

Deep and shallow crustal structure control on the late-stage volcanism in Syria Planum (Mars).

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Abstract

Long-lasting widespread volcanism in Mars is testified by the Tharsis volcanic province, one of the largest volcanic provinces with the largest shield volcanoes of the Solar System. However, volcanism on Mars is characterized also by the occurrence of broad volcanic fields, either in form of small lava shields or monogenic volcanic cones. The region of Syria Planum (SP), located east of the Tharsis province and between Noctis Labyrinthus to the North and Claritas Fossae to the southwest. It is an example of diffuse volcanism, presenting hundreds of small edifices (namely Syria Colles) which occur on top of a large bulge roughly 300 km x 200 km in size. SP exhibits a complex magmatic and volcano-tectonic evolution spanning from the early-Noachian to the more recent Amazonian. In this work, we investigate the geometry of the plumbing system of the SP volcanic field as well as geometries of the volcanic constructs (i.e., vent elongation and vent alignment) that may be linked to the structures that fed the magma presenting a possible tectonic and volcanic evolution of the distributed volcanism phase in this area. The spatial distribution of vents and the overall map view shape of the volcanic field were studied in terms of vent clustering and spatial distribution. We show that the widespread and diffuse volcanism in SP presents clear vent clusters that are related to a deep source magma reservoir located at ~100 km depth with the vents exhibiting levels of maturity and evolution related to their relative age, becoming younger towards the NW. We also show that Syria Colles vent elongations and azimuth distributions suggest that the magma exploited the inherited regional structural framework, coherent with the Syria Colles late-stage Amazonian magmatic event, and highlighting the role of a shallow crustal tectonic framework in shaping the Martian volcanism.

HIGHLIGHTS

- The spatial distribution of vents of the volcanic field of the Syria Planum (Mars) is studied
- The plumbing system of the volcanic field is derived from volcanism distribution

- Late stage volcanism on Syria Planum exploited inherited crustal structures that formed earlier during the growth of the main structural features of the area (NE-SW Tharsis Montes; E-W Valles Marineris, N-S to NNE-SSW Noctis Labyrinthus)

Keywords: Volcanic vents clustering, vent spatial distribution, plumbing system, structural inheritance, Mars

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1. Introduction

Syria Planum and the associated volcanism occur on a broader volcanic area known as Tharsis rise, one of the largest volcanic provinces of the Solar System including five large lava shields and another 12 smaller edifices (Baptista et al., 2008; Hauber et al., 2009; Richardson et al., 2013) including small lava shields, and tholuses related to both effusive and explosive activity (Brož and Hauber, 2012; Plescia, 2000). Throughout the years the increasing amount of images and topography datasets with high spatial and spectral resolution have allowed us to define absolute ages for all the volcanic constructs in the Tharsis Rise (Neukum et al., 2004; Werner, 2009; Robbins et al., 2011). These new chronological results reveal a complex volcano-tectonic evolution and magmatic history of the area spanning from the early-Noachian to the more recent volcanism such as the 130 Ma Arsia Mons' single caldera and the 140 Ma Pavonis Mons' composite calderas (Neukum et al., 2004; Pozzobon et al., 2015; Robbins et al., 2011; Werner, 2009; Pozzobon et al., 2021). Although through the years Syria Planum has been considered the by-product of the enormous volcano-tectonic activity forming the Tharsis rise (Anderson et al., 2004; Hiesinger et al., 2007; Baptista et al., 2008) it has been shown that this volcanic area could be related to large multiple episodes of mantle upwelling forming minor edifices that do not necessarily overlap with the major volcanic centres (Richardson et al., 2013, 2021, Greeley 1977, Mege and Masson, 1996; Wilson and Head 2002, Anderson et al, 2004). Moreover, the NW-SE elongated Syria Planum volcanic field occurs south of the Noctis Labyrinthus canyon systems that form a dissected highland (Bistacchi et al., 2004; Kling et al., 2021) and is located at the western tip of the Valles Marineris (Figure 1).

In the ~4000 km-long WNW–ESE-trending subparallel troughs system forming the Valles Marineris, Amazonian volcanism is reported in one of its segments (Brustel et al., 2017; Broz et al., 2017). The large left lateral strike slip offset along the southern faults of Valles Marineris may have caused possible E-W extension in Noctis Labyrinthus and Syria Planum (Yin, 2012).

In this work, we investigate the depth of the plumbing system of the dispersed late-stage volcanism in Syria Planum as well as the geometries of the volcanic constructs (i.e., vent elongation and vents alignment) linked to the structures that fed the magma in order to forward a possible tectonic and volcanic evolution of the area. The spatial distribution of vents and the overall shape of the volcanic field have been studied in terms of vent clustering and spatial distribution. Moreover, analyzing the lineament pattern on Syria Planum and surrounding areas, structural links with the formation and evolution of the Noctis Labyrinthus graben, the Valles Marineris and the Tharsis province are forwarded.

2. Data set

An extensive dataset with sufficient resolution for identifying the local morphologies of volcanic features in Syria Planum has been used. In order to obtain this dataset, we combined a reference base map made of the MOLA (Mars Orbiter Laser Altimeter onboard Mars Global Surveyor) gridded data (Smith et al., 2001) at 463 m/pixel resolution and a THEMIS daytime IR global mosaic at 100 m/pixel resolution (Edwards et al., 2011; Table 1). We cross-checked the presence of additional volcanic centres with respect to the existing mapping by means of HRSC (High Resolution Stereo Camera, Neukum et al., 2004; Jaumann et al., 2007) ND4 nadir images and DA4 DTMs (Digital Terrain Models, level 4 data products comparable with the MOLA aeroid) **analyzing slope and curvatures to check for the emergence of these features along with the related nadir nd4 images.** Additional mapping was carried out on a CTX (Context Camera onboard Mars Reconnaissance Orbiter, Malin et al., 2007) mosaic created using ISIS3 (Torson and Becker, 1997).

