Structural Analysis of Victoria Crater: Implications for Past Aqueous Processes on Mars

By

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Under the supervision of Dr. Julie Bartley

ABSTRACT

Visible across the surface of Mars, sedimentary structures are all that remains of the liquid water that once covered the planet. Despite their excellent exposure and wide extent, little is known about the exposed stratigraphy found in impact craters on Mars. With the next Mars rover mission scheduled for 2020, impact craters preserve multiple structural features formed both during impact and later during diagenesis, making them an ideal place to look for aqueous markers and therefore conditions suitable for ancient life. Analyses of exposed structural features in Victoria crater permits calculation of the orientation of these features and, combined with mineralogical evidence, provide definitive support for past regional aqueous processes. In this study, three images of the well-exposed promontory *Cabo Anonimo* in Victoria were analyzed using the program ImageRover. These analyses suggested evidence for multiple types of sedimentary bedding, including bedding within clasts in the crater wall and bedding within the wall itself. Bedding within the clasts suggests primary bedding pre-impact, possibly formed by aqueous processes.

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Introduction

Rovers on Mars thus far have demonstrated that Mars had liquid water in its ancient past (Head, 2007). As one of four terrestrial planets in our Solar System, it is important to understand why Earth contains liquid water, whereas the other planets do not. Because the surface of Mars was once reworked by fluvial processes but now is a dry, barren planet, we must wonder happened and if, perhaps, it could be indicative of Earth's future. Since Martian exploration is currently a major topic within the field of planetary geology, it is important to analyze exposed stratigraphic sections, where time is preserved vertically, in order to understand the planet's evolution from a wet world to a dry, frigid one. On Earth, geologists look to river valleys and streambeds to see the passage of time. Impact craters do that for Mars' surface, and are highly visible because they are unconcealed by water, vegetation and habitation. Because of this, impact craters are like windows into the subsurface of a planet otherwise obscured by dust. Furthermore, a better understanding of Martian geology will help us better understand not only the evolution of the surface of the planet, but also possibly the evolution of past life forms on Mars. This study of exposed stratigraphic sequences in in Mars' Victoria crater provides useful methods for decoding the geologic history of the planet from the largest resource available: images taken by the Mars Exploration Rovers (MER).

Launched in 2003, NASA's twin robot geologists Spirit and Opportunity were sent to Mars in search of answers about the history of water on the planet's surface. Designed to function as field geologists, the rovers' mast-mounted cameras provided 360-degree, stereoscopic, humanlike views of the terrain. In addition, three spectrometers (Miniature Thermal Emission Spectrometer, Mossbauer

Spectrometer and Alpha Particle X-Ray Spectrometer), a Microscopic Imager, the Rock Abrasion Tool and magnets mounted onto the rovers (NASA Jet Propulsion Laboratory, 2004) provided unprecedented capability to analyze geologic materials. Over the course of eleven years, the rovers have taken over 200,000 raw images of the planet, with their primary traverses focused on impact craters, where stratigraphic sections (that normally include impact breccia) are exposed for analysis.

Meridiani Planum was chosen as the landing site for Opportunity based on detection of the mineral hematite (Fe_2O_3) by the Thermal Emission Spectrometer instrument on the Mars Global Surveyor spacecraft (Golombek et al., 2003). Because high hematite concentrations are plausible mineralogical markers for aqueous processes, and because it was a viable landing site, Opportunity was sent to *Meridiani Planum* where the Miniature Thermal Emission Spectrometer identified the plain as a sulfate-rich outcrop surface (Morris et al., 2005). Opportunity first landed near Eagle crater, where sedimentary outcrops were exposed, to the western rim of Endeavour crater and later to Victoria crater. These craters were chosen because the three craters were along a nearly straight traverse and all had stratigraphic sections of sedimentary rock exposed (NASA Jet Propulsion Laboratory, 2014).

It is especially important to find layered sedimentary features on Mars because they imply some sort of gravitational settling induced by either aeolian or aqueous processes. Sedimentary beds are thin, laterally extensive layers of rock that form parallel to the Earth's surface. As such, sedimentary beds should lie horizontally on the surface, unless deformation changes the orientation of these beds. Therefore, by determining the orientation of the sedimentary beds exposed in Victoria, understanding might be gained about what shaped the sediments in the regional *Meridiani Planum*. The three prominent layered features identified in Victoria—horizontal features within the clasts, horizontal features within the crater wall and vertical fractures within the crater wall—are shown by black, red and blue colored arrows, respectively (**Figure 1**).

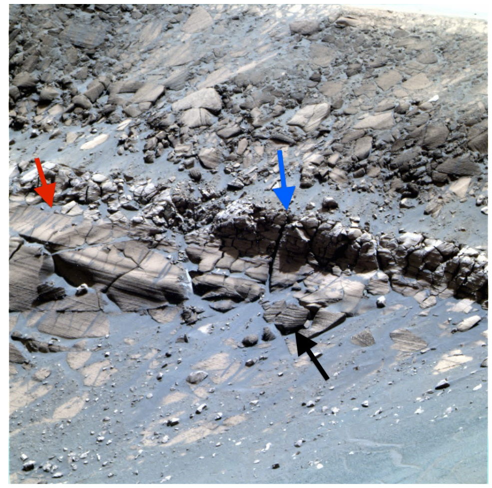

Figure 1 (a) Arrows point to noticeable horizontal and vertical features in image 1p223527116eff78w4p2361l2m1.img. Victoria crater, Mars.

