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Ongoing Exhumation and Recent Exposure of Sedimentary Outcrops on Mars

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ONGOING EXHUMATION AND RECENT EXPOSURE OF
SEDIMENTARY OUTCROPS ON MARS

By Joshua M. Williams

Accepted in Partial Completion of
the Requirements for the Degree
Master of Science

Kathleen L. Kitto, Dean of the Graduate School

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MASTER’S THESIS

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Joshua M. Williams

26 May 2017
ONGOING EXHUMATION AND RECENT EXPOSURE OF SEDIMENTARY OUTCROPS ON MARS

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment of the Requirements for the Degree Master of Science

By Joshua M. Williams
May 2017
ABSTRACT

Determining the habitability of ancient environments on Mars and their biosignature preservation potential is a primary goal of all recent Mars exploration missions. Because cosmogenic radiation destroys organic biosignatures at the Martian surface, freshly-exposed outcrops that have been previously protected by overburden provide potential sites where organic biosignatures could be observed. Scarp retreat is one common mechanism for exposing fresh outcrop surfaces. The absence of liquid water on Mars leaves aeolian processes to be the dominant eroding agent, and aeolian erosion drives scarp retreat by undercutting erosion-resistant cap rock that fails and breaks off from outcrops. This continual action creates bays and headlands. This study uses three methods to identify regions with freshly-exposed scarp surfaces using orbital images: (1) scarp orientation mapping; (2) identification of calved boulders; (3) identification of dust and drift deposition by color stretch analysis. These methods were consistent with surface observations from the Mars Science Laboratory (MSL) Curiosity rover in Gale crater. Scarp orientations in Gale crater show a distinct bay-signal (from the pattern of bays and headlands) that can be directly correlated with the known direction of ongoing aeolian scarp retreat. The bay-signal was also apparent at two of the Mars-2020 rover mission candidate landing sites: Eberswalde crater and Jezero crater. In a similar analysis of the Mars-2020 candidate landing sites Holden crater and Melas Basin, however, no clear bay-signal was identified. This work developed methods to detect recent scarp retreat on Mars and may provide a useful tool for identifying locations with high biosignature protection potential.
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0. INTRODUCTION

A primary goal of many modern Mars exploration missions is to determine the habitability of ancient environments and search for materials with high biosignature preservation potential. To achieve this goal, it is critical to identify outcrops at the Mars rover landing sites that have the strongest potential for preserving biosignatures from several billion years ago. Mars’ thin atmosphere and lack of a substantive magnetic field allow a large flux of high-energy radiation to bombard the surface. Collisions at the Martian surface with galactic and solar cosmic rays (GCRs and SCRs) or any secondary cascade particles would result in the destruction of organic compounds (e.g., Kminek and Bada, 2006; Pavlov et al., 2012). Therefore, organic biosignatures, if they exist, would immediately begin to degrade upon near surface exposure and would be completely destroyed within 100-300 million years by exposure to cosmogenic radiation (Dartnell et al., 2007a, Pavlov et al., 2012). GCRs can penetrate 1-2 meters into rock and ice compositions typical for Mars (Pavlov et al., 2012), which suggests it would be necessary to drill at least an equivalent depth to have a significant chance of detecting three billion-year-old amino acids on Mars (Dartnell et al., 2007a-b). For perspective, the normal background radiation in North America is ~6.24x10^-3 Gy/yr, whereas it is at least an order of magnitude higher on Mars (> 0.07 Gy/yr, where 1 Gy is equivalent to 1 J of radiation energy per kilogram of matter and 1 rad is equal to 0.01 Gy). This dose decreases to less than 0.02 Gy/yr at 1 m beneath the surface, and to less than 0.005 Gy/yr at 2 m (Dartnell et al., 2007).

To maximize the likelihood of finding organic biosignatures that have not been destroyed by cosmogenic radiation, Mars surface missions can strategically sample outcrops that have been recently exposed from beneath at least 2 m of overburden. This technique was first applied by the Mars Science Laboratory (MSL) rover mission in Gale crater (Grotzinger et al., 2014; Farley et al., 2014). Cosmogenic exposure dating by MSL suggested that the Sheepbed mudstone at Yellowknife Bay remained buried by the Gillespie Lake sandstone until its exposure less than 100 Ma by wind-driven scarp retreat (Farley et al., 2014) (Fig. 1). MSL’s Sample Analysis at Mars (SAM) instrument measured the cosmogenically-produced isotopes $^{36}$Ar, $^{21}$Ne, and $^3$He, which yield concordant surface exposure ages of 78 ± 30 Ma at the Cumberland drill hole, which was located
approximately ~1 m from the actively-eroding Sheepbed-Gillespie Lake scarp face and 60 m from a scarp that has 2 to 3 meters of overburden (implying that the scarp is retreating at a rate of ~0.75 m/My) (Farley et al., 2014). At the Cumberland drill hole, SAM detected in situ organic compounds for the first time on Mars (Freissinet et al., 2015). The specific molecules detected (chlorobenzene 150–300 parts per billion by weight (ppbw) and C$_2$ to C$_4$ dichloroalkanes (up to 70 ppbw)) are interpreted as being the reaction products of chlorine and organic carbon derived from various sources: igneous, hydrothermal, atmospheric, or biological, and/or exogenous sources such as meteorites, comets, or interplanetary dust particles. Although the Cumberland organics are not taken to be biosignatures, they do provide evidence that burial can preserve potential biosignatures in recently exposed Martian outcrops. Therefore, outcrops at the base of rapidly retreating scarps are high-priority sampling targets for future, biosignature-seeking missions.