Table 1: list of the datasets used for mapping and fractal clustering analysis

Type of Dataset	Processing level	Spatial/grid Resolution (m/pixel)	Format
MOLA	MEGDR	460	GeoTiff, Shapefile
THEMIS	Daytime IR global mosaic	100	GeoTiff
THEMIS	Nighttime IR global mosaic	100	GeoTiff
HRSC	DA4	100	GeoTiff
HRSC	ND4	12.5	GeoTiff
CTX	level2	6.0	GeoTiff
Vents Mapping	N/D	N/D	shapefile, geodatabase
Global tectonics	N/D	N/D	shapefile, geodatabase

The dataset consists of the vent locations, vent elongation (azimuth of the maximum axis of the ellipse inscribing the vent), length and strike of the faults. In this contribution, the small shields volcanoes in Syria Planum (Baptista et al., 2008) are named monogenic vents because are dispersed and similar to the lava shield in Smith and Nem  th (2017). The vent data set (292 vents) consists of the data in the supplementary material of Bleacher et al. (2009) and Richardson et al. (2013) plus the new vents mapped in this work. We took into account only the vents falling within

102 the borders of the Syria Planum unit according to the geologic map of Tanaka et al. (2014)
103 managing them in a GIS environment.

104 The main structures (faults, graben and fossae) have been mapped from Tanaka et al. (2014) and
105 from Richardson et al. (2010) and (2021). The sinusoidal projection has been used with the
106 reference meridian (260.5°E) placed in the barycenter of the convex hull of Syria Planum vents
107 population as a whole. The sinusoidal projection allows minimizing deformation around the dataset
108 in the proximity of the central longitude, which is a fundamental point in the reliability of the
109 results, and results optimal since it is elongated and roughly oriented in NW-SE direction.

110

111 **3. Methods**

112 The extent of a volcanic field, defined by the spatial distribution of its vents, has been used
113 previously to gain information on the volcanic feeding systems and on the tectonic setting at
114 regional and local scales (Spörli and Eastwood, 1997; Tadini et al., 2014; Cañón-Tapia, 2021).

115 In the Syria Planum, vent clustering has been performed by using the nearest neighbour distance
116 distribution (or vent separation, s). A multivariate analysis of the spatial distribution of the vents
117 was performed using clustering approach based on an agglomerative hierarchical method and by
118 analyzing the vent self-similar clustering (Mazzarini and Isola, 2010; Mazzarini and Isola, 2021;
119 Pozzobon et al., 2015; 2021). The shape of the volcanic field was investigated by Principal
120 Component Analysis (PCA) and Vent to Vent Distance (VVD) analysis as in Mazzarini et al.
121 (2016).

122 *3.1 Spatial clustering*

123 *3.1.1 Clustering analysis*

124 Vents in volcanic fields typically cluster (Connor, 1990; Connor et al., 1992; Mazzarini, 2007; Le
125 Corvec et al., 2013a). The determination of clusters is method sensitive and the use of different
126 methods is recommended for a robust definition of the clusters (e.g., Cañón-Tapia, 2016; 2020).
127 The vent's nearest neighbour distance (s) for each vent in the volcanic fields is investigated by
128 applying the CV and R-c statistics and the agglomerative hierarchical method (see Appendix A1).

129 *3.1.2 PCA and VVD analysis*

130 The PCA and the VVD methods (see Appendix A2) proposed by Mazzarini et al. (2016) have been
131 used for investigating the overall shape of the volcanic field. The shape of the volcanic field is then
132 compared with the feeder azimuthal distribution derived from the mapping of vent elongations, vent
133 alignments and coalescence and eruptive fissures (e.g., Le Corvec et al., 2013a; Isola et al., 2014;
134 Mazzarini et al., 2016).

135 *3.1.3 Self-similar clustering*

136 In volcanic areas, the spatial distribution of monogenic vents (Mazzarini and Armienti, 2001;
137 Mazzarini, 2007; Mazzarini and Isola, 2010) is linked to the fracture network that allows an
138 efficient hydraulic connection between crustal/subcrustal fluid reservoirs and the surface (see
139 Appendix A3). The actual geometric and physical properties of a percolating network are described
140 by the percolation theory (Orbach, 1986; Stauffer and Aharony, 1994; Song et al., 2005).
141 Percolation theory can thus be applied to the analysis of the fracture networks that allow fluids to
142 move within the crust (i.e., Bonini and Mazzarini, 2010; Mazzarini and Isola, 2010; De Toffoli et
143 al., 2018).

144 3.1.4 Two-dimensional symmetric Gaussian kernel

145 The spatial distribution of the vent density in the volcanic field (see Appendix A4) is computed by
146 applying a two-dimensional, symmetric Gaussian kernel density estimate (e.g., Connor and Connor,
147 2009; Kiyosugi et al., 2012).

148 3.2 Structural analysis

149 A direct link between fractures and vents has been proposed for monogenetic constructs (cinder and
150 spatter cones, domes, etc.) where their morphometric features (vent elongation, vent alignment) and
151 their spatial distribution are closely related to fracture systems that feed them (e.g., Nakamura,
152 1977; Tibaldi, 1995; Takada, 1994, Le Corvec et al., 2013b; Muirhead et al., 2015).

