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Investigating Sedimentary Rocks to Understand Past Wet Climate of Mars

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INVESTIGATING SEDIMENTARY ROCKS TO UNDERSTAND PAST WET CLIMATE OF MARS

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Abstract

The "deltaic" geomorphology in the Eberswalde Crater is often considered a "smoking gun" for the warm-and-wet ancient climate of Mars. The Crater displays sedimentary features, which many argue, can only be found in a river-delta system (Bhattacharya et al., 2005). However, with the advent of high-resolution images, the Eberswalde Crater delta's geomorphology has been revealed to be more complicated than could be seen previously. These high-resolution data suggest that the development of the Eberswalde delta is likely more episodic (Schieber 2007). While better resolution data has placed doubt on the wet Mars hypothesis at the Eberswalde Crater, the opposite is true of the Gale Crater. Recent images acquired by the Mars Curiosity Rover have revolutionized the hypotheses explaining the formation of Mount Sharp in the Gale Crater. The new prevailing hypothesis is that Mount Sharp was formed by a series of crater lakes (NASA, 2014). This study provides evidence supporting the crater lake hypothesis, using bedding architecture diagrams, facies diagrams, lithologic logs, paleocurrent map and rose diagram, and minimum water depth estimations of the exposed sedimentary layers. Reconstructing a detailed depositional history of the Gale Crater Lake provides a window into a more ancient Mars where life could have evolved in a wet habitable climate that is absent today.

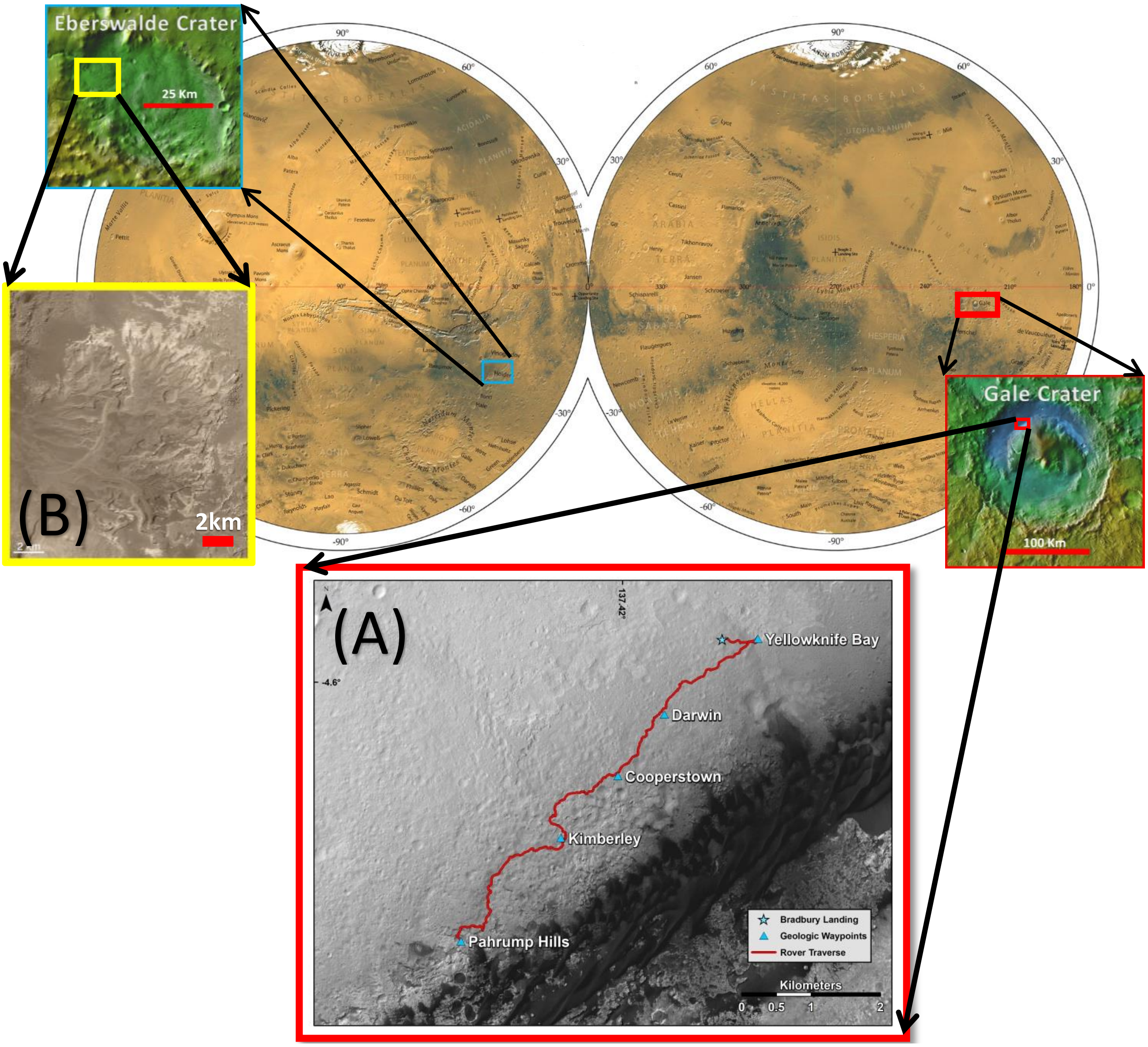
Introduction

The advent of high-resolution images of the Martian surface, generated by both the High Resolution Science Experiment (HiRISE) and the Curiosity Rover's MASTCAM, has revolutionized the way scientists study Mars. The combination of HiRISE images and MASTCAM images allow aerial and outcrop views of Martian features. Having access to outcrop views through the Curiosity MASTCAM is nearly equivalent to having an actual scientist photographing the Martian surface. These advances are invaluable to Martian geology, and have allowed scientists new insights into the presence of liquid water on Mars' surface during the Noachian period (3.8-3.5 Ga). Studies on both the Eberswalde Crater deposits and the strata of the Gale Crater (Fig. 1) have advanced significantly due to the availability of these new images.

