Title: Fluids mobilization in Arabia Terra, Mars: depth of pressurized water table from mounds self-similar clustering

Abstract

Arabia Terra is a region of Mars where the occurrence of past-water has been recorded with several landforms indeed recognized, mapped and used to indirectly infer models of fluid circulation. This is the case of the mounds found in Firsoff crater and two nearby unnamed craters resembling terrestrial fluid expulsion-related morphologies, testifying the occurrence of pressurized deep fluid reservoir.

In this work we apply a new landform analysis to retrieve an accurate mapping of putative mud volcanoes which are subsequently analyzed through spatial clustering. The fractal clustering of mapped mounds yielded information about the possible thickness of the percolating fracture system below the craters' floors and, consequently, the depth of the fluid reservoir which has been fixed underneath all carters between ~2.5 and 3.2 km. Hence, we foreword a unique process linking fluid sourcing from mounds and fissure ridges: we propose a fluid expulsion process that accounts both for the presence of mounds and fissure ridges as a responsible for creation of large scale spring deposits.

1 Introduction

Fluid expulsion-related morphologies on Earth form when deep thick sedimentary sequences undergo high pore fluid pressures conditions, that are often triggered by compaction through loading or tectonic deformation such as crustal shortening and often exploit pre-existing fracture networks (e.g. Dimitrov et al., 2002; Kopf, 2002; Skinner and Mazzini, 2009; Bonini et al., 2012; Oehler and Etiope, 2017). They are inferred to be the surface expression of deeply rooted vertical structures where sediment extrusion is driven by a mobile fluid fraction (water, hydrocarbons, gas), migrating upward from reservoirs up to several kilometers deep (Deville et al., 2003).

Putative mud volcanic fields on Mars were spotted in several areas (Arabia Terra, Acidalia Planitia, Isidis Planitia, Utopia Basin, Chryse Planitia and Galaxias Phossae) presenting both pitted cones and smooth mound morphologies, both (Skinner and Mazzini, 2009; Oehler and Allen, 2010; Komatsu et al., 2015; Okubo, 2016) and are often associated to impact craters (e.g. in Arabia Terra Firsoff and neighboring craters but also in the large Hellas basin, where pitted mounds are present). Fluid expulsion may involve clastic (i.e., mud volcanism) or evaporitic depositional processes (i.e., spring mounds).

The favored hypothesis for the formation of large mud volcanic fields, such as Acidalida and Chryse Planitia presenting more than 18.000 pitted cones, is the interplay between high-rate deposition of sediments carried by outflow channels and compaction (Tanaka et al., 2013a). These processes generate high pressure at depth and disruption of the sedimentary sequence along fractures acting as conduits for expulsion of mud breccia (Skinner and Mazzini 2009, Bonini, 2012, Okubo 2016, Oehler and Etiope, 2017). Indeed, pre-existing structural grain in the Martian crust in some cases seems to control occurrence of mounds alignments (Skinner and Mazzini, 2009).

In presence of thick sedimentary sequences, with a deep source associated to long term compaction, fluid extrusion rates mainly control the cones morphology; high extrusion rates form pitted cones whereas low extrusion rates generate un-pitted domes (Skinner and Mazzini, 2009; Bonini 2012; Allen and Oehler, 2008; Okubo 2016; Pondrelli et al., 2011; Oehler and Etiope, 2017).

Impact craters can also play an important role on the generation of mud volcanoes and springs since they strongly modify planet landscape and surface/subsurface hydrology (e.g. Skinner and Mazzini, 2009; Rodríguez et al., 2005, Carrozzo et al., 2017). Indeed, it is demonstrated that impact processes produce a pervasive network of fractures (Melosh, 2007; Collins et al., 2004-2011; Wunneman et al., 2006) that increase the secondary permeability and thus favor fluids circulation within the crust (Oehler and Etiope, 2017). Moreover, it has been hypothesized the presence of long-lasting impact-induced hydrothermalism on Mars, calculated for several crater diameters (Abramov and King, 2005) that can last up to 380,000 years in ~200 km-wide basins and shown in the case of Auki crater in Carrozzo et al., (2017).

In all cases, the actual presence and depth of the fluid reservoir feeding the mounds within Arabia craters remains debated. However, by analyzing the spatial distribution of mud volcanoes and investigating the possible fractal clustering of such populations, it is possible to infer the depth of the fluid source (e.g. Bonini and Mazzarini, 2010). The effectiveness of the self-similar (fractal) clustering approach has been proved both on Earth on monogenic volcanic vents along the East African Rift as well as on Ascraeus Mons dykes in Mars (Mazzarini and Isola, 2010; Mazzarini et al., 2013; Pozzobon et al., 2014). Indeed, monogenic vents and dykes shows a self-similar clustering (with a fractal exponent) in a defined size range comprised between a lower and upper cutoff, the value of the upper cutoff well matches the actual depth of the magmatic reservoir (i.e. Mazzarini and Isola, 2010). Such approach has been successfully also applied to derive the depth of pressurized layers feeding mud-volcanoes in the foreland of the Greater Caucasus in Azerbaijan (Bonini and Mazzarini, 2010).