A scarp is a small step or vertical relief usually associated with contact between different geologic units. Scarps formation and evolution on Mars that are dominantly formed by aeolian erosion occur where winds and sand cause deflation (removal of fine grain particles) by abrasion. Scarps typically have an erosion-resistant rock cap overlying a less erosion-resistant unit. As the less erosion-resistant rock layer is removed by aeolian scour, the undercut, erosion-resistant rock cap fails leading to mass wasting of the unit. Over time, the calved blocks will eventually become completely eroded away. The continual action creates the retreat of the scarp face broadly perpendicular to the dominant wind direction. Scarp retreat appears to be occurring at Yellowknife Bay by erosion of the softer Sheepbed mudstone leading to the undercutting and calving of the Gillespie Lake Sandstone blocks (Fig. 1). Calved-off blocks of sandstone occur at the base of the scarp with a thin lag of blocks meters outboard (Fig. 2), indicating recent boulder shedding. The Sheepbed-Gillespie Lake scarp can be traced around the width of Yellowknife Bay and is elongated in the NE-SW direction creating a theater-shaped bay with the Sheepbed unit making up the floor (Fig. 3a) (Farley et al., 2014).

Ventifacts and yardangs are abundant within Gale crater implying persistent aeolian abrasion (Day and Kocurek, 2016), whereas migrating ripples and dunes there demonstrates wind
is an important contemporary process (Silvestro et al., 2013). Further evidence suggesting ongoing aeolian erosion at Yellowknife Bay includes microscale abrasion patterns such as wind tails and ventifacts in Gale crater identified in observations by MSL’s Mars Hand Lens Imager (MAHLI) instrument and the Chemistry and Camera (ChemCam) instrument Remote Micro-Imager (RMI) (Farley et al., 2013; Bridges et al., 2014). Gale crater ventifact orientations indicate that they were formed by predominantly westerly high-speed winds (Bridges et al., 2014). Studies of dune and ripple orientations and displacements indicate strong bidirectional winds from the NW and ENE (Silvestro et al., 2013); however, the longer-lived wind direction is thought to be from the ENE due to the dune migration direction and cosmogenic age dated scarp retreat orientations (Bridges et al., 2014). The easterly ventifact direction may be due to observation bias, and/or the ventifacts were formed due to extremely rare, ancient high speed winds that are not representative of the longer-lived NE to SW wind regimes (Bridges et al., 2004; 2014).

The Sheepbed-Gillespie Lake scarp can be observed from orbit in images obtained from the High Resolution Imaging Science Experiment (HiRISE) on board the Mars Reconnaissance Orbiter (MRO) with a resolution of 25 cm/pix (Fig. 3a). This is also the case for other scarps along the Curiosity traverse, such as those at the Kimberley, where cosmogenic exposure ages also indicated relatively recent exposure (Vasconcelos et al., 2016). Several scarps beyond Yellowknife Bay with the same orientation as the Sheepbed-Gillespie Lake scarp have also been identified in HiRISE observations (Rice et al., 2017). However, previous studies have not mapped the larger distribution of scarp orientations to test how the dominant orientations relate to the known directions of wind. Understanding the regional distribution of scarps could allow for the identification of the most recently-exposed outcrops at other locations on Mars.

In our study, we used the region surrounding Curiosity’s traverse in Gale crater as a test case for correlating scarp orientation with the direction of active scarp retreat and dominant wind direction, providing a tool for identifying recently-exposed material. Additionally, we identified boulder-shedding from cliffs and ledges as a second method for supporting active scarp retreat (Grant et al., 2008). Using these methods for identifying recently-exposed outcrop in orbital images, we evaluated scarps and their potential for recent activity at other locations on Mars:
Eberswalde crater, Jezero crater, Holden crater and Melas Basin. These sites were selected for this study because they have similar sedimentary depositional histories (in fluvial, alluvial, lacustrine and/or deltaic systems) to that of Gale crater, and therefore are more likely to contain similar lithologies and erosional expressions. This study was intended to inform future mission to Mars, including the landing site selection for the Mars-2020 rover by helping to identify sampling locations with an increased potential of biosignature identification.

1. METHODS

1.1. Scarp Mapping

In this study, scarps were defined as vertical steps in topography or outcrops having a vertical relief. For efficiency, we only mapped scarps with a length greater than 50 m in orbital images. Scarps were identified by differences in albedo and texture associated with the cap and underlying rock units, and by shadows associated with the vertical relief. Actively-eroding scarps are less likely to have substantial sediment accumulation on the scarp face and can have evidence of boulder-shedding (blocks from the upper unit that have fallen below the scarp). Inactive scarps are more likely to be mantled, at least partially, with sand and/or dust; scarps that are obscured and deemed inactive were not mapped for this study.

Scarps are broadly linear but sometime form semi-circular reentrants and are unlikely to be scalloped terrain formed in periglacial terrains (Banks et al., 2008; Levy et al., 2009). Mapping was performed in ArcGIS using HiRISE images. Scarp azimuth orientations were mapped (Fig. 4b) and then processed with a Python script to weight the scarp segments by length. Each scarp segment has a length of 1 m and a series of connected scarp segments comprises a continuous scarp. The segments were entered into a rose diagram program to show overall scarp orientation (Fig. 4c). The dominant orientation range is defined as the smallest range of bins that contain 50% of the sample. Statistical analysis of scarp orientation was performed to quantify how ordered scarp orientations were in rose diagrams by measured the angular dispersion (r-value) to determine level of order. An r-value closer to 1.0 is more ordered, and values closer to 0.0 are less ordered. In addition to analyzing scarp azimuths, we also analyzed the up-slope direction,
which we defined as the direction towards the scarp face that is perpendicular to the scarp’s azimuth. Unlike scarp azimuth, which is bidirectional, the up-slope scarp direction is a unidirectional vector. The up-slope scarp-face directions were identified and characterized in HiRISE images, usually by overhanging ledges or by vertical relief that cast shadows (Fig. 4a).

### 1.2. Boulder Identification

Another indicator of scarp retreat is scarp boulder shedding (Fig. 2). Scarp related boulders are defined as 1 m to 10 m, rounded to subangular blocks of material located at the base of a scarp. Sites with little to no scarp related boulder shedding was documented as such. Sites with extensive boulder shedding were mapped and the scarp orientations were exported to create rose diagrams. Boulders of diameter 1m and larger are resolvable in the 25 cm/pixel images from MRO’s HiRISE camera.

