# COALESCED SMALL SHIELD VOLCANOES ON SYRIA PLANUM, MARS, DETECTED BY MARS EXPRESS - HRSC IMAGES.

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**Introduction:** The Tharsis province has a complex geologic history in relation to its number, type and variety of volcano-tectonic landforms. This study focus on Syria Planum, located at the center of Tharsis bulge, at 6 to 8 km of altitude. Syria Planum was previously recognized as a center for tectonic activity, but not as a main system for volcanic activity, despite its centrality over the bulge. Using high resolution images from HRSC/MEx instrument, we have identified and characterized a volcanic system that is unique over the Tharsis bulge as on the whole Mars. We identified a swarm of tens of shallow volcanic edifices which are located very close together. They are typically 10-20 km diameter and 100-200 m high and have less than 2° steep slopes. These characteristics correspond to those of small shield volcanoes and show that Syria Planum experienced a very specific style of volcanism which we have dated to the Hesperian period. It is possible that this volcanism was the first phase of the emplacement of a giant volcano that aborted due to the thick crust at this location.

**Data:** We used high resolution images from the HRSC instrument, orbits 2021, 2032 and 2055, with 15 m/pixel resolution, and overlaid on altimetry MOLA (Mars Orbital Laser Altimeter – Mars Global Surveyor mission) data, with 128 pixel/degree resolution, to construct a local crossover-corrected topography grid. A suite of tools under a GIS were used to measure local slope, volcano's diameter, height, volume, area, crater diameter and count craters to determine ages. In addition, we used THEMIS (Thermal Emission Imaging system), IR-day and IR-night 100m/pixel images [1] and MOC (Mars Orbiter Camera) images with 2,8 m/pixel of spatial sampling [2]. The THEMIS data permit to obtain measurements of the surfaces brightness temperature and allows defining each structure of the volcanoes, degree of degradation of the surface, which means an increased knowledge for morphologic correlations.

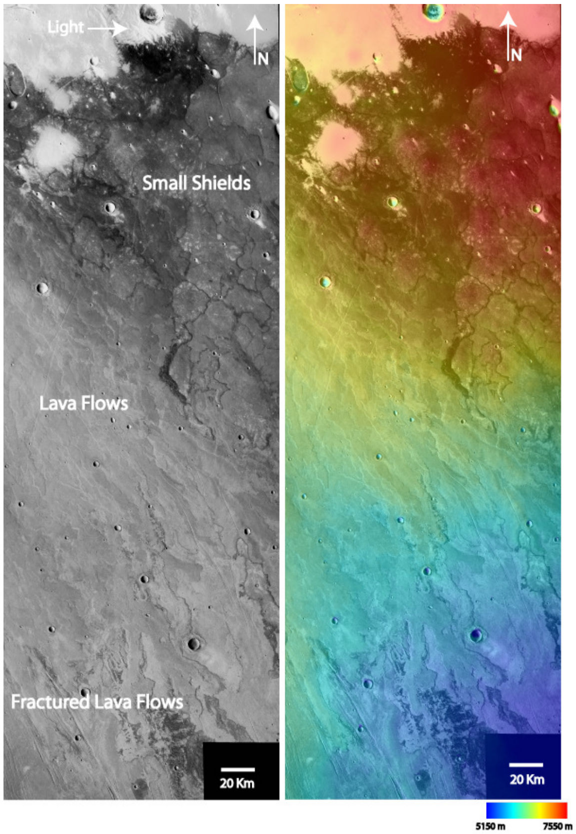

Figure 1. Left - HRSC (Mars Express mission) mosaic of the Syria Planum studied region. The higher albedo surfaces show areas highly covered by dust, while the lower albedo surfaces put in evidence the contours of some circular features (on the East), extensive lava flows (coming from the Northwest) and two families of faults, more visible on the southern terrains. Several impact craters are also distinguished. Right – The same mosaic as on the left image but superimposed to MOLA altimetry data. The altitudes vary from about 7550 m on the Northeast to 5150 m on the Southeast. Both images are centered at approximately 16,8ºS; 101,2ºW.

