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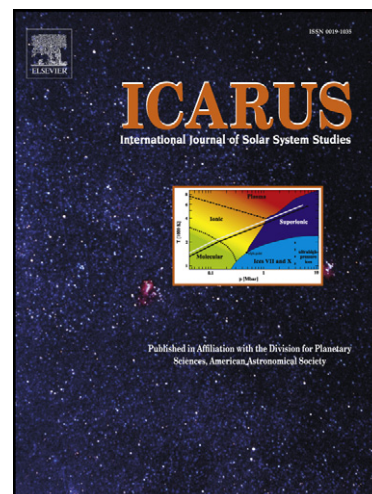
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1 **High albedo dune features suggest past dune migration and possible geochemical**
2 **cementation of aeolian sediments on Mars**

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46 **Abstract:**

47

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

57

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

59 **1. Introduction:**

60

61 The availability of liquid water on the surface of Mars has been confirmed spectrally
62 and geomorphologically (Carr, 1996; Mangold et al., 2004; Bibring et al., 2006). These data
63 have shown that water abundance has varied through time with the earliest period of Martian
64 history recording the wettest phase (Poulet et al., 2005). Yet there are several intriguing
65 observations that suggest that liquid water has been stable at the surface or in the near
66 subsurface in recent times (*i.e.* several thousand years), even at low latitudes (Mangold et al.,
67 2003; Balme et al., 2006). In addition, modeling has demonstrated the potential stability of
68 brine at even higher latitudes (Edgett et al., 2002; Richardson and Mischna, 2005).

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

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

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

83

84 2. Methodology:

85

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

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

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106

107

108

109 **3. Results**

110

111 *Dune field morphology*

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

115 To the north of the dune field, several asymmetric barchan dunes are observed and
116 suggest the influence of a bimodal wind regime from west and north (Bourke, 2010). Towards
117 the center of the dunefield the barchans are symmetrical with slipfaces orientated towards the
118 south-east suggesting that the resultant wind is from the west to west-north-west. The average
119 width of the dark dunes is about 205 m (horn to horn). All these dark dunes are covered by
120 small ripples and have a low albedo with DN values ranging between 8 and 30 with a mean of
121 16 (Fig. 2). The slipfaces of the barchans in the eastern part of the dune field are less visible
122 and they are probably a transient form either evolving from or devolving to dome dunes.

123 **[Figure 2]**

124

125 *High Albedo features*

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

133 **[Figure 3, Figure 4 and Figure 5]**

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

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

142 **[Figure 6 and Figure 7]**

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

150 **[Figure 8]**

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

159 **4. Discussion**

160

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

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

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

189 The composition of the cementing agent is unknown (Clark et al., 1982; Sullivan et al.,
190 2008; Hecht et al., 2009; Szyrkiewicz et al., 2010). Soils at some locations on Mars are
191 enriched with a variety of salts. For example sulfate minerals have been detected on the
192 surface of dunes in the North Polar area (Langevin et al., 2005 ; Horgan et al., 2009); and
193 perchlorate was found at the Phoenix landing site (Hecht, et al., 2009); sulfur was detected in
194 crusts at Viking 1 (Clarke et al, 1982) and magnesium, sulfur, chlorine, and bromine were
195 excavated by rover wheels at Gusev (Sullivan et al., 2008). Unfortunately, the width of the
196 high albedo features is not sufficient for spectral analysis using data from the OMEGA or
197 CRISM instruments (Bibring et al., 2004; Murchie et al., 2007) which have a spatial
198 resolution of hundreds of meters to 18 meters per pixel, respectively. Such compositional
199 measurements would enable a test of the geochemical cementation hypothesis proposed here
200 and perhaps elucidate on potential sources of the soluble minerals.

