the nearly horizontally layered rocks seen in Gale crater and the Lower formation. A lacustrine environment readily explains the bedded and nearly horizontal nature of the rocks and additionally accounts for both clastic and chemical sediments (e.g., sulfates). This hypothesis does talk about the formation process of the Upper formation, attributing it to a crater-filling event that allowed for dune fields to cover the Lower formation, simultaneously addressing the differences in dip and chemistry between the two formations. This hypothesis also explains the conglomerates seen near the crater rim. The erosion pattern required to create the present-day topography would predict a relatively young exposure age, and thus is consistent with the inferred exposure age of 78 Ma. However, this hypothesis does require an unusual erosion pattern to leave the Upper formation in place only at the center of Gale crater. Another issue is this hypothesis does not explain the slightly dipping layers of the Lower formation nor the channels in the Lower formation.

Ice Weathering:

This hypothesis proposes that seasonal melting of snow pack created the sedimentary rocks of both Gale crater and Mount Sharp. (Niles et al., 2014, Niles, P.B., and Michalski, J., 2012, Niles, P.B., and Michalski, J., 2009)

The lower layers of sedimentary rocks on the crater floor and of the lower formation of Mount Sharp were created in a complex impact crater that filled with dust, ice, and sulfur rich aerosols. The sediments within the ice were then weathered within the ice matrix during periods of slight warming. This occurred because the sediments absorbed more heat than the ice and that extra heat caused small amounts of ice to melt around the sediment, creating an environment where the particles could be weathered. Then, during a climatic shift, the ice sublimated away leaving behind the chemically weathered and highly hydrated siliciclastic fine grained sand mixed with sulfate salts. As the ice sublimated, it retreated from the crater walls, causing sediment to accumulate in the center of the crater. This cycle would occur cyclically until the sediment supply or obliquity changed. There is a potential for ephemeral lakes to form during periods of sublimation as well (see fig. 2).

The explanation for the difference in the Upper and Lower formations of Mount Sharp is that as Mars went from a period of active volcanism and numerous impacts to a time of little to no volcanism or impacts the source material for Mount Sharp changed, creating the two different formations.

As for the Upper formation of Mount Sharp, the ice weathering hypothesis suggests that a long period without liquid water occurred, which built up a large accumulation of ice and particles above the proto Mound Sharp. This large amount of ice then sublimated and water driven diagenesis occurred while ephemeral melting formed the channels seen in the Lower formation and fed ephemeral lakes. As the ice sublimated, it again retreated from the crater walls, causing sediment to accumulate in the center of the crater. A difference in chemistry between the Upper and Lower formations is explained as a change in source material as Mars became less volcanically active and experienced fewer impacts. From there, the mound was eroded into the configuration we see presently.