The study of the Eberswalde Crater delta (Jerolmack et al. 2004, Moore et al. 2003, Bhattacharya et al., 2005) had been limited due to the lack of high quality imaging until 2006. Before then, it was not possible to determine the grain size of the strata. Now, large boulder sized clasts are visible through HIRISE images. However, Eberswalde Crater delta studies are still limited to map-view images and their interpretations, such as deltaic lobe maps, facies maps, and sequence stratigraphy (Pondrelli et al., 2007 2008 2011). This is not the case with Gale Crater studies due to the presently active Curiosity Rover. This has allowed the analysis of samples taken from the Martian surface at the Gale Crater using the Curiosity's on-board instruments (NASAfacts) and has provided high-resolution images comparable to an outcrop-visit by a geologist. The fluvial origins of the Gale Crater strata, for example the Link and Hottah conglomerates (Williams et al., 2013), would be completely unknown without the Curiosity Rover.

This study sets out to construct spatial and temporal variations of paleocurrents, lithologic logs of both outcrops and clinoform successions, bedding architecture diagrams, and facies diagrams using the revolutionary images of the Gale Crater strata now available because of the Curiosity Rover.

Study Area



Study area on planet Mars. (Image sources: NASA, JMARS, Ralph Aeschilman) **Figure 1a**. Curiosity Rover traverse from Yellowknife Bay to Pahrump Hills at Gale Crater **Figure 1b**.Eberswalde Crater delta.

This research mainly focuses on the Gale Crater (Fig. 1a) on Mars with a brief emphasis on the Eberswalde Crater (Fig. 1b). The “delta” in the Eberswalde Crater, -23° latitude and 326.3° longitude, lies on the northeastern side of the crater which lies northwest of the Holden

Crater (Fig. 1b). At -4.603° latitude and 137.447° longitude, lies the Gale Crater study area (Fig. 1a). The Gale Crater contains the mysterious Aeolis Mons, also known as Mount Sharp. The main focus is on the area of the Gale Crater traversed by the Curiosity Rover between its landing site and Pahrump Hills (Fig. 1a). This includes a portion of the Aeolis Palus, the plain separating the northern crater wall from the foothills of the Mount sharp. Mount Sharp has an elevation of 5.5 km, and both HiRISE and Curiosity Rover images suggest that it is entirely composed of stacked sedimentary strata.

Methods

The methods employed by this study involved acquiring relevant images from the NASA, JMars, and HiRISE websites. HiRISE images, featuring resolutions of approximately 25 cm per pixel, were viewed using the program HiView. All images were manipulated using the program Adobe Illustrator. The program JMars, "a geospatial information system (GIS) developed by ASU's Mars Space Flight Facility to provide mission planning and data-analysis tools," was used for initial investigation of the study areas (JMARS). The program GeoPlot was used to create the Gale Crater paleocurrent rose diagram.

When the areas of interest have appeared in the background of the Curiosity Rover's images, the background scale has been estimated using the foreground scale bar. All scale bars present in MASTCAM images apply to the foreground only. The apparent dips of photographed clinoforms at the Kimberley and Zabriske Plateau sites have been estimated using the height and length of the clinoforms in conjunction with the trigonometric function inverse tangent.

$$\tan^{-1}\frac{Clinoform\ Height}{Clinoform\ Length} = Degrees\ of\ Apparent\ Dip$$

Minimum and maximum water depths at the time of deposition of dune cross-sets have been estimated using the following calculation (LeClair and Bridge, 2001):