201 Arcuate features associated with dunes have also been reported in the interdune
202 areas of Olympiae Undae (Szyrkiewicz et al., 2009) and Chasma Boreale (Bourke et al.,
203 2008). The Olympia Undae features are suggested to be preserved dune cross-strata that
204 formed during periods of higher groundwater (similar to the model proposed here). They may
205 also be preserved strata of a significantly older, deflated surface (Szyrkiewicz et al., 2009).
206 The Chasma Boreale arcuate features have morphological differences to those reported in
207 this study and are proposed to result from either ground ice cementation of dune sediments or
208 geochemical cementation (Bourke, 2010).

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

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

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

231

232 **5. Conclusions**

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

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

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358 Figure Captions:

359 Figure 1:

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

363

364 Figure 2:

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

367

368 Figure 3:

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

371

372 Figure 4:

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

375

376 Figure 5:

377 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.

393

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.

397

398

399

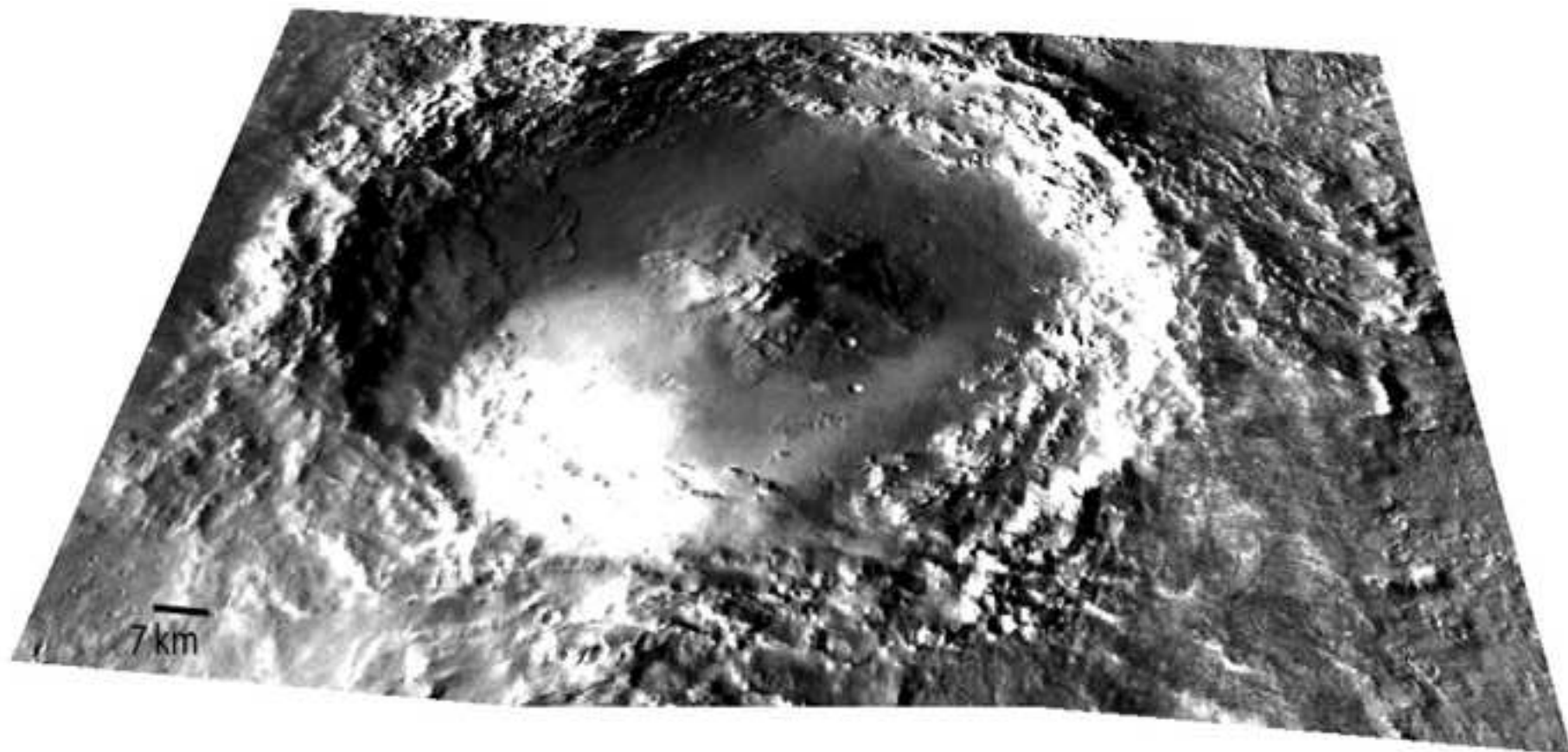
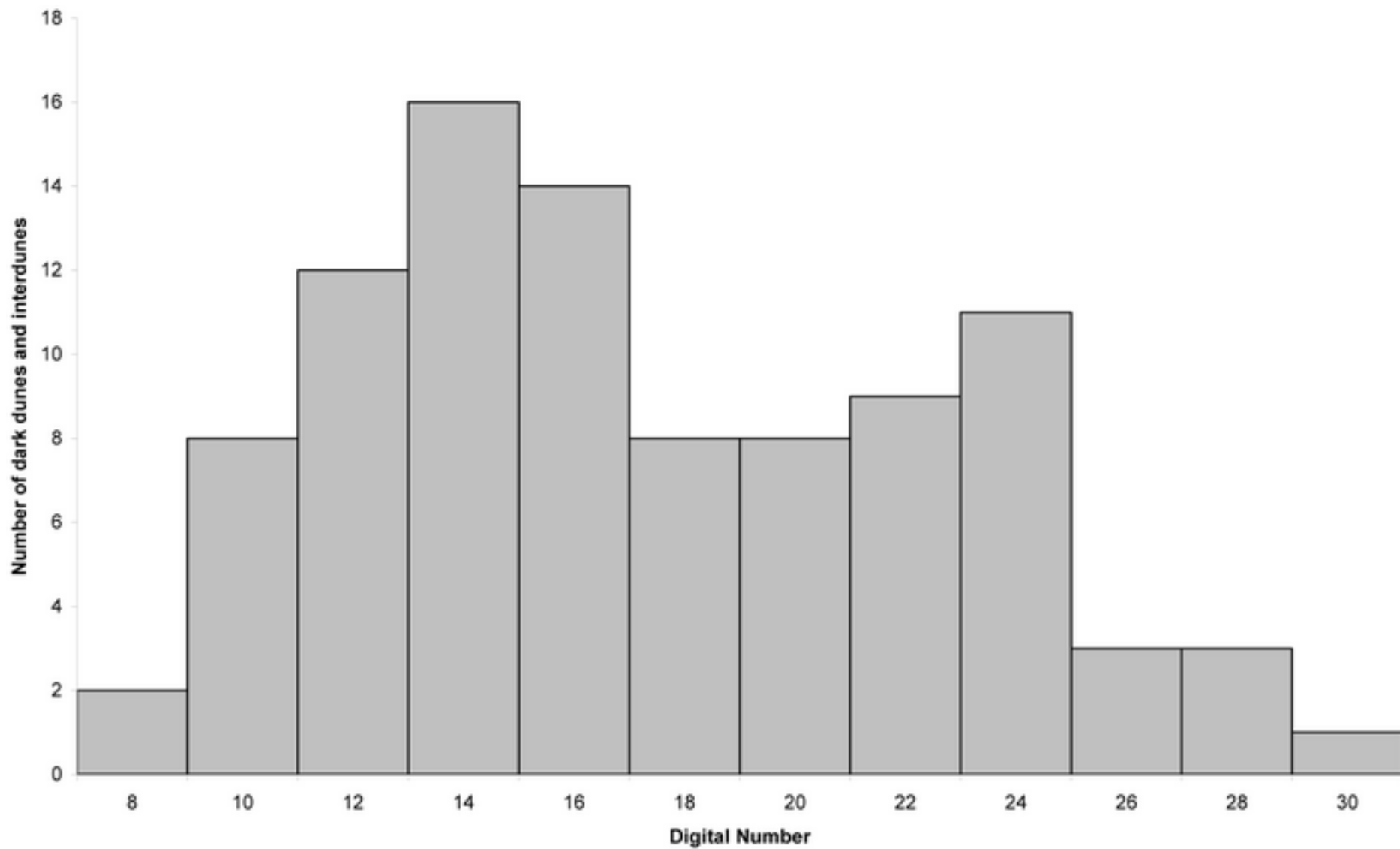