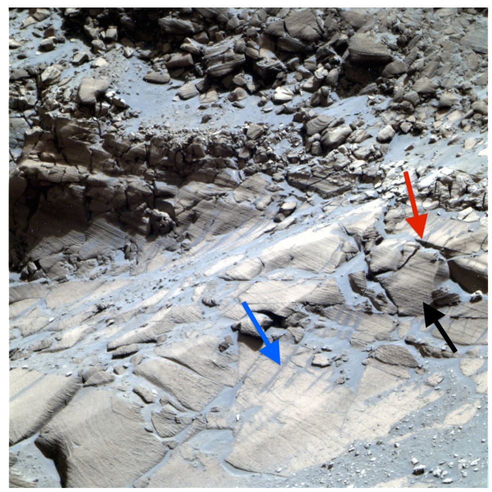

Figure 1 (b) Arrows point to noticeable horizontal and vertical features in image 1p223527015eff78w4p2361l2m1.img. Victoria crater, Mars.

Determining the true orientation of each identified feature required an image with camera model linearization and radiometric correction to remove distortion (Reduced Data Records, or RDR). RDR images were available for one particular promontory in the crater, *Cabo Anonimo*, and displayed all three identified features, making it an ideal place to study. This study will characterize *Cabo Anonimo* by measuring the orientation of observed features and characterizing the geologic material within the crater wall to provide preliminary data about the formation of the crater.

Figure 1 (c) Arrows point to horizontal and vertical features in image 1p223536917eff78w4p2361l2m1.img. Victoria crater, Mars.

Furthermore, this study will provide a means to easily identify possible aqueous-related structural features, such as primary bedding and secondary bedding, on Mars. Primary bedding, if present and preserved within the crater, could provide insight as to whether the sediment in *Meridiani Planum* was deposited by aqueous processes prior to impact. Secondary bedding, if present and preserved within the crater, could provide insight into any aqueous processes that affected the crater post-impact. Differentiating between primary bedding features and secondary bedding features could provide insight as to whether there was liquid water present before the impact, after the impact, or even both before and after. With the first sample return mission scheduled for 2020, easy identification of these structures are the key for determining sampling sites that might retain evidence for past life on Mars.

Geologic Setting

Victoria crater (**Figure 2**), an impact crater with sand dunes at its center, was photographed by Opportunity from Sols 951-1634 (Sol = Martian day) (Rayl, 2008). Located in a plain on Mars at 2.05°S, 5.50°W, Victoria is in Noachian age sediment located in the westernmost portion of *Terra Meridiani* (**Figure 3**) in a specific area called *Meridiani Planum* (Grant et al., 2008). First explored by the Mars Exploration Rover Opportunity, *Meridiani Planum* hosts minerals that form in the presence of water on Earth including hematite, many different sulfates, and multiple types of salt (Squyres et al., 2009).

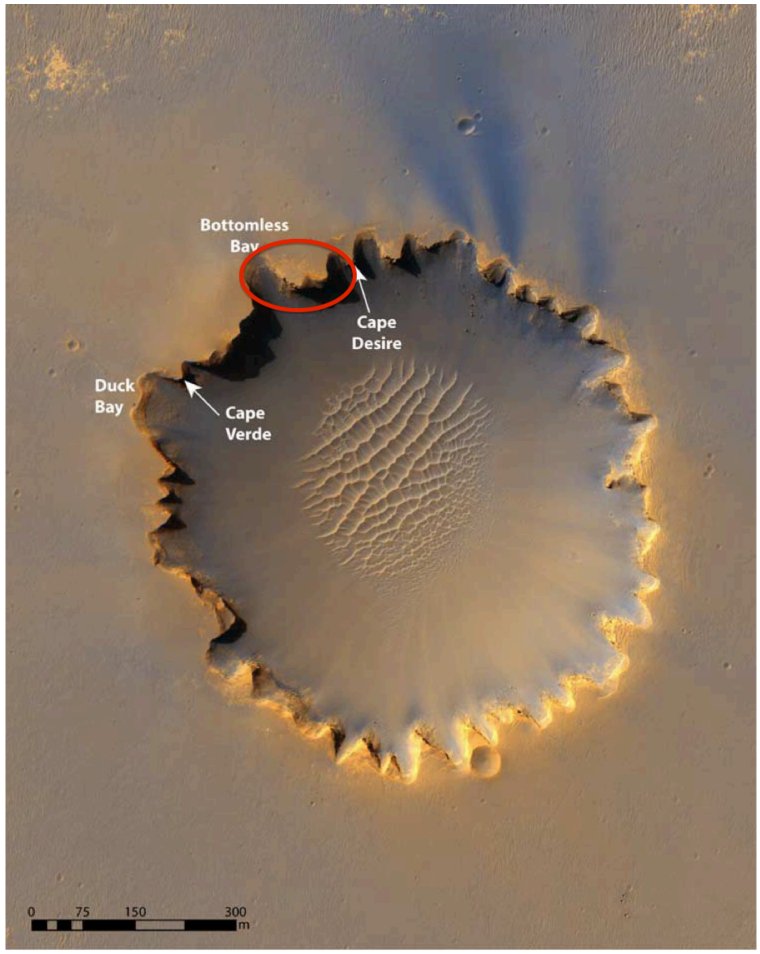

Figure 2 Victoria crater, a ~750m impact crater located in *Meridiani Planum*. Alternating promontories and alcoves define the serrated edge of the crater. The promontory *Cabo Anonimo* is circled in red. *Credit: Mars Reconnaissance Orbiter HiRise camera.*