153 The vents in Syria Planum were thus analyzed in terms of the azimuth distribution of the vent
154 elongation weighted by the vent eccentricity; the eccentricity weight is computed for each vent as
155 the ratio of its eccentricity to the minimum eccentricity value, the higher the vent eccentricity the
156 higher the weight. Vent alignments were analysed using the azimuth of the $N(N-1)/2$ lines
157 connecting vents with lengths less or equal to a certain threshold (e.g., Richardson et al., 2021).
158 According to Cebrià et al. (2011), the closer the vents the higher the probability that they are fed by
159 the same fissure and, consequently, that they are aligned along a fracture. The threshold used in
160 Cebrià et al., (2011) is $d \leq (\mu - \sigma)/3$, where μ is the average vent to vent distance and σ is the
161 standard deviation. The structure of the volcanic field is compared to the azimuth distribution of the
162 main fault systems in the neighbouring areas. The studied region where the Syria Planum volcanic
163 field is located was gridded with cells 400 km in size; the azimuth distribution of fault segments in
164 each cell was then displayed. At the scale of the volcanic field, a grid with cells 100 km in size was
165 set up, and for each cell, the fracture intensity along with the azimuth distribution of the fractures
166 was computed. Two trends are considered parallel or structurally similar within a $\pm 10^\circ$ of azimuthal
167 variation. The definition of the main structural trends is performed by visual inspection of the
168 azimuth distribution and by the assessments of a unimodal (vov Mises) distribution of the trends (see
169 Appendix B).

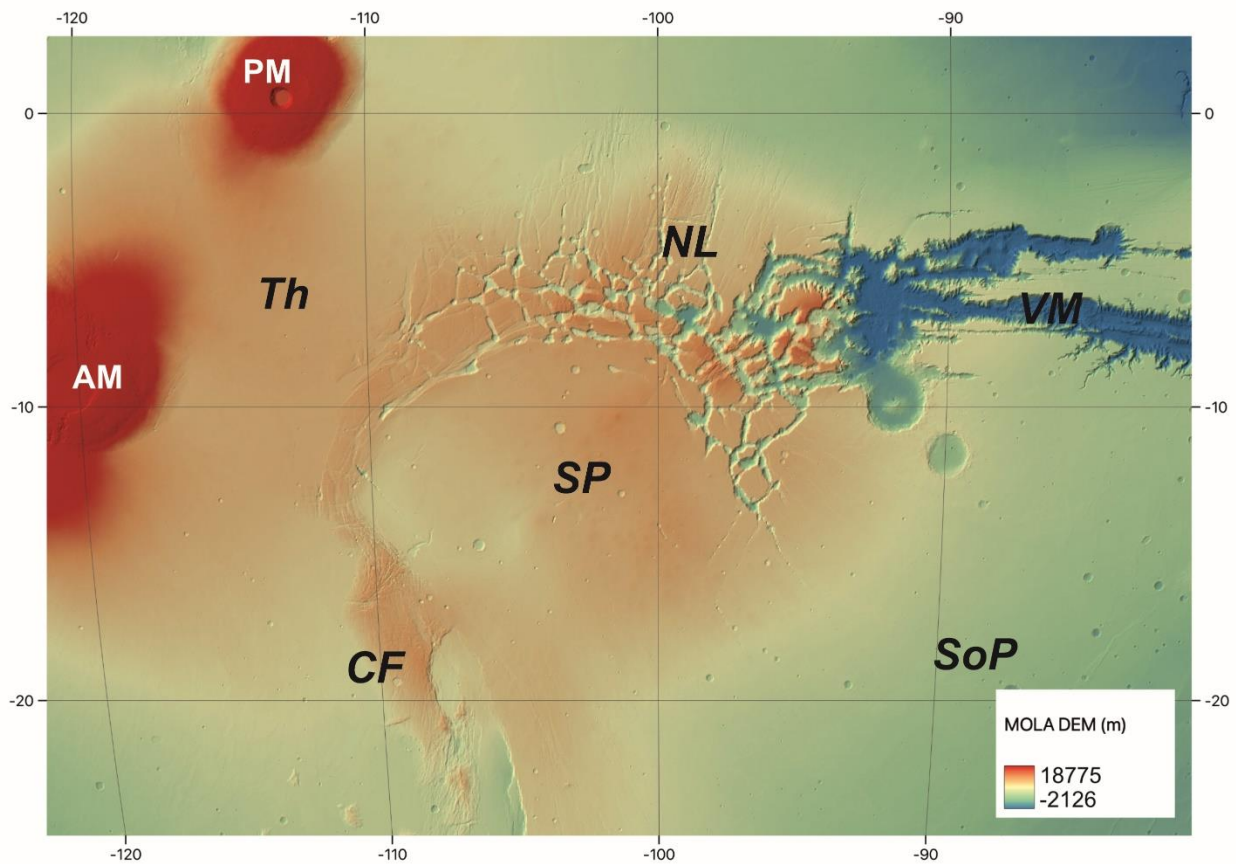
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171 4. Geological Background

172 Syria Planum is located at 12°S 104°W (Nahm and Schultz, 2010), and it is bordered to the north
173 and northwest by the Noctis Labyrinthus graben system, on the west by Claritas Fossae and on the
174 SW and S sectors Solis Planum (Figure 1).

175 On the eastern side, a large plain of ridged lava flows and tectonic structures are present (Nahm and
176 Schultz, 2010). Covering a surface of 400x700 km Syria Planum belongs to the upper member of
177 the Syria Planum Formation (namely Hsu) according to the global geologic map of Mars by
178 (Tanaka et al., 2014).

179



180

181 **Figure 1:** Map of the main structures in the studied area (see inset). Th: Tharsis bulge; NL: Noctis Labirintus; SP: Syria
182 Planum; CF: Claritas Fossae; VM: Valles Marineris; SoP: Solis Planum; AM: Ascreus Mons; PM: Pavonis Mons.
183

184 The vents have been divided into three main morpho-structural units by Baptista et al., (2008): (i) a
185 group of 30 conical protuberances with 10-60 km diameter detected with MOLA, THEMIS and
186 HRSC images identified as small volcanoes with slopes less than 3-10°, whose steepness is
187 comparable to that of the large Tharsis Montes; (ii) widespread lobate-shaped lava flows erupted by

the NW sector that can reach hundreds of km length, and (iii) highly fractured terrain on the Southern sector with large NE-SW trending grabens possibly related to the Tharsis Montes bulge. Volcanic structures in Syria planum date back to 3 Ga (Richardson et al., 2021, Baptista et al., 2008, Hauber et al., 2011, Richardson et al., 2013), whereas the highest rate of magma emplacement activity is debated to be either Hesperian/early Amazonian or fully Amazonian with the activity peaking at ~1 Ga (Hauber et al., 2011). The Syria planum major vents (with diameters larger than 250 m) have been dated with the crater counting technique (RICCARDO PLEASE; add just a simple explanation on this in brackets) resulting in an Hesperian age (3.5-3.6 Ga) by (Baptista et al., 2008). Richardson et al., (2013) performed a more detailed analysis of the crater retention age using the 521 ppd THEMIS IR daytime global mosaic on craters larger than 500 m in accordance with vent groups and morphologic units.