Figure 2



ACCEPTED

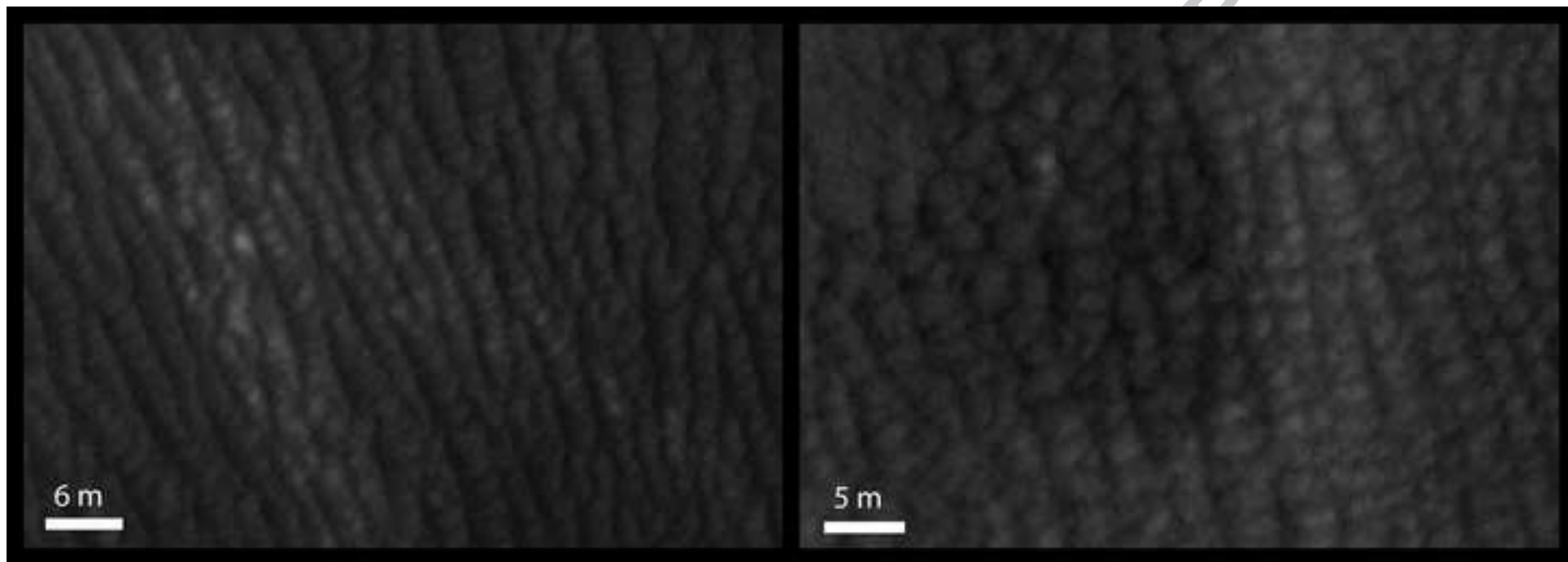


Figure 4

