Ancient Shoreline in Cydonia

Analysis of THEMIS Multispectral Imagery of Mars provides further evidence that the Face and City are located along an ancient shoreline in Cydonia

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1. Introduction

The origin of the Face and other anomalous features in Cydonia has been debated for over a quarter of a century. The key question — are they artificial, or are they natural — has led to claims of artificiality based on symmetry and geometry\(^1\), non-fractal structure\(^2\), and other properties\(^3\), and to counter-claims that these structures are the result of natural processes on Mars. For example, planetary scientist Michael Malin believes that differential erosion has been responsible for sculpting the terrain in this part of Cydonia\(^4\). His theory is that the area was once covered by several kilometers of soft sediment, which was strip away by the wind and other erosive forces leaving the more durable knobs and mesas that we see today. Geologists James Erjavec and Ron Nicks have shown that this explanation is not consistent with crater count statistics, which show two distinctly different kinds of terrain in Cydonia\(^5\). Offering another natural explanation, JPL scientist David Pieri argues that the Face and other nearby features were formed in a subaqueous (underwater) environment\(^6\). However, countering this Erjavec and Brandenburg have found what appear to be rills on several

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Cydonian landforms — strong evidence that these features were aerially exposed and that erosion occurred as a result of precipitation and surface runoff.7

The Independent Mars Investigation Group8 first noted that the City and Face were located near the 0 km datum — what would be sea level if Mars had an ocean. Recent results from the MOLA instrument aboard MGS9 and Mars Odyssey’s Neutron Spectrometer10 support the ancient ocean hypothesis: that a large body of water once existed for a considerable period of time in Mars’ northern hemisphere.

This paper presents an analysis of a recent THEMIS multispectral image (E0201847.gif) acquired by the Mars Odyssey spacecraft11 over Cydonia which provides further evidence that an ocean once existed to the north, and that the features known as the City and Face are located along what was once its shoreline. It is shown that there are three spectrally distinct regions that are spatially correlated with MOLA-derived elevation data. One region is correlated with the higher terrain to the south, another with the low-lying plains to the north, and a third with a transition zone between the two. From its topography, relationships to the terrain to the north and south, spectral characteristics, and morphology of its features, it is conjectured that this transition zone was once the shoreline. The City, Face, and D&M Pyramid all lie in this zone. As either shoreline features, or even possibly islands, their proximity to water provides a possible explanation for how these once-symmetrical structures could have been transformed into their present, collapsed and highly eroded, state.

Section 2 begins by reviewing techniques for mapping terrestrial land cover in multispectral imagery. This serves as a point of departure for analyzing the THEMIS imagery over Cydonia in Section 3. A discussion of our findings in the context of the debate over the origin of the features in Cydonia is provided in Section 4. Suggested areas for future work are outlined in Section 5.
2. Spectral Analysis of Land Cover

Each pixel in a conventional black and white image is a single number representing the brightness at that point in the image. In a color image, three pixel values represent the red, green, and blue color components. Multispectral image (MSI) sensors are capable of imaging well beyond the range of human vision, beyond the red into the longer reflective and thermal infrared (IR) wavelengths. In contrast to a three band (red, green, and blue) color image, MSI sensors can collect imagery over many more bands.

Fig. 1 Landsat image of Boston MA. Landsat bands 1, 2, and 3 are show in blue, green, and red. This is close to a true color rendition of the image.

Landsat\textsuperscript{12} is a commercial terrestrial multispectral imaging system, which has been in operational use for almost a quarter of a century. It has been employed in agriculture, geology, oceanography, meteorology, and many other applications. Landsat collects images in three visible, three reflective IR, and one thermal IR band. Fig. 1 shows the first three (visible) bands of a Landsat image acquired over Boston MA.

Displaying the first three Landsat bands in blue, green, and red produces an almost true color rendition of the image. Assigning colors to different Landsat bands can show different features in the scene. For example in Fig. 2, mapping bands 2, 3, and 4 to blue, green, and red produces an image in which healthy vegetation appears red.

\textsuperscript{12} http://landsat.gsfc.nasa.gov/
Fig. 2 Landsat bands 2, 3, and 4 show in blue, green, and red. Band 4 is a reflective IR band that responds to green vegetation. As a result in this depiction vegetation appears red. Boston Common is left and slightly below the center of the image.

Fig. 3 First three principal component images shown in blue, green, and red. The interpretation of PC images depends on what is present in the scene. Here water is blue, vegetation red, and man-made features yellow. PC images provide a convenient means of assessing the spectral diversity of a scene.
Table 1 Weights (eigenvectors) for PC bands 1-3 over Boston. Bands 1-5 and 7 are the three visible and three reflective IR bands. The thermal band (band 6) is not included in this analysis.