We thus performed the self-similar clustering analysis on mounds occurring within three craters in Arabia Terra in order to derive an indication on the depth of the fluid source of fluid expulsion features. However, the correct interpretation of mound features as mud volcanoes, which is biased in some cases especially where the image resolution is not sufficient to distinguish finer details and textures, is pivotal. Thus, before applying the fractal analysis, we provide a more constrained mapping rationale of mud volcanic morphologies within our study areas. In particular, we relied on the numerical characterization of DTMs of mounds - already interpreted as mud volcanoes according to their morphologic and textural characters on high resolution images (Pondrelli et al., 2011, Pondrelli et al., 2015) on high-resolution and mid-resolution DTMs for validation of the technique. Afterwards, we extrapolated the obtained morphometric parameters to neighboring craters in order to map only similar objects.

Geologic framework

Arabia Terra region (~3000 km^2) extends from the southern heavily cratered highlands to the northern lowlands, gently dipping (0.09°) northward with an elevation drop of 4 km over a distance of 2500 km (Fig. 1). In the studied area (0°25'N to 3°25'N and 7°07'W to 10°27'W) several impact craters show the presence of light albedo inner large central bulges often presenting a thin layering interpreted as large-scale spring deposits (Rossi et al., 2008), kilometer-size mounds interpreted as springs (Allen and Oehler, 2009), and small mounds, pitted cones and knobs (Pondrelli et al., 2011, 2015, Allen and Oehler, 2008).

All the craters within this Arabia Terra sector are embedded within the so-called Cratered Unit (CU, Tanaka et al., 2014; Pondrelli et al., 2015), a Noachian plateau sequence consisting of pyroclastites, lava flows and brecciated material (Scott and Tanaka, 1986).

The deposits found within crater interiors can be classified in two major units: a layered unit (ELD) and a mounds unit (MU). The ELD consists in a high albedo layered material, in some cases interbedded with darker material often disrupted in polygonal pattern that overprints the original deposit, sometimes resembling the etched terrain seen in Meridiani Planum (Hynek et al., 2002). This entire unit has gentle dip angles that appears to be adapted to the pre-existing topography and mantling the inner crater terrace. It forms sequences that can reach up to 2 km of thickness inside craters (measured within Firsoff) while are much less pronounced in the outer plateau, where the sedimentary succession reaches a maximum thickness of 10 m overlaying in unconformity the CU (Pondrelli et al., 2015, Franchi et al., 2014). In places the ELD unit is buried by a Hummocky Material unit likely made of volcanic dark-toned rocks (Franchi et al., 2014, Pondrelli et al., 2011, 2015). Indeed, in the southern sector of Arabia Terra, Hesperian flood basalts (Ridged Plain Materials Unit) bury entirely all the previously described successions (Scott and Tanaka, 1986). Hence it appears clear that the ELDs are thus stratigraphically constrained between the Noachian plateau sequence and the Hesperian flood basalts in a time range where liquid water was stable in Martian surface and in subsurface, creating lacustrine, fluvial landforms and large amounts of alteration minerals (e.g. Flahaut et al., 2015, Pondrelli et al., 2015, Franchi et al., 2014).

The MU unit is associated and found within ELDs and presents mounds of few hundred meters in diameter, consisting of a layered/non-layered breccia mixed with fine grain matrix (Pondrelli et al., 2011) sharing similar compositional characters with ELD (Pondrelli et al., 2015).

Mounds within craters

Small mounds and their relationship with ELDs were first described in detail by Pondrelli (2011, 2015) within Firsoff crater, which presents an inner bulge mainly composed by ELDs. More in detail, mounds consist of simple cones (sub-circular or slightly elliptical, 50-300 m in diameter and 20-120 m height), and coalescent cones (500 m in diameter and several hundred meters high). In some cases, a main circular body and a sub-circular secondary appendix are also visible (Figs. 2a, b; and figures in Pondrelli et al., 2011). At HiRISE resolution, the mounds appear to have a fine-grained supported texture with metric-size light-albedo boulders, whose occurrence is higher at their base, Fig. 2a, b), and in some other cases a coarser boulder supported texture. Larger mounds (~100 m in height) show boulder-rich layers alternated with fine grain-supported layers, sometimes slightly outward-dipping. In these latter cases, a coarse breached layering is often in clear continuity with ELDs, suggesting a common genetic process related to fluid expulsion alternating periods of activity and quiescence (Pondrelli et al., 2011). Depending on their position related to the winds, some of the mounds appear to be more eroded exhibiting a sharper crest and a slightly elongated shape in plan-view.

Several evidences support the fluid related origin hypothesis, linking the ELDs and the small mounds formation processes:

- In the south-eastern part of the Firsoff crater, apical depressions on ~35% of the mounds have been observed, especially in those mounds presenting boulder supported coarse-textured; such a large percentage of mounds with apical depression statistically rules out the impact origin of these depressions that, instead, could represent a central vent. Circular depressions on the flanks or at the base of the mounds could instead represent secondary vents. The lack of vents in the remaining mounds presenting similar overall shape was explained by erosion or dust mantling, or to less intense extrusive activity (Pondrelli et al., 2011).
- In some cases, flow-like features are present on the mounds' flanks spreading from the apical depressions (Fig. 2c).
- Whereas the majority of the mounds appears to be scattered, in several cases they can be found along alignments interpreted as tens of meters-high fissure ridges due to fuid extrusion and hardening (Pondrelli et al., 2015). In fact, mounds populations and in particular the alignments (Fig. 3), show strong resemblance with the fluid expulsion indurated outcrops identified in the near Vernal Crater, (Fig. 5, Allen and Oehler, 2008). They also show also strong analogies with Azerbaijan mud volcanoes and gryphons (Bonini, 2008, Bonini and Mazzarini 2010, Dimitrov, 2002) and the Dashgil gryphons (Mazzini and Etiope, 2017).

