MARTIAN VOLCANIC AND SEDIMENTARY LAYER STUDY: MORPHOLOGIC AND MORPHOMETRIC CRITERIA FOR DIFFERENT ORIGINS.

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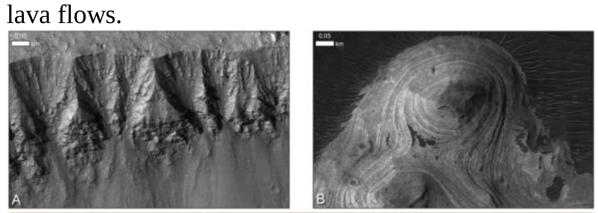
Introduction: Stacks of layered rocks are observed in many different Martian geological settings, exposed in scarps and crater walls that cut surface materials. Two principal processes, effusive volcanism and sedimentation, can lead to formation of the layered sequences. Thus, just the observation of the exposed layered structure is not sufficient for the interpretation of the main processes that were responsible for the formation of the terrain in question.

In order to characterize layered suites of different origin we conducted a systematic analysis of high-resolution images of CTX and HiRISE (Context Camera and High Resolution Imaging Science Experiment) in key regions. These included several certainly volcanic provinces (Olympus, Ascreus, Pavonis, and Arsia Montes, and Alba Patera) and those that show layered deposits of the delta-like fans in craters Gale, Holden, and Eberswalde. In our earlier study, we did note that the fine-scale details could not be identified from the poorer resolutions (up from ~4.5 m/px), although the coarser characteristics were identified up to THEMIS-VIS resolution [1]. For the key locations, we selected the HiRISE images with the highest resolution (~0.26 m/px) that showed abundant layers. We believe that the layers exposed in these sites represent the volcanic and sedimentary end-members of a variety of possible modes of origin of layered sequences and can be used as a foundation for morphologic and morphometric identification criteria. The developed criteria were used for several test sites with encouraging results.

Morphologic criteria: As the typical volcanic provinces, sites with exposed layering from the large volcanoes were selected. In these regions, we analyzed images from the caldera walls as well as from impact craters near the central calderas. The sites showed abundance of thick stacks of layers, interpreted as volcanic lava flows. In all sites, the stacks of lava show remarkable similarities to each other. The most prominent features of the walls are their spur and gully pattern of erosion in the upper part and extensive talus aprons that cover about two thirds of the lower portions of the walls (Fig. 1a). The spurs and gullies occur at different scales up to the largest (hundred meters scale) seen in the MOC and THEMIS images. Due to this pattern, the outer edge of the layers appears to be highly serrated. The HiRISE images (resolution 0.25-0.5 m/px) show that layers are highly disrupted and consist of rounded and plate-like blocks meters to tens of meters across that give the layers very rough appearance.

The sedimentary provinces on Mars are not as obvious and the end-member sites for these environments should be selected with caution. Interiors of Gale, Holden and Eberswalde craters that are interpreted as locations where sedimentary rocks formed within the possible crater lakes [e.g. 2-14] were chosen.

The rhythmic sequences consisting of numerous lighter and darker layers characterize the deposits on the floor of these craters (Fig. 1b). The walls of the deposits are smooth and gently winding and they lack extensive talus aprons. The deposits are heavily degraded and demonstrate cliff-and-bench pattern of erosion. The characteristics of the deposits are consistent with the horizontal emplacement of fine-grained and low-strength materials in broad regions and may be indicative for the aqueous or sub-aqueous deposition [6]. Regardless of the specific mode of origin, the layered sequences of the analyzed delta-like formations of Gale and Holden craters are significantly different in their morphology from those related to emplacement of lava flows.



Volcanic layers		Sedimentary layers
Yes	Spurs and gullies	No
Yes	Serrated outline	No
Yes	Talus aprons	No
Yes (irregular)	Blockyness	Yes (regular)
No	Stair-steps or cliff-bench	Yes
No	Rhytmic layers	Yes
No	Smooth walls	Yes

Fig. 1. Examples of end-member morphologies. A) Olympos Mons, Pangboche crater wall; B) Holden crater delta-like fan layers. **Table:** Morphologic criteria based on the characteristics of both end-member type layering.