$$Dune\ Cross\ set \times 3 = original\ Dune\ Height$$

$$Original\ Dune\ Height \times 6 = minimum\ water\ depth$$

$$Original\ Dune\ Height \times 10 = maximum\ water\ depth$$

Results

Eberswalde Crater Delta Outcrop

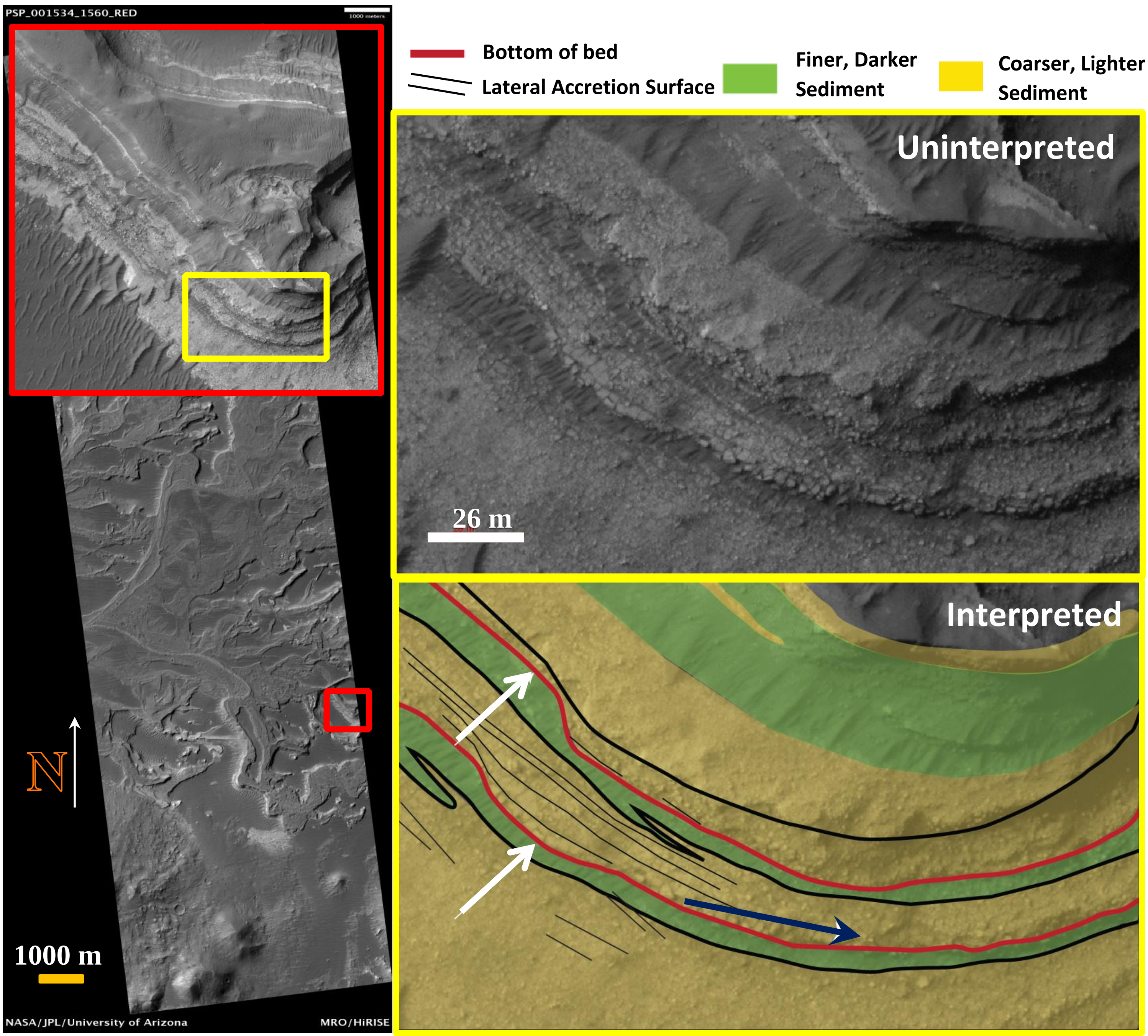


Figure 2. HiRISE image of Eberswalde Crater delta cliffside outcrop. 1 pixel is equal to 25cm. The white arrows indicate a fining upward succession. The blue arrow indicates the disorganization of the boulder size clasts.

The beds at the cliff outcrop shown in fig. 2 display alternating beds of light and dark facies. The darker facies are clearly being shaped by eolian processes, forming dunes. This puts clear parameters on the grain size of the darker sediment, because larger grain sizes cannot be reworked by eolian forces. The lighter colored facies is characterized by boulder sized clasts. The beds (Fig. 2) display a fining upward succession, transitioning from coarser/lighter facies to darker/finer facies (indicated by white arrows in Fig. 2). The large clasts (~1 m) also become less organized (indicated by a dark blue arrow in Fig. 2). Lateral accretion surfaces are present crudely (Fig. 2). The combination of these characteristics suggests that these strata were deposited by fluvial meandering channels possessing helical flows. These channels likely represent delta-plain distributary channels.

Gale Crater

(A) Gale Crater Dataset			
Site Name	**Paleocurrent Direction**	**Minimum Water Depth**	**Dip Angle**
Hottah/Link	n/a	0.03-0.9 m*	n/a
North Kimberley	South West	2m	6°
Kimberley	South	n/a	n/a
Zabriske	South	2.5m	14°
Hidden Valley	South East	n/a	n/a
Whale Rock, Pahrump Hills	South East	33.75cm-2.25m	n/a

(B)

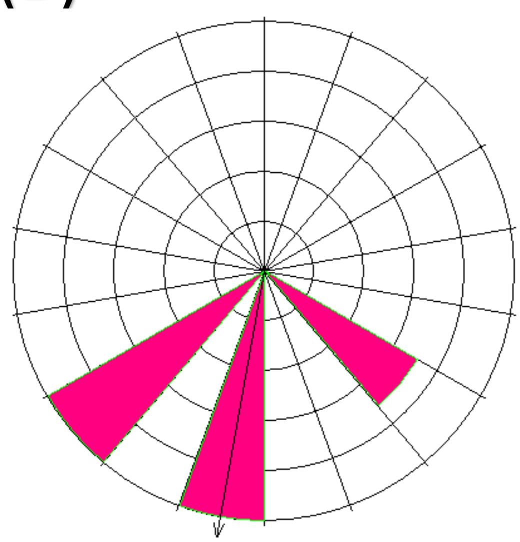


Table 3a. Data collected from Gale Crater by image analysis and calculations. n/a indicates no answer. *(Williams et al., 2013) **Figure 3b**. Gale Crater Paleocurrent Direction Rose Diagram.

Hottah and Link Conglomerates

Williams et al. (2013) point out pebble imbrication and alternating layers of finer sediment between pebble layers, indicating the necessity of flowing liquid water to deposit the sediment that formed this rock unit. Flow velocity at the time of deposition was ~0.20 to 0.75 m/s corresponding to a minimal flow depth of ~0.03m-0.09m (Williams et al., 2013). However, Williams et al. (2013) did not identify the presence of ripple trough cross-stratification within the Hottah conglomerate outcrop (Fig. 4). The pebbles can be seen lined up along a trough, with finer material inbetween the pebbles forming the ripple trough cross-strata (Fig. 4). The cross-set is too small (~1.5cm) to measure minimum water depth (Fig. 4).

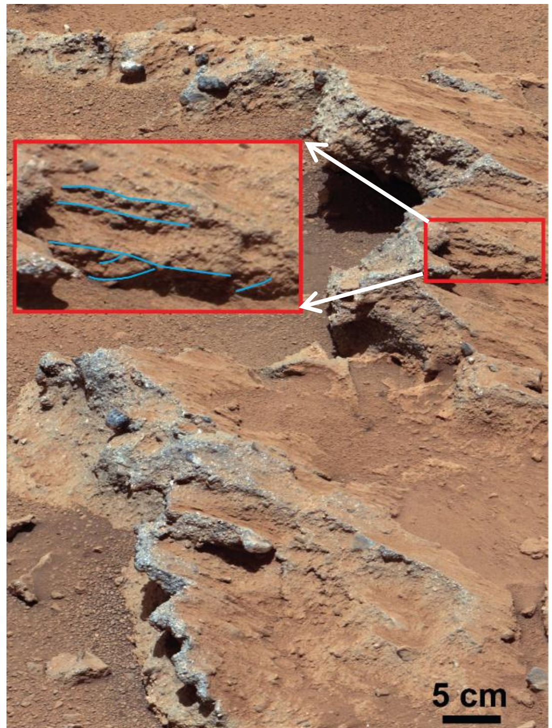
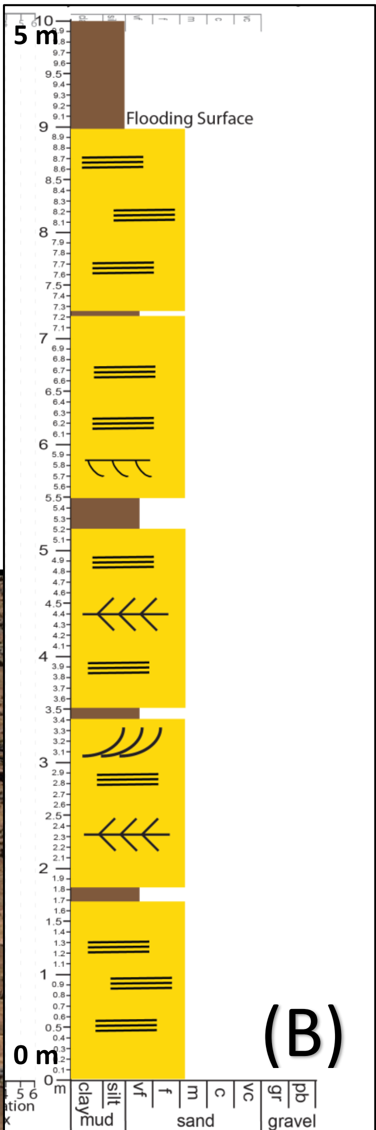


