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Mars periglacial punctual features analyses

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ABSTRACT

The presence of patterned grounds on Mars has been reported in several papers, especially the study of polygons distribution, size and formation processes. In the last years, the presence of basketball terrains has been noticed on Mars. Studies were made to recognize these terrains on Mars through the analysis of Mars Orbiter Camera (MOC) images. We have been developing an algorithm that recognizes automatically and extracts the hummocky patterns on Mars related to landforms generated by freeze–thaw cycles such as mud boils features. The algorithm is based on remote sensing data that establishes a comparison between the hummocks and mud boils morphology and size from Adventdalen at Longyearbyen (Svalbard—Norway) and hummocky patterns on Mars using High Resolution Imaging Science Experiment (HiRISE) imagery.

1. Introduction

Some areas on Mars described as basketball-textured terrains (Malin and Edgett, 2001; Head et al., 2003) have been characterized based on shape, size and texture. Malin and Edgett (2001) mentioned the presence of basketball textured surface amid north polar dunes at 78.5° N, 215.7° W, on MOC image ♯M01-00063. They commented that the periglacial processes appear to have modified the upper plains surfaces in many regions, creating several types of features such as small polygons, extremely large polygons on the floors of some craters, boulder-bounded polygons near Lyot Crater, and bumpy and ridged textures that resemble the surfaces of basketballs and corduroy fabric. Head et al. (2003) considered that the basketball terrain and its variants, and polygons, represent the net effect of long-term orbital variations on relatively stable, debris-covered ice-rich deposits. Mangold (2005) cited the presence of hummocky terrains on Mars at MOC image ♯M03-04266, (54.1° S, 229.5° W) associated with large and random orthogonal-type polygons and classed them as S3 type (smaller than 15 m) of patterned ground. This classification only corresponds to a size, not to a single process. Most of S3 type would be degraded polygons in pure cold conditions, not potential hummocks or mud boils. These degraded polygons show a basketball texture type formed by the desiccation of ground ice and the effect of ice sublimation (Mangold, 2005). Most polygons on the surface of Mars are mainly formed by thermal contraction. Mangold (2005) mentions a few landforms on Mars whose formation may couple to freeze–thaw cycles, such as large homogeneous polygons on crater floors, some of the small polygons with very homogeneous patterns, polygons associated with stripes and striated soils on hill slopes.

Levy et al. (2009) made a morphological comparison of cold-desert landforms at the Phoenix landing site (68.21 N, 234.25 E) with those found across a variety of microclimate zones in the Antarctic dry valleys. His work refers that thermal contraction and sublimation, in the absence of near-surface melting, is the dominant process operating at the Phoenix landing site today and that climate conditions measured at Phoenix are inconsistent with the development of wet landforms.

According to Laskar et al. (2004), thermodynamic conditions for ice melting would have never been met in the last 3 M. These authors calculated that the maximum temperature in the northern plains ("or elsewhere on Mars for that matter") would not have surpassed 255 K. This reasoning is right for the thermodynamic properties of pure water, not brines. Rennó et al. (2009) found possible physical and thermodynamical evidence of the presence of liquid water at the Phoenix landing site. These authors also show that the thermodynamics of freeze–thaw cycles can lead to the formation of saline solutions with freezing temperatures lower than current summer ground temperatures at those latitudes. Rennó et al. (2009) conclusions are consistent with the finding of perchlorates on the soil of the same site (Hecht et al., 2009) and may explain the formation of recurring slope lineage (McEwen et al., 2011), which grow during warm seasons and fade in cold seasons, albeit at lower latitudes (48° S–32° S).

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Johnsson et al. (2011) compared lobate forms from Adventdalen valley (Svalbard) and two Martian impact craters, which display particularly well-defined lobate forms and concluded that the presence of lobes on Mars may be an indicator of a freeze and thaw process. The seasonal thaw may have existed in local environments such as the interior of craters or on hill slopes (Johnsson et al., 2011). A credible mechanism to supply moisture for freeze and thaw cycles may be the melting of water-rich snow that has been transported from the poles to mid-latitudes during periods of high obliquity within the past 10^5–10^6 years (Costard et al., 2002; Christensen, 2003).

Doubts remain over the spatial distribution and origin of Martian hummocky patterns related to freeze–thaw cycles and even on the presence of hummocks and mud boils on Mars. Due to the fact that such features are of metric scale, their remote sensing analysis was not possible until recently. Some landforms on Mars, namely large homogeneous polygons on crater floors have been associated to hummocks (Mangold, 2005), although on a decameter scale. Recall that Mangold's (2005) work is based on Mars Global Surveyor (MGS) imagery, whose best resolution (on narrow-angle mode) is of 1.5 m/pixel (mpp). Today we have access to High Resolution Imaging Science Experiment (HiRISE) of Mars Reconnaissance Orbiter (MRO) images of 0.25 mpp resolution. Furthermore, super-resolution of HiRISE stereo pairs should be able to yield images of resolution better than 0.15 mpp (Alves et al., 2010). These resolutions ought to be enough to detect hummocks and mud boils of comparable dimensions to those on Earth.