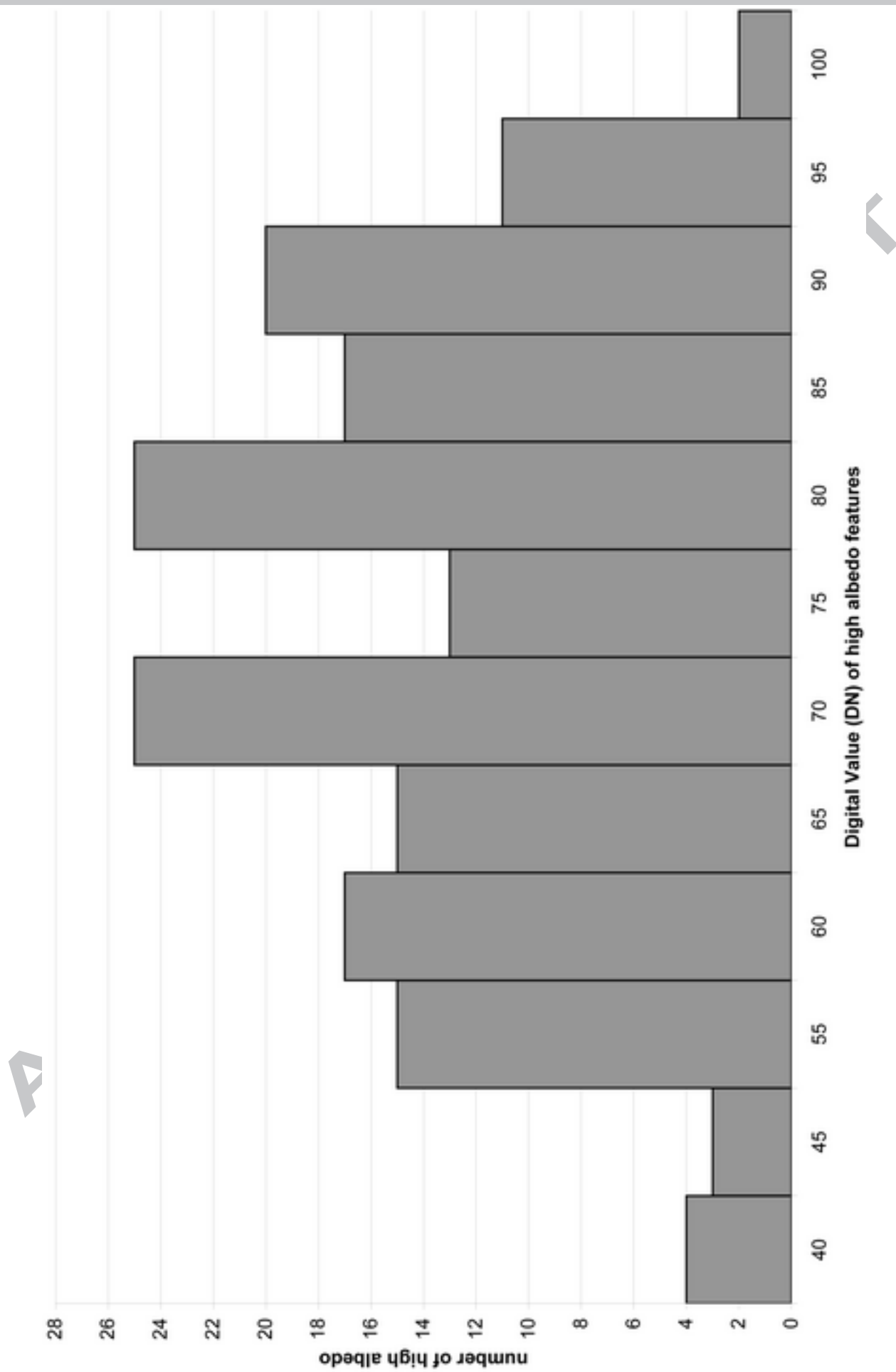


Figure 5