The crater walls in Victoria were exhumed by impact, and continually modified by erosional processes (Grant et al., 2008). Images of the crater wall (see **Figure 2**) show three prominent structural features. Structural features within impact craters can be relicts of the processes that formed them as well as diagenetic processes, and the orientation of these features can be affected by many factors. Structural features identified in Eagle crater, the first impact crater explored by Opportunity, revealed a layered, exposed bedrock with evidence of both aeolian and aqueous processes (Squyres et al., 2006). Structural features identified in Endurance crater, such as beds and crossbeds, led the MER science team to conclude that sediments within the crater were deposited in water when a shallow sea evaporated (Bortman, 2004).

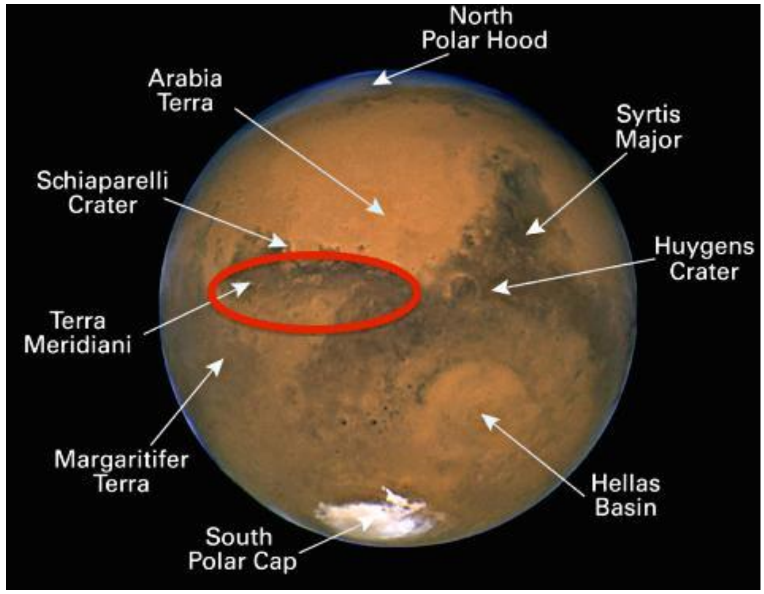

Figure 3 Terra Meridiani is located in the westernmost portion of Mars. ***Credit: NASA/STSci/Hubble***

Victoria reaches ~750 m in diameter, making it the second largest crater explored by Opportunity to date. Like most craters explored by Opportunity, Victoria has a simple, bowl-shaped structure with a ~5 m serrated rim consisting of 1-2 m of uplifted rocks overlain by ~3 m of ejecta at the rim crest that rises slightly above the surrounding, mainly flat, landscape (**Figure 4**) (Grant et al., 2008). The serrated rim of the crater alternates between alcoves referred to as “bays” and

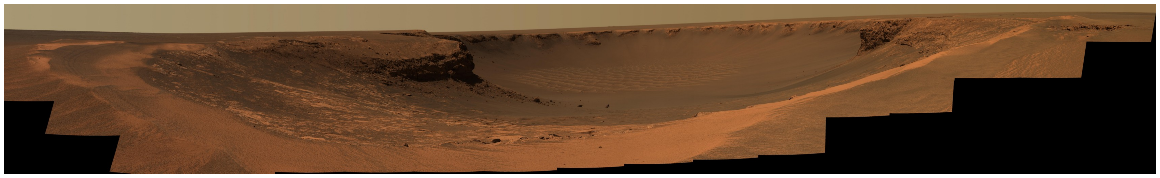

Figure 4 Mosaic image of Victoria crater. ***Credit: Mars Exploration Rover Mission, Cornell, JPL, NASA***

promontories referred to as "capes." One cape along the rim of the crater, *Cabo Anonimo*, located at 2°02'46''S, 5°29'54''W along the brecciated rim, seems to have nearly horizontal bedding extending well down the exposed wall. In fact, all capes along the rim of Victoria expose a sequence of rocks in their original place Grant et al., 2008). These exposed sequences are essential to this project because they allow a glimpse of the Martian subsurface.

Methods

Three images[1] taken by the Mars Exploration Rover Opportunity were chosen based on their content and accessibility (**Figure 5**). In order to study the stratigraphy of a Martian landscape, it is necessary for geologic material to be exposed. The surface of Mars is constantly abraded by dust and sand, and is often covered by mobile debris; therefore the subsurface is only exposed within impact craters, where erosion reveals the subsurface.