<table>
<thead>
<tr>
<th>PC Band</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
<th>Band 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>0.203793</td>
<td>0.335072</td>
<td>0.379513</td>
<td>0.422762</td>
<td>0.516276</td>
<td>0.506849</td>
</tr>
<tr>
<td>PC2</td>
<td>-0.495493</td>
<td>-0.557065</td>
<td>-0.30868</td>
<td>-0.035521</td>
<td>0.340785</td>
<td>0.48113</td>
</tr>
<tr>
<td>PC3</td>
<td>-0.054508</td>
<td>-0.019405</td>
<td>-0.401331</td>
<td>0.851877</td>
<td>-0.329062</td>
<td>-0.040117</td>
</tr>
</tbody>
</table>

The three colors in a color image are easy to visualize in a 3-dimensional color space. Landsat has seven spectral bands (i.e., the data are 7-dimensional). A variety of techniques have been developed for analyzing multidimensional data like multispectral images. One of the most useful — the principal components (PC) transformation\(^\text{13}\) — measures the information content in an image across all bands, and combines the bands in such a way as to map the most information into the smallest number of output image bands. It does so by projecting the multispectral data into orthogonal directions in a 7-dimensional space. These principal directions or components of the data are defined by eigenvectors. Fig. 3 is a false color image composed of the first three PC image bands computed from the Boston image in Fig. 1. In general, the interpretation of PC images depends on what is present in the scene. In the Boston image water is blue, vegetation red, and man-made features yellow. Table 1 shows the weights for the first three PC bands. Each row is an eigenvector, a direction, in the multispectral data space. A PC band is a weighted sum of the data bands. If \(x_1 \cdots x_7\) are the input data ands, the first PC band is equal to:

\[
PC1 = 0.203793x_1 + 0.335072x_2 + 0.379513x_3 + 0.422762x_4 + 0.516276x_5 + 0.506849x_7
\]

and is, more or less, the average of all six bands. As noted above, Landsat band 4 responds strongly to healthy green vegetation. This is seen in the third PC band (which is displayed in red), which weights band 4 much more than the other bands.

3. Analysis of the THEMIS Multispectral Image

MSI sensors have also been used in planetary applications. In the mid1990s the composition of the lunar surface was mapped using MSI sensors aboard the Clementine spacecraft\(^\text{14}\). The material composition is determined by examining the spectral response of the surface. For example we saw above that a peak in the Landsat spectral response in the near IR (band 4) indicates the presence of vegetation.

The THEMIS data considered here (Fig. 4) consists of 8 image bands ranging from 6.62 – 12.58 microns, from the far IR into the thermal IR (Table 2). Instead of attempting to

\(^{13}\) http://planetmath.org/encyclopedia/HotellingTransform.html
\(^{14}\) http://wwwflag.wr.usgs.gov/USGSFlag/Space/clementine/clementine.html
determine the material composition over this portion of Cydonia, our goal is to differentiate material type, i.e., to map the spectral diversity of materials in the region.

Fig. 4 THEMIS MSI displayed by band

Table 2 THEMIS multispectral bands (wavelengths in micrometers)

<table>
<thead>
<tr>
<th>Band 1,2</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
<th>Band 6</th>
<th>Band 7</th>
<th>Band 8</th>
<th>Band 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.62</td>
<td>7.88</td>
<td>8.56</td>
<td>9.30</td>
<td>10.11</td>
<td>11.03</td>
<td>11.78</td>
<td>12.58</td>
</tr>
</tbody>
</table>

It is evident in the images that those parts of the scene in direct sunlight are brighter (more thermally emissive) than those in shadow. In performing a principal component analysis on the THEMIS image (Table 3) we find that PC1 is responding, more or less, to the average of all eight bands. PC2 is responding to the spatial shift between bands. (Instead of imaging all bands at the same time, THEMIS images one band at a time as it flies over the Martian surface. As a result there is a slight shift between bands. PC2 contains this component in the data.)

Table 3 THEMIS principal components analysis for Cydonia image

<table>
<thead>
<tr>
<th>PC</th>
<th>Band 1</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
<th>Band 7</th>
<th>Band 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.203793</td>
<td>0.335072</td>
<td>0.379513</td>
<td>0.422762</td>
<td>0.516276</td>
<td>0.506849</td>
</tr>
<tr>
<td>2</td>
<td>-0.495493</td>
<td>-0.557065</td>
<td>-0.308680</td>
<td>-0.035521</td>
<td>0.340785</td>
<td>0.481130</td>
</tr>
<tr>
<td>3</td>
<td>-0.054508</td>
<td>-0.019405</td>
<td>-0.401331</td>
<td>0.851877</td>
<td>-0.329062</td>
<td>-0.040117</td>
</tr>
<tr>
<td>4</td>
<td>0.065944</td>
<td>0.103374</td>
<td>0.070780</td>
<td>-0.188398</td>
<td>-0.676170</td>
<td>0.690363</td>
</tr>
<tr>
<td>5</td>
<td>-0.194396</td>
<td>-0.510968</td>
<td>0.759443</td>
<td>0.242518</td>
<td>-0.220130</td>
<td>-0.130750</td>
</tr>
<tr>
<td>6</td>
<td>0.817218</td>
<td>-0.552498</td>
<td>-0.133625</td>
<td>0.002749</td>
<td>0.058129</td>
<td>0.075217</td>
</tr>
</tbody>
</table>
PC3, PC4 and PC5 provide insight into thermal variations due to the diversity of surface materials in the scene, which are shown as a color image in Fig. 5. The images have been contrast stretched to bring out subtle differences.