The origin and evolution of periglacial features on Earth are associated to water phase transitions, namely freeze–thaw cycles, and their effective detection on Mars could be signatures of liquid groundwater seasonal presence and useful for understanding Martian climate, hydrology and potential biological niches.

To map the hummocky pattern surfaces related to freeze and thaw cycles on Martian terrains, we have developed an algorithm to automatically extract these features from remote sensing imagery, geometrically and texturally characterizing them in the process. Besides mapping the features, it is essential to understand the freeze and thaw mechanisms involved in their features formation. For this, we need to understand very well the Earth hummocks and mud boils complex genesis, extending this knowledge to the Mars climatic environment coupled to simulations of periglacial processes in the laboratory.

Earth hummocks and mud boils have received much research interest, perhaps because they develop in a variety of environments and are widespread in both permafrost and seasonally frozen regions. Recent studies (Boike et al., 2008;Grab, 2005; Peterson and Krantz, 2008; Walker et al. 2004, 2011) have made considerable advances in helping to understand the polygenetic nature of Earth hummocks and mud boils and have promoted their value as contemporary and paleoenvironmental indicators. However, our current understanding of the genesis of these small cryogenic landforms is still incomplete. Further detailed clarification concerning the permafrost functions and seasonal freeze and thaw cycles is required in discussions concerning Earth hummocks and mud boils initiation.

The expression “mud boil” has been widely used, although this term is problematic considering that often no evidence of active frost boiling is present in the central portion of these features (Walker et al., 2004). Terms such as frost medallion and frost scar have also been proposed to avoid implying a specific genesis.

The formation of hummocky terrains on Mars probably involves freeze–thaw cycles as on Earth. Some authors (Russell et al., 2003; Schorghofer and Aharonson, 2003) identified the crater floors or poleward facing slopes as specific locations for water ice stability and deposition of ice. Seasonal thaw may result from the melting of water ice in the top few meters of the Martian subsurface at high obliquity (Costard et al., 2002). Hecht (2002) proposes a model that the liquid water in the ground would be stable enough time before being sublimated, which could supply moisture to thaw cycles.

Hummocks and mud boils distribution on Earth is well known (Grab, 2005; Peterson and Krantz, 2008), nevertheless, their genesis, especially in the case of the mud boils, still raises some doubts: (1) Are hummocks and mud boils essentially different? (2) If so, are their differences of geomorphological, hydrological, climatic or other origins? (3) What is the water phase role in the features evolution during the freeze and thaw periods? (4) What is the role of biological processes on the features genesis and evolution? and (5) What are the features' relations with other periglacial geoforms, such as polygonal terrains? We hope that the study of Earth periglacial features may assist us on answering all or nearly all questions mentioned and that we can apply the acquired knowledge to better understand Martian periglacial features formation. The Earth analogous study can guide us to comprehend the any freeze–thaw possibility on Mars.

Earth hummocks and mud boils are formed by several interacting mechanisms including but not limited to differential frost heave, frost cracking, mass displacement and sorting processes (Walker et al., 2004). The most widely accepted model for Earth hummocks and mud boils development is the differential frost heave (cryoturbation), which is induced through differences in ground temperature or moisture conditions (Williams and Smith, 1989; Van Vliet-Lanoë, 1991).

The current understanding of the studied periglacial landforms genesis needs additional clarification concerning the functions of permafrost and seasonal freeze. Long-term monitoring studies on Earth hummocks and mud boils, and their physical modeling through laboratory simulations, may help us to improve our current understanding of the process dynamics operating on these landforms.

The present work aims to develop an algorithm that recognizes automatically and extracts the hummocky patterns on Mars related to landforms generated by freeze–thaw cycles such as mud boils features. The algorithm is based on Earth analogs (Adventdalen area, Svalbard).

2. Methods

The rationale of our methodology is that if we have the most comprehensive knowledge possible on Earth mud boils and hummocks, namely their genesis, evolution, characteristics, and differences, if any, we may be able to identify and distinguish these features on Mars high-resolution imagery. So, our work proceeds along two lines: first we try to characterize as completely as possible Earth mud boils and hummocks; then we use the knowledge acquired in the first step to identify, and possibly distinguish, mud boils and hummocks on Mars imagery.

To characterize and distinguish Earth mud boils and hummocks we began by mapping the spatial distribution of periglacial features on Longyearbyen, using GPS, aerial photos, and satellite data, while geometrically describing features on parameters such as size, shape, and composition based on field notes. Field work at Svalbard allowed us to sample mud boils in order to sedimentologically characterize the soil, namely in grain size distribution, sphericity, roundness, and mineralogy (using the X-ray diffraction facilities at Federal University of Rio Grande do Sul—UFRGS—Brazil). To assess the role and dynamics of fluids in the formation of these features, we intend, on future field missions, to perform 3-D resistivity imaging (e.g. Kneisel et al., 2009) using our Center's IRIS SysCal equipment to acquire resistivity data in high resolution Wenner configuration grids (0.2 m electrode spacing) covering well-defined, individual hummocks and mud boils, and also to acquire longer, lower-resolution, Wenner profiles with (2 m electrode spacing) linking polygonal terrains and areas dominated by mud hummocks and boils. With this technique, we expect to very accurately characterize the distribution of water phases within and among hummocks and mud boils. At the same time, we are trying to physically model Earth hummocks and mud boils formation in our laboratory, the first Portuguese periglacial features modeling lab, equipped with a fast (1 h) cycling Peltier effect (Nolas et al., 2001) cooling/heating plate, by varying relevant parameters, such as sediment grain size and composition, water content, or pre-existing structures either in the sediment or its bedrock (see Section 3).