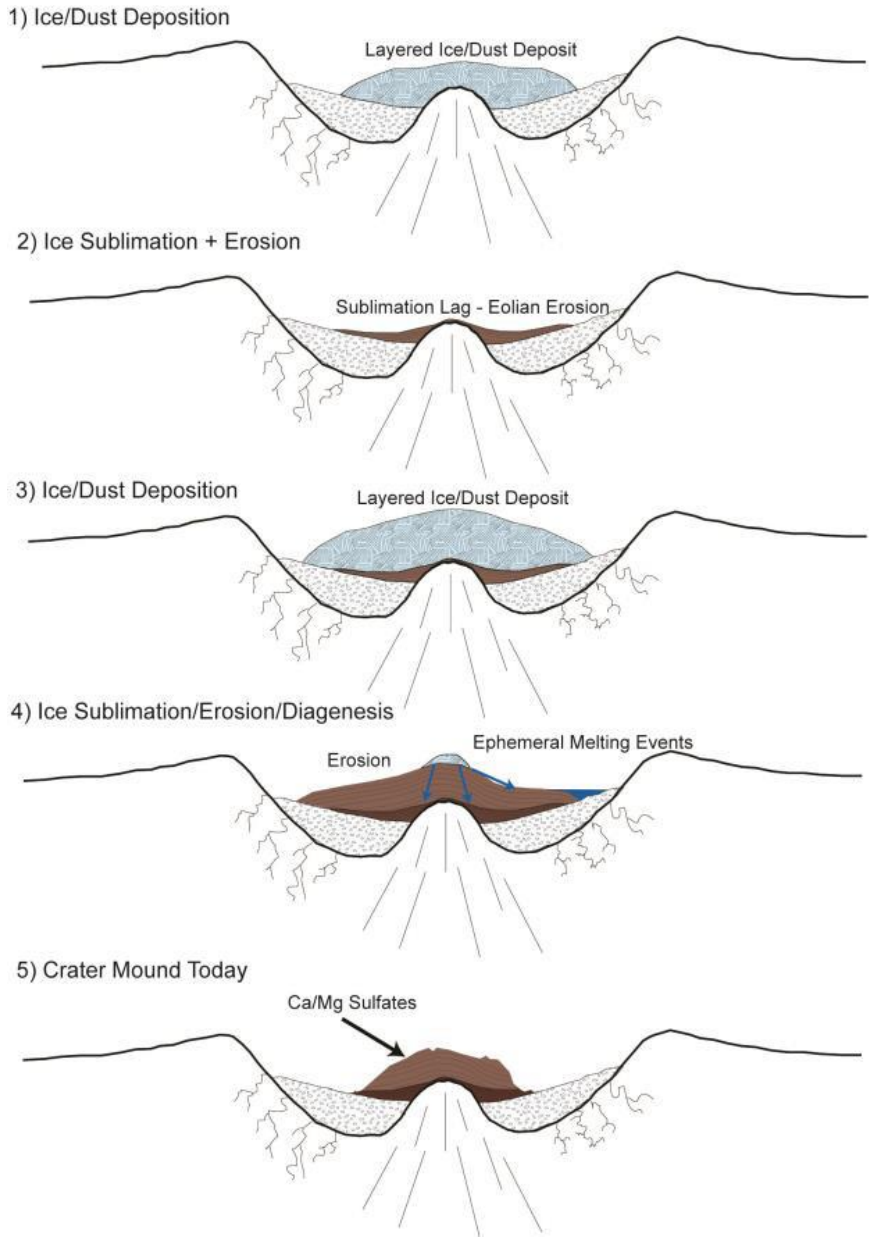

Figure 5. Formation sequence of Gale crater sediments according to the ice weathering hypothesis. Taken from Niles et al., 2014.

A strength of this hypothesis is that it takes into account the different global conditions Mars experienced in its very early stages. In doing this, it explains the difference in chemistry between the Upper and Lower formation, however, it does not explain the difference in dip seen between the two formations. This hypothesis has Mount Sharp growing as a series of sedimentary rock deposits within Gale crater, meaning no erosional processes are required to explain the current topography. It also explains the channels seen in the Lower formation. It does not predict a young exposure age – in this hypothesis the rocks exposed at the present time became exposed when the glacier last disappeared from the crater. A young exposure age would be observed only if there was a period of erosion during that time which uncovered previously unexposed rock. It also does not explain the conglomerates seen near the crater rim.

Seasonal Melting:

According to the seasonal melting hypothesis, Gale crater, a complex impact crater, was filled with snow, which melted and created playa lakes. Climatic cycling provided oscillation between snow-filled, wet, and dry conditions for the crater interior. (Kite et al., 2013a)

The seasonal melting hypothesis states that the sedimentary rocks of the crater floor and the lower formation of Mount Sharp are from an early period in Mars's geologic history where impacts and volcanic eruptions were still common. As the dust and ash settled onto the snow pack in Gale crater it lowered its albedo, which in turn led to melting of the snow. It is this dependence on volcanism and impacts that created the irregular bedding seen in the sedimentary rocks in Gale crater and the lower formation of Mount Sharp as perennial playa lakes came and went. Later, as volcanism and impacts decreased, the seasonal melting became dependent on orbital eccentricities which resulted in the rhythmically deposited layers of the upper formation of Mount Sharp. (Kite et al., 2013a)