Preliminary vent mapping has been performed by Baptista et al. (2008), resulting in 30 small volume shields cones. These small volume shields cones are similar to the small shields in Iceland (Rossi, 1996). Richardson et al. (2013) provided a more systematic study of the Syria Planum volcanic area mapping a significantly larger number of shields (263). The spatial relationship of the vents has been studied in terms of nearest neighbour and two-point azimuthal analysis (Richardson et al., 2013). The nearest neighbor analysis shows that all of the vents in Syria planum are clustered (Richardson et al., 2013) and this vent clustering has been interpreted as a record of different magma production episodes.

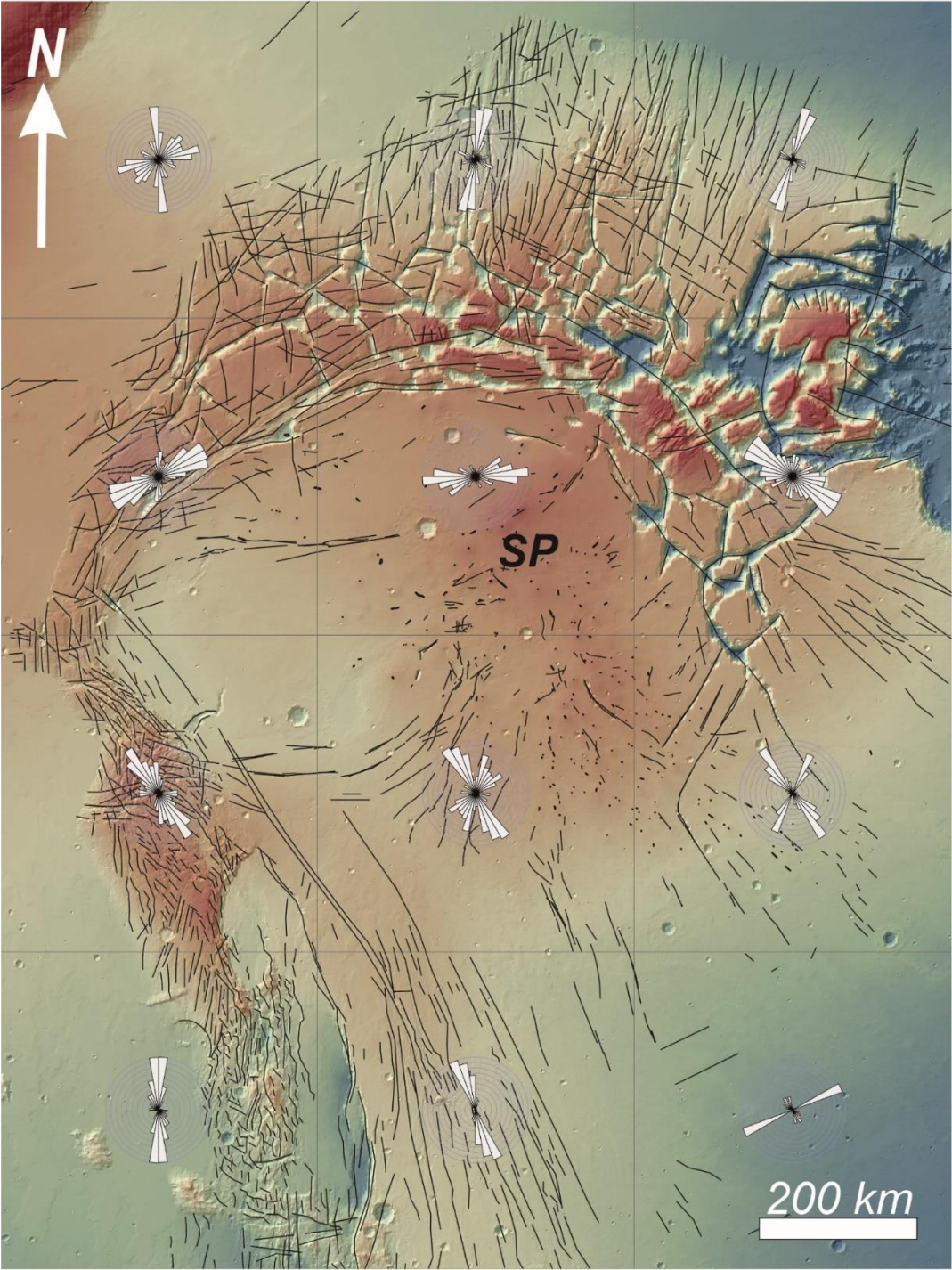
In Syria planum, fissure/vent shapes are roughly preferentially oriented towards the north-west, and with a possible radial orientation with respect to a hypothesized tectonic center between Noctis Labyrinthus and Pavonis Mons (Bleacher et al., 2021, Anderson et al., 2001 and references therein). The short inter-vent relationship was analyzed with a two-point azimuth method, in order to verify local correlations between eruptive centres and their neighbours (Bleacher et al., 2021).