- Spectral signatures on ELDs and mounds showed the prevailing presence of polihydrated sulphates and hydrated phases, (Pondrelli et al., 2015, Grotzinger et al., 2005) implying the presence of groundwater similarly to those evidenced in the nearby Meridiani Planum (Flahaut et al., 2015).

Case study craters

We concentrated our efforts in characterizing and mapping mounds in three adjacent craters with a widespread presence of ELDs and mounds.

The Firsoff crater (2.61°N–9.21°E) has a diameter of ~90 km and its interior presents widespread ELDs and a large central bulge (35-40 km of diameter and ~2 km high). The crater's interior is formed essentially by ELD and MU units and appears to be strongly affected by degradation, presenting a number of erosional features and aeolian deposits such as dark sand deposits. Most of the mounds are concentrated in the south-eastern part, where they appear fresher and less degraded by erosion, as well as in the eastern sector although less in number (Pondrelli et al., 2015; Pondrelli et al., 2011). In the rest of the crater mounds are still present but a clear distinction from erosive morphologies is more complex and sometimes always possible.

Kotido crater (11°N–91°E) is located southern from Firsoff and has a diameter of ~40 km with a depth between 800 and 1000 m below the regional surface. A well-preserved ELD formation entirely covers its floor (Franchi et al., 2014; Pondrelli et al., 2015). HRSC DTM (~100 m/px, Gwinner et al., 2005) topographic profiles show a small bulging (Fig. 1d) much less pronounced than that in Firsoff (Fig. 1b, c, d). MU unit is present in patches, however mounds do not necessarily occur only within this unit but are widespread: they are both grouped in the southeastern side and also towards the center of the crater in the small central bulging (Fig.

1d). The mounds are sub-circular features with the same albedo of the ELDs, in stratigraphic continuity and most of the times presenting fine grained texture while showing an apical depression in only a few cases.

The “unnamed” crater, 20 km eastern from Firsoff, is the smallest of the three (~40 km), and presents a relatively smooth floor, scattered with several knobs and mounds that in places appear to be aligned along concentric fractures, contouring a subtle bulge visible from HRSC DTMs (100m) (Fig. 1d). Most of them seem quite well-preserved, although several have a slight drop shape and sharp crest due to wind erosion. In neither of these objects an apical vent is present, however, from HiRISE observations, they show strong similarities to those mapped by Pondrelli et al., (2011) in terms of texture and morphology as well as to the indurated mound-like outcrops shown in Vernal crater by Allen and Oehler (2008).

We started by calibrating our analyses on mounds in the Firsoff impact crater where large amount of observations point towards fluid expulsion related processes and analogies with mud volcanism (Pondrelli et al., 2011, 2015).

3 Methods

3.1 Datasets

For our analyses we utilized HiRISE (High Resolution Imaging Science Experiment, McEwen et al., 2007) with a resolution of 0,25 m/px images as well as stereo-derived DTMs (1m) to verify geomorphologic characters of the mounds within the three case study craters.

We first verified morphometric parameters on a known area (the mapped mounds in Pondrelli et al., 2011) on HiRISE and, since its observations are targeted to specific areas, to extend them to a broader area we took advantage of the wider coverage of the CTX camera (Context

Camera, Malin et al., 2007) with a ground resolution of 6 m/px that encompasses completely the craters, providing enough overlap to generate stereo DTMs (18m resolution).

We selected for all the three craters the best overlapping CTX images for stereo DTM reconstruction (see table 1 for image details). Pre-processing was performed by means of USGS ISIS3 software suite that was used to calibrate, de-stripe and map project the images. the DTMs were generated using ISIS3 (Integrated Software for Imagers and Spectrometers, Torson and Becker, 1997) and ASP (Ames Stereo Pipeline by Moratto et al., 2010; Beyer et al., 2014; Shean et al., 2016) with the procedures and wrapper scripts from Mayer and Kite, (2016) that more efficiently create CTX DTMs using ISIS and ASP routines. Bundle adjusted CTX point clouds, obtained from stereo matching, were aligned to MOLA (Mars Orbiter Laser Altimeter onboard Mars Global Surveyor, Smith et al., 2001) PEDR (Precision Experiment Data Records) shots using iterative closest point algorithm and interpolated to a DTM with 18 m resolution. An orthorectified CTX image of 6 m/pixel was also generated.

We obtained 2 DTMs for Firsoff and 1 for Kotido that entirely cover the craters. In the case of the eastern crater the desired quality of the CTX DTMs was not sufficient, hence we used HiRISE frames provided by the HiRISE team webpage re-interpolating the resulting DTMs at 18 m point spacing.

All the datasets were projected in sinusoidal centered on each crater.

Even though it is still possible to identify most of the mounds at CTX image resolution a clear distinction between mounds and erosional features such as mesas and yardangs is often ambiguous and not sufficiently reliable.