In this reconstruction of Martian paleoenvironment, spin-orbital, climate, and surface material parameters were all taken into account. Based on the calculations, Mars would have experienced episodic melting when the parameters lined up in a specific way (Niles et al., 2014, Niles, P.B., and Michalski, J., 2012, Niles, P.B., and Michalski, J., 2009)

This is a strong hypothesis because it explains the chemical differences between the rocks of the Lower formation and Upper formation as a transition from a young Mars that was volcanically active and was constantly being impacted to a Mars dominated by sediment created and mobilized by aeolian means. It also explains how the horizontally layered rocks of the crater floor were created. It even goes so far as to explain why the Upper formation contains more rhythmic layering than the Lower formation. However, this hypothesis does not explain the 78 mya exposure date.

Spring Environment:

In this hypothesis, the sedimentary rocks of Gale crater and Mount Sharp are the result of spring deposits in a complex impact crater. The impact that created Gale crater would have fractured the rocks, increasing permeability, in addition to making a topographic low. These two factors worked together to make Gale crater an ideal environment for spring deposits to form in. (Rossi et al., 2008)

While this hypothesis does account for the 78 mya exposure date as it says this process was is a recent one, happening until about 100 mya, it does not take into account the unconformity in Mount Sharp. It also does not explain the difference in chemistry between the Upper and Lower formations or the conglomerates near the crater rim. This hypothesis does have a strength in that it would explain the sulfate veins seen by Curiosity.

Slope Wind Enhanced Erosion and Transport (SWEET):

The SWEET hypothesis states that the walls of Gale crater served to intensify winds traveling into the crater and that, because of this increase in wind velocity, erosion was increased on the outer portions of the crater. However, once that wind reached the center of the crater, it would have slowed enough to cause the deposition of the newly eroded sediment. This erosional pattern could have led to the moat and mound structure seen today. The authors calculated that it took $10^{7\text{-}8}$ years for Mount Sharp to form, assuming Martian dust settling rates measured currently were the same during Mount Sharp's formative years. The SWEET hypothesis acknowledges that the horizontal layers seen around Mount Sharp were formed by water processes, including ice-weathering, snowmelt, or rainfall. In order to account for the periodically wet environment, the SWEET hypothesis proposes that Gale crater experienced long dry periods followed by short, interspersed wet periods.

As for the unconformity in Mount Sharp, the SWEET hypothesis addresses it only in that it must be oriented away from the center of Mount Sharp because the sediments would have been built from the outside in with sediment accumulating preferentially in the center of the crater where the wind velocity would have been at its smallest. It does not address how the upper formation was formed.

A potential strength of the SWEET hypothesis is that it invokes multiple processes to form the sedimentary rocks of Gale crater and Mount Sharp. It says that Mount Sharp is an accumulation of windborne sediments that lithified. It then goes on to say that the horizontal layers seen around Mount Sharp could have been formed by water processes, including ice-weathering, snowmelt, or rainfall. However, this hypothesis does not address the unconformity in Mount Sharp, the chemical differences seen between various layers, or the conglomerates near the crater rim. Because this hypothesis says that the process which formed Mount Sharp are still active, an exposure date of 78 mya for some of the rocks in Gale crater is feasible.

Rapid Dune Cementation:

This hypothesis proposes that the sedimentary rocks of the Lower formation of Mount Sharp were created by dunes that were preserved with their original topography. In order for their original topography to be so well preserved, the dunes must have either been quickly stabilized and later buried or rapidly buried in a nondestructive environment. In the case of rapid burial, the dunes would have then been lithified when the groundwater table rapidly rose and flooded the surface followed by rapid sedimentation and lithification of the buried dunes. In this situation, the clay minerals seen in the lower formation are hypothesized to be diagenetic pore fluids or infiltrating surface waters. In the case of rapid burial, the clay-bearing material seen would bury the dunes. After the burial, the dunes would be lithified. (Milliken et al., 2014)

The authors believe that liquid water was once present in the crater but are unsure whether groundwater or surface runoff were the main contributor of that water. This hypothesis also proposes that some strata onlapping the Lower formation are sandstones that extend outward from

Mount Sharp for hundreds of feet and form horizontal or low-angle bounding surfaces. These strata are interpreted to be 20 to 40m thick sets of dune stratification (Milliken, R. E., et al., 2014).