To extrapolate our Earth observations to Mars we have acquired images of Svalbard periglacial punctual features fields on two scales: close-up at ground level and at 100 m altitude (Norwegian Polar Institute—NPI). Identified hummocks and mud boils on these images are downsampled to HiRISE resolutions (0.25 and 0.50 m per pixel—mpp) to form a database for image super-resolution (see Section 4) and, finally, training our automatic recognition algorithm based on Barata et al. (2004).

The grain size analysis of the mud boils soil samples were performed at Laboratory of Sedimentology of the University of Coimbra. These analysis were made using a Coulter LS320 (2 mm to 0.04 μm) laser granulometer, which allowed computing grain-size particle distributions in volume and statistical parameters. The vegetal particles found in the soil samples were removed by hand before performing the analysis.

3. Results and discussion

3.1. Hummocks and mud boils from Adventdalen

The studied Earth hummocks and mud boils are located in Adventdalen area, Spitsbergen Island (Svalbard Archipelago) (Fig. 1A, B), ~30 km long and ~4 km wide U-shaped valley. It extends eastward from Svalbard's main town Longyearbyen (78°13′00″N, 15°38′00″E).

Hummocks are closely spaced mounds composed of silty soils and covered with a continuous blanket of vegetation. They occur outside of polygons and in much less quantity than mud boils. Their height varies between 0.10 and 0.35 m and the diameter between 0.15 and 0.50 m.

Most studied mud boils are not located within well-delimited polygons. They have a maximum diameter of about 3 m, with average diameter of 0.50–1 m. They are rounded, abundant, distributed in various degrees of development and show sparse vegetal coverage around shallow depressions that form the rims (Fig. 2). The central areas are slightly elevated (0.10–0.50 m) and cracked (Fig. 2), dominated by fine silty soil fraction and little organic matter. Pebbles with diameters between 0.05 and 0.15 m (Fig. 3) are randomly distributed on the elevated surfaces.

Fig. 2. Mud boil in Adventdalen area, Spitsbergen Island, Svalbard.

Fig. 3. Details of mud boil at Adventdalen area (Spitsbergen Island) with clasts/blocks expelled during the freeze and thaw cycles.

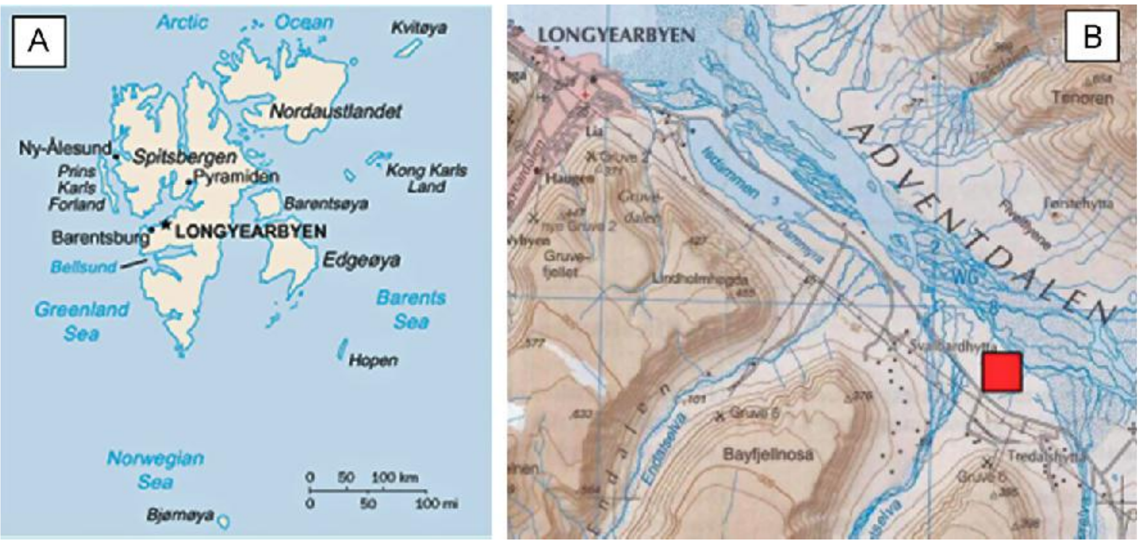

Fig. 1. A: Location of Svalbard Archipelago, B: field site (red square) in Adventdalen area topographic map by the Norwegian Polar Institute. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The vertical elevation in the central portion of the mud boils suggests some vertical movement.

Mud boils that are contained within polygons display lighter color, less rounded shapes, are composed by barren soils and do not show an elevated center or pebbles. They may represent an early mud boil phase formation.