We adopted a supervised morphometric approach based on DTMs, in order to distinguish with morphometric variables mounds from yardangs and ELDs erosional remnants. To achieve this goal it was important to calibrate the analysis in a well-known site, thus we extracted the morphometric parameters of the small mounds mapped in Firsoff crater and interpreted as mud volcano candidates in Pondrelli et al., (2011, 2015), than we used them as base line for further mounds extraction on less known areas (i.e. Kotido crater, the unnamed crater and locations in Firsoff crater not covered by HIRISe data) by using a HiRISE DTM resampled at CTX DTM resolution (18m).

The TPI (Topographic Position Index, Weiss, 2001; Jenness 2006) is the basis of our morphometric classification (see also appendix A.1). TPI relies on the difference of elevation between a cell and the average elevation of its neighborhood. TPI along with the cell slope value can be used to classify the cells into classes related to different specific morphologies (hills, narrow valleys, plains, etc., Jenness et al., 2006). TPI is scale dependent; the presence of a small hill top within a narrow valley will be hidden if the chosen kernel size is larger than the valley itself and on the other way round a hill top may not be visible if the window size is smaller than the hill itself. Hence the relation between the window size and dimensions of the analyzed morphological features must be taken into account. For this reason we used a multi-scalar approach based on the combination of large and small DTM cell neighborhoods in order to combine small positive topographic expressions (i.e. mounds, set as 100 m treshold) within larger ones, (i.e. the inner crater topography, set to 1000 m, Jenness et al., 2006). Ten categories have been derived according to those identified in Weiss (2001) and are displayed in table 2.

The TPI values equal or larger than 8 are those that identify small positive reliefs such as the mounds and yardangs crests.

However, to better constrain the mound morphologies and for the automatic mapping of putative mud-spring/mud-volcanoes, the TPI classification was used along with the *profile* *curvature*, that has been calculated on the same DTM using the *r.param.scale* GRASS module (Hofierka et al., 2009).

The *profile curvature* is the curvature calculated along the maximum slope directions and is very sensitive to slope variations (Wood, 2009). The obtained values allowed assigning to the different TPI geomorphological classes a specific range of profile curvatures, being convex, concavie or flat (Fig. 4b). Moreover, we used the zero-profile curvature (corresponding to the point in the mounds slopes where curvature changes from concave at the base to convex towards the top) and its intersection with TPI< 8 to automatically contour the mounds in class 8-9 and gather the most realistic shape in plan-view: this technique allows to avoid any interference with eventual topographic irregularities of the surrounding terrains, being open slopes, plains with a certain degree of roughness or narrower valleys. (Fig 4c).

We have found that the mounds populating the south-eastern sector of Firsoff crater, studied by Pondrelli et al. (2011), present positive profile curvatures generally between 0.002 and 0.004 and fall in the TPI category 8 and 9, whereas the sharp crests of yardangs fall uniquely within category 9 and present curvatures between 0.004 and 0.02.

To filter high frequency noise or artifacts, objects smaller than 50 m were filtered according to the 4-pixel thumb rule used also in crater counting (a rounded object needs to be at least 4 pixel in diameter to be recognized). Yardangs, false positives and large artifacts of the DTM were instead filtered using aspect ratios in plan-view that were obtained extracting minimum and maximum axes for every contoured feature (see also Appendix A.1.2). All objects with aspect ratio <0.5, thus very elongated (i.e., yardangs, crater rim, ridges), were discarded. This minimum threshold was chosen in accordance to the aspect ratio calculated on the mounds mapped in Pondrelli et al., (2011) that display an aspect ratio equal or greater than 0.5Applying these filters to mounds mapped in the same area used by Pondrelli et al. (2011) an automated data set has been collected (see also Appendix A.1). In addition, since the mapped mound area is defined within the ELD and MU geologic units (Pondrelli et al., 2015), and some knobs or positive reliefs resulted to be the emergence of eroded strata banks we considered only the mounds within broad areas with slope < 15°. The automated data set and the original one by Pondrelli et al., 2011 show a strong correlation with the majority of the original mounds correctly mapped (see also Appendix A.2) (Fig. 6d).

This method has been calibrated on a known Firsoff area using HiRISE DTMs resampled at the CTX DTM resolution (18m post-spacing). Than it has been applied on the 2 CTX DTMs covering the Kotido and the unnamed craters respectively. We finally used 6m/pixel CTX orthoimages, and HiRISE single images (where available) for a visual checking of the results. order to evaluate the presence of still ambiguous objects.

The barycenters of the contoured mounds, corresponding to the position of the putative mud volcano centers, were then extrapolated (Fig. 6c) and studied in terms of self-similar clustering of their spatial distribution.

