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Emilie Gardin, Mary C. Bourke, Pascal Allemand, Cathy Quantin. High albedo dune features suggest past dune migration and possible geochemical cementation of aeolian sediments on Mars. *Icarus*, 2011, 212 (2), pp.590. 10.1016/j.icarus.2011.01.005 . hal-00734593

HAL Id: hal-00734593

<https://hal.science/hal-00734593>

Submitted on 24 Sep 2012

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Accepted Manuscript

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PII: S0019-1035(11)00006-6
DOI: [10.1016/j.icarus.2011.01.005](https://doi.org/10.1016/j.icarus.2011.01.005)
Reference: YICAR 9684

To appear in: *Icarus*

Received Date: 28 September 2009
Revised Date: 3 January 2011
Accepted Date: 6 January 2011

Please cite this article as: Gardin, E., Bourke, M.C., Allemand, P., Quantin, C., High albedo dune features suggest past dune migration and possible geochemical cementation of aeolian sediments on Mars, *Icarus* (2011), doi: [10.1016/j.icarus.2011.01.005](https://doi.org/10.1016/j.icarus.2011.01.005)

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**High albedo dune features suggest past dune migration and possible geochemical
cementation of aeolian sediments on Mars**

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Number of manuscript pages: 17

Number of tables: 0

Number of figures: 9

21 **Proposed running head:**

22 Dune cementation on Mars

23

24 **Editorial correspondance and proofs to:**

25

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Abstract:

High albedo features are identified in association with barchan dunes in an equatorial inter-crater dune field on Mars using data from the High Resolution Imaging Science Experiment. This paper describes the morphometric properties of these features and their association with the present barchan dune field. We propose that these features are cemented aeolian deposits that form at the foot of the dune avalanche face. A possible terrestrial analog exists at White Sands National Monument, in south-central New Mexico, USA. The presence of these features suggests past episodes of dune migration in inter-crater dunefields and liquid water in the near sub-surface in sufficient quantity to cause the cementation of aeolian dune sediment.

Keywords: Mars, Mars surface, geological processes, dunes, aeolian processes, liquid water

1. Introduction:

The availability of liquid water on the surface of Mars has been confirmed spectrally and geomorphologically (Carr, 1996; Mangold et al., 2004; Bibring et al., 2006). These data have shown that water abundance has varied through time with the earliest period of Martian history recording the wettest phase (Poulet et al., 2005). Yet there are several intriguing observations that suggest that liquid water has been stable at the surface or in the near subsurface in recent times (*i.e.* several thousand years), even at low latitudes (Mangold et al., 2003; Balme et al., 2006). In addition, modeling has demonstrated the potential stability of brine at even higher latitudes (Edgett et al., 2002; Richardson and Mischna, 2005).

Dark aeolian sand dunes are amongst some of the youngest landforms on Mars, having no evidence of impact craters reported at present. Some of these relatively young landforms in the mid southern latitudes show modification of their avalanche face by fluid flow in the form of gully channels and deposits (Mangold et al., 2003; Reiss and Jaumann, 2003; Dickson and Head, 2006; Gardin et al., 2010). These too may be evidence of liquid surface water in recent times, although other hypotheses also exist.

On Earth, dunes are known to form in climatic regions that extend through the humidity spectrum from hyper-arid to humid. In many locations, aeolian systems interact with fluvial, lacustrine and high groundwater systems. Dunes have a range of features that can be used to indicate the presence of water. These include soil horizons, cemented layers, vegetation and geochemical alteration (Schenk and Fryberger, 1988).

Here we report on a detailed study of an inter-crater dune field on Mars where a series of high albedo features associated with barchan dunes are identified. We suggest that these features were formed in a period where liquid water was available in the close sub-surface.