Fig. 5 PC3, PC4, and PC5 mapped to green, blue, red (left). PC1 represents the average brightness across all bands (right).
Image noise generally appears in the higher order PC bands. In the THEMIS image the noise is mostly due to gain differences between photodetectors in the camera which cause a striping pattern in the along-track direction. In order to remove the striping, the image was rotated and a de-striping algorithm applied\(^\text{15}\). The resultant image was converted to an

\(\text{http://www.newfrontiersinscience.com/martianenigmas/Articles/April5anal/index.html}\)
intensity-hue-saturation (IHS) representation\textsuperscript{16}. The intensity component was then replaced with PC1, and the inverse mapping from IHS back to RGB (color) space was made. This image is shown in Fig. 6.

\textsuperscript{16} http://www2.ncsu.edu/scivis/lessons/colormodels/color_models2.html
To better visualize the spatial distribution of different spectral regions, the image is segmented into three regions based on color (Fig. 7). Color is defined here by the values in PC3, PC4, and PC5. As shown in the image, the highlands terrain is red (high PC5), the low-lying terrain to the north is blue (high PC4), and the transitional zone between the two is green (high PC3).

Recall that each row in Table 4 defines a PC image in terms of the original THEMIS bands. Each row is an eigenvector, which represents a different spectral response in the scene (Fig. 8). The response of PC5 is highest in the highland terrain. Materials in this part of the scene have a spectral peak near 8.56 microns as seen in Fig. 8. The response of PC3 is highest in the transition zone. Materials in this part of the scene have a spectral peak near 9.3 microns. The response of PC4 is highest in the low-lying terrain to the north. Materials in this part of the scene have a wide valley in their spectral response at 11.03 microns.

4. Discussion

Although there is not sufficient spectral information to identify the surface materials several tentative hypotheses can be made.

First, the spectral differences in this scene do not appear to be consistent with differential erosion. If differential erosion were responsible for sculpting these features one would expect to see two different material types: one corresponding to the overburden (the material presumably stripped away by erosive forces), the other corresponding to the more durable features (the mesas and knobs) underneath. Although the Face, City, and D&M Pyramid do appear to be spectrally similar to the highlands material, we find that thy lie in a spectrally
distinct transition zone in between the two. Laboratory analysis of Mars analog materials\(^\text{17}\) suggests that although dust layers do alter the spectrum of an underlying material, its key features (peaks and valleys) are still evident (Fig. 9). How, then can one explain the presence of a third spectral component?

Fig. 9 Curves for basaltic andesite with no dust layer (bottom), and with dust layer 46±12 microns thick (top)\(^\text{18}\).

Fig. 10 is a MOLA-derived elevation image over this part of Cydonia. Comparison between this image and Fig. 7 shows a correlation between height and spectral response. Red areas correspond to the higher topography to the south, blue areas to the low-lying plains to the north, and green areas to the boundary between the two terrains. The spectral response of the

\(^{17}\) http://astrogeology.usgs.gov/Projects/Spectroscopy/dust/dust.html

\(^{18}\) ibid.
lower terrain (PC4) is not inconsistent with that of clay materials such as montmorillonite and kaolinite, and that of the transition zone (PC3) is not inconsistent with that of an evaporite such as gypsum\textsuperscript{19}. It is conjectured that areas in blue in Fig. 7 were, at one time, below water, and areas in green were in a zone (tidal?) in which the water level changed perhaps leaving a mineral residue on the surface. That these spectral differences are still evident today suggests that conditions to support the existence of a large body of water on Mars may have persisted longer than previously thought.

Fig. 10 MOLA-derived elevations (left) over corresponding area from THEMIS image (right).

If the City, Face, D&M Pyramid, and other features did exist in close proximity to the shoreline, according to Erjavec, they would have been “subject to greater modification by eolian, fluvial and glacial processes as well as creep and mass wasting.\textsuperscript{20}” It has long been recognized that while the Face on Mars possesses a high degree of symmetry in terms of its overall structure, internally it is far from symmetrical. It became clear in the April 2000 image taken by the Mars Global Surveyor that the Face is not only asymmetrical but also highly eroded. This image provided some new clues as to why the right side of the structure


does not match the left. Verified a year later in the almost overhead, fully illuminated April 2001 MGS image, it appeared that a combination of erosion and deposition are responsible for what we see today. There are indications that internal features have collapsed and become highly eroded, like the rest of the formation. Computer-generated perspective views suggest the presence of sand dunes on the right side. It is possible that the dunes are the result of the prevailing winds scouring the western side of the Face, and depositing the eroded material on the leeward side. It has been proposed that the Face is a highly symmetrical artificial structure that has been transformed into an eroded asymmetrical landform — not unlike the neighboring mesas and buttes in this part of Cydonia — as a result of its long-term exposure to the Martian environment.

The proximity of the Face and other features at one time to a large body of water provides a plausible explanation for their present condition. Future work should attempt to determine the composition of these features and other surface materials in Cydonia.

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