3 Mounds spatial distribution

The spatial distribution of monogenic vents in volcanic areas on Earth (Mazzarini and Isola, 2010) and on Mars (Pozzobon et al., 2015) are linked to fracture systems that allow an efficient hydraulic connection between the surface and crustal/subcrustal fluid reservoirs. The percolation theory describes the geometric and physical properties of a percolating network (Stauffer and Aharony, 1992; Orbach, 1986; Song et al., 2005) and can be applied to fracture networks that serve as a pathway for fluids to move within the crust (Mazzarini and Isola, 2010). The first step in the analysis of spatial distribution of mounds/mud volcanic features in the Firsoff and nearby craters was the computation of the nearest neighbor distance (NN or point separation) for each data set. The clustering of data has been analyzed by computing the coefficient of variation (CV) and R-c test on the point separation values. The CV is the ratio between the standard deviation and the mean of the sampled population (Gillespie et al., 1999). A value of $CV > 1$ results from the points clustering, $CV = 1$ indicates a random or Poisson distribution, and $CV < 1$ indicates anticlustering (a homogeneous distribution). CV investigates how close points are to one another, so gives information on short range clustering and does not probe the pattern of point distribution. R-c statistics (Clark and Evans, 1954) compare actual NN distance distribution with that expected for a Poisson distribution of N points. $R < 1$ indicates clustering. To identify statistically significant departures from randomness at the 0.95 and 0.99 confidence levels, $|c|$ must exceed the critical values of 1.96 and 2.58, respectively (Clark and Evans, 1954). The reference density is obtained by the ratio between the actual point number and the area of the convex hull containing them (e.g., Baloga et al., 2007; Beggan and Hamilton, 2010).

The spatial distribution (self-similar clustering) of mounds has been investigated by applying the two-point correlation function method. For a population of N points (e.g. mounds within the crater), the correlation integral is defined as the correlation sum (C(l)) that accounts for all the points at a distance of less than a given length l (Bonnet et al., 2001; Mazzarini and Isola, 2010). The term is computed as

$$C(l)=2N(l)/(N(N-1)) \quad (1)$$

where N(l) is the number of pairs of points whose distance is less than l. The fractal distribution is defined by

$$C(l) \sim bl^D \quad (2)$$

With b as normalization constant and D being the fractal exponent. The slope of the curve in a log(C(l)) versus log(l) diagram yields the D value. The computed D value (fractal exponent of clustering) holds for a defined range of distances (size range) where the equation is valid. For each analysis, the size range of samples is in turn defined by a plateau in Δlog(C(l))/Δlog(l) (i.e., the local slope) versus log(l) diagram: the wider the range the better the computation of the power-law distribution (Walsh and Watterson, 1993). The derivation of the cutoffs bounding the size range is a crucial point and is generally not trivial, especially when the local slope does not show a regular and wide plateau (see also Appendix B). The choice of the zones where the plateau is well defined and the determination of the lower and upper cutoffs (*Lco* and *Uco*, respectively) are done by selecting the wider length range for which the correlation between log(l) and local slope is greatest (Mazzarini, 2004). A size range of at least one order of magnitude and at least 150 samples is required to extract robust parameter estimates (Bonnet et al., 2001; André-Mayer and Sausse, 2007; Clauset et al., 2009). By analyzing the volcanic vent clustering (Mazzarini and Isola, 2010), it has been showed that the random remove of 20% of the analyzed samples from large datasets (i.e. >200 vents) does not affect the estimation of fractal dimension (less than 0.01% of variation) and the error introduced into the estimation of the cut-offs is less than 1%–2% (Mazzarini and Isola, 2010). Mazzarini et al., (2013) in order to test the effect of uncertainties in point-like feature locations added random errors to the sampled points (in the 0–100 m, 0–300 m and 0–500 m ranges, i.e. errors as high as 5 to 25 times that of the coarsest image resolution used to locate the points). The 0–100 m errors randomly added to the point (vent) locations generated fractal exponent and cut off values identical to those computed for the original dataset. In the case of 0–500 m random errors, the resulting fractal exponent was 3% higher than that computed for the original dataset, and the cut offs were very similar to those computed for the original dataset (Mazzarini et al., 2013). The upper cut off value (*Uco*) obtained analyzing several volcanic fields linearly scale to the depth of the fluid source (e.g., Mazzarini and Isola 2010). This relationship has been observed for volcanic vents in the East African Rift (Mazzarini, 2007; Mazzarini and Isola, 2010), in the southern Patagonia (Mazzarini and D'Orazio, 2003; Mazzarini et al., 2008), in the TransMexican Volcanic Belt in Mexico (Mazzarini et al. 2010) and for mud volcanoes in the Greater Caucasus in Azerbaijan (Bonini and Mazzarini, 2010). The best linear fit between the computed Uco values and the depth of the fluid reservoir (T) is Uco = 0.98T – 0.6 with R^2=0.95; errors are 20% for T derived from independent geophysical data sets and 10% for Uco estimates (Fig. 7).

6 Results

From the automatic extraction of mounds it appears that mounds in the craters show asymmetric distribution being more frequent in the upstream side (referred to the regional hydraulic gradient) of the Firsoff crater. In Kotido they appear mostly concentrated in the middle of the bulge in accordance to the direction of the regional slope whereas mounds are more homogeneously scattered in the unnamed crater (Fig. 5). The applied fractal clustering analysis on the mounds distributions results as follows:

Firsoff crater (numero vents) has average NN distance 0.51 km, CV = 1.44 and R-c statistics of 0.34 and -26.2; Eastern Crater (no outliers; N=1036) CV = 1.61 and R-c statistics of 0.57 and -26.42 Eastern Crater (with outliers; N=1811) CV = 0.72 and R-c statistics of 0.59 and -33.37. Finally Kotido crater (833) has CV 0.65, R-c statistics of 0.79 and -5.6. Firsoff craters display both short and long-range clustering whereas the Kotido crater, where a well-defined central bulge is not present, shows clustering only at large scale. The unnamed crater shows fractal clustering with a well-defined plateau.