In Syria Planum, volcanism evolved from a central vent volcano to dispersed shield field development over several hundred million years (Richardson et al., 2013) forming a NW-SE elongated volcanic field (the Syria Planum trend, SPT). During this period, independent magma bodies related to each small volcano interacted to some extent with one or more buried inherited fault systems, which are the NE-SW to ENE-WSW Tharsis Mons trend, the N-S to NNE-SSW Noctis Labyrintus trend, the NNW-SSE to N-S Claritas Fossae trend and the WNW-ESE to E-W Valles Marineris trend, respectively (Figures 1 and 2).

5. Results

5.1 Fault Systems

222 The analysis of the azimuth distribution of the main fractures (Figures 2 and 3) indicates that the
 223 Syria Planum volcanic field developed as a whole nearly parallel to the NNW-SSE Claritas Fossae
 224 trend with portions with well developed NE-SW Tharsis trend (Figures 2, 3). In the north portion of
 225 the volcanic field, the NE-SW to ENE-WSW Tharsis Montes trend is well developed (Figure 3).
 226



227
 228 **Figure 2:** Map of the Syria Planum volcanic field (SP) and surroundings. The black solid lines are the main faults in the
 229 area derived from Tanaka et al. (2014) and from Richardson et al. (2008; 2021). The squared cells are 400 km wide; the
 230 rose diagrams represent the azimuth distributions of the fractures that fall within the cell (bin 20°).
 231

232 In the Syria Planum area, the higher fracture intensity is located at its western and eastern borders,
 233 respectively (Figure 3). In the west portion of the volcanic field, the highest fracture intensity values
 234 (44×10^{-3} and 33×10^{-3}) result from the occurrence of fault systems with TMT and NLT trends. In the
 235 east portion, the higher fracture intensity values (29×10^{-3} and 20×10^{-3}) are linked to faults with the
 236 NLT and SPT trends. At the scale of the volcanic field (Figure 3), fracture systems with the NE-SW
 237 trend (TMT) are widespread in the northern and central part of the Syria Planum, while fracture
 238 systems with the NNW-SSW (CFT), the NNE-SSW (NLT) and the NW-SE (SPT) trends are most
 239 developed in the south.

240
 241 **Table 2:** Results of spatial clustering and PCA analysis for the Syria Planum volcanic
 242 field and its clusters

Data	N	SM (m)	sm (m)	$\hat{s}$ (m)	CV	R	c	p (<0.05)	az(°)	e
all	292	81412	447	12334	1.12	0.7157	-9.2926	1.5×10^{-20}	134°	0.40
cl1	29	76971	865	17440	1.20	0.9095	-0.9322	0.3513	46°	0.20
cl2	95	51236	587	11294	0.96	0.8673	-2.4744	0.0133	48°	0.24
cl3	70	81412	447	13851	1.35	0.8323	-2.6847	0.0073	98°	0.11
cl4	98	52645	659	10746	0.75	0.9983	-0.0328	0.9738	36°	0.18

243 *N: number of vents; SM: maximum nearest neighbour distance; sm: minimum nearest neighbor distance; $\hat{s}$:*
 244 *average nearest neighbour distance; CV: coefficient of variation; R, c: values of R-c statistics; p: the probability*
 245 *that distribution is not clustered (H_0 hypothesis); az: azimuth of the maximum eigenvector from PCA; e:*
 246 *eccentricity from PCA.*
 247

248 5.2 Vent clustering

249 Syria Planum has an average nearest neighbour distance (i.e., the vent separation, s) of 12.3 km
 250 showing a short- (CV>1 in Table 2) and long- (R-c statistics in Table 2) range clustered distribution
 251 of the vents. The density distribution of the vents (Figure 4) obtained by applying the two-
 252 dimensional, symmetric Gaussian kernel estimate (see Appendix A4, equation A4.1) clearly shows
 253 a clustering of the vents. The agglomerative hierarchical clustering (see appendix A1) detected four
 254 clusters (Table 2; Figure 4). Cluster 1 shows only short-range clustering while cluster 2 has only a
 255 long-range clustering (Table 1). Cluster 3 is clustered at all scales while cluster 4 is not clustered at
 256 all scales (Table 2).