**Characterization:** Syria Planum has an extension of about 450 by 700 km, centered at 12ºS, 104ºW and is characterized as a broad plateau with little topography separated from the large Tharsis Montes by Noctis Labyrinthus on the North and Northwest and Claritas Fossae on the West [3], [4], [5]. This magmatic/tectonic driven province has been interpreted to have been active from the Noachian to the late Hesperian [6]. Syria Planum has been distinguished by two periods of formation [4]. First, the Late Hesperian formation (Hsu) that surrounds the highest topographic summits to the east and southeast of Syria Planum and overlays Noachian and Early Hesperian-aged fractured terrains (e.g. Claritas Fossae to the south and Noctis Fossae on the north). Second, the relatively earlier formation (Hsl2), which is more highly cratered and faulted, that occurs on the southeast of Syria Planum [7]. Within this tectono-volcanic Syria Planum province, we can observe possible small edifices, usually named protuberances due to the lack of good imagery to certify the volcanic origin (e.g., [8], [9]). It is also observed radial volcanic flow pattern (e.g., [4]), isolated vents, volcanic eruptions along tube and vent-fed flows (e.g., [10], [11]).

We isolated 3 principal morpho-structural units (figure 1) on Syria Planum: (1) in the northern and eastern side, nearly circular shape that resemble small volcanoes and appears as protuberances on MOLA data; (2) in the western and central part, extensive lobate shape lava flows; (3) in the southern part, a highly fractured terrains displaying graben-like structures. The first unit, which is described in this work, is characterized by a relatively dark albedo. The protuberances display a distinct mosaic-like pattern (between 12-21ºS; 96-100ºW) on the highest plateau of Syria Planum, where its summit reaches approximately 7500m altitude.

**Morphometry and Dimensions**: The swarm of protuberances covers an area of about 250 NS-by-150 EW km. The lateral extent of each protuberance is well defined on the HRSC images by the darker limits delimiting quasi-circular features (Figure 2) because the topographic limits coincides with these darker limits except for some located at the northern edge of this area, which are covered by dust (see on figure 1). These landforms are limited to the north at 12.40º N and to the west to about 103ºW. Other might exist further east, but the unit has not been mapped due to the lack of HRSC images.

Each of these protuberances varies in base diameters from 7 km to approximately 30 km and individual heights from 10 to 400 m using MOLA data. The flank slopes of the individual features are between 0.2° and 1.7°, confirming their shallow and flat shape. A predominant central fissure is present on most of these landforms (for example number 3 and 27 on figure 2). It likely represents a vent, from where an eruption might have occurred, as on many volcanoes. Therefore, given these sizes and observations, we interpret each quasi-circular protuberance to be individual volcanoes.

These volcanoes have some variations around the conical shape. First, some of these volcanoes (number 2 on figure 2) have a slope dissymmetrical pattern, showing more exposition to the west and less to the east side. Their slope tends to be higher to their west side, in the contact with the lava flows, as it is observed on figure 3. The volcanoes that are surrounded by other volcanoes tend to have a rounder shape and no preferential higher dip flank. Second, volcanoes tend to be circular north of 15ºS but the shape can be N-S elongated, following the regional topography (number 20 on figure 2). Therefore, we can observe that these volcanoes tend to elongate their shape with the decrease of the topography, below 6500m.

Each volcano volume range from ~1 $Km^3$ to ~150 $Km^3$, as estimated from their respective thickness. These volumes should be considered minimum values once many of the volcanoes may be embayed by younger materials, such as lavas from the adjacent volcanoes, and any loading phenomena that would have depressed some volcanic material. An increase of the volume is observed in from East to West and from North to South together with the increase of altitude (Figure 3). The increase to the West might correspond to an increase close to the lava flows because the volcanoes tend to have a bigger size there (e.g. number 5, figure 3) than those that have another volcano as limit (e.g. volcanoes 14, 16 or 18, figure 3). The decrease to the south is correlated to a decrease of elevation and an increase of the slope and of the volcanoes elongation. This might be due to the fact that the slope impedes the development of circular well developed volcano. As a consequence, the volcanoes of quasi-circular shape and high volumes occur in the northern part where the terrains are more flat (e.g. volcanoes 2 and 3, figure 2 and 3).