In table 3 are summarized the obtained fractal clustering results on the datasets in the three craters. The analysis of mounds clustering in the Firsoff crater provided a source depth (*Uco* value) of 2.6±0.3 km from the crater's floor (both in the subset and the broader area, Fig. 6a). We chose to maintain the analysis in south-eastern Firsoff being the mounds more preserved from erosion and with clear evidences of alignments along ridges. Similar results (Fig.6b) have been obtained also from the fractal analysis of the mounds in the unnamed crater (*Uco* = 3.2 ±0.4 km) and for mounds in the Kotido crater (*Uco* = 2.7 ±0.3 km) (Fig. 6c and Appendix B). The Lco and Uco are calculated according to the method described in Mazzarini (2004): for both of them we selected the wider length range for which the correlation between log(l) and the local slope is greatest.

The actual fluid depth derived by the analysis of mound self-similar clustering (Uco) is referred to the elevation of mapped mounds thus we must add to the Uco the difference in elevation (Δh) between the mounds and the actual surface nearby the craters, then actual depth (H) of the "fluidized horizon" that fed the mounds is H=Uco + Δh (see table 4 for further details).

In order to assess the depth of the fluid table from the depth of the pristine craters and thus, to verify if it is nested within the layered unit or below the crater, and thus likely related to a pre-existing setting we needed to extract the possible pristine depth of the three craters.

In Forsberg-Taylor et al. (2004) are provided estimates of craters degradation in terms of diameter increase due to mass wasting, faulting and collapse of the inner walls (10% of diameter increase) and basin infilling (up to 2/3) caused by airfall, aeolian and fluid erosion and it is thus possible to estimate the most likely pristine crater' diameter.

The pristine depth of the craters was calculated using the equations from Robbins and Hynek, (2013) that derived the morphometric relationship ruling the complex craters diameter/depth over different terrains comprised between 40°S and 40°N. By applying this approach, we could derive the depth of excavation at the time of the impact (Table 4) and constraining the possible thickness of the inner deposits. In table 4 the resulting Uco are located beneath the pristine depth of the crater placing the fluid source in each crater just below its floor.

7 Discussion

Fluids and water-related activity on ancient Mars surface has been described by several authors (Zabrusky et al., 2012; Andrews-Hanna et al., 2010; Andrews-Hanna et al., 2011b; Michalski et al., 2013; Grotzinger et al., 2008; Flahaut et al., 2015) based on the occurrence of alteration minerals of water-rock interactions and on stratigraphic evidences (i.e. ELDs, Pondrelli et al., 2015; Franchi et al., 2014; Rossi et al., 2008).

Numerical simulations (Andrews-Hanna et al., 2010, Andrews-Hanna and Lewis, 2011) tested the hypothesis of the inner craters layered deposits as the consequence of the oscillation of a fluid table through time filling the craters and creating layered sequences that are interbedded with fine aeolian material during quiescence in the fluctuations. However, this model accounts solely for the presence of inverted craters in southern Arabia and Meridiani Planum where the maximum concentration of them outside the highest latitudes is present, but does not clearly explain the presence of the large layered symmetric outward-dipping bulges within craters that, in some cases, are even slightly higher than the actual crater rims (such as Firsoff). These evidences account, instead, for the presence of a different mechanism of emplacement than lacustrine deposition (Zabrusky et al., 2012). Indeed, the pedestal craters, inverted and intra-crater mounds have been used to model a pre-erosional depositional surface with an average thickness of sediments removed of 6.2-11.6 m thick (Zabrusky et al., 2012): being this value averaged on the whole Arabia and Meridiani, this will imply a removal of more than 1 km of sediments by wind erosion within some craters and a much less thick sequence in the surrounding plains happening when all the depositional processes ceased. Indeed, although several formation processes within this framework (Zabrusky et al., 2012) can be invoked for ELDs formation, such as interplay between aeolian deposition, groundwater fluctuation with evaporites formation (Andrews-Hanna et al., 2010; Grotzinger et al., 2006) and orbital ciclicity (Lewis et al., 2008), the rounded small mounds should have been more prone to erosion but most of them present a morphology that does not appear wind shaped. Our observations suggest their origin more likely by localized fluid upwelling along fractures (Franchi et al., 2014; Rossi et al., 2008, Allen and Oehler, 2008) corroborated by the similarities with putative spring mounds within Auki crater (Carrozzo et al., 2017). Indeed a series of evidences suggest that mounds are intra-formational with ELDs (Pondrelli et al., 2015) and likely a manifestation of subsurface fluid upwelling as testified by mounds alignment along fissure ridges and annular fractures within craters. This is still partially consistent with models from Andrews-Hanna et al., (2010, Andrews-Hanna and Lewis, 2011) and Zabrusky et al., (2012) considering the groundwater fluctuation, and indeed water activity is also well constrained from mineralogical analyses (Pondrelli et al., 2015; Michalsky et al., 2013; Flahaut et al., 2015; Poulet et al., 2008), however does not provide a clear explanation for the outwardly dipping layers of the bulges or to the mounds presence.