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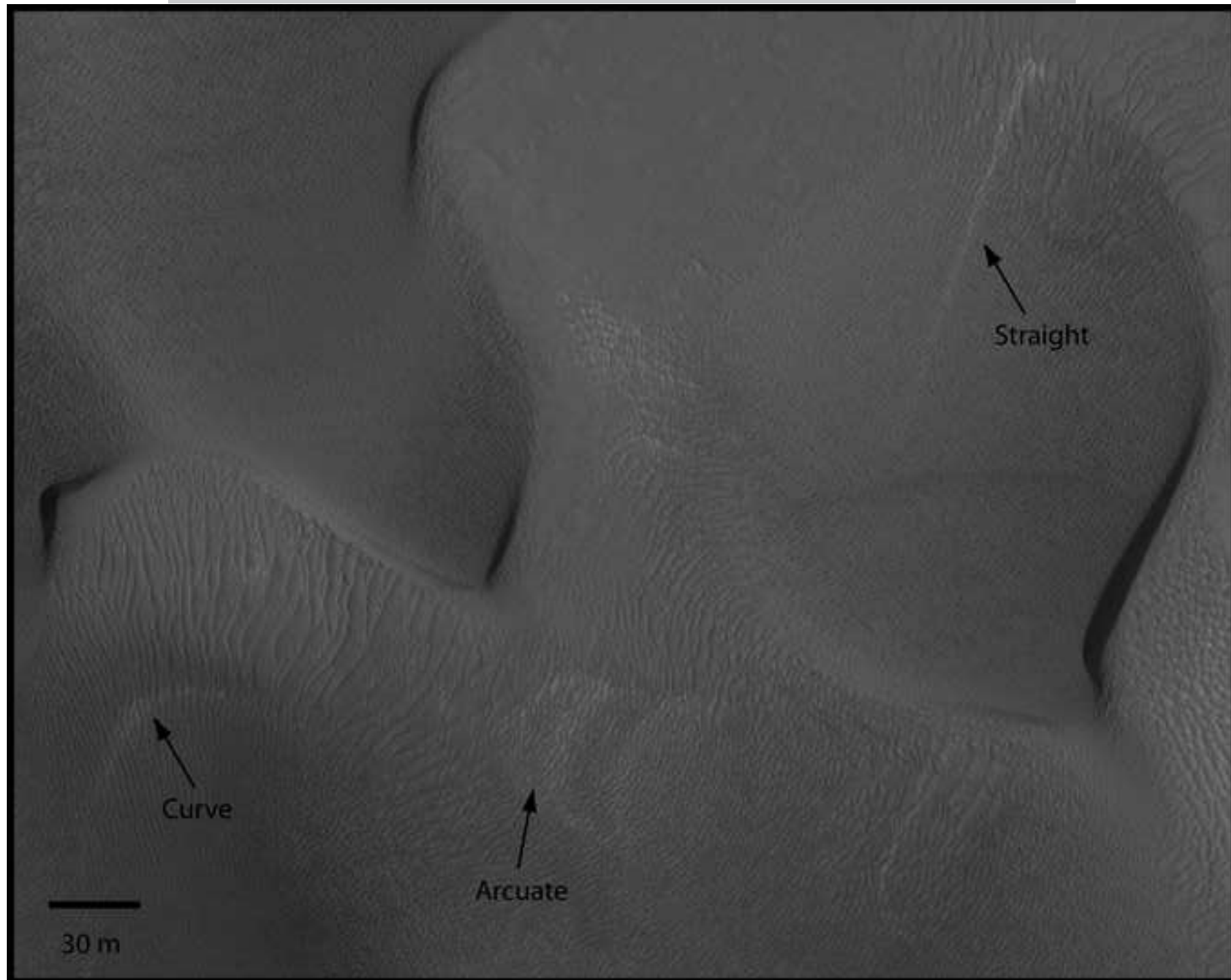