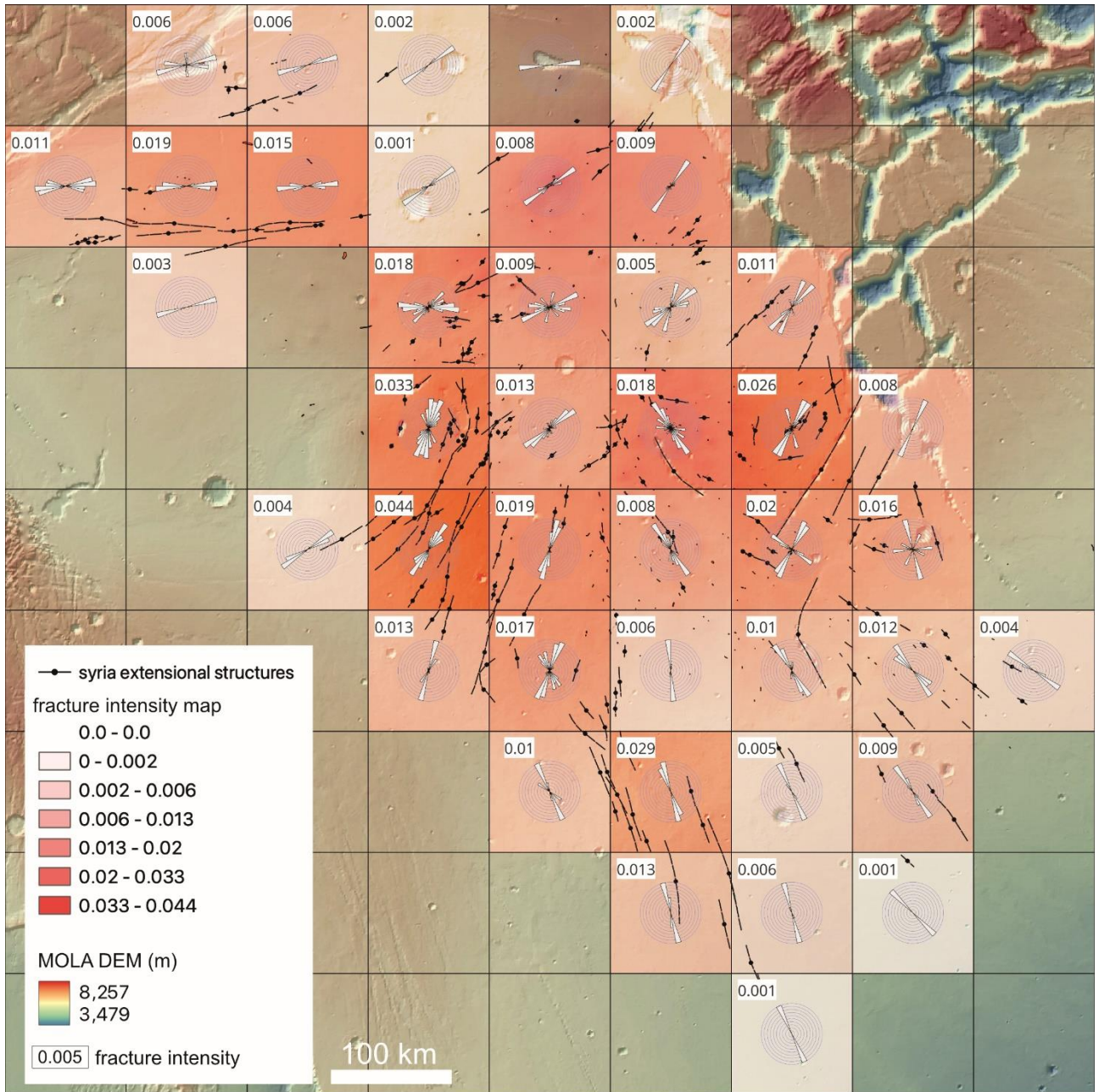
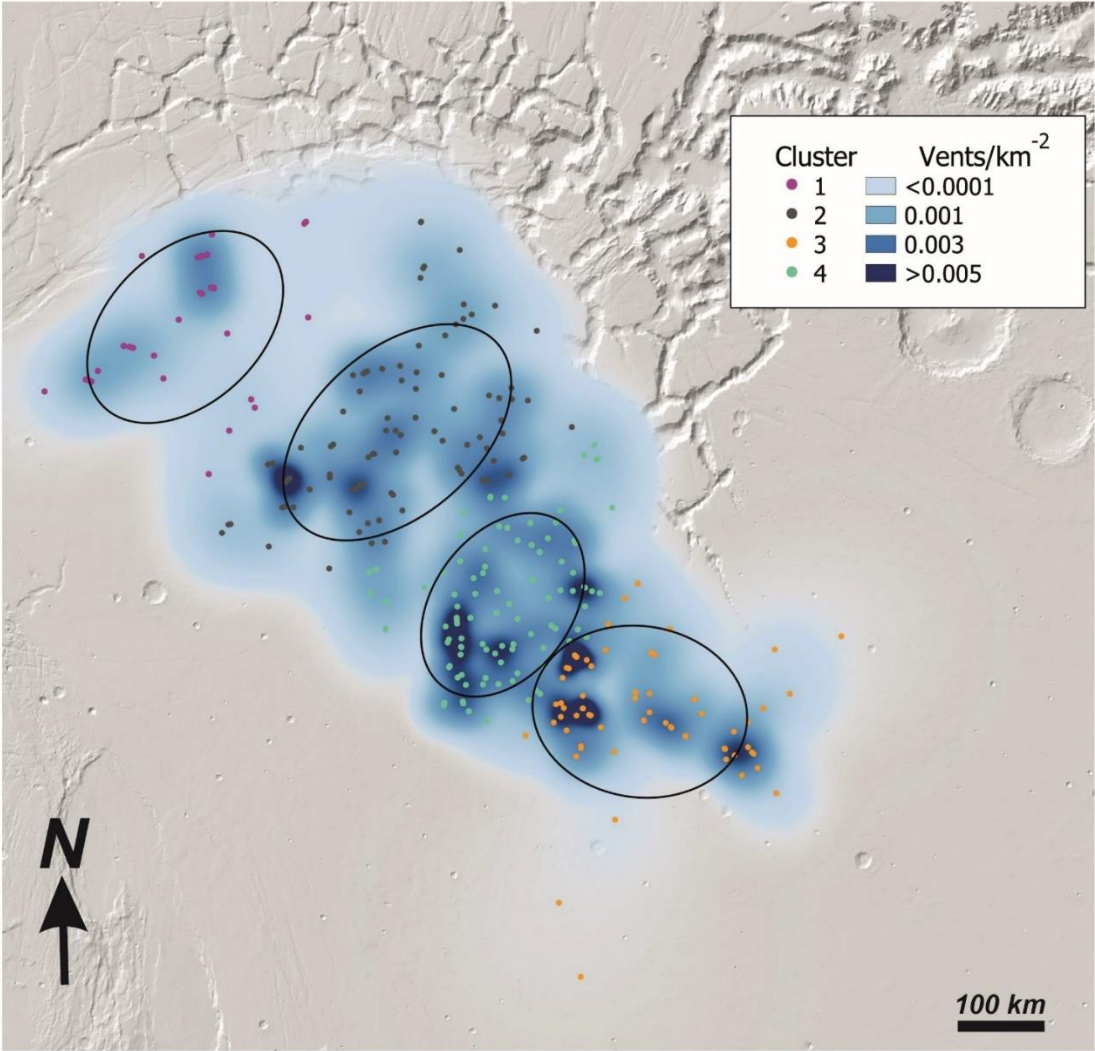


Figure 3: Fracture intensity map in the Syria Planum. The fractures in the area are derived from Tanaka et al. (2014) and from Richardson et al. (2008; 2021) and integrated with our observations. The squared cells are 100 km wide, the rose diagrams represent the azimuth distributions of the fractures that are within the cell (bin 10 km). The fracture intensity in each cell is represented by the color of the cell and by the number in each cell.