On the bases of self-similar clustering analysis of mounds distribution, we suggest a 3.2-4.2 km deep water table as a likely source for mounds as well as large scale spring deposits formation (Rossi et al., 2008).

By comparing the pristine depth of each craters with the corresponding derived depth of fluidized horizon (H) obtained with the fractal clustering shows that the source underneath these craters is from 300 m to 1.9 km to the pristine crater's depth, where fracturing is very pervasive providing preferential pathways towards the surface where more fractures are expected (Fig. 7 and table 4).

The minimum conditions to obtain fluid pressurization and expulsion can be inferred from the nowadays average elevation of areas where mounds are present in Firsoff, Kotido and the unnamed eastern crater with respect to the surrounding plains, that is between 0.6-1.2 km Considering the loss of overburden due to impact crater excavation a vertical load drop $\Delta\boldsymbol{\sigma}_{\mathrm{n}}=\Delta P_f=\rho_o g\Delta h$ (where ρ_o the density of crustal rocks and Δh the pristine depth of the crater) can be foreseen. Fluid overpressure and hydrofracturing likely occurred if $\Delta P_f > T$, being T is the tensile strength of the rock. Crustal rocks are basalts with tensile strength varying in the range 0.2-17 MPa depending on the integrity of the rock volume (Schultz, 1993; Jaeger and Cook, 1979). The 6.6-11.5 MPa pressure drop computed assuming a range of Δh between 0.6 and 1.2 km and an average density of basalt rocks of ~3 g/cm^3 likely provided ΔP_f sufficient to overcome the tensile strength of basalts and hence, also favoring the opening of fractures also within ELD (most likely with lower tensile strength according to their composition). It is straightforward that such pressurization conditions would have been even larger in the past thus we could infer that hydrofracturing phenomenon related to fluid upwelling would have been enhanced in the past when crater infilling was still ongoing.

Processes of crustal unloading can be either erosive or derived by impact: in this work we take into account almost instantaneous processes and since impact process causes an instantaneous load drop in the aftermath, in our opinion, aeolian surface modification would have taken place only as a late stage by sculpting already emplaced units giving rise to lower scale morphologies such as yardangs.

From all these observations we propose the following main evolution stages that led to mounds formation within impact craters (Fig. 8):

1. Before the impacts a fluid table is present between ~3.2 and ~4.3 km underneath a still undisturbed surface (Fig. 11, stage 1)

~~2.~~ Impact crater formation give rise to a pervasive fracture network that can likely be exploited by fluids and initiate fluid overpressure due to sudden unloading. This event can additionally cause opening of sealed pre-existing fractures thus facilitating fluid upwelling. (Fig. 11, stage 2). The fluid outflowing to the surface undergo sudden evaporation due to the low atmospheric pressure and consequent deposition of the ELDs forming the inner bulges. Fluids piped within the fracture system give origin to spring mounds, that in the first stages, given the considerable thickness of the ELD can be assumed as large spring mounds of tens of km, as those described by Allen and Oehler (2009). The mounds associated to this event, as pointed out in Pondrelli et al. (2015), are indeed continuous with the ELD layers, also presenting the same composition. Later small mounds with coarser brecciated texture forms inter-fingered within the central ELDs bulge (Pondrelli et al. 2015).

3. Accumulation of ELDs increased the overburden with consequent decrease of permeability and sealing the fractures in the central bulge (Fig. 11, stage 3). The pressurized fluid tends to outflow around the perimeter of the central mound where the overburden is less pronounced (Fig. 1b, c). The formation of a late stage mounds ring around big spring mound that underwent compaction and impermeabilization has been

also hypothesized by Allen and Oehler (2013).

The annular mound distribution is not observed where a central bulge is not present (or with more subtle topographic expression) as in the Kotido and in the unnamed craters, although the small mounds show the same appearance and profile curvature.

The different distribution of the mounds and the different expression of the inner bulge can be due to I) different stage of the general evolution of the same process or II) controlled by the size of the impact itself: however we do not have enough statistics to assess the most likely process.

5. Conclusions

The occurrence of a water table of regional extent in Arabia Terra as well as a fracture network required to mobilize pressurized fluids upward was invoked by several authors to explain the layered deposits within and outside the craters (Zabrusky et al., 2012; Michalski et al., 2013; Andrews Hanna et al., 2010, 2011; Allen and Oehler, 2009, Allen et al., 2013; Rossi et al., 2008; Franchi et al., 2014).

Our results based on the mounds fractal clustering are consistent to the presence of a pressurized water table at ~2.6-3.2 km of depth interacting within large impact craters such as Firsoff, Kotido and an unnamed crater 20 km towards the east. The aquifer pressurization may have likely initiated by overburden removal due impact cratering excavation, that contextually created a pervasive fracture network. The pressurized acquifer and the exploitation of the fracture network by fluids is likely to have played multiple roles: producing depositional spring-related features such as large spring mounds and ELDs, produce hydrofracturing both within basaltic bedrock and ELDs themselves as well as later mud volcanism or small spring resurgences whose evidence are rounded necks in both morphological and compositional continuity with ELDs. As a consequence, similar subsurface fluid flow processes could be expected in other craters within Arabia Terra, expressed by cones, knobs or large layered mounds.