The small volcanoes have a strong variation in their size, their shape, their volume, or the existence of an observable vent. Their shape can be interpreted as being formed by the progressive accumulation of lavas, like small shield volcanoes. [14] testes this hypothesis looking at other Martian volcanoes and analogues on Earth.

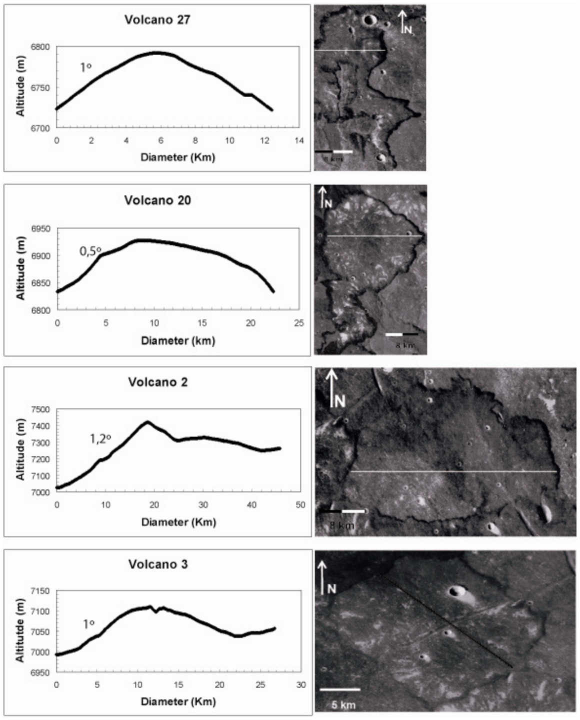

Figure 2. Detail of some shield volcanoes on Syria Planum as seen by HRSC and their correspondent profile West-East (illumination from West). From the top to the bottom we can see that volcanoes 27 and 20 show a NS elongated shape, volcano 2 shows different flank sides slope, from West to East. Volcano 3 shows a vent on its summit, that crosses its section NE/SW. The western flank slope is indicated in each profile.

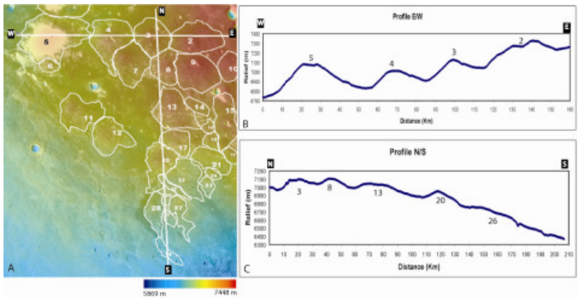

Figure 3. Image A – HRSC image superimposed to MOLA data. The white contours limit the swarm of Syria Planum small shield volcanoes, numbered from 1 to 31. The centre of the image is approximately 15,40ºS; 101,1ºW. Image B and C – Profiles E-W and N-S, respectively, located in image A. From West to East are well in evidence the small shield volcanoes, which from North to South assume a more elongated shape, following the decreasing of topography.

**Chronology:** The craters with more than 250 m were counted and classified over a surface of 7760 Km$^2$ corresponding to the small shield volcanoes. The craters were first counted for each isolated volcano and then summed over the all surface in order to be able to date individually, and as a whole, the small shield volcanoes. A preliminary dating use the N(1) which corresponds to the cumulative number of impact craters with diameter of more than 1 km. Plotted on the model of [12], these counts show ages between 3.5 and 3.7 Gy for the small shield volcanoes. The interval of ages varies once, for the volcanoes, the number of craters with diameter (D) up to 1Km varies between 22 and 25. We considered an area of 7760 Km$^2$ where we observe shield volcanoes. Although, some uncertainty due to the fact that some other features may also be considered as shield volcanoes, would enlarge that area, and, as consequence, will include more other larger craters. As a consequence, the given shield volcanoes ages are lower than the expected (once stratigraphic observations reveals the previous emplacement of the unit (2) in comparison to the shield volcanoes eruption), by using crater counting with craters up to 1 km diameter.