2. Methodology:

We used data from the Mars Digital Dune Database (Hayward et al., 2007) to build our GIS. This includes Visible Thermal Emission Imaging System (THEMIS) images acquired by the Mars Odyssey mission (Christensen et al., 2004) and Narrow Angle Mars Orbiter Camera (MOC) images acquired by Mars Global Surveyor (Malin et al., 1992). The image resolution for THEMIS images (V01766006, V04375003, V16781005 and V22921014) is 18 m per pixel and 4.41 m per pixel for the MOC image (M0303621). We also use High Resolution Imaging Sciences Experiment (HiRISE) images (McEwen, 2007) which have a resolution of 28.2 and 29.0 cm per pixel (PSP_001882_1920 and PSP_002594_1920, respectively). This resolution permits small-scale morphologies to be determined. Images were processed using ENVI (Environment for Visualizing Images). This tool is commonly used for the visualization, analysis and geo-processing of images including vector and raster GIS capabilities. Images processed by ENVI were imported into a Geographic Information System (GIS) using ESRI's ArcGIS software.

We collected 277 morphometric measurements on the width, length and spacing of high albedo features and their distance from the modern dunes. In addition we determined the Digital Number (DN) of the high albedo features and of the large dark dunes using ENVI software. The DN represents the brightness of each pixel and ranges between 0 and 255 values (0 for low albedo pixel and 255 for brighter pixel on the image). Reported values are the average of eight sample points.

3. Results

Dune field morphology

The dune field is situated in an unnamed crater, 90 km in diameter, located at a low latitude in the north hemisphere of Mars (11.89°N and 185.87°E). The dune field is positioned in the lower elevation south-western part of the crater floor (Fig. 1). **[Figure 1]**

To the north of the dune field, several asymmetric barchan dunes are observed and suggest the influence of a bimodal wind regime from west and north (Bourke, 2010). Towards the center of the dunefield the barchans are symmetrical with slipfaces orientated towards the south-east suggesting that the resultant wind is from the west to west-north-west. The average width of the dark dunes is about 205 m (horn to horn). All these dark dunes are covered by small ripples and have a low albedo with DN values ranging between 8 and 30 with a mean of 16 (Fig. 2). The slipfaces of the barchans in the eastern part of the dune field are less visible and they are probably a transient form either evolving from or devolving to dome dunes.

[Figure 2]

High Albedo features

A series of high albedo features are identified in HiRISE images. They are predominantly located in the interdune areas with some visible through the thin sediment cover on the lower windward slope of dunes. All the high albedo features are overlain by ripples (Fig. 3). The ripples do not appear to be deflected or display a change in pattern or spacing as they approach and/or overlie the high albedo areas indicating that the latter have a very low topography. This suggests that the high albedo features are not 'bright dunes' (*sensu* (Thomas et al., 1999)) or transverse aeolian ridges.

[Figure 3, Figure 4 and Figure 5]

The DN of the high albedo features ranges between 54 and 89, with a mean of 70 (Fig. 4). There is an area of high albedo topography adjacent to the dune field. This has an average DN of 123. That none of the high albedo features have similar DN values to the dark dunes suggests that the material composition is different.

Observations of the planform of the high albedo features were made on the entire dunefield and three types were identified (Fig. 5); straight (34.5%), curved (25.5%) and arcuate (40%). The difference between the latter two is the relative angle of curvature. No single planform dominates the study area.

[Figure 6 and Figure 7]

The length of each high albedo feature was measured from the HiRISE image (Fig. 6) and they range between 54 and 164 m with a mean of 102 m. The length along the base of the dark dune slipfaces ranges between 32 and 187 m with a mean of 125 m (Fig. 6), nearest in length to the high albedo features. The spacing between the most upwind high albedo features and the brink of the nearest downwind dune is between 110 and 242 m (mean is 180 m). The spacing between consecutive high albedo features ranges between 5 m and 60 m with a mean of 23 m (Fig. 7).