The possibility to apply such approach to other areas of the Martian surface, such the widespread mud volcanic fields of Acidalia Planitia could help reconstruct the history of Mars' hydrologic cycle, subsurface water activity and fluid expulsion events both at a broader and local scale. Moreover, this approach will be useful for targeting possible fluid reservoir within large craters (Oehler and Etiope, 2017) for further exploration in the framework of ExoMars TGO and targeting of CaSSIS imager observations.

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Appendix A. Testing the methods

A1. Mounds characterization and automatic extraction parameters

To morphologically characterize mounds we have firstly applied the TPI combined with profile curvatures on the dataset from Pondrelli et al., (2011) resampling a higher resolution (1m) HiRISE DTM at CTX DTM resolution (18m). This was done to calibrate our method in order to automatically detect the same features (filtering outliers) on other terrains in which CTX DTM where available.

In Fig. A1 it is shown the profile curvatures belonging to specific geomorphological classes extracted with TPI from the DTM in the dataset mapped in Pondrelli et al., (2011). We have seen that the emergence of small hills and convex morphologies fall within both category 8 and 9 and thus we contoured these objects following the points of zero curvature on their flanks (the flex point). This is the only way to preserve the actual aspect ratio of these objects and avoid the interference of the rough sloping terrain at their base.

From an analysis on the aspect ratio in plan-view of the objects mapped in Pondrelli et al., (2011), we have seen that every mound has an aspect ratio >0.5. To get rid of ridges, artifacts and yardangs (that are often drop-shaped and elongated) we calculated the minimum bounding geometry of the contoured shapes, extracting major and minor axes, and filtering them according to their aspect ratios (i.e. every object with aspect ratio <0.5 was deleted).

However, several yardangs still remained in our automated mapping, but the analysis of profile curvatures showed that almost all of them present a specific set of curvatures mostly in category 9. In fact, both categories 8 and 9 present a prevalence of three ranges of curvatures: 0.0005-0.002, 0.002-0.004, 0.004-0.02 that are however differently distributed within the two categories. In category 8 the ranges or curvatures are almost equal, meaning that the related objects present gentle transition from low to high curvatures and results in a rounded profile. By contrast in category 9 the prominence of the sharpest curvatures (>0.004) result in a sudden transition form no curvature to a very sharp edges. This typical of yardangs that having an aspect ratio >0.5 exhibit a very sharp crest. Hence, we verified that the dataset from Pondrelli et al., 2011 mostly corresponds to category 8 and partly 9, with all the mounds presenting curvatures <0.004. It is still possible that some yardangs could actually be heavily eroded mounds, but we chose not to incorporate them in the analyses due to this uncertainty.

Flat top mesas belong mostly to category 6, and have a sharp contact between 0.00008 and 0.001 curvatures. Visually, they are easily identifiable because they present an annular high-curvature region surrounding an almost flat portion (Fig. A2).

By filtering them according to what exposed above and the parameters in table A1 ,we obtained an almost perfect match between the automatic extraction and the manual mapping (see Fig. 4. In addition to that, the obtained contouring shapefiles a final supervised inspection was performed to locate possible outliers and ambiguities.

To test the reliability of the automatic extraction method in correctly locating the mounds, we have compared the position of the centroids from the contoured features with those from Pondrelli et al., (2011)

In Fig. A3 we visually represented the location analysis where we have calculated the minimum distance between automated and manually mapped points and evaluated their difference. In the plot in Fig. A4 it is visible that ~60% of the automatically extracted dataset fall within less than 20 meters from the points derived from Pondrelli et al. 2011 mapping, with another 10% falling within 60 m. The remaining 30% either belong to newly mapped points, that were not considered in the manual mapping, or to the subdivision of coalescent features into multiple features. Indeed, as it is visible in the subsets of Fig. A3, there are several cases of coalescing mounds, mapped as single morphologies in Pondrelli et a., (2011) that are actually composed of 4/5 objects almost equally distributed around the centroid of the composite mound as correctly detected by our algorithm. In fact, with the automatic extraction we were able to map 343 mounds versus the 259 of the manual mapping by Pondrelli et al. 2011. However, 44 out of 84 newly mapped features belong to 16 composite objects, whereas 40 features are effectively new detections. Hence, 70% of automatically mapped features are within less than 20 m from the manual mapped centroids, 12.8% correspond to coalescing mounds and 11.6% are newly mapped features that, from a visual analysis we are confident to asses that are actually mounds. The good reliability of our detection method is further confirmed by the consistency between the nearest neighbor analysis of the two datasets (table A2).

Appendix B. Cutoff estimation for mounds spatial distribution

Each point corresponding to mounds position has been analyzed according to the equations in (1,) and (2) resulting in the plots l vs $C(l)$ that show how is the D average value. Additionally, the black box in the plots R^2 vs $\Delta log(l)$ in Fig. B1(a, b, c, d) contains the maximum fractal correlation (i.e. the size range between Lco and Uco) that presents the highest possible R^2 value for the largest possible size-range (*Lco-Uco*). The comparison of R^2 vs $\Delta log(l)$ with the local slope of l vs $C(l)$ is shown for each analyzed dataset (fig B1).