3.2. *Soils analysis of hummocks and mud boils from Adventdalen*

Goldthwait (1976) defined the sedimentary prerequisites for the development of patterned ground as primarily being the existence of poorly sorted, heterogeneous sediments with a relatively high amount of silt and clay (more than 15%). According to Washburn (1980), the amount of silt and clay is important for effective frost heave and frost sorting.

The mud boils are generally associated with fine and medium textured soils, and are uncommon in coarse-textured sandy and gravelly soils. The development and maintenance of mud boils is heavily dependent on soil properties (Walker et al., 2004). Thereby, the soil characteristics such as water content and distribution, texture and depth to permafrost become important to hummocks and mud boils expression and persistence (Michaelson et al., 2008).

The grain size analyses of mud boils soil samples from Adventdalen show that the samples are very similar and corresponding to fine-grained sands to medium silts, with negative asymmetry (excessive fine material) and poorly sorted (except one sample). These characteristics are typical of loess-type sediments resulting of low-energy aeolian transport, attending to the average dimension of grains, aeolian transport with a velocity of $\sim$2 ms^{-1}, 0.01 m above ground can be inferred. The most different sample shows finer grain size, worst sorting and higher clay content, suggesting some degree of hydrolysis. It probably indicates a mixed deposition in aquatic environment, probably a drenched zone.

The mineralogical composition of soils is controlled by the mineralogy of local deposits, climatic conditions, and the effect of permafrost (Alekseev et al., 2003). The chemical weathering of some minerals within the active layer and the crystallization of others at the cryogenic barrier, as result of weathering, show us that the geochemical processes are strongly influenced by the permafrost table. The boundary between the seasonally thawing soil and the permanently frozen ground is an important geochemical barrier, which can work as a tool to study the formation of hummocks and mud boils formation. Because of this, we consider important to have a control of the mineralogical composition of hummocks and mud boils soils, especially of the variations along soil profiles.

The mineralogy found in the studied mud boils soil samples (centers and rims) and adjacent polygons rims, do not show significant differences. The soil mainly consists of secondary minerals: illite, kaolinite, and chlorite according to X-ray diffractometry analysis (Fig. 4). These minerals are a product of chemical weathering caused by water action due the moisture present in the mud boils soil. Our analyses also suggest the presence of primary minerals such as quartz, K-feldspar and plagioclase (Fig. 4). The constant water supply from reactive snow together with the melting of the permafrost water favours the chemical weathering, at least in the late spring. The kaolinite may be formed by chemical weathering of K-feldspar and plagioclase (hydrolysis process), that needs minimum moisture content to occur. Illite may be a weathering product of K-feldspar, and chlorite of plagioclase. The persistent low temperatures during the year in the area do not contribute to a significant chemical weathering.

It is necessary to make additional X-ray diffractometry analysis in layers of a soil profile to check for possible mineralogical changes that could be associated to freeze and thaw cycles. The mineralogical changes in the soil can be an important tool to investigate the presence of thaw cycles on Mars in the future, when sample collection is possible.

3.3. *Comparison between Martian and Earth hummocky terrains*

We have made the visual comparison using selected HiRISE images (Figs. 5–7) and aerial photos from the studied area in

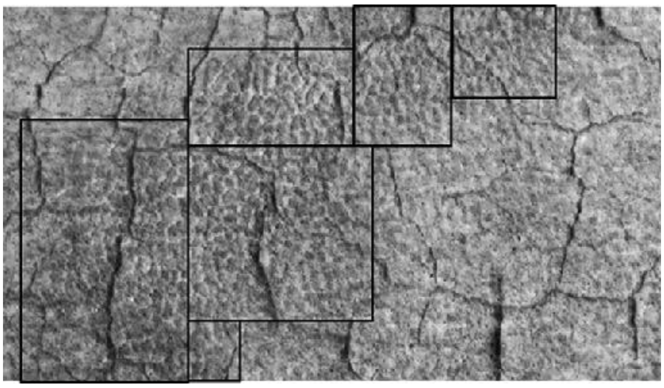

Fig. 5. Polygon network and hummocky terrain in Western Utopia Planitia (PSP_010034_2250; 44.5° N; 87.9° E) (0.50 m/pixel; North is up).

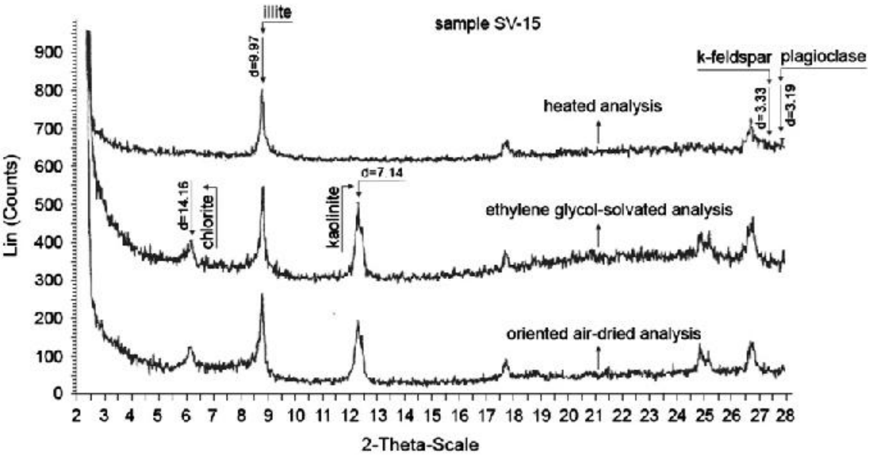

Fig. 4. X-ray diffractometry patterns of primary and secondary minerals from a mud boil soil sample.