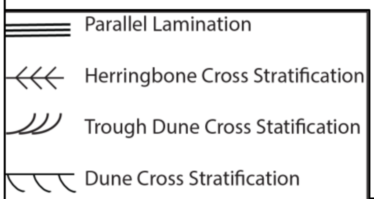
Figure 4. Curiosity Rover image of the Hottah Conglomerate Outcrop. Blue lines mark the cross-bedding of the pebbles as well as the top of the beds. (Image source: NASA, Curiosity MASTCAM)

Kimberley Clinoforms

Kimberley exhibits distinct clinoforms made up of sandstone beds (Fig. 5). The beds north of Kimberley dip to the southwest (Fig. 5a), whereas the beds at Kimberly dip to the south. The shape, size, orientation, and apparent dip of the clinoformal strata suggest that they are part of a delta system. Clinoform geometry allows the measurement of minimum water depth at the time of deposition, which is ~2 m. The apparent dip of the most clearly defined clinoform is ~6°.

Measurement is limited to minimum water depth because the leading edges of the clinoforms have likely been eroded away. This outcrop likely also exhibits evidence of tidal activity (?), as the alternation of coarse and fine grained strata suggests some type of periodicity and the dune cross-strata (highlighted in blue in Fig. 5a) oppose the clinoform direction, suggesting a reversal of flow. There appear to be herringbone cross-strata and dune cross-strata (Fig. 5).





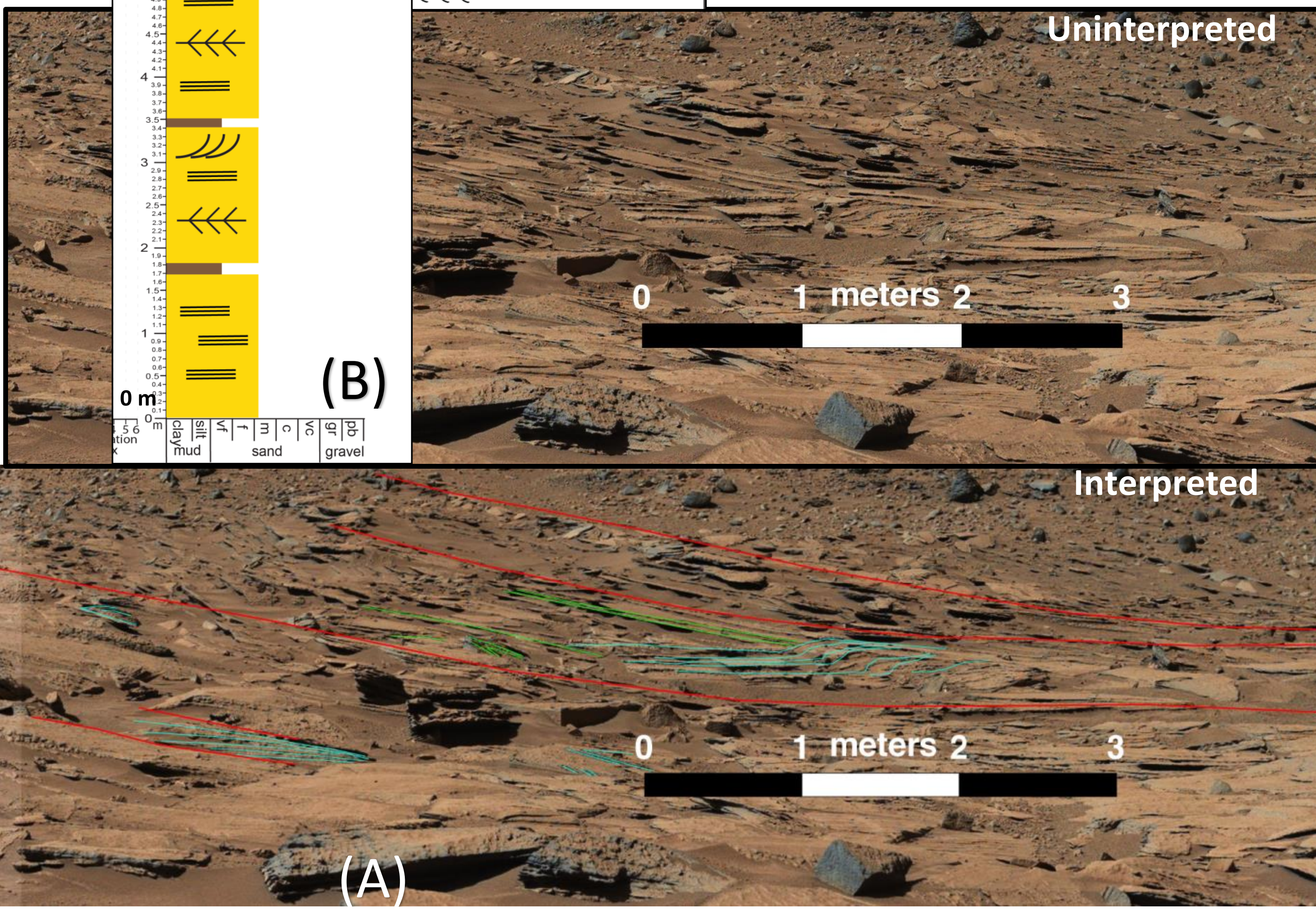


Figure 5a. Kimberley clinoformal strata. Red lines indicate a clinoform top. Blue and green lines indicates features noted in the Lithologic log. (Image source: NASA, Curiosity MASTCAM) **Figure 5b**. Lithologic Log

Zabriske Plateau Clinoforms

Zabriske Plateau exhibits several clinoforms made up of sandstone beds which all dip to the south and are approximately 25 m higher in elevation than the clinoforms at Kimberley. Fig. 6b illustrates the lithology and sedimentary structures of this clinoformal package. At both Zabriske and Kimberley (Fig. 6a and Fig. 5a), there are clinoformal packages visible in the distance. This demonstrates the long-term existence of a delta system. There are possible subaqeous clinoforms visible at the Zabriske Plateau, indicated in fig. 6a with an arrow. The minimum water depth has been estimated to be ~2.5 m and the apparent dip of the nearest clinoform is ~14°.