The diameters were also measured by $\sqrt{2}$ bin increments and plotted on the isochrones of the model of [12]. These isochrones correspond to the density of craters that should be observed on a surface preserved from erosion and deposition since its formation. The model takes in account the production function of the Moon which fixes the slope of craters smaller than 1 km and is adapted to show turndowns and variations of populations that could be interpreted in terms of obliteration, erosion or deposition [12]. We also obtain the frequency of each interval of crater size, for the volcanoes. The more recent ages for craters fewer than 500 m correspond to surface degradation due to resurface since the formation of lava.

The dating of these volcanoes, as well as their topographic analyses, confirm previous propositions [13] for the fact that they might have occurred during a short period of time, probably not more than some hundreds or tenths of thousands of million years. From this work, and using HRSC images and MOLA data on crater-counting, we assume that these events may have lasted from the early till the middle Hesperian, which means that the main volumetric increasing of the volcanic features is due to this period.

Then, we tried to date individually each volcano, although, statistically it is not valid once recent resurfacing processes obliterates the smaller craters. The smaller sizes of craters may be a good indicator of resurfacing and erosion periods, while, for precise age, the bigger sizes (up to interval 250-350 m) are better.

**Synthesis and Discussion:** The observations of the HRSC images conclude for a much more complex vision of the geologic history of Syria Planum than previously expected, especially with the identification of a unique swarm of small shield volcanoes that occur in the most elevated part of the region.

This suite of volcano-tectonic episodes in Syria Planum has two specific characteristics that require comments. First, small shield volcanoes are not usual in the Tharsis region. What kind of volcanic phase did they sign? Second, our work shows that the volcanism in this area stopped during the Hesperian epoch. Why did it stopped whereas the northern and western part of Tharsis continued to display a volcanic activity during three billion years? To answer the first question, first note that the early study of Martian volcanism, and also other recent works [13], proposed that the older volcanoes have smaller volumes and lower sizes than the younger giant shields. Syria Planum small shield volcanoes are of relative older age than the Tharsis shield volcanoes, at least to their current surface. In this case, the small shield volcanoes might sign a late activity with scattered dikes intrusion that never reach the stage to built a larger volcano at this place. In addition, small shield volcanoes have been observed in the flanks of Pavonis Mons and in the caldera of Arsia Mons [15]. They are therefore date of Late Amazonian age, an age much younger than the Syria Planum volcanoes. Nevertheless, as being posterior to the caldera or to the last volcanic episodes on flanks, they might sign a late activity as well. Thus, it is possible that the volcanism observed on Syria Planum corresponds to an aborted giant volcano.

The second point to solve, the end of the activity, might invoke to look at the crustal structure. Indeed, Syria Planum small shield volcanoes are located in the thickest part of the Martian crust, with about 80 km thick (from the degree 1-85 Martian Crustal Thickness Model of [16] ), and at the highest altitude of Tharsis region (Figure 1). Furthermore, according to [16], the deepest mantle, or the Moho deepest interface, occurs in southern Tharsis, near Syria and Solis Planum.

We are able to say that these landforms were already formed when the main crust was thick, as it is in the present - from 45 km to 120 km crustal thickness [17].

The higher crustal thickness is probably due to the superimposition of the Tharsis anomaly and the previous presence of highlands terrains, whereas the crustal thickness to the north corresponds to the crust of the northern terrain beyond the dichotomy, which is now no more visible here. We therefore can propose that the abortion of a large volcano on Syria Planum might sign the presence of a thicker crust in that part of the bulge.

**Conclusions:** HRSC images combined with MOLA and THEMIS data permit to better understand some geophysical processes, structures and processes on the surface of Mars. The Syria Planum region reveals a pattern of volcanic features singular in the context of the Martian tectonics and volcanism.The Syria Planum small shield volcanoes are placed above the deepest mantle on Mars. The higher thickening of the crust may have aborted a giant construction on the surface, like the Tharsis Montes, and permitted to create several smaller shield volcanoes.

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