Adventdalen (Fig. 8). The photos from Adventdalen have very high resolution. They were made by Norwegian Polar Institute using an Ultracam-XP of four spectral bands (RGB+NIR) and a ground sampling distance of 0.20 m. They allowed visualizing polygons with 1 m of width with a few centimeters of spatial resolution (0.04–0.06 cm). The photos were obtained by compact camera set on board of a remotely controlled airplane.

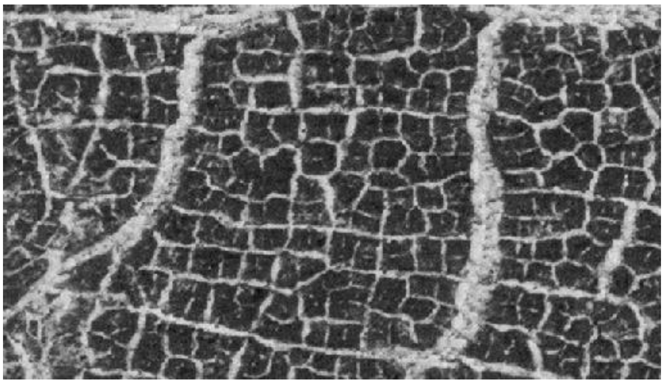

Fig. 6. Polygonal features and hummocky terrain (ESP_015942_2445; 64.3° N; 70.4° E) (0.25 m/pixel; North is up).

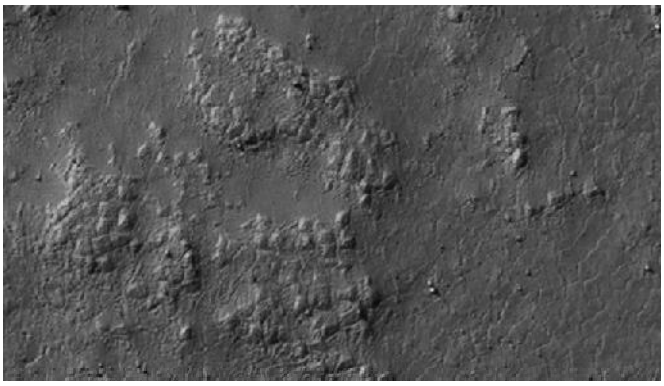

Fig. 7. Hummocky terrain and polygonal textures (PSP_006605_1260; 53.9° N; 130.8° E) (0.25 m/pixel; North is up).

The images comparison coupled to fieldwork data, suggests that almost all Martian hummocky terrains (Fig. 5) would be located within large well-delimited and/or randomly orthogonal polygons (Figs. 5, 6). Those features on Adventdalen area usually appear outside polygons (Fig. 8). The Martian potential hummocks and/or mud boils are much bigger (Fig. 7) than corresponding Earth features, 1–15 m (Mangold, 2005) versus 0.50–3 m of diameter in Adventdalen area (Fig. 8). Pronounced ridges (Fig. 6) limit some large and randomly orthogonal polygons on Mars that may contain hummocks and/or mud boils. Some Martian hummocks and/or mud boils seem to present a lighter color in some portions of the surface (Figs. 5, 6). This could be related to concentrations of ice lenses.

The visual identification of hummocks and mud boils on Mars using MOC and HiRISE images is difficult. We believe that our algorithm may be able to automatically identify the periglacial features on Mars using the morphology and size data, and will be useful in the identification of Martian hummocky terrains.

4. Mud boils recognition on HiRISE images

4.1. Recognition

Since mud boils on Earth are seldom wider than 2 m their recognition on Mars would be very difficult, even with the best HiRISE resolution of 0.25 mpp.

The problem of recognizing a mud boil in an image is not unlike that of recognizing a human face in a scene.

Since mud boils still are not known to display recognizable relevant, constant features, their recognition must be performed by some variation of template matching. This approach, however, faces another problem: that of finding appropriate templates.

Such problem was also dealt with, and solved, in the facial recognition community, by introducing the concept of eigenfaces (Turk and Pentland, 1991), which corresponds to the principal