[Figure 8]

The high albedo features and brinks of the dunes were mapped on the HiRISE PSP_001882_1920 image (Fig. 8). The features are, in most of cases, parallel to the slipface of the dunes (Fig. 8). We have represented our interpreted linkages between the high albedo features and the slipface of the dunes in our map with red arrows (Fig. 8). While most of the features parallel the dune orientation, the few that are not completely aligned with the current position still mirror the foot-slope shape of the avalanche face (Fig. 9). The orientation of the features is predominantly to the SSW and NNE. From the orientation of the dune slipface we infer that the dune migration pathway is to the south-east. **[Figure 9]**

4. Discussion

Because the high albedo features are observed throughout the entire dune field and they have similar DN values, planforms and dimensions, we suggest that they have formed by a similar process. Furthermore, they have a higher DN than the sand dunes suggesting a different composition. The features are predominantly located in the interdune, and their planform mirrors that of the foot of barchan avalanche faces. The length of the high albedo features is similar to the length of the foot of the dune slipfaces (Fig. 6). This suggests that these features are associated with sediments deposited at the base of the dune slipface. Together these observations suggest that the dunes play a role in their formation.

On Earth, features with a similar morphology and relationship to dunes have been noted in the interdune of the White Sands National Monument, in south-central New Mexico (McKee, 1966; Simpson and Loope, 1985; Schenk and Fryberger, 1988; Kocurek et al., 2007; Langford et al., 2009). Schenk and Fryberger (1988) found that 20 cm high ridges in the interdune areas were cemented dune sediments that were remnants of dunes that had migrated across the interdune area. Diagenesis of the dune sediments during periods of high groundwater was identified to have caused dissolution of the gypsum grains and reprecipitation in a gypsum cement that bound the sediments. Two types of facies were preserved in the interdune features. The first represents the basal portion of a dune preserved by early cementation; these features have an arcuate shape that is similar to the planform of the base of the dune footslope. The second facies is composed of avalanche face strata (ripple and grain flow) (Schenk and Fryberger, 1988). One difference between this analog site and our site on Mars is the composition of the dunes. At White Sands National Monument the dunes are composed of soluble gypsum grains, whereas on Mars the dunes are likely composed of basaltic sand.

The interpretation that the Martian high albedo features are caused by chemical cementation of dune sediments requires that there was liquid water close to the surface. On Mars, surface liquid water is unstable under current atmospheric pressures and temperatures; however, briny water may have played a role both in supplying the water and the salts to cement the sediments.

The composition of the cementing agent is unknown (Clark et al., 1982; Sullivan et al., 2008; Hecht et al., 2009; Szyrkiewicz et al., 2010). Soils at some locations on Mars are enriched with a variety of salts. For example sulfate minerals have been detected on the surface of dunes in the North Polar area (Langevin et al., 2005 ; Horgan et al., 2009); and perchlorate was found at the Phoenix landing site (Hecht, et al., 2009); sulfur was detected in crusts at Viking 1 (Clarke et al, 1982) and magnesium, sulfur, chlorine, and bromine were excavated by rover wheels at Gusev (Sullivan et al., 2008). Unfortunately, the width of the high albedo features is not sufficient for spectral analysis using data from the OMEGA or CRISM instruments (Bibring et al., 2004; Murchie et al., 2007) which have a spatial resolution of hundreds of meters to 18 meters per pixel, respectively. Such compositional measurements would enable a test of the geochemical cementation hypothesis proposed here and perhaps elucidate on potential sources of the soluble minerals.

Arcuate features associated with dunes have also been reported in the interdune areas of Olympiae Undae (Szyrkiewicz et al., 2009) and Chasma Boreale (Bourke et al., 2008). The Olympia Undae features are suggested to be preserved dune cross-strata that formed during periods of higher groundwater (similar to the model proposed here). They may also be preserved strata of a significantly older, deflated surface (Szyrkiewicz et al., 2009). The Chasma Boreale arcuate features have morphological differences to those reported in this study and are proposed to result from either ground ice cementation of dune sediments or geochemical cementation (Bourke, 2010).