A strength of this hypothesis is that it explains the slight dip seen in the Lower formation as cross bedding. This hypothesis also explains the sulfate veins seen by Curiosity. However, this hypothesis remains focused on the Lower formation with some mention of potential lacustrine environments forming to explain the horizontally bedded rocks seen. This hypothesis does not explain the formation of the Upper formation, the conglomerates near the crater rim, or the 78 mya exposure date.

DISCUSSION

Each Hypothesis explains (or doesn't) the features we are seeing at Gale crater and Mount Sharp. In order to simplify the effectiveness of each hypotheses' explanation of each individual feature, the follow table has been produced.

1=well explained 2=partially explained 3= poorly explained 4= could be explained 5=not explained	Feature seen	Nearly horizontal beds on crater floor	Phyllosilicates and sulfates on crater floor	Conglomerates on crater floor	Irregular bedding on crater floor	Low angle dip of the Lower formation	Irregular bedding in Lower formation	Phyllosilicates and sulfates in Lower formation	Dipping beds of the Upper formation	Regular Bedding in Upper formation	Martian dust spectral signature in Upper formation	Unconformity between Upper and Lower formations
Hypothesis												
Lacustrine		1	1	2 (fluvial)	1	1	1	1	1	1	1	1
Ice weathering		2	1	5	2	1	2	1	1	1	1	1
Seasonal Melting		1	1	4	1	1	1	1	1	1	1	3
Spring Environment		3	1	5	2	1	2	1	1	5	5	5
SWEET		2	4+	5	5	1	5	4+	1	1	1	5
RDL		1	1	5	4	1	4	1	5	5	5	5

Strength/Weaknesses of each hypothesis:

Table 1. A numerical representation of the strengths and weakness of each hypothesis in relation to the features seen at Gale crater and Mount Sharp.

Predictions for Gale crater and Mount Sharp:

Each of the hypotheses discussed provides unique predictions for the geologic features that would occur on the crater floor, Lower, and Upper formations. Tables 1-3 summarize these predictions in relation to the features actually observed (see Geologic Setting).

1=present 2=potentially present 3=not present	Feature predicted	Nearly horizontal bedding	Phyllosilicates and sulfates	Conglomerates	Standing water	Irregular bedding
Hypothesis						
Lacustrine		1	1	2 (fluvial)	1	1
Ice weathering		1	1	3	2	1
Seasonal Melting		1	1	2	1	1
Spring Environment		1	1	3	2	1
SWEET		1	2	3	3	2
RDL		1	2	3	2	2

Table 2. A numerical representation of the features predicted by each hypothesis for the floor of Gale Crater. In order to conserve space, rapid dune lithification is represented in the tables as RDL

1=present 2=potentially present 3=not present	Feature predicted	Dipping away from peak radially outward	Dip unidirectional throughout	Phyllosilicates and sulfates	Conglomerates	Standing water	Irregular bedding
Hypothesis							
Lacustrine		3	1	1	2 (fluvial)	1	1
Ice weathering		1	3	1	3	2	1
Seasonal Melting		1	3	1	2	1	1
Spring Environment		1	3	1	3	2	1
SWEET		1	3	2	3	3	2
RDL		1	3	2	3	2	2

Table 3. A numerical representation of the features predicted by each hypothesis for the Lower formation.

1=present 2=potentially present 3=not present	Feature predicted	Unconformity between formations	Dipping away from peak radially outward	Dip unidirectional throughout	Martian dust spectral signature	Regular bedding
Hypothesis						
Lacustrine		1	3	1	1	1
Ice weathering		1	1	3	1	1
Seasonal Melting		1	1	3	1	1
Spring Environment		3	1	3	3	3
SWEET		2	1	3	1	1
RDL		3	3	3	3	3

Table 4. A numerical representation of the features predicted by each hypothesis for the Upper formation.