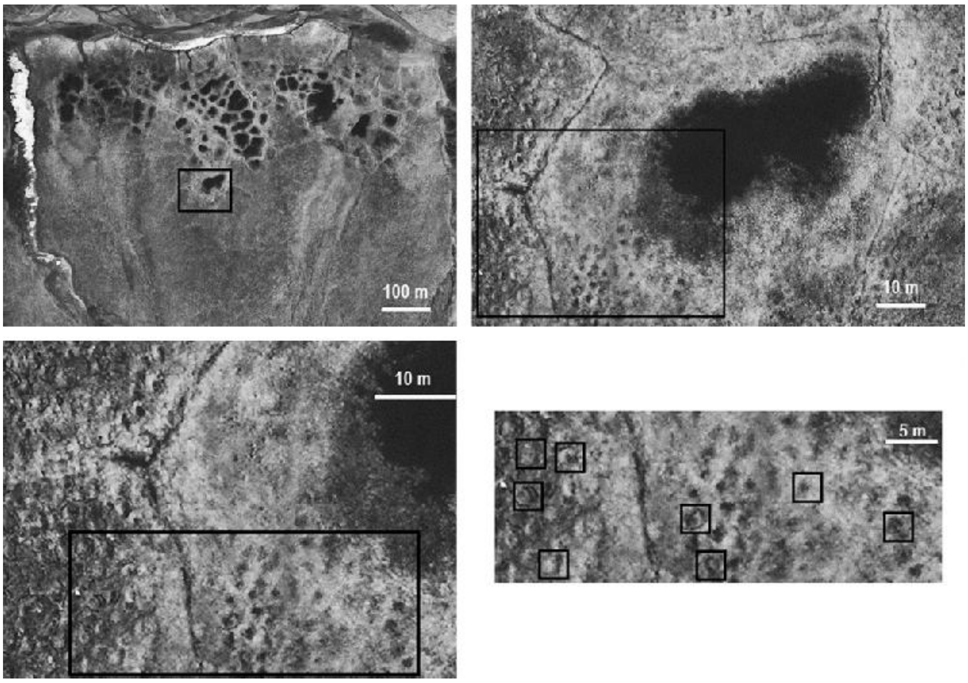

Fig. 8. Image sampling area: periglacial terrain at Adventdalen, Svalbard.

components of the distribution of faces—the eigenvectors of the covariance matrix of the set of face images. Each individual face in the training set (the set of face images used to build the eigenfaces) can be exactly represented as a linear combination of the eigenfaces.

One of the main advantages of this approach is that it can be greatly simplified because our purpose is not to recognize a specific mud boil (as is generally the case in face recognition applications) but only to identify if our test image is indeed a mud boil or not.

There is still another problem which has to do with the different resolutions of the template Earth mud boil database, typically 0.05 mpp, and the problem Mars image database, at best 0.25 mpp. To deal with this problem we resort to an image up-sampling or, as is more widely called, super-resolution technique.

4.2. Super-resolution

Super-resolution (SR) is a set of signal processing techniques to obtain a high-resolution (HR) image from observed low-resolution (LR) images (Park et al., 2003). Super-resolution methods can be divided into two main groups: time varying imagery SR (TVSR-using several images of the same scene) and time invariant imagery SR (TISR-using a single image).

Super-resolution techniques have already been used to process Martian imagery: for the petrogenetic interpretation of rock textures at the Pathfinder landing site (McSween et al., 1999) and for enhancing Mars Exploration Rovers panoramic images (NASA, 2010).

As a naive working hypothesis we can say that the "best" interpolated image is the one which:

(a). Has at least the same information content as the original image;
(b). Is efficiently computable (i. e. using reasonable hardware produce results in a reasonable amount of time);
(c). Is smooth (i. e. mappable to a twice continuously differentiable function);
(d). Does not exhibit artifacts (low-frequency features not present in the original scene that were produced by the interpolation method, such as blocking, ringing, aliasing or blurring).

All image processing packages include routines to interpolate images respecting conditions (a) and (b) above, but do not respect conditions (c) and/or (d).

The implementation that will be used in the present work is based on the so-called Lánczos resampling algorithm (Duchon, 1979).

The Lánczos filter is defined as:

$$L(x) = \begin{cases} \operatorname{sinc}(x)\operatorname{sinc}(x/a), & -a<x<a \\ 0, & \text{otherwise} \end{cases}$$

where the $\operatorname{sinc}(x)$ function is

$$\operatorname{sinc}(x) = \sin(\pi x)/(\pi x).$$

4.3. Our algorithm: eigenboils

The eigenboils procedure aims to help decide whether a feature on an image of the surface of Mars is a mud boil or not. To that purpose two steps must be taken: upscaling the image

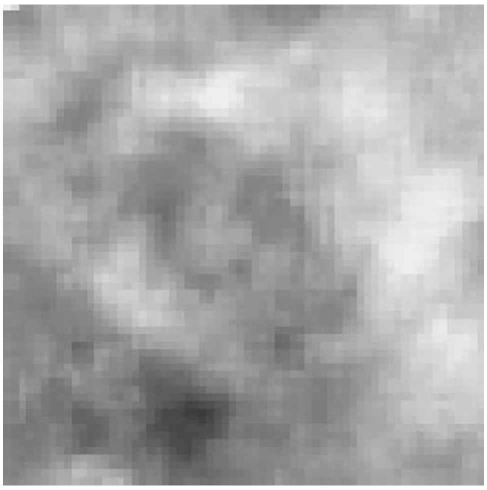

Fig. 10. The average mud boil. Image side: 64 pixels, ~3.2 m.