### 2. RESULTS

#### 2.1. Gale Crater

Gale crater scarp mapping was confined to nine 1 km² informally-named quadrangles (Fig. 5a) along the rover’s traverse from the landing site at Bradbury rise in the Yellowknife Bay quadrangle (Fig. 4a, b) to the Murray Buttes quadrangle, Curiosity’s location as of Sol 1441. Overall the concentration of scarps along MSL’s traverse in Gale crater was dense (11,668 m per km²) with a varied distribution across the mapping area (Fig. 5a; Table 1). The rose diagram of all Gale crater scarp orientations (or strike) showed scarps populating all 10° bins but with a large bias in the NE – SW directions, with the largest population in the 20°- 30° (strike will always be presented in northern hemisphere) (10 % of the sample) (Fig. 5a, b; Table 1).

The rose diagram of up-slope unidirectional scarp orientations or vectors towards the scarp-faces in the Yellowknife Bay (YKB) quadrant showed scarp-faces in the SW hemisphere ranging from 130° to 310° (60% of sample) (Fig. 4d; Table 1). The up-slope scarp orientations are not evenly distributed but appear to cluster into lobes towards the NW 290° to 340° (17% of sample) and SE (22% of sample) (Fig. 4d; Table 1).
The scarps in the vicinity of Yellowknife Bay showed the most consistent directionality of all mapped quadrangles in Gale crater. The r-value value for the 1 km² mapped Yellowknife Bay area was 0.18 and the average scarp orientation was 52.3°. For comparison, the overall 9 km² mapped MSL traverse area r-value was 0.03 and the average scarp orientation was 44.8°. The average directions in each quadrangle changed slightly along the traverse of MSL (Table 1).

Where possible all orbital scarp identifications were confirmed by Mastcam and Navcam images. The comparison to MSL ground-based imaging verified the criteria defined in Section 2.1 can be used to identify scarps in HiRISE images that formed from different lithologic units. The MSL-observed scarps with partial sand accumulation generally have a NE-SW orientation (Fig. 6a, b; Table 1).

Mastcam white-balanced images show bluer hues that can be correlated with scarp faces throughout the traverse of MSL (Fig. 7). Scarps with “bluer” scarps have a dominant orientation in the NW-SE directions (Fig. 6a, d; Table 1).

Boulders identified from HiRISE data were less prevalent than boulders identified by Mastcam observations across the traverse of MSL. However, boulder-shedding scarps was identified from orbital images throughout the traverse of Curiosity, including Murray Buttes, Naukluft Plateau, Pahrump Hills areas (Fig. 7a, b, c) and the drill locations that yielded cosmogenic exposure age, Yellowknife Bay (Fig. 3a, b) and the Kimberley (Fig. 5b).

Modeled wind directions and observations of Transverse Aeolian Ridges (TAR’s) along the traverse of Curiosity in Gale crater indicate a dominant NE to SW (247°) wind direction (Day and Kocurek, 2016). This wind direction correlated well with the Sheepbed-Gillespie Lake “up-slope” scarp orientation of 243° in Yellowknife bay (Fig. 3a).

2.2. Eberswalde Crater

The proposed landing site in Eberswalde crater contains a delta deposit that is a high-priority astrobiology exploration target and onlaps various crater-floor units interpreted to be ejecta from the Holden-crater forming impact to the south (e.g., Grant et al., 2010; Irwin et al., 2015). All
materials in Eberswalde crater are variably covered with a mantling unit that forms scarps along its boundaries (Rice et al., 2013). This mantling layer appears as a very thin layer on top of the Eberswalde crater delta, but on the crater layer floor it appears to be thicker. Scarp mapping was expanded from the proposed landing ellipse to include the entire Eberswalde crater delta, totaling 163 km² (Fig. 8a; Table 2). The Eberswalde crater mapping area was divided into three regions: the crater floor, delta and delta front to better understand the scarp orientations for these subgroups. The spatial distribution of scarps ranges from a dense even distribution (4,343 m per km²) on the delta to a higher density at the delta front (11,836 m per km²), to the sparse crater floor spatial distribution (2,110 m per km²) (Fig. 8b; Table 2). The Eberswalde crater scarp orientations shows scarps with a dominant orientation in the NE – SW directions (Fig. 8c; Table 2). The crater floor, delta and delta front mapping areas all show scarp orientations with alignment of scarps in the NE – SW directions (Fig. 8b, c; Table 2). Like Gale crater, the up-slope scarp orientations of all Eberswalde crater scarps are not evenly distributed but appear to cluster into lobes towards the NW 280° to 340° and SE (Fig. 8d; Table 2). Boulder shedding scarps were identified from orbital images at the Eberswalde crater delta and delta front, but not the crater floor (Fig. 9).

The r-value for scarps in the 98 quads containing delta deposit was 0.32 and the average scarp orientation was 58°. The r-value for the 15 km² mapped for only the Eberswalde crater delta front area was 0.19 and the average scarp orientation is 58°. The r-value for the 71 km² mapped for the crater floor area was 0.03 and the average scarp orientation was 42°. The overall 163 km² mapped Eberswalde crater area r-value is 0.05 and the average scarp orientation was 52° (Table 2).

2.3. Jezero Crater

The proposed landing ellipse in Jezero crater contains the distal end of a delta in the west that onlaps various crater floor units interpreted to be a volcanic floor unit exposing carbonate-bearing bedrock in erosional windows (e.g., Goudge et al., 2015). North of the landing ellipse lies a heavily eroded second delta that is stratigraphically equivalent to the western delta (Goudge et al., 2015). Jezero crater scarp segment mapping was expanded from the proposed landing ellipse to include the Jezero crater western and northern deltas, totaling 280 km² (Fig. 10a; Table 2). The spatial
distribution of scarps ranges from a dense, even distribution (3,309 m per km²) on the western delta to a high-density delta front (4,859 m per km²). The off-delta spatial distribution was sparse (396 m per km²) (Fig. 10a, b; Table 2). The total Jezero dominant scarp orientation, including the Jezero crater floor, west delta and west delta front was in the NE – SW directions (Fig. 10c; Table 2). The highest degree of order (r-value of 0.08) for up-slope scarp orientations was found at the Jezero delta front which showed alignment towards the SW hemisphere ranging from 190° to 340° (Fig. 10a; Table 2).