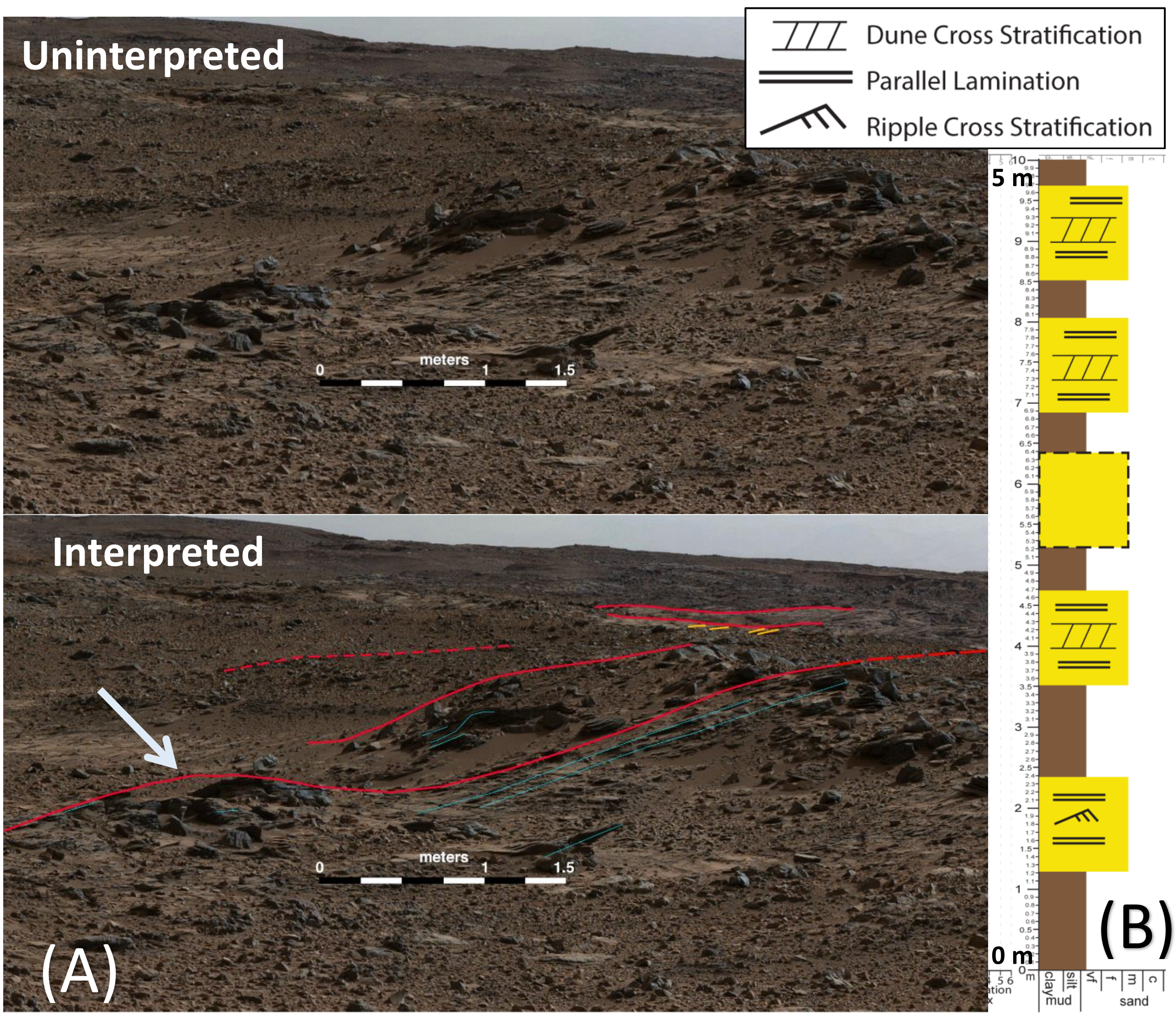


Figure 6a. Zabriske Plateau Clinoforms. (Image source: NASA, Curiosity MASTCAM) **Figure 6b**. Lithologic log of clinoforms at Zabriske Plateau. Each sand lobe represents a clinoform.