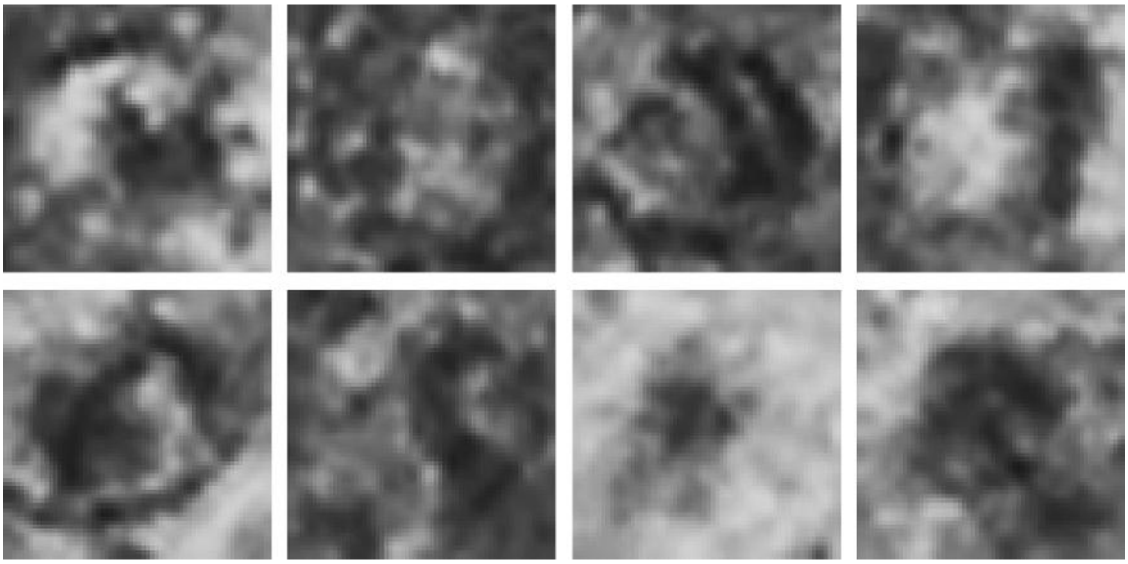

Fig. 9. The eight sampled training images containing mud boils, which were identified in our field work. Image side: 64 pixels, ~3.2 m.

problem feature, and comparing the upscaled image with a database of images of Earth mud boils.

Our algorithm can be thus described:

Given m Earth training images ($E_1, E_2, \ldots, E_m$) of known mud boils, $n \times n$ pixels in size, with p meters per pixel resolution, and a problem image F, with q meters per pixel resolution, $np/q \times np/q$ pixels in size:

(1). Choose training image set (Figs. 8 and 9);
(2). Compute the training set mean vector, or "average boil" (Fig. 10);
(3). Compute boil-space principal components: the eigenvectors of the covariance matrix of the training set ("eigenboils") and preserve those which account for the largest eigenvalues (Fig. 11);
(4). Rescale image F by q/p, using Lánczos transform, producing a super-resolved F' image (Fig. 12).
(5). Compute the difference between test image and average boil; stretch its histogram (Fig. 13);
(6). Project stretched image onto each eigenboil (Fig. 14);
(7). Project stretched image onto boil-space (Fig. 15);
(8). The histogram of the projection evidences statistics of the distance between test image and training set.

The projection can be viewed as an image and as such its gray values can range between all black—a case where there would be no difference between each pixel of the test, super-resolved image, and the boil-space: a "perfect mud boil" and all white—a case where every pixel would be different: "not a mud boil".

The results shown in Figs. 9–15 intend to be a proof of concept, meant to show that the methodology is sound and can work "in the field", supported by large databases of Mars problem mud boils and Earth mud boils.

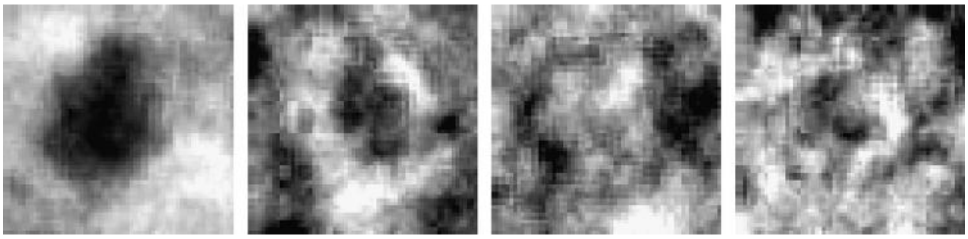

Fig. 11. Four principal components, or eigenboils, in the eight training images, which account for 79.6% of inter-image variance. Image side: 64 pixels, ~3.2 m.