Crater wind streaks have been used to infer a formative wind direction (Day and Kocurek, 2016). Crater wind streaks are thought to form in the lee end of craters due to collecting airfall dust (Sagan et al., 1972). We have mapped many (67) small wind streaks from HiRISE orbital images within 192 km² in the Jezero crater mapping area (Fig. 11a). The wind streaks were found in the western direction, 240°-280° (Fig. 11b; Table 2).

Boulder shedding scarps and scarps with partial sand accumulations were identified from orbital image at the Jezero delta (Fig. 13; Table 2). Boulder shedding scarps at the delta front had a dominant orientation in the NW-SE directions (Fig. 13a, b; Table 2). The scarps with partial sand accumulations at Jezero were found in the NE-SW directions (Fig. 13a, d; Table 2).

2.4. Melas Chasma

The proposed landing ellipse at Melas Chasma contains evidence of a mature fluvial network, including a subaqueous fan from turbidite flows that was formed in a closed lake (Williams and Weitz, 2014; Metz et al., 2009). The Melas Chasma mapping area was divided into two sections: the subaqueous fan and Melas Chasma floor to better understand the scarp orientation of these subgroups. The general orientation of scarps in Melas Chasma align with this dominant E-W orientation. Melas Chasma segment mapping included the proposed landing ellipse, totaling 101 km² (Fig. 14a; Table 2). The spatial distribution of scarps generally dense (102,652 m per km²) on the subaqueous fan and a dense scarp distribution for the Melas Chasma valley floor (294,008 m per km²) (Table 2). The total Melas Chasma scarp dominant orientations, including the basin floor, were in the E – W directions (Fig. 14c; Table 2), however the scarp orientations of the Melas
Chasma subaqueous fan scarp orientations were aligned in the NE – SW directions (Fig. 14b; Table 2). The Melas Chasma basin floor had the highest order of orientation (r-value of 0.48) (Table 2). The up-slope dominant scarp orientations were towards the North ranging from 140° to 350° (Fig. 14d). Boulder shedding scarps were identified from orbital images throughout the Melas Chasma (Fig. 15).

2.5. Holden

The proposed landing ellipse at Holden contains a series of exposed impact megabreccia and sedimentary units. The alluvial fan lower unit is capped by a dark toned alluvial unit. Early distal alluvial or lacustrine deposition were followed by high magnitude flooding into the late Noachian epoch (e.g., Grant et al., 2010). Holden scarp segment mapping was expanded from the proposed landing ellipse to include a larger swath of the light-toned layered sequence, totaling 112 km² quads or 112 km² (Fig. 16a; Table 2). The spatial distribution of all scarps varies from sparse to clustered distribution (1,945 m per km²). The alluvial fan appears to have a sparse distribution (118,117 m per km²) (Fig. 16b; Table 2) and the light-toned layered sequence has a dense localized distribution (3,038 m per km²) (Table 2). The Holden dominant scarp orientations in the NE – SW directions (Fig. 16c; Table 2). The Holden mapping area was divided into two sections: the alluvial fan, and Light Toned units to better understand the scarp orientation for these subgroups. The alluvial fan and Light Toned units all show scarp orientation with alignment of scarps in the NE – SW directions (Fig. 16c; Table 2). The Holden alluvial fan had the highest order in distribution (r-value of 0.19) Table 2). The up-slope dominant scarp orientations for Holden were in the NW ranging from 280° to 350 (Fig. 16b; Table 2). Boulder shedding scarps were not clearly identified from orbital images at Holden.

3. DISCUSSION

3.1. Gale Crater Ground-Truth Study and Interpretations

At Gale crater, the relatively-young exposure ages obtained by MSL at Yellowknife Bay and the Kimberley correlate with scarp faces that are generally perpendicular to the estimated scarp retreat direction (Farley et al., 2013; Rice et al., 2017). Overall, the mapped scarp orientations at
Gale crater are not randomly distributed, but show relatively high order. The dominant scarp azimuth orientation suggest scarp retreat to the SW driven by a northeasterly inferred scarp retreat direction (Fig. 5c). This is correlation may be useful for identifying dominant wind directions on other locations on Mars where other informative landforms (e.g., dunes, wind streak) are not present. Our criteria for identifying recently-exposed outcrop using images is supported at the two localities with known exposure ages: the Cumberland sample at Yellowknife Bay at \( \sim 80 \pm 30 \text{ Ma} \) (Farley et al., 2013) and the Windjana sample at the Kimberley yielded an age of \( \sim 46 \text{ Ma} \) (Vasconcelos et al., 2016). These are both within the time window that organic matter will not be completely destroyed by galactic and solar cosmic rays (Farley et al., 2013, Pavlov et al., 2012). Organic molecules were only reported in the Cumberland sample, and not Windjana (Freissinet et al., 2015; Rice et al., 2017), but we note that recent exposure is a precondition that must be met prior to other analyses.

The up-slope scarp orientations at mapped around the traverse of Curiosity in Gale crater generally populate a hemisphere of the rose diagram centered in the on the dominant wind direction from NE to SW and show a distinct shape (Fig. 5d). The scarps populated in this hemisphere are not evenly distributed, but rather have higher concentrations of scarp orientations in the NW (roughly 20\(^{\circ}\) – 80\(^{\circ}\)) and SE (roughly 200\(^{\circ}\) – 260\(^{\circ}\)) (Table 1). These orientations are parallel to that of the dominant wind direction, and therefore we interpret scarps with this orientation as less actively eroding scarps. The remaining scarps in the populated hemisphere are perpendicular to the dominant wind direction, and we interpret these as the more rapidly retreating scarps since they have the largest scarp face surface area that directly faces the dominant wind vector and would sustain the highest flux of sand blasting. The distinct hemispheric shape of the up-slope scarp orientations could therefore be a strong indicator of recently-active scarp erosion under a single, long-term dominant wind direction.