Hidden Valley Outcrop

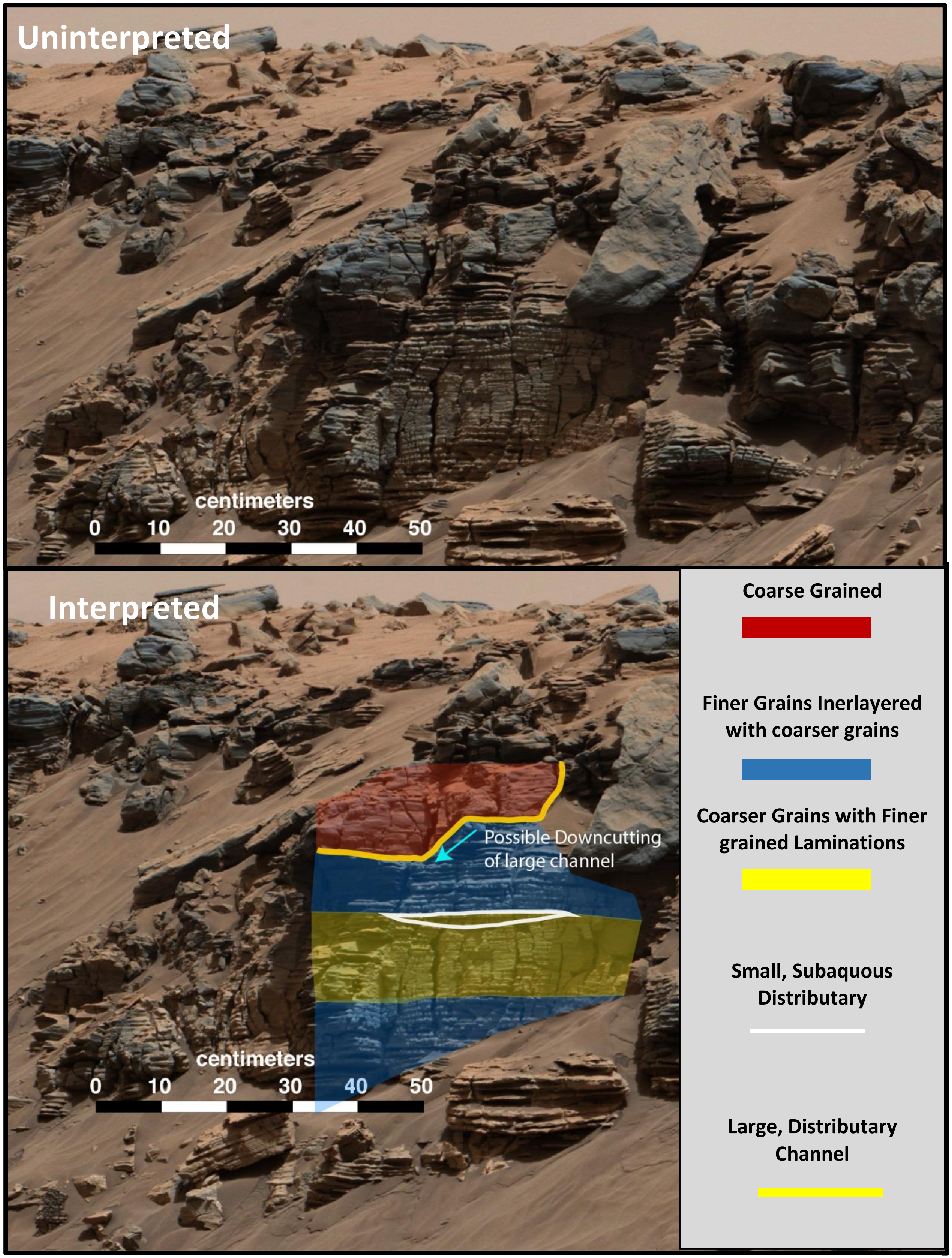


Figure 7. Outcrop of sedimentary rock viewed from the floor of Hidden Valley, Gale Crater. (Image source: NASA, Curiosity MASTCAM)

This outcrop in the wall of Hidden Valley was photographed from the valley floor by the Curiosity Rover. The outcrop shows alternating layers of fine and coarse grains, shown by the variation of weathering throughout the outcrop. The blue overlay in fig. 7 indicates layering dominated by finer grains, while the yellow overlay indicates a depositional period dominated by coarser grains. This difference is evident through the weathered spacing between the individual strata. The spacing is larger in the strata overlain by blue than it is in the strata overlain by yellow. The strata overlain by red are distinctly more coarsely grained than the underlying strata. These red strata indicate a down cutting into the layers below it, represented by a bold yellow line (Fig. 7). This red overlain layer is a large distributary channel. There are layers within the yellow overlain strata which pinch out on either side, cutting down into layers below, marked by a white line(Fig. 7), indicating a subaqueous distributary channel within an overall coarsening succession (Fig. 7 and 8). This vertical change from a small subaquous distributary channel to a large distributary channel, with a time gap in between the different channels suggests the progradation of a delta at the lake margin. Fig. 8 illustrates a detailed lithology of the Hidden Valley outcrop showing an overall coarsening upward trend. Using location information for the curiosity rover, the estimated paleocurrent direction is approximately southeast.

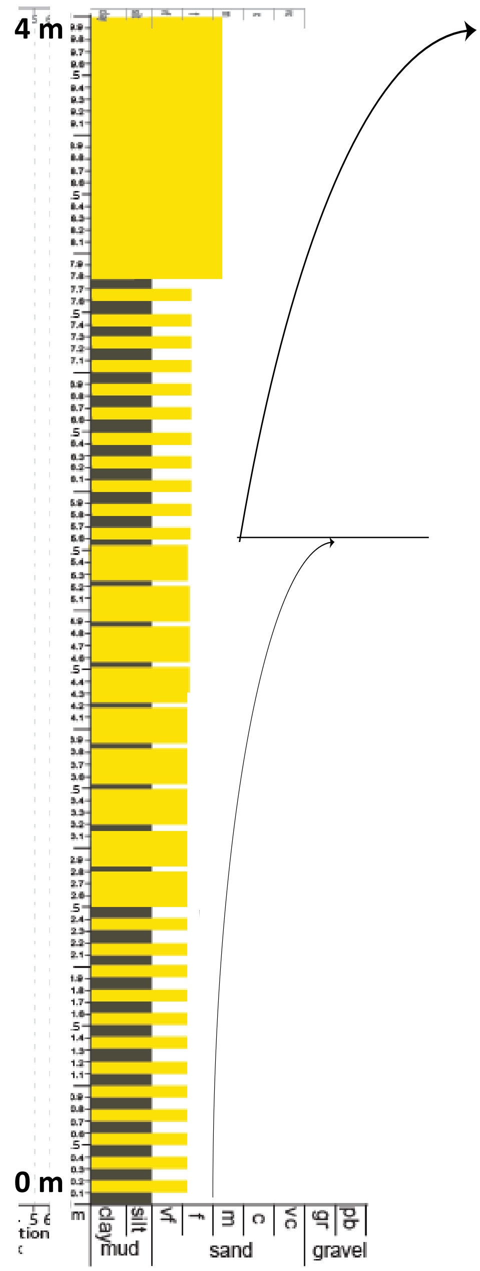


Figure 8. Lithologic log of the Hidden Valley outcrop.