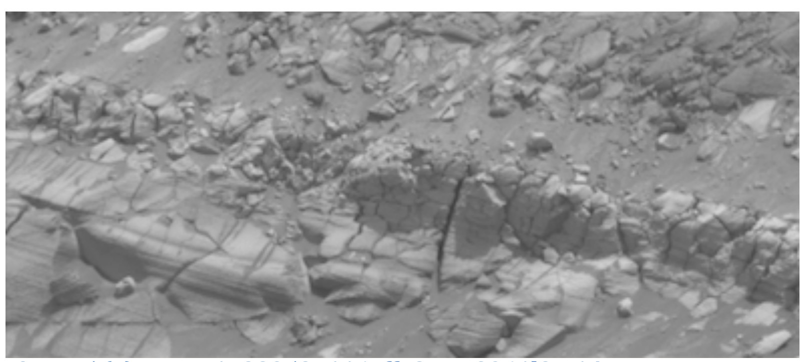

Figure 5 (a) Image 1p223527116eff78w4p2361l2m1.img

Impact craters are rimmed by brecciated material that is exposed near the top of the

[1] The three images used for this study are 1p223527116eff78w4p2361l2m1.img, 1p223527015eff78w4p2361l2m1.img, and 1p223536917eff78w4p2361l2m1.img and were all found using the java-based freeware software ImageRover (Willis, Eppes).

crater; and because the rover is not able drive into the crater, the brecciated rock at the rim of the crater is the best area to study (see **Figure 5**). Unfortunately, there is no complete collection of impact breccia images from Mars, meaning that in order to find suitable images one must first wade through all 202,829 raw images. Because Opportunity sends back its pictures from every Martian solar day (Sol), suitable images tend to clump together among different Sols.

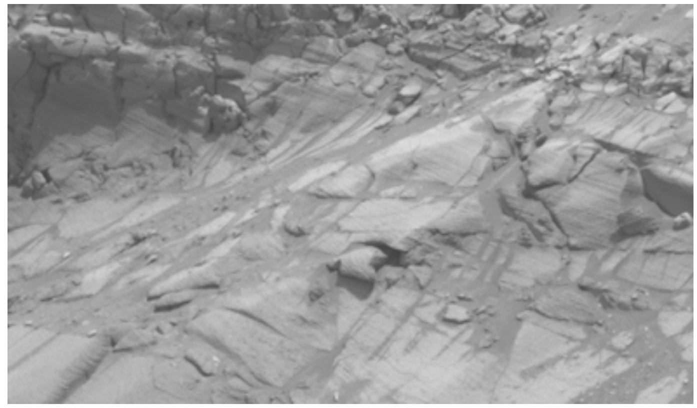

Figure 5 (b) Image 1p223527015eff78w4p2361l2m1.img

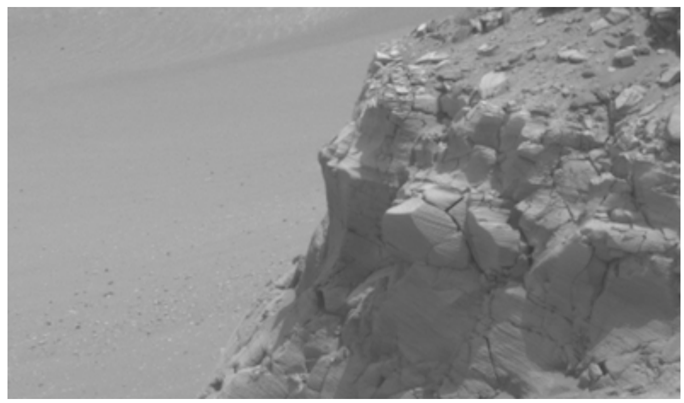

Figure 5 (c) Image 1p223536917eff78w4p2361l2m1.img

Once suitable impact breccia images are collected, only certain images can be analyzed. Raw images, or EDRs (Experiment Data Records), with no camera model linearization or radiometric correction cannot produce real-world measurements; rather RDRs (Reduced Data Records) are used because distortion is removed (Zhou, 2013). The software used to analyze these images, java-based freeware software called ImageRover, allows users to search by Sol and to limit the results to only RDR images with 3-D data available. The images that met all three requirements—suitable content, an RDR classification and 3-D capability—were taken when Opportunity was traversing the rim of Victoria crater on Sols 901-1683. The pool of images was further narrowed to three adjacent images of a cape, taken on Sol 1074 when Opportunity explored *Cabo Anonimo*, which appeared to display horizontal fractures on its face.

The images from *Cabo Anonimo* were then analyzed with the ImageRover software. Wherever intra-clast horizontal features appeared on any of the three chosen images, the strike[2] and dip[3] of the planes were measured and recorded using the first 3-D measurement tool (**Figure 6**). After intra-clast horizontal features were measured, horizontal and vertical features in the crater wall were measured and recorded. Finally, the sizes of the clasts in the outcrop were measured and recorded using the third 3-D measurement tool (**Figure 7**).

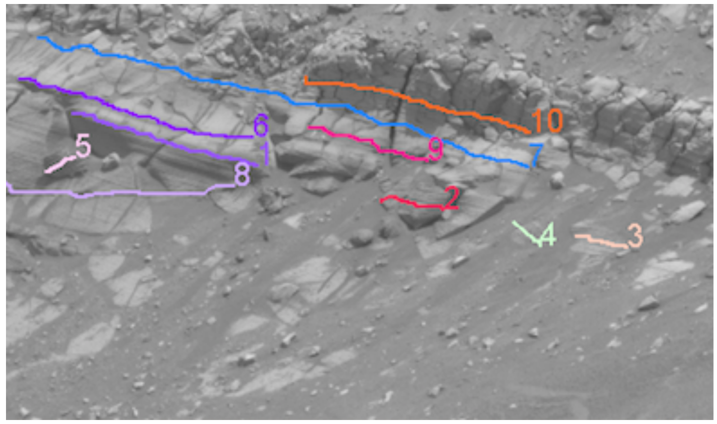

Figure 6 (a) The tool for measuring strike and dip in ImageRover is shown above. Lines 1-5 represent horizontal features within the clasts, while 6-10 represent horizontal features within the crater wall.