Lacustrine Environment:

As Curiosity continues to traverse the Lower formation it should continue to see nearly horizontal sulfate-bearing rocks until reaching the unconformity. After passing the unconformity, Curiosity should travel across rhythmically deposited cross bedded layers that should consist of material with a similar composition to Martian dust. The dip of these layers should be unidirectional throughout the Upper formation.

Ice Weathering:

As Curiosity travels further up Mount Sharp, according to this hypothesis, it should see a transition from phylosilicate beds dipping radially outward to beds of Ca/Mg sulfates dipping radially outward.

Seasonal Melting:

In transitioning from the Lower formation of irregularly bedded clay rich beds dipping radially outwards, to the Upper formation, Curiosity should begin to see regular bedding which dips radially outwards and is compositionally more similar to Martian dust than the Lower formation.

Spring Environment:

In this hypothesis, Curiosity should not see a large shift in bedding or chemistry as it continues up Mount Sharp from the evaporitic layers that are dipping radially outwards.

SWEET:

As Curiosity travels farther up Mount Sharp, this hypothesis predicts that it will continue to see bedding that is dipping radially outward with the unconformity dipping away from the center of Mount Sharp as well.

Rapid Dune Cementation:

As this hypothesis does not deal with the Upper formation of Mount Sharp, it isn't possible to predict what Curiosity should see as it continues upwards. However, it does predict that if the clays overlie, are finer grained than, and onlap the dunes of the Lower formation that the rapid burial portion of the hypothesis would be correct. In contrast, if the clays are found to reside within the sandstones, the rapid cementation portion would be the correct one of this hypothesis. In terms of dip, this hypothesis predicts that dip in the Lower formation is unidirectional.

Which hypothesis is strongest?

Based on this examination of what is seen at Gale crater and Mount Sharp, the lacustrine and seasonal melting hypotheses are deemed the strongest contenders for being the most correct. Fortunately, based on observations from Curiosity, it is possible to differentiate between the two hypotheses. A more three dimensional model of the layers of Mount Sharp is needed in order to see how the layers are dipping throughout the entire mountain. Once the dip of either the Lower or Upper formation can be extrapolated out through Mount Sharp, we will be able to see if the layers within the two formations dip radially or unidirectionally. Once that is known, it will either disprove all hypotheses so far besides the lacustrine hypothesis, or disprove the lacustrine hypothesis, leaving the seasonal melting hypothesis as the strongest contender for having the most correct geologic history of Gale crater and Mount Sharp. It is this author's opinion, based on available orbital imagery, that the seasonal melting hypothesis is the most correct.

Where is Curiosity now?

While no literature has been published, there have been numerous mineral veins found in the Lower formation. While very little is known about the veins as of yet, due to difficulties measuring mineralogy of small veins which are dark on the edges and white in the middle, they do provide some information helpful in evaluating the hypotheses. These veins indicate that there had to be some kind of groundwater influx into the Lower formation. We do not know when this would have happened, but it does show that Mars previously had groundwater playing a role in the Martian paleoenvironment.

Implications for habitability:

The hypotheses can be divided into three different categories in terms of what they predict for habitability. First, the hypothesis which sets forth a habitable environment is the lacustrine hypothesis. This environment would be similar to environments seen on Earth and would provide the nutrients, liquid water, and neutral pH needed for life to exist. Second, are the potentially habitable environments proposed by the spring environment and seasonal melting environment. These are considered probably due to the fact that the liquid water may or may not have a constant presence, not to say that life can't adapt to an environment such as the ones proposed by these two hypotheses, it is just less likely than the lacustrine environment. Lastly, the SWEET, ice weathering, and rapid dune lithification propose environments that are unlikely habitable. It is the lack (or near enough to a lack to be unimportant) of liquid water that prevents these environments from being potentially habitable.

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