Figure 6

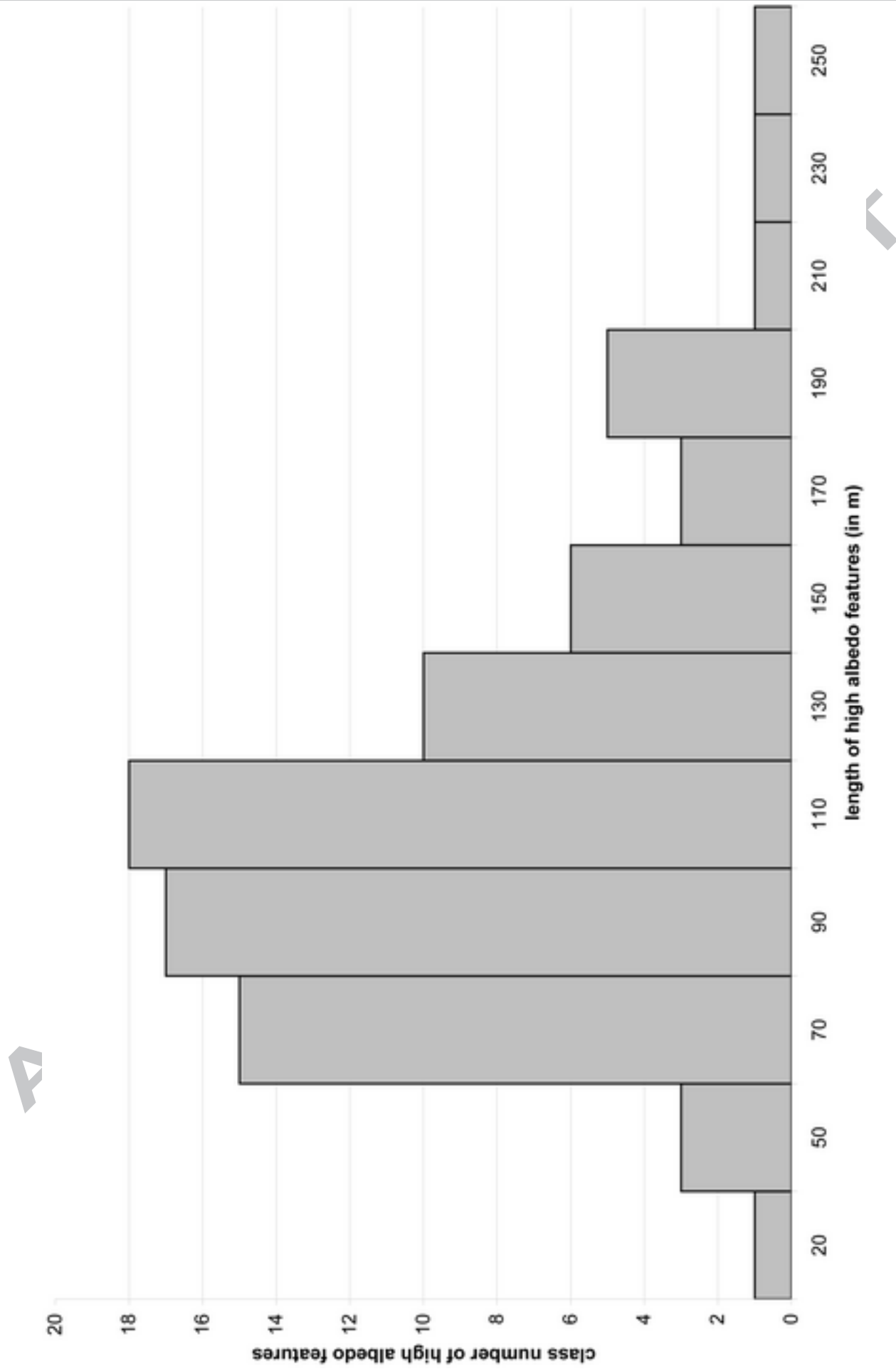