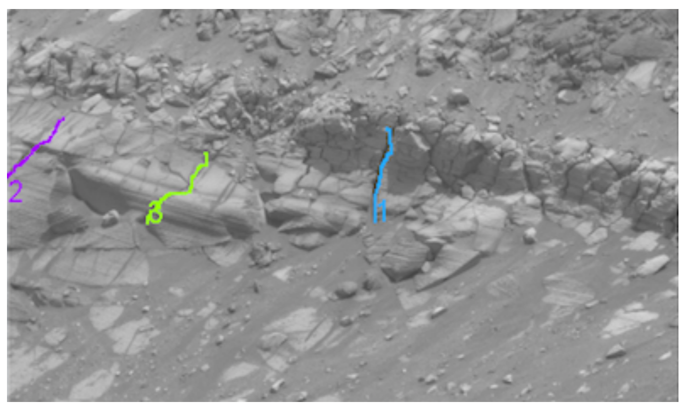

Figure 6 (b) The tool for measuring strike and dip in ImageRover is shown above. Lines 1-3 represent vertical features within the crater wall.

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[2] The strike line of a planar feature is a line representing the intersection of that feature with a horizontal plane. Strike is recorded in this study in by a three digit azimuth between 0°-360°.

[3] The dip of a bed gives the steepest angle of descent relative to a horizontal plane and is recorded by a two digit angle between 0°-90° and with a rough dip direction (N, W, E, S).

Results

All three images of *Cabo Anonimo* were analyzed for horizontal features (such as bedding), vertical features (such as joints), and average clast size using ImageRover's strike and dip measurement tool and clast size by manual delineation. The outcrops seen in all three images are brecciated. The breccia clasts vary in size, but are all considered to be boulder-sized, or >25.6 cm (Norton, 1917). Multiple features are displayed within the crater wall: first, horizontal beds appear within each clast; second, horizontal beds appear to cut through clasts down the crater wall; and third, vertical joints appear on the wall. Orientation measurements made by tools in ImageRover showed that horizontal features both within the clasts and within the crater wall were both sub-horizontal. The vertical joints measured, however, did not reveal

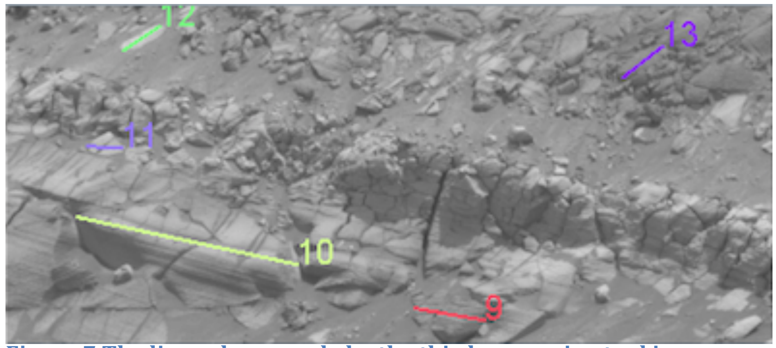

Figure 7 The lines above made by the third measuring tool in ImageRover represent the length of clasts.

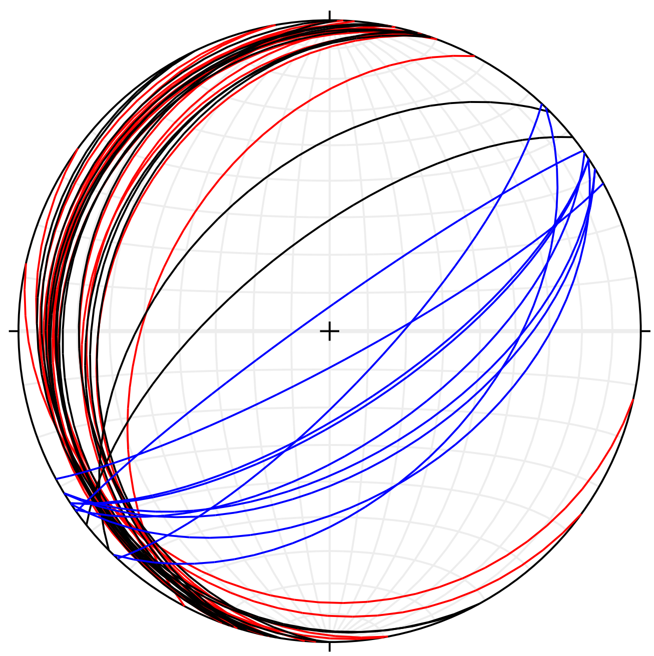
Figure 8 An equal area stereonet with 40 orientation measurements plotted as planes. Black lines represent horizontal features within the clasts, red lines represent horizontal features within the crater wall and blue lines represent vertical features within the wall.

any relevant information. All orientation measurements were plotted as planes on an equal area stereonet (**Figure 8**) and color-coded by the feature it represents, i.e., sub-horizontal features within the clasts, sub-horizontal features within the crater wall and vertical features within the crater wall. Black planes on the stereonet represent sub-horizontal features within the clasts, red planes represent sub-horizontal features within the crater wall, and blue planes represent vertical features within the wall.