The characteristics of both end-member types are presented in the Table 1. These were checked in the chosen test sites, and in regions of likely volcanic origin (Syrtis Major, Lunae Planum, Hesperia Planum, Harmakhis and Dao Valles, Nili Fossae, and Noctis Labyrinthus) the layered structure of their interiors is well presented, and it displays the same features that characterize the walls of the calderas of the large volcanoes. The remarkably similar characteristics of the layered sequences of the volcanic regions reflect the basic properties of lava flows that form brittle and coarse-grained layers of different thickness, which were emplaced episodically and locally. Also, sedimentary test sites (Terby, Jezero, Galle craters) followed the morphologic criteria nicely with similar layer characteristics as the end-member examples.

Morphometric criteria: In addition to the morphologic characteristics we studied the end-member site layering seeking for morphometric quantities that can help to discriminate the layers of different origin. We noted that the most obvious difference between the volcanic and presumably sedimentary layers is the degree of their sinuosity. Sinuosity represents the pattern of erosion of the layers and probably depends upon the characteristic grain size of materials that compose the layers.

Within each HiRISE image all exposed layers were mapped and morphometric parameters collected: (1) Total length of the exposure ("true" length, or number of pixels); (2) Total sinuosity (ratio of the total length to the length of a straight line connecting the first and the last pixel of the mapped exposure); (3) Length of the exposure measured by a set of straight rods whose length changed from 2 to 128 pixels; (4) Mean local sinuosity $((1/n)*\Sigma(l_i/r)$, where n - number of measurements, l_i - "true" length of a portion of the exposure between the beginning and end of a measuring rod, of specific length r). In the analysis of the end-member and test sites, we used only the dimensionless parameters such as total and local sinuosity. The total sinuosity includes the short- and long wavelength components of the shape of the exposure. Because of this, the characteristic values of the total sinuosity of the volcanic and "sedimentary" layers overlap each other significantly and this quantity alone is poorly sensitive for discriminating of the layers.

In contrast, the mean local sinuosity gives a spectrum of values reflecting the shape of layers for different wavelengths. In general, the power of spectra for the layers of the volcanic sites rapidly increases as the size of the measuring rod increases. For the layers of the delta-like fans, the spectra are much flatter and often the power of the spectra decreases as the length of the rod increases. In many cases, entire spectrum for a specific layer consists of two parts separating by a prominent break in slope.

Analyzing these spectra, we defined the short wavelength (measuring rod 4-16 px, 1-4 m) and the long wavelength (measuring rod 17-127 px, 4-32 m) components of the spectra and determined the characteristic slope of the spectrum for each component. Most of the end-member volcanic layer sites (black circles in Fig. 2) are in the field of positive values of the slopes. This means that the short- and long wavelength sinuosity of the volcanic layers increases as size of the measuring rod increases. Layers from the delta-like fans are clustered around zero-slopes and often display negative values of the slopes for both the short- and long wavelength components of spectra (black crosses in Fig. 2).

Characteristic points of the layers from the test sites selected in likely volcanic regions all fall into the field of the volcanic sites (red squares in Fig. 2). Layers from the delta-like fans in Terby and Jezero crater test sites occur in the cluster of points characterizing the sedimentary sites (green squares in Fig. 2). However, layers from Galle crater test site show wide range of the slope values and most of the points are in the field corresponding to the volcanic sites (purple squares in Fig. 2). This suggests that although the characteristic slopes of the sinuosity spectra appear as good discriminating factor, additional criteria are necessary for more robust distinguishing between the layered sequences of different origin.

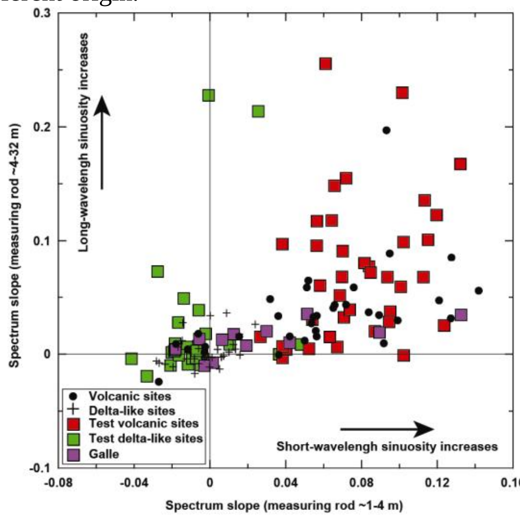


Fig. 2. Diagram of the short- (1-4 m) vs. long wavelength (4-32 m) spectrum slopes for layered sequences of different origin.

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