Curiosity rover obtained images of scarp faces with bluer hues (interpreted as less-dusty and potentially active) at Gale crater have a preferred orientation of SE-NW (Fig. 6d; Table 1), perpendicular to that of the dominant wind direction and parallel with scarps inferred to be the most actively-eroded. The absence of redder hues at the scarp face strongly indicates that the
scarp is not accumulating airfall dust, but that material is being actively removed. This observation, coupled with the perpendicular orientation of these scarps to the dominant wind direction, supports the interpretation of active erosion.

Scarps with sand accumulations (interpreted as inactive) have a preferred orientation of NE-SW (Fig. 6b; Table 1), roughly parallel to the dominant wind direction. The presence of this drift material suggests that these scarps are not undergoing parallel retreat. This coupled with the large scarp orientation signal indicates that the majority of scarps in Gale crater are associated with headlands that could indicate a direct connection with that of the more active scarps cutting out erosional bays (see Section 4.2).

Although boulder-shedding scarps were not easily identified from orbital images at Gale crater, images obtained from MSL verified evidence of boulder shedding where active scarp retreat is occurring at Yellowknife Bay (Fig. 3b) and at the Kimberley (Fig. 5b). Boulder shedding at scarps clearly occur along the entire traverse of MSL, further verifying recent erosional processes have occurred at Gale crater.

3.2. Bay Signal Landform Evolution Model

The observations at Gale crater give insight into aeolian-dominated erosion, supporting a progressive landscape evolution model interpreted for Gale crater (Fig. 17). This model assumes that a single wind direction has been the predominant source of erosion over timescales of $10^7$- $10^8$ Myr (as inferred from the MSL exposure age experiments), leading to the formation of headland- and bay-shaped landforms. In this concept, for simplicity the landscape originates with a simplified scarp face that is aligned in the N-S orientation (Figure 17a). The second step of the model initiates variability in the scarp-face orientation due to heterogeneities in resistance to erosion. At this stage, the general scarp orientations are still N-S, and the up-slope rose diagram shows scarp faces eroding towards the west along the direction of the dominant wind (Fig. 17b). The next intermediate stage shows the scarp differentially eroding to create bays with small headlands. At this point, there is a relatively even distribution of scarp-face orientations, which are reflected in by a large dispersion of scarp orientations in the rose diagram. This is the point
where the up-slope rose diagram shows a preferred clustering of scarps with roughly \( \sim 180^\circ \) distributed around the center of the dominant wind direction (Fig. 17c). The final stage depicts the mature theater-shaped scarp bay and headland promontories, as seen at Yellowknife Bay and other locations. At this point, the inactive scarps populated along the headland margins dominate the scarp orientation rose diagram. The final rose diagram shows that the remaining scarp population is dominated by these inactive scarps, which are aligned with that of the dominant wind direction. The up-slope diagram indicates that the majority of the scarps populated in the north and south representing the passive headland scarps, while the less populated active scarps are shown in the west (Fig. 17d).

The resulting landscapes under this model have scarp orientations with a distinct bay-signal or signature in the up-slope rose diagram. For locations on Mars, where the wind direction is unknown and cosmogenic exposure ages (and other ground-based observations) are unavailable, this bay-signal is a potential indicator of the long-term, dominant direction of erosion. However, there are uncertainties associated with applying this landform evolution model to other sites on Mars including the potential for highly variable lithologies (and resistances to erosion) and wind regimes. Additionally, locations with a suitable target rock and unidirectional winds will erode slower if the landscape is a sediment-limited state (Kocurek and Lancaster, 1999). Potentially a modified or different landscape evolution model could be developed. However, we can minimize this uncertainty by limiting any analysis to primarily fluvio-lacustrine sedimentary units. Presumably the suite of lithologies are similar and their relative proportions are comparable.

Our analysis also includes the assumption that the patterns of scarps at these landing sites are formed primarily by erosion from aeolian abrasion (and were not formed through other processes, such as by regional tectonic stresses). Another assumption is that the wind is unidirectional over long timescales. It is unclear if these winds are slow and steady over these very long timescales, leading to a relatively constant rate of erosion, or whether the majority of the erosion might happen in isolated, strong-wind events.

3.3. Sedimentary Sites

3.3.1. Eberswalde crater
Wind direction has not been determined directly at Eberswalde crater. However, based on the scarp retreat model described above, the overall NE-SW scarp orientation (Fig. 8c; Table 2) indicates alignment with a NE to SW dominant wind direction. The up-slope scarp orientation generally populates a hemisphere of the rose diagram centered in the SW direction of the NE-SW preferred scarp orientation. The up-slope rose diagrams for the three areas mapped at Eberswalde crater (delta, delta front, and crater floor) portray a range of r-values with the highest order found at the Eberswalde delta front (Fig. 8e; Table 2). The delta front was mapped separately from the rest of the delta (Fig. 8b; Table 2) to decouple scarp orientations derived purely from aeolian processes from the preexisting landforms on the top surface of the delta (where scarp patterns appear dominated by sinuous inverted channels).

As seen at Gale crater, the Eberswalde delta front up-slope scarps show a distinct rose diagram shape, with the preferred orientation of scarps in the hemisphere centered on the axis of the NE-SW scarp orientation (Table 2). Also like Gale crater, the scarps populated in this hemisphere are not evenly distributed, but rather have higher concentrations of scarp orientations in the NW and SE. If these orientations are parallel to the dominant wind direction, they could indicate passive or inactive scarps. By extension, the remaining scarps in the populated hemisphere are perpendicular to the dominant wind direction and the scarp face toward the NE, which could represent the active scarps that directly face the dominant wind vector. The hemispheric shape or bay-signal of the up-slope scarp orientations could therefore be a strong indicator of the presence of relatively active scarp erosion at Eberswalde crater. The orientations of scarps found in the crater floor do not show a clear bay-signal pattern in the rose diagrams as described in 4.2. The scarp orientations are less well defined compared to the delta and delta front, most likely due to a different depositional environment of the crater floor units.