	Within Clasts	Within Wall (horizontal)	Within Wall (vertical)
Average Strike	191.5°	180.6°	72.4°
Average Dip	21.2°	16.9°	64.2°
SD Strike	+/-20.98	+/-29.33	+/-57.27
SD Dip	+/-16.16	+/-9.19	+/-13.91

Table 1 The average strike and dip (as well as their standard deviations) of all three features within the crater.

The average orientation of each figure measured (**Table 1**) and the standard deviation of these averages showed that between the three images, the strike and dip of sub-horizontal features within the clasts (average strike 191.5° with standard deviation of +/-20.98; average dip 21.2° with standard deviation of +/-16.16) and within the crater wall (average strike 180.6° with standard deviation +/-29.33; average dip 16.9° with standard deviation +/-9.19) were relatively consistent whereas the vertical features were less consistent (average strike 72.4° with standard deviation of +/-57.27; average dip 64.2° with standard deviation of +/-13.91). Although the dip angles of the vertical features were relatively consistent, the strike measurements were more variable, however, if dips are relatively shallow any minor variation will seem greater than if the dips were steeper. All relevant data collected from ImageRover's measurement tools are reported in **Appendix I**.

Discussion

All sub-horizontal features within the clasts represent primary bedding planes and therefore retain the original structure of the pre-impact surface. Based on these results, sub-horizontal features within the crater wall represent either primary bedding at a different scale, fractures or secondary bedding from fluvial processes. All conclusions are based on the assumption that horizontal features within the clasts are bedded rather than abraded by aeolian processes. Color images of the sites (**Appendix II**) show random orientation of the clasts within the breccia. This indicates that the pre-impact surface was bedded, and either impact or fluvial processes broke and redeposited the clasts rather than only aeolian abrasion, as Squyres et al. and Grant et al. suggest. Evidence of aeolian driven erosion exists within the crater, as seen by the large dunes on the crater floor, but aeolian driven erosion does not explain the random orientation of the beds within the clasts. Furthermore, because the average clast size within the breccia is classified as boulder size, fluvial processes are not a likely means of transport of the clasts

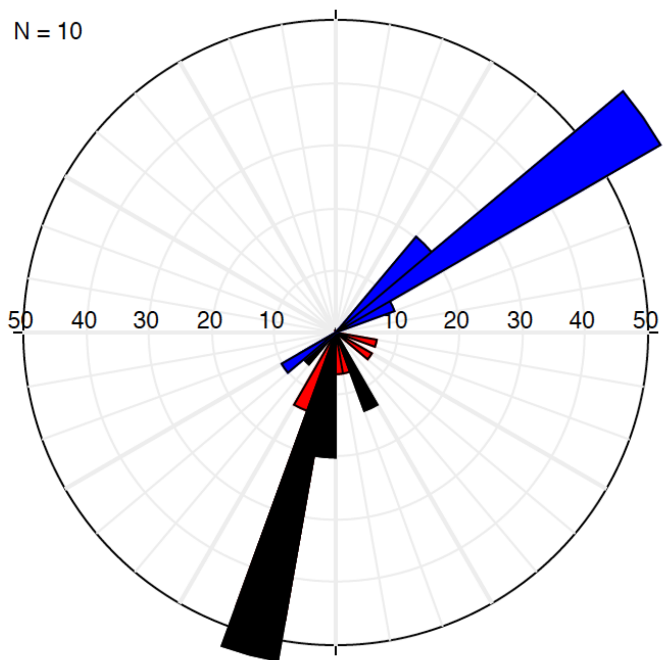

Figure 9 Rose diagram with orientation measurements plotted as planes. Horizontal features within the clasts are black, horizontal features within the crater wall are red and vertical features within the crater wall are blue.

observed.

Immediately after impact, the shock wave could have loaded the rocks in tension, causing them to fracture horizontally in place. A rose plot (**Figure 9**) of the orientations of each feature, e.g. sub-horizontal features within the clasts (black), sub-horizontal features within the crater wall (red) and vertical features within the crater wall (blue), showed that the sub-horizontal features within the wall are parallel to the bedding strike within the clasts. Therefore, the sub-horizontal features in the crater wall are strike joints[4], or joints that form by extension.

The vertical features perpendicular to the strike joints imply extension because extension joints form as transverse joints[5]. Transverse joints form as an orthogonal pair (Singhal and Gupta, 2010). This would not be unusual in impact craters wherein competent sedimentary rocks overlie weaker sedimentary rocks, or vice versa. When impact occurs, strain localizes along the interface between the strong and weak layer, which causes mechanical decoupling between the layers (Osinski, 2013). Vertical features around the crater would likely be radially oriented, as seen in most impact craters, but could only be determined if more measurements were made.

It is important to note that only one small promontory of Victoria crater was analyzed and that these observations may not extend regionally around the crater. Further analysis of horizontal and vertical features around the entire crater would provide a comprehensive conclusion about whether or not the horizontal bedding

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[4] Strike joints strike parallel to the strike of the bedding of the rock (Singhal, Gupta, 2010).

[5] Transverse joints are transverse, or oriented at right angles to the general strike or trend, to the strike of the strata (Bates, Jackson, 1976).

within the crater wall occurred immediately after impact or if other diagenetic processes were responsible.

Conclusion

Structural analysis of the brecciated *Cabo Anonimo* promontory in Victoria crater showed similar sub-horizontal structures both within the clasts and within the crater wall. Strike and dip measurements taken throughout three images of *Cabo Anonimo* revealed important information about both pre- and post-impact surfaces. Sub-horizontal features within the clasts that appear to have been caused by aeolian abrasion could actually be primary bedding as the orientation of the clasts within the breccia are somewhat random. A comparison between sub-horizontal features within the clasts and within the crater wall showed that some relationship exists between the two; it is possible that strata varied in consolidation and allowed for slippage along these planes during impact extension.