An important implication of our hypothesis is that moisture was close to the surface at this low latitude location on Mars in recent times. We suggest that it is recent because of the young age of the dunes relative to other surface features on Mars. Recent dating efforts of aeolian bedforms and their underlying surfaces suggest aeolian bedforms may be younger than 100 ka and as young as 10 ka (Bourke et al., 2010 ; Fenton and Hayward, 2010). While we can report that no impact craters were observed on the study site dunes, no crater retention age estimates are available for this location.

A second implication of our findings comes from the fact that the high albedo features mark the former position of the slipface, and thus represent a former location of the dune. The identification of arcuate features upwind of barchans dunes suggests that dune migration has occurred at this low latitude location in recent times on Mars. Measurement of the distance between the high albedo features and the dune brink indicate that the preserved dune migration distances are between 110 m and 242 m with a mean of 180 m. The rate of dune migration cannot be estimated as there is no data on the age of the high albedo features.

A third implication of our findings comes from observations regarding the alignment of the arcuate features with the current dune position. These data indicate that the dune migration direction can be constrained by the azimuth angle between the mid-point locations of the high albedo feature and the dune brink. Our high albedo feature data suggest that the overall dune movement has been to the SE and SSE. The current dune slipfaces are oriented to the SE. This difference suggests that there has been some variability in the wind direction over time. These data can be used to reconstruct the resultant wind direction at this location and test the output from meso-scale climate models.

5. Conclusions

A dune field located in an equatorial crater (centered at 11.89°N and 185.87°E) preserves a series of high albedo arcuate features in the interdune area. We hypothesize that these features are likely geochemically cemented aeolian sediments that are remnants of migrating dunes. We propose that cementation occurred during periods of recent high groundwater. Similar interdune features are found at the White Sands National Monument in New Mexico, USA.

These features are evidence of dune migration at this equatorial location. In addition the difference in orientation between the remnant aeolian sediments and the dunes suggests a change in the resultant wind direction at this location.

Acknowledgements:

Funding for this work came in part from NASA MDAP grant NNG05GQ60G. This is PSI Publication # 470. We also thank the region Rhône-Alpes of France for the financial support project CIBLE 2006. We also thank the HiRISE team for the public availability of images. We thank both reviewers for useful discussions.

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Figure Captions:

Figure 1:

Location of the study area. The dunefield is located in the south-western part of the
crater (centred at 11.89°N and 185.87°E). MOLA Background. Arrows represented north (N)
and solar (black circle) azimuths.

Figure 2:

DN values for the large dark dunes and the interdune areas. Value given is an
average of eight sample points taken from each dune and interdune location.

Figure 3:

Enlargement of a portion of HiRISE image (PSP_001882_1920), showing the
exposure of the underlying high albedo material between the ripples.

Figure 4:

DN values across high albedo features. Each value is the calculated average of eight
sample points.

Figure 5:

The three different planforms of high albedo features: straight, curved and arcuate.

378

379 Figure 6:

380 Length of dark dune slipface compared with length of high albedo feature located
381 upwind of sampled dune.

382

383 Figure 7:

384 Distance between high albedo features and the nearest dune brink. Spacing between
385 consecutive high albedo features.

386

387 Figure 8:

388 Left: HiRISE images PSP_001882_1920. Measured dunes are indicated by arrows.

389 Left corner: Close-up of the HiRISE image shows high albedo features adjacent to dunes.

390 Right: map of high albedo features (black lines), crest of measured slipfaces (blue lines), and
391 inferred directional between the high albedo features and the associated dunes (red arrows).

392 Right corner: Close-up of high albedo features located in the interdune.

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394 Figure 9:

395 High albedo features which are not parallels to the slipface crest but perpendiculars
396 to the edge of dune. Black arrows indicate the solar azimuth.

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398

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Figure 1

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Figure 2

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