The bay-signal observed in rose diagrams obtained from the mapped scarp orientations, is consistent with active erosion at the delta front. However, scarps with sand accumulations are observed throughout Eberswalde crater more abundantly than at Gale crater, indicating either higher sand influx, and/or less erosion occurring in Eberswalde crater, or different wind strengths, or shielding effects by local topography. Boulder-shedding scarps were easily identified from
orbital images, indicating that scarp retreat is occurring on timescales shorter than the time required for the boulders to undergo substantial weathering and erosion. These boulder-shedding scarps clearly occur along the entire face of the Eberswalde crater delta front.

4.3.2. Jezero Crater

The overall NE-SW scarp orientation (Fig. 10c) and easterly wind streaks (Table 2) in Jezero crater could imply a possible NE-SW wind direction, but the E-W wind streaks could imply a modern wind direction. The up-slope scarp orientation (Fig. 10d) is not distributed into an easily identifiable hemispheric shape in the rose diagram as previously observed at Gale crater and Eberswalde crater. As was done in Eberswalde crater, the Jezero crater western delta front was mapped separately (Fig. 10b; Table 2) to decouple the previously existing bedform shape from the scarp orientations presumably derived purely from aeolian processes. The delta front up-slope scarps mapped showed, at least partially, the signature rose diagram shape, with the preferred orientation of scarps in the hemisphere centered on the axis of the NE-SW scarp orientation (Table 2). As at Gale crater, the scarps populated in this hemisphere are not evenly distributed, but rather have higher concentrations of scarp orientations to the NW and SE. These up-slope NW and SE lobes are perpendicular to the dominant wind direction inferred from the bidirectional scarp orientations and are not centered on the wind streak directions. Continuing with this concept, the remaining scarps in the 180° spread are parallel to the dominant wind direction and the scarp face toward the NE, which could represent the active scarp. The hemispheric shape or bay-signal of the up-slope scarp orientations could therefore be a strong indicator of relatively active scarp erosion at Jezero crater. Scarp orientations on the crater floor did not show a clear bay-signal pattern as described in Section 4.2. The crater floor orientations appear to outline erosional windows in the crater floor and do not appear to be related to the delta and have low relief compared to the delta area.

The bay-signal observed in mapped scarp orientations, is consistent with active erosion at the delta front. However, scarps with sand accumulations (inactive) are observed throughout Jezero in a higher abundance than those at Gale crater. This indicates either higher sand influx, and/or less erosion occurring at Jezero. Inactive scarps, or scarps with sand accumulation suggests
that these scarps are not active, or fossil scarps. Unlike at Gale crater, boulder shedding scarps were well defined from orbital images, indicating that scarp retreat is relatively actively occurring on timescales shorter than the time required for the boulders to undergo substantial weathering and erosion. These boulder-shedding scarps clearly occur along the entire face of the Jezero delta front.

4.3.2. Melas Chasma

Wind direction is not well defined at Melas Chasma, however current modeling through sand dune and ripple migration suggest a westerly wind direction (Williams and Weitz, 2014). The Melas Chasma is located inside the Valles Marineris canyon system and the topography is controlled by the E-W orientation of the chasm. The up-slope scarp orientation resembled the Chasma topography and was populated in a ~70° swath of the rose diagram centered on north (Fig. 14d). The north-trending up-slope scarp orientations for the Melas Chasma basin and fan did not conform to the bay-signal as seen in Gale crater. The Melas Chasma fan scarp orientations were most likely a result of morphology of the subaqueous fan deposits (Metz et al., 2009).

Unlike at Gale crater, boulder shedding scarps were well defined from orbital images, indicating that scarp retreat is relatively actively occurring on timescales shorter than the time required for the boulders to undergo substantial weathering and erosion. These boulder-shedding scarps clearly occur along the entire face of the light-toned layered units.

Boulder-shedding scarps were well defined from orbital images, indicating that scarp retreat could be occurring. Boulder shedding scarps clearly occur along the Melas Basin area and abundant boulders associated with the Melas Chasma Fan were not abundant throughout the fan complex and not only located at scarp faces. This indicates that this surface is not undergoing erosion as seen at Gale crater, but has gone through a different landscape evolutionary process.

4.3.3. Holden Crater

In Holden crater, an overall preferred scarp orientation is well-defined with a relatively narrow angular dispersion with an r-value of 0.19 on the alluvial fan (Table 2), similar to that of Gale crater scarp orientation. The wind direction is unknown at Holden, but the overall NE-SW
scarp orientation (Fig. 16c) could indicate alignment with a possible NE to SW dominant wind direction. However, the overall up-slope scarp orientations (Fig. 16d) are poorly ordered and do not exhibit the bay-signal signature rose diagram shape as observed at Gale crater. The absence of the bay-signal of the up-slope scarp orientations indicates that Holden is a poor example of the bay-signal landform evolution model.

Scarps with sand accumulations (inactive) are observed throughout Holden at a higher frequency than that at Gale crater. This indicates either higher sand influx, and/or less erosion occurring at Holden. Inactive scarps, or scarps with sand accumulation suggests that these scarps are not active, or fossil scarps. Unlike at Gale crater, boulder-shedding scarps were well defined from orbital images, indicating that scarp retreat is occurring on timescales shorter than the time required for the boulders to undergo substantial weathering and erosion. These boulder-shedding scarps clearly occur along the entire face of the Light-toned Layered Units.