While the data presented here suggest primary sedimentary beds preserved within the clasts, it is important to include the mineralogy of the material. Squyres et al. (2009) provided evidence that fluvial processes, instead of aeolian ones, formed the primary bedding within the clasts. While the data presented here are consistent with Squyres' observations, more precise measurements around the perimeter of the crater are needed to determine regional scope.

Appendix I.

Image	Strike	Dip	Azimuth
1	190.0°	13.2°	117.8°
1	151.3°	7.6°	117.8°
1	180.1°	9.6°	117.8°
1	225.2°	47.8°	117.8°
1	231.4°	66.3°	117.8°
2	191.5°	10.9°	131.1°
2	189.1°	13.5°	131.1°
2	199.0°	24.1°	131.1°
2	198.8°	11.9°	131.1°
2	198.0°	15.0°	131.1°
3	196.4°	25.3°	144.5°
3	154.3°	9.1°	144.5°
3	181.3°	20.5°	144.5°
3	190.7°	15.6°	144.5°
3	195.4°	27.4°	144.5°

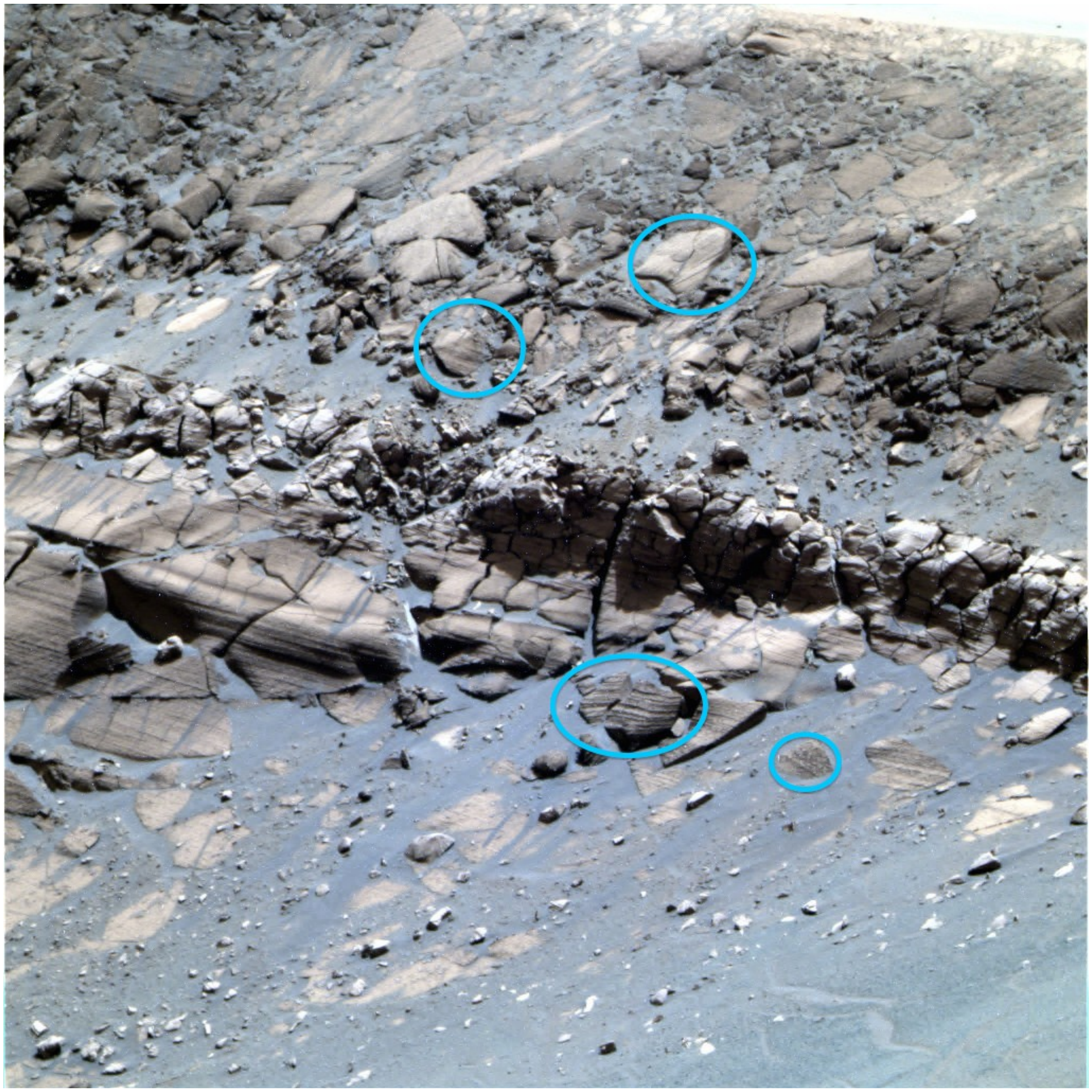
Image	Strike	Dip	Azimuth
1	200.2°	14.9°	117.8°
1	192.2°	9.1°	117.8°
1	102.6°	14.0°	117.8°
1	197.2°	11.4°	117.8°
1	182.5°	12.9°	117.8°
2	199.0°	12.7°	131.1°
2	126.0°	11.4°	131.1°
2	191.1°	10.3°	131.1°
2	184.6°	20.7°	131.1°
2	169.2°	12.5°	131.1°
3	198.4°	27.8°	144.5°
3	198.4°	22.8°	144.5°
3	170.0°	7.8°	144.5°
3	190.7°	23.4°	144.5°
3	207.8°	42.6°	144.5°