The layered strata within the Hidden Valley outcrop are evidence of a delta prograding into its basin. The two coarsening-upward bed-set cycles within an overall progradational parasequence (Fig. 8) likely suggests distributary channel switching.

Dunes and Ripples at Whale Rock, Pahrump Hills

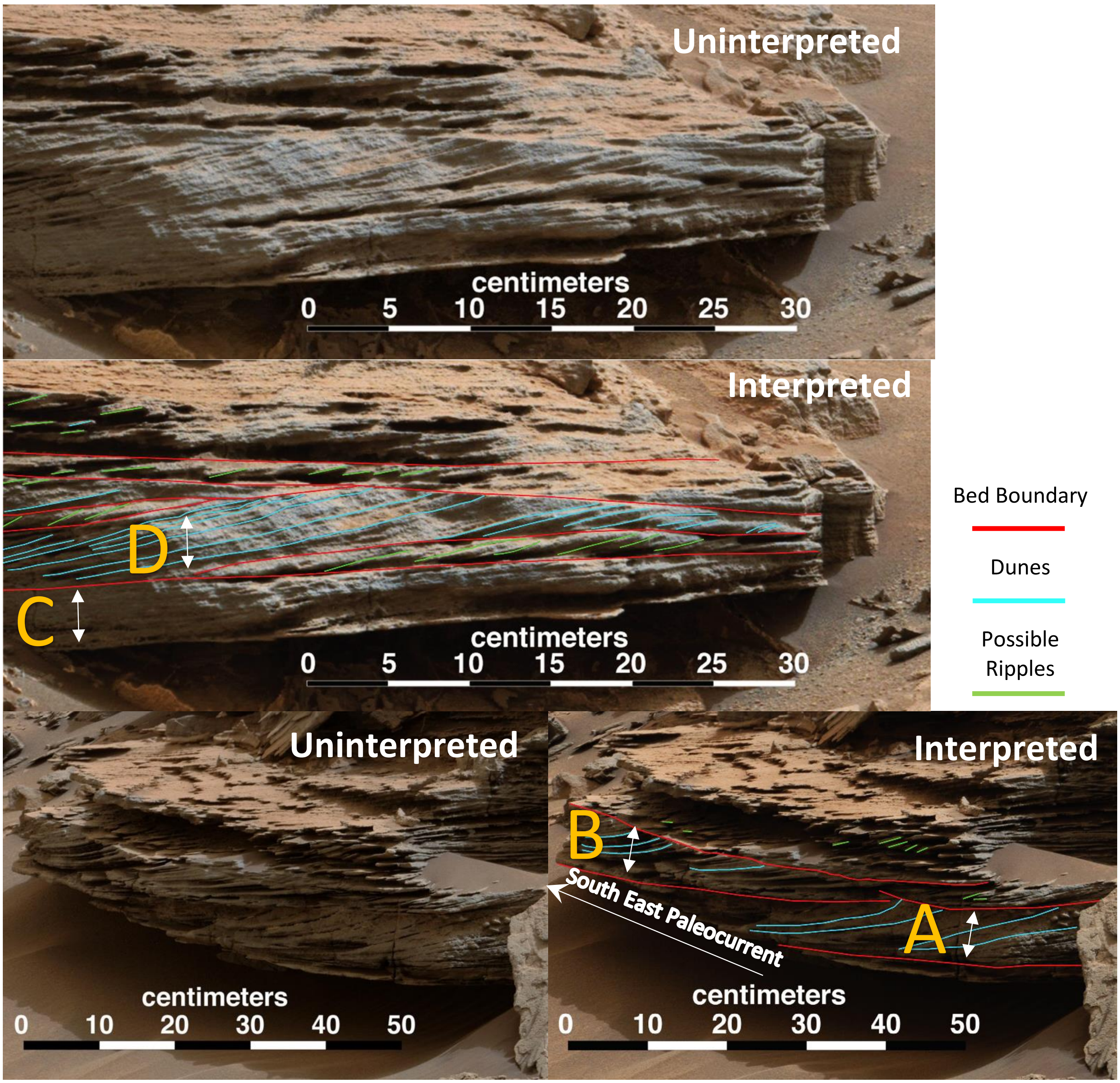


Figure 9. Whale Rock at Pahrump Hillls, Gale Crater. (Image Source: NASA, Curiosity MASTCAM)

Whale Rock shows a series of stacked cross-stratified layers, mostly representing trough cross-stratified, compound dunes. However, ripple cross-laminations may be present farther up in the stratigraphy. These cross-sets are likely of aqueous origins, instead of eolian, due to their trough shaped geometry and vertical stacking (Grotzinger et al., 2005). The estimated water depth at the time of deposition has been calculated at three different points (A, B, C, and D in Fig. 9). The water depth at the times A and B is ~1.35 m-2.25 m. The water depth at the time C is ~1.26 m- 2.10 m. The water depth at the time D is ~90 cm – 1.5 m.

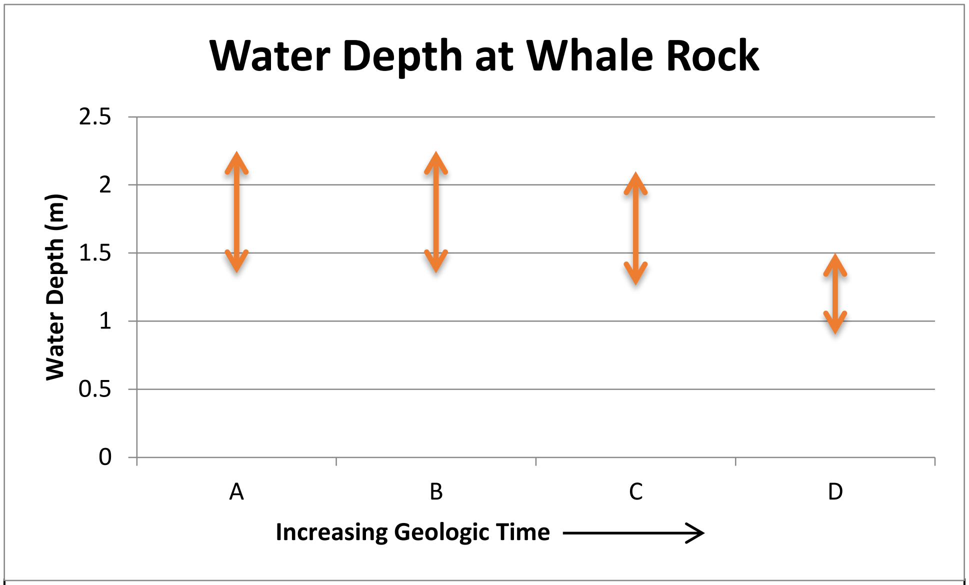


Figure 10. Chart of changing water depths through time at Whale Rock, Pahrump Hills. Each data point represents a range, indicated by the double sided arrows.