4.4. Future work

After the completion of this work, the scientific community met at the Third Mars 2020 Landing Site Workshop after which NASA announced three finalist sites: Jezero crater, NE Syrtis and Columbia Hills. Therefore, the method of defining active erosion that exposes “fresh” surfaces described in this study is the most applicable to the Jezero crater site. If Jezero crater is selected as the finalist landing site, the landform evolution model developed in this work can be used to detail the best locations at the landing site to identify recently-exposed surfaces. A prime example of this is at a location of the Jezero western delta front that extends within the proposed landing ellipse (Fig. 10). In addition to the delta front scarps exhibiting the bay-signal upslope rose diagram, and abundant boulder shedding (Fig. 10), there is evidence of an active ripple field (Fig. 10) that in some locations has overprinted other ripples and TAR’s, suggesting a dynamic and actively changing wind regime (Chojnacki, 2017). Further analysis has uncovered wind shadows trailing behind calved off scarp boulders. Dune and ripple migration will allow for a detailed wind flow model of the area, aiding in scarp retreat models. The landform evolution model suggests that the deepest locations of the bays would harbor the freshest outcrop exposures. Therefore,
the rover should go as far as possible into these bays to sample the outcrop at the base of the scarps (Fig. 12).

The bay and headland landform evolution model can also be tested on the other Mars-2020 sites. For example, stretched HiRISE IRB images at the Mars-2020 crustal landing site NE Syrtis show abundant boulder shedding with evidence of scarp faces that have a lack of dust. Detailed scarp analysis would be needed to see if the bay-signal in upslope rose diagrams of the NE Syrtis scarps was evident. This landform evolution model could also be tested at the Columbia Hills site, where some boulder shedding scarps are present in the Gusev lava plains. However, the majority of the proposed Columbia Hills landing site has extensive dust cover, and no in-situ observations from the Mars Exploration Rover Spirit’s traverse across the Gusev plains and the Columbia Hills support ongoing modern, aeolian-dominated scarp retreat.

5. CONCLUSIONS

Ground observations by MSL at Gale crater successfully verified orbital scarp mapping to characterize landform evolution via scarp erosion. We have shown that characterizing scarp orientations from orbital images is a useful way to identify relatively fresh outcrops on Mars. Such outcrops, defined as being exposed within the last ~100 Ma, have the highest potential of having been shielded from cosmogenic radiation by overburden. This overburden was then removed through aeolian induced scarp retreat. Based on mapped scarp orientations, color stretch analyses, observations of boulder-shedding and sand accumulations, we conclude:

(1) At Gale crater, scarp orientations show a distinct bay-signal that directly correlates with the known direction of ongoing aeolian scarp retreat;

(2) The similarity between the scarp orientation bay-signal at Eberswalde and Gale craters indicates that the Eberswalde delta front is likely eroding through the same landscape evolution process and has a high potential for exposing fresh outcrop surfaces;
(3) Scarp orientations at the Jezero delta front also exhibit a bay-signal, although to a lesser extent that has been observed at Gale and Eberswalde craters. Therefore, the wind regime is either more complicated or is not the dominant process;

(4) Scarp orientations at Holden crater and Melas Chasma are not consistent with this same scarp-retreat landform evolution model.

This study establishes a new tool to interpret the relationship between wind direction and scarp evolution. In the future, these methods could be used to identify locations on Mars with freshly-exposed surface material that could have the potential of preserving signs of past extraterrestrial life.
REFERENCES


Tsai, B.-J., and B.-S. Shiau (2009), Measurement on the wind flow characteristics for a turbulent boundary layer flow over the trapezoidal embankment with mild slope, *Wind Engineering*.


Fig. 1. Schematic of parallel scarp retreat at Yellowknife bay (YKB) indicating three points in time going back more than 80 million years. Parallel scarp retreat occurs at YKB by undercutting of the softer Sheepbed mudstone leading to blocks of the Gillespie sandstone calving off. Figure modified from JPL press release 2013.
Fig. 2. Boulder shedding off a scarp at Gale crater, Mars. Calved-off blocks (indicated by white arrows) of erosion resistant material near eroding scarps are common on Mars and have been observed by MSL at Gale crater. (from HiRISE observation ESP_027834_1755)
Figure 3. (Caption on next page)

(a) Scarp Orientation

(b) Wind Direction

Scarp

Yellowknife Bay

"Up-slope"