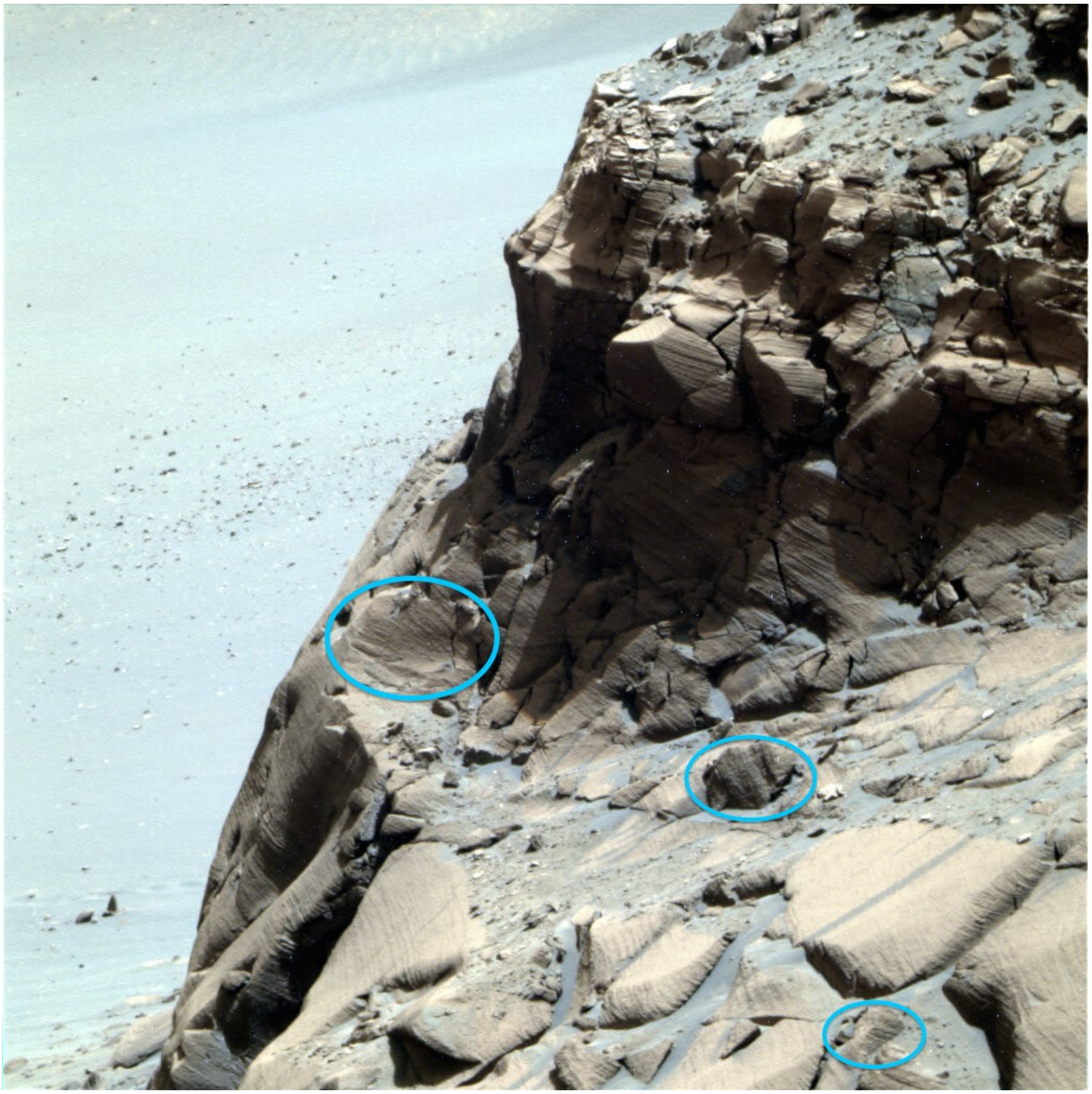
Image	Strike	Dip	Azimuth
1	61.6°	81.6°	117.8°
1	234.5°	84.8°	117.8°
1	56.2°	45.6°	117.8°
2	55.0°	59.9°	131.1°
2	58.6°	55.9°	131.1°
2	58.5°	53.2°	131.1°
2	56.4°	69.6°	131.1°
2	56.4°	68.5°	131.1°
3	43.0°	75.6°	144.5°
3	44.0°	47.4°	144.5°

Image	Clast Size (m)
1	2.011
1	3.440
1	0.843
1	1.056
2	1.755
2	2.166
2	0.873
2	17.911
2	0.966
3	3.781
3	1.601
3	28.578
3	29.609
3	1.855
3	1.212
3	1.118
3	0.511
Average	5.840
Standard Deviation	+/-9.346

Appendix I. All orientation measurements of (a) horizontal features within the clasts, (b) horizontal features within the crater wall, (c) vertical features within the crater wall, and all clast measurements (manually delineated) (d).

Appendix II.





Appendix II Images with blue circles showing overturned clasts.

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