5.3 VVD and PCA analysis

Syria Planum volcanic field has a NW-SE (134°) elongated shape with an eccentricity of 0.4 as defined by the VVD and PCA analysis (Table 2; Figure 5a). The VVD and PCA analysis have been performed also for the vent clusters that have eccentricity lower than that of the volcanic field (Table 2; Figure 4).

268 Notably, none of the clusters has elongation parallel to that of the volcanic field; the southeastern
 269 most cluster (cluster 3, Table 2; Figures 4 and 6) is elongated nearly parallel to the Syria Planum
 270 trend, whereas the other clusters have NE-SW elongations (Table 2; Figures 4 and 6).
 271



272
 273 **Figure 4:** Vent density distribution map by applying the Gaussian Kernel (see Appendix A4). The black ellipses are the
 274 PCA ellipses for each vent cluster in the Syria Planum volcanic field (Table 2).
 275

276 *5.4 Volcanic field structures*

277 The elongation of the vents and the vent alignments in the volcanic field have a polymodal azimuth
 278 distribution (Table 3) where the main peak trends NW-SE and the other minor peaks are almost
 279 parallel to the main structural trends in the area (Figure 5b).
 280

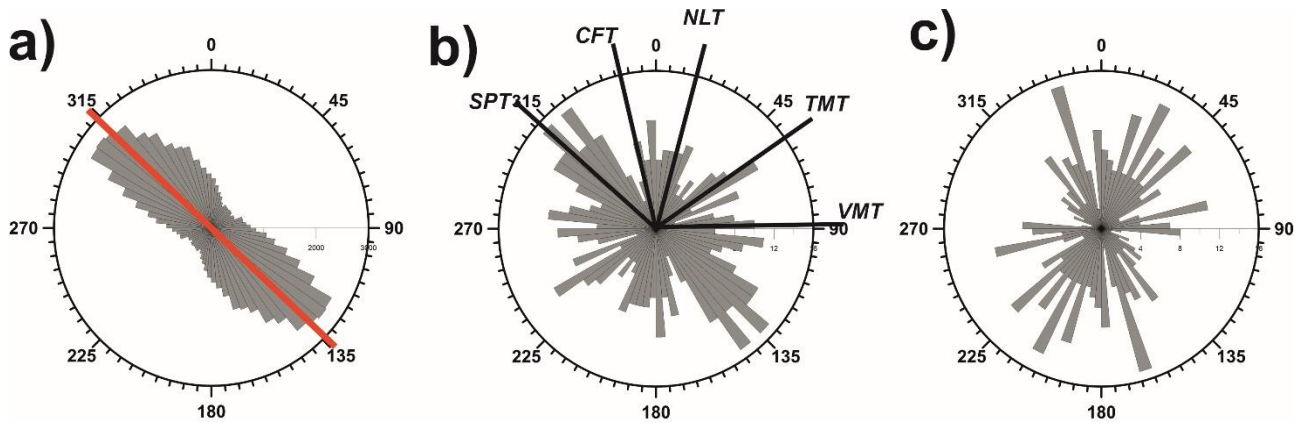


Figure 5: **a)** Azimuth distribution of the vent-to-vent distances (VVD) and of the principal eigenvector of the PCA analysis (i.e. the main axis of the ellipse) of the Syria Planum volcanic field. **b)** Azimuth distribution of vent elongations, vent alignments and volcanic structures in the Syria Planum volcanic field (Table 3). SPT: Syria Planum trend; CFT: Claritas Fossae trend; NLT: Noctis Labyrinthus trend; TMT: Tharsis Montes trend; VMT: Valles Marineris trend. **c)** Azimuth distribution of extensional fractures (Figure 4) in Syria Planum.

The degree of vent alignments has been analysed by applying the method of Cebrià et al., (2011) to the lines connecting vents derived from the VVD analysis; this analysis shows an overall vent alignment in the NW-SE direction with a greater azimuth dispersion than the VVD analysis (Figure 6a, first and second panels). The vent elongation weighted for the vent eccentricity (i.e., the higher the eccentricity the higher the weight) identifies the main NW-SE (SPT) trend which is more prominent than the NE-SW (TMT) trend (Figure 6a, third and fourth panels). The PCA and VVD analyses have been performed also for the clusters (Figure 6; Table 2).

Table 3: Circular statistics of the azimuth of the main structural trends in Syria Planum.

Trend	n	θ	95% conf int	R	P (< 0.005)
SPT	87	132°	130° - 135°	0.9444	2.37×10^{-32}
CFT	36	167°	164° - 170°	0.9603	6.12×10^{-14}
NLT	45	015°	013° - 018°	0.9536	4.54×10^{-17}
TMT	50	055°	053° - 057°	0.9561	5.09×10^{-19}
VMT	32	089°	085° - 093°	0.9253	9.85×10^{-12}

n: number of elements; θ : circular mean (clockwise from North); conf int: confidence interval; R: Rayleigh's value; p: H_0 vs. von Mises distribution