Figure 7

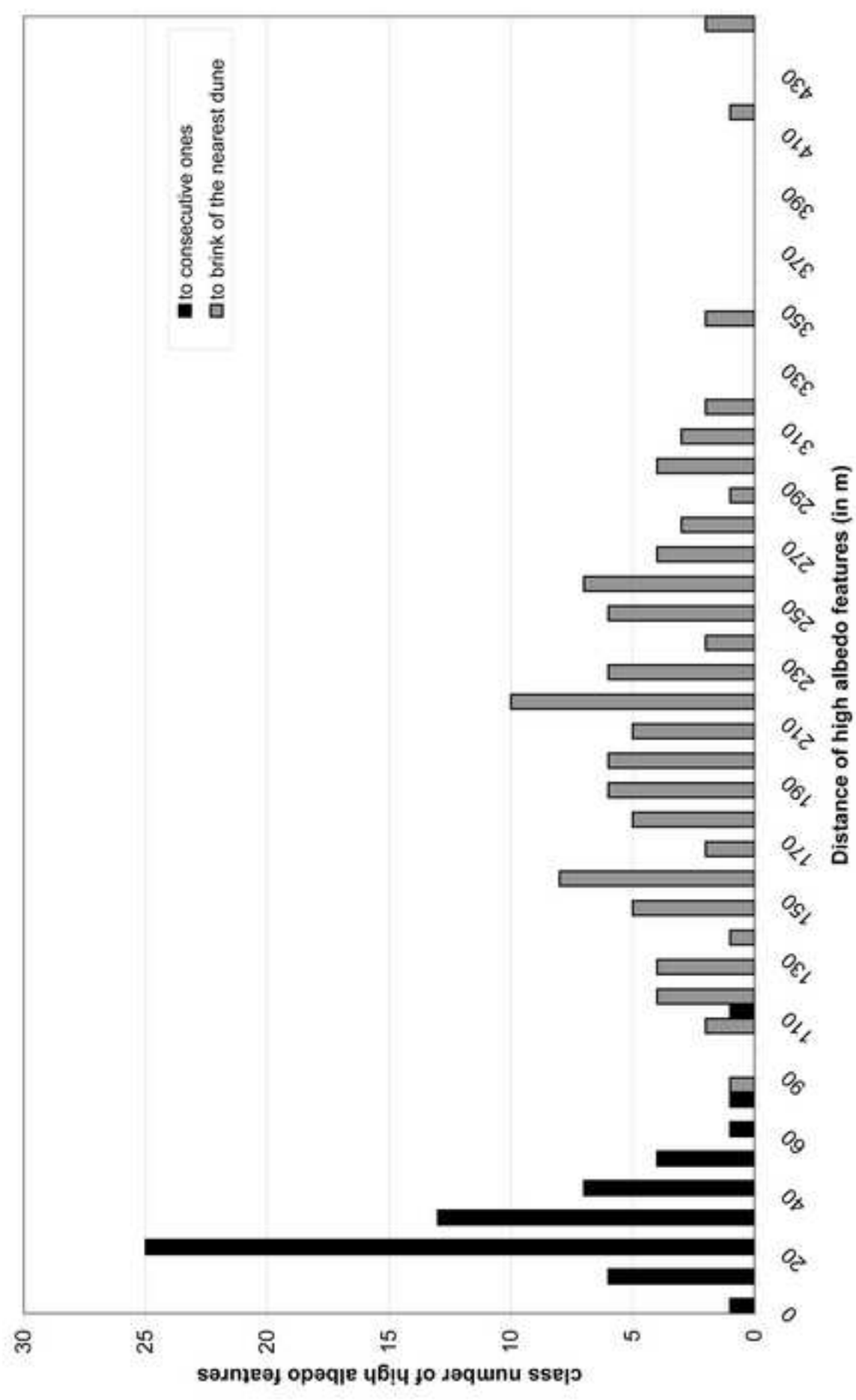


Figure 8