The water depths decrease through time (Fig. 10), suggesting a shallowing-upward succession of deeper water dunes transitioning to shallower water dunes and perhaps ripples. This is consistent with the depositional fill of a basin by a prograding delta.

Discussion

The Eberswalde Delta could have once been considered one of the major pieces of evidence for the permanent presence of water on the Martian surface due to the presence of fluvial meanders and “numerous avulsions” in the remnant geomorphology (Bhattcharya et al 2005). However, the advent of HiRISE images with resolutions of 25 cm/pixel complicated the sustained delta interpretation of the Eberswalde Crater. HiRISE images reveal that the grain sizes within the delta are much larger than what was thought previously, showing boulders ranging in size from 1 to 2 m (Howard et al. 2007). Schieber (2007) suggests that these boulders and meanders are the result of short lived, high energy flow instead of a long sustained flow. However, Howard et al. (2007) offers that the boulders may have come from the crater walls and could have been transported a short distance by the normal, sustainable channel flow that built the delta, given the bimodal nature of the sediment load. Therefore, although permanently sustained flow at the Eberswalde crater may have been possible, it is no longer the clearest example of a permanent presence of liquid water on the Martian surface.

Gale Crater provides a strong case for sustained liquid water on the Martian surface, as it is now hypothesized to be the site of a series of ancient crater lakes which formed Mount Sharp (NASA 2014). The results of this study piece together a paleogeographic setting of the lake margin. The clinoforms at Zabriske Plateau are at a higher elevation than the Kimberly clinoforms, likely suggesting a younger stratigraphic succession for the Zabriske Plateau. However, although less likely, they could also be affected by isostatic uplift resulting from unloading or eroding of the lake sediment. The difference in elevation may also be a combination of these two factors. The photo of Zabriske Plateau also shows a lot of ex-situ coarse weathered materials (Fig. 6a) occupying the landscape that are likely a direct result of its higher elevation and close proximity to Mount Sharp.

The herringbone (?) cross-strata marked on the clinoforms and litholog at Kimberly (Fig.

5a and 5b) may suggest possible tidal processes or other processes which result in the periodic reversal of flow. The sizes of Mars' moons are likely too small for generating appreciable lunar tides affecting lake water, although they do create a diurnal tide within the modern Martian atmosphere (Forbes and Miyahara 2006).

This study begins near the Rover landing with conglomerates and concludes with ripple and dune fields at Whale Rock, Pahrump Hills. The water depth begins with a shallow ~0.03 to 0.09 m (Williams et al., 2014) at the conglomerates, and then deepens to an average water depth of 2 m. The estimated paleocurrent directions all correspond with flow toward the ancient Gale Crater basin (i.e. southward). The study has shown that deltaic activity was long-lived in the area, and that the deltas were likely prograding into the basin. Acquiring more elevation data will aid in establishing more temporal relationships between the features investigated in this research. With the results available now, the area represents an ancient shallow lake margin, characterized by prograding delta distributary channels. This is encouraging for the pursuit of micro-fossils, as such a watery environment would be a promising habitat for the evolution of life.

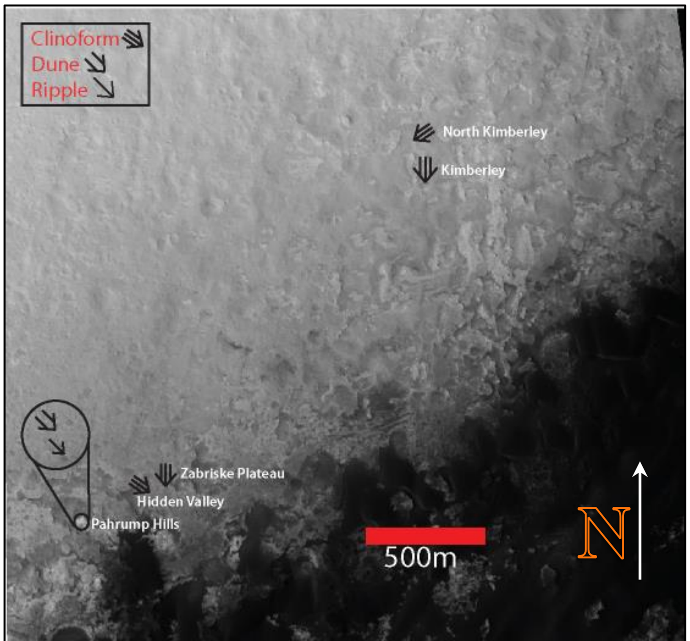


Figure 11. HiRISE image of Gale Crater Study Area. Link and Hottah outcrops are not visible in this image. North is up.

Conclusions

Both the Eberswalde and Gale craters demonstrate the activity of liquid water on the

Martian surface. However, the Gale Crater has emerged as a stronger example of permanent, sustained water flow than the Eberswalde Crater. Clinoform successions have been identified in multiple locations, with dip directions and dip amounts consistent with delta deposition. The studied outcrops at the Gale Crater suggest a stratigraphic transition from older to younger strata, and a transition from fluvial and alluvial deposition to lacustrine delta deposition : Hottah/Link conglomerates, clinoforms at Kimberley and Zabriske Plateau, subaqueous distributary at Hidden Valley, and subaqueous dunes at Whale Rock. This strongly supports the Gale Crater lake hypothesis and suggests that life may have been present on Mars during the Noachian (3.5-3.8 Ga) when it was both wetter and more habitable.

Acknowledgements

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APPROVAL SHEET

This is to certify that Emily Harper has successfully completed her Senior Honors Thesis, entitled:

Investigating Sedimentary Rocks to Understand Past Wet Climate of Mars

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Royhan Gani

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