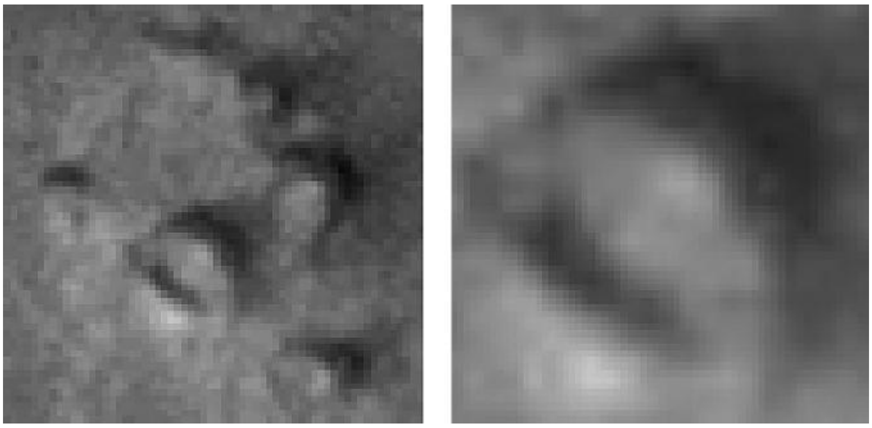

Fig. 12. Sample of HiRISE image ESP-011816-2300_RED (0.50 mpp) (left). Test image, triple resolution (0.17 mpp) of possible mud boil (right). Image side: 64 pixels, ~3.2 m.

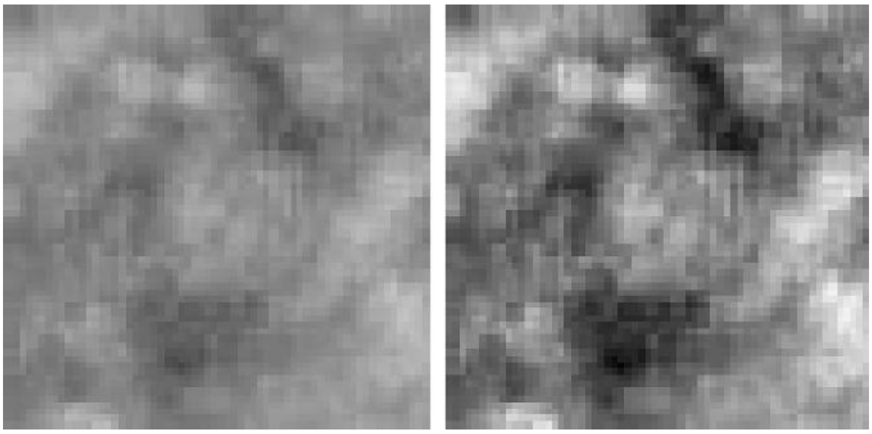

Fig. 13. Difference between test image and average boil (left). Same with stretched histogram (right). Image side: 64 pixels, ~3.2 m.

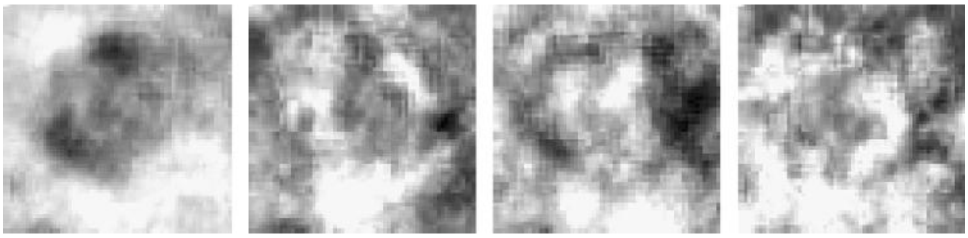

Fig. 14. Projections of test image onto each eigenboil. Image side: 64 pixels, ~3.2 m.

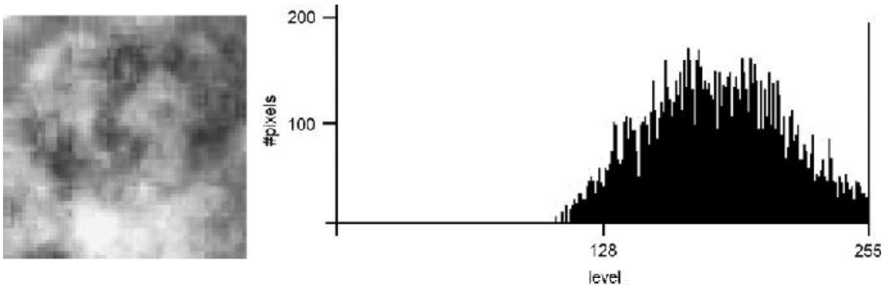

Fig. 15. Projection of test image onto boil-space (left), and its histogram (right). Image side: 64 pixels, ~3.2 m.

5. Conclusions and future work

For the detailed study of periglacial features, we suggest that long-term monitoring studies on Earth hummocks and mud boils may help improve our current understanding of the dynamics operating on morphologically similar landforms in dissimilar ground environments and use the detailed terrestrial geoforms mapping to start investigating the Martian periglacial features.

The information just described, together with new data to be collected in 2012/2013, will be used to develop an algorithm for the detailed automatic characterization of Martian hummocky terrains so as to distinguish, identify and characterize hummocks and mud boils according to their size, shape and texture.

We are not sure to find true hummocks and mud boils on Mars; nevertheless, at the work completion, we will have to contribute to improve the knowledge on hummocks and mud boils genesis, and develop a software package to analyze automatically the information produced by HiRISE imagery, based on the prototype eigenboils algorithm.

If we are to effectively recognize hummocks and/or mud boils on Mars, based on Earth images, improvements must be made, namely on the decision about the degree of similarity between test images and the training set. We hint on a possibility with the use of the test image's projection histogram, which can provide the basis for a probabilistic degree of belonging.

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