Gilespie Lake
Sheepbed

Wind Direction

John Klein drill site

Cumberland drill site

Print Lake
**Fig. 3. a)** YKB scarp (red), YKB scarp orientation is perpendicular to that of the NE-SW dominant wind direction (yellow arrow). YKB up-slope (light blue arrow) is parallel with the dominant wind direction. YKB imaged by the HiRISE instrument onboard MRO. (from HiRISE observation PIA17080) **b)** YKB scarp face (red line), with wind direction (yellow arrows) and up-slope direction (blue arrows). Imaged by Mastcam instrument on the Mars Science Laboratory (MSL.). Image modified from Grotzinger, 2013 (Source: Grotzinger et al., 2013).
Figure 4. (Caption on next page)
Fig. 4. a) Yellowknife Bay area, Gale crater, Mars. Blue line indicates the traverse of MSL. (from HiRISE observations ESP_027834_1755_RED and ESP_023957_1755) b) Yellowknife Bay area mapped scarps (red)s. c) Rose diagram of the diametrically bimodal (two direction) circular distributions of scarp orientations. Scarp orientation angular dispersion or $(r)$ = 0.18. d) Up-slope scarp rose diagram, indicating directions toward the scarp face.
Figure 5. (Caption on next page)
Fig. 5. a) Gale crater scarp segment map area of nine 1 km$^2$ quads along MSL’s traverse from the landing site at Bradbury rise in the Yellowknife Bay to Murray Buttes. (from HiRISE observation mosaic MSL_HIRISE_Mosaic_EDL_1m1) b) Gale crater 142,233 m of mapped scarps. c) Gale crater total scarp orientations. d) Gale crater up-slope scarp rose diagram orientations.
Figure 6. (Caption on next page)
**Fig. 6.** a) Gale crater scarp segment map. Blue scarps segments are ground verified observations of orbitally mapped scarps that have blue hues observed on scarp faces. Purple scarps are ground verified observations of orbitally mapped scarps that have partial sand accumulation. b) Gale crater scarp rose diagram orientations with partial sand accumulation. c) Gale crater up-slope scarp orientations with partial scarp orientations. d) Gale crater scarp rose diagram orientations with scarp faces exhibiting blue hues Mastcam images. e) Gale crater up-slope scarp orientations with scarp faces exhibiting blue hues in Mastcam images.
Fig. 7. a) Mastcam image taken on sol 1441 of a Murray Buttes scarp, Gale crater. b) Mastcam image taken on sol 1421 of a Naukluft Plateau scarp, Gale crater. c) Mastcam image taken on sol 992 of a Pahrump Hills scarp. Gale crater.
Figure 8. (Caption on next page)
Fig. 8. a) HiRISE image of Eberswalde with the scarp mapping area (yellow) 163 km², and Mars-2020 proposed landing ellipse (green). Eberswalde crater floor (grey), delta (black) and delta front (thick black). (from CTX observation B01_010052_1559_XI_24S033W) b) Eberswalde scarp map of 644,396 m of scarps. c) Eberswalde crater scarp rose diagram orientations. d) Eberswalde crater up-slope scarp orientations. e) Eberswalde crater delta front scarp rose diagram orientations. f) Eberswalde crater delta front up-slope scarp orientations.
Fig. 9. Boulder shedding off a scarp at Eberswalde crater delta front, Mars. Calved-off blocks of erosion resistant material near eroding scarps are common on Mars and have been observed by MSL at Gale crater (from HiRISE observation ESP_047119_1560).
Figure 10. (Caption on next page)
Fig. 10. a) HiRISE image of Jezero with the scarp mapping area (yellow) 280 km$^2$, and Mars-2020 proposed landing ellipse (green). Jezero crater floor/volcanic floor unit (grey), deltas (black) and west delta front (dark black). (from CTX observation D14_032794_1989_XN_18N282W) b) Jezero scarp map of 644,396 m of scarps. c) Jezero crater scarp rose diagram orientations. d) Jezero crater up-slope scarp orientations. e) Jezero crater west delta front scarp rose diagram orientations. f) Jezero crater west delta front up-slope scarp orientations.
Fig. 11. a) Wind streaks found at Jezero crater (red) b) Rose diagram of wind streaks at Jezero crater.
Fig. 12. Color stretched image example at the Jezero crater delta front, Mars (from HiRISE observation ESP_046060_1985_COLOR). Enhanced hues in HiRISE IRB (Infrared, Red, Blue). Dusty materials are represented by redder color (not actively eroded). Less-dusty outcrop or active sand tend to be bluer or purplish in IRB (actively eroded). Image credit: NASA/JPL
Figure 13. (Caption on next page page)
Fig. 13. a) Jezero crater boulder shedding scarps (purple). Jezero crater scarps with partial sand accumulation (green). b) Jezero crater boulder shedding scarp rose diagram orientations. c) Jezero crater boulder shedding up-slope scarp orientations. d) Jezero crater scarps with partial sand accumulation rose diagram orientations. e) Jezero crater up-slope scarps with partial sand accumulation orientations.
Figure 14. (Caption on next page)
Fig. 14. a) HiRISE image of Melas Chasma with the scarp mapping area (yellow) 101 km$^2$, and Mars-2020 proposed landing ellipse (green), including the Melas Chasma subaqueous fan and basin floor. (from CTX P07_003685_1711_XI_08S076W) b) Melas Chasma scarp map of 294,008 m of scarps. Melas Chasma basin floor (grey), subaqueous fan (black). c) Melas Chasma scarp rose diagram orientations. d) Melas Chasma crater up-slope scarp orientations. Image credit: JPL/NASA.
Figure 15. (Caption on next page)

Fig. 15. Boulder shedding off a scarp at Melas Chasma (from CTX observation B01_010052_1559_XI_24S033W).
Figure 16. (Caption on next page)
Fig. 16. a) HiRISE image of Holden with the scarp mapping area (yellow) 112 km$^2$, and Mars-2020 proposed landing ellipse (green). Holden alluvial fan and light toned units. (from HiRISE observation ESP_046060_1985_COLOR). b) Holden scarp map of 217,793 m of scarps. Holden alluvial fan (grey), Light Toned units (black) and west delta front (dark black). c) Holden scarp rose diagram orientations. d) Holden up-slope scarp orientations.
Fig. 17. Schematic model of scarp erosion and retreat. The landform evolution model of scarp erosion inducing the bay and headland theater morphology. The subsequent up-slope rose diagram in 4 illustrates the “bay-signature” hemispheric shape. This model assumes a single wind direction has been the predominant source of erosion over timescales of 107-108 Myr (as inferred from the MSL exposure age experiments), leading to the formation of headland- and bay-shaped landforms. 

a) Landscape originates with a scarp face aligned in the N-S orientation. 

b) Initial variabilities in the scarp face orientation due to heterogeneities in resistance to erosion. Scarp orientations still N-S, and the up-slope rose diagram shows scarp faces eroding towards the west along the direction of the dominant wind. 

c) Scarp differentially eroding to create bays with small headlands. Relatively even distribution of scarp face orientations which is reflected in by a large dispersion of scarp orientations in the rose diagram. Up-slope rose diagram shows a preferred clustering of scarps with roughly “180°” distributed centered on the direction of the dominant wind direction. 

d) Final stage depicts the mature theater-shaped scarp bay and headland promontories, as seen at Yellowknife Bay and other locations. The inactive scarps populated along the headland margins dominate the scarp orientation rose diagram. Final rose diagram shows that the remaining scarp population is dominated by these inactive scarps, which are aligned with that of the dominant wind direction. The up-slope diagram indicates that most of the scarps populated in the north and south representing the passive headland scarps, while the less populated active scarps are shown in the west.
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<th>Species</th>
<th>Genome Size (Mb)</th>
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<th>Taxonomic Family</th>
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**Table 1:** Summary of mapped canine center scrap contamination

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</tr>
</tbody>
</table>

**Table 2:** Summary of mapped feline center scrap contamination
|------|------|------|------|------|------|------|------|------|------|------|------|

Table 2. Summary of the mapped trends 2020 sedimentary loading time series.