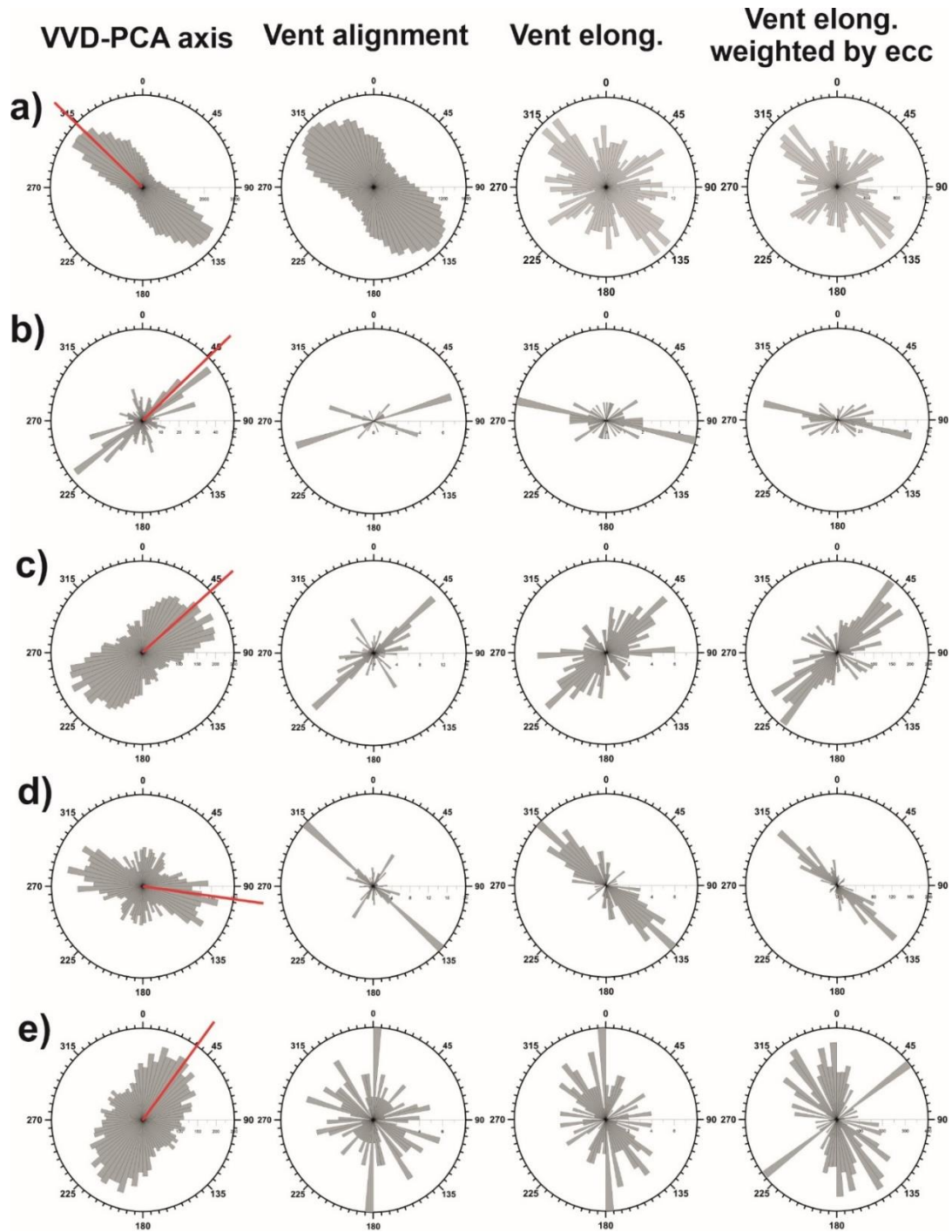


Figure 6: In each row, from left to the right, the panels represent: the azimuth distribution of the vent-to-vent distances (VVD) and of the principal eigenvector of the PCA analysis (red line); the azimuth distribution of the vent alignment by applying the method of Cebrià et al. (2011); the azimuth distribution of the elongation of the vent; and the azimuth distribution of the vent elongation weighted by the vent eccentricity (the higher the eccentricity the more the weight). **a)** Syria Planum volcanic field; **b)** Cluster 1 (see Table 2); **c)** Cluster 2 (see Table 2); **d)** Cluster 3 (see Table 2); **e)** Cluster 4 (see Table 2).

The northernmost cluster (cluster 1) shows a NE-SW elongated shape (9° anticlockwise to the TMT trend) and a bimodal azimuth distribution of the vent alignments with a main WSW-ENE rotated 12° anticlockwise to the VMT trend and 22° clockwise to the TMT trend; a secondary WNW-ESE (21° clockwise to the VMT trend) peaks (Figure 6b, first and second panels). The vent elongation

313 shows a main WNW-ESE (13° clockwise to the VMT trend) peak (Figure 6b, third and fourth
314 panels).

315

316 **Table 4:** Statistics of the self-similar clustering analysis for the Syria Planum volcanic field and for
317 its clusters

Data	N	b	D	R ²	p (uncorr)	Lco (km)	Uco (km)
all	292	4×10^{-10}	1.7023	0.9995	1.8×10^{-64}	13 ± 3	110 ± 10
cl2	95	1×10^{-9}	1.6896	0.9983	3.6×10^{-47}	18 ± 2	110 ± 10
cl3	70	5×10^{-8}	1.3869	0.9994	2.0×10^{-71}	9 ± 3	100 ± 10
cl4	98	5×10^{-10}	1.7887	0.9986	2.3×10^{-49}	16 ± 3	95 ± 10

318 *N: number of vents; b: normalization coefficient; D: fractal exponent; R²: correlation coefficient; p: the probability*
319 *that correlation does not exist; Lco: lower cut-off; Uco: upper cut-off*

320

321 Cluster 2 shows a dispersed VVD azimuth distribution with a NE-SW elongated shape (7°
322 anticlockwise to the TMT trend) and a vent alignment characterized by a main NE-SW (8°
323 anticlockwise to the TMT trend) peak and a secondary NW-SE (20° anticlockwise to the SPT trend)
324 peak (Figure 6c, first and second panels). The vent elongation has an azimuth distribution
325 characterized by a well-defined main NE-SW (10° anticlockwise to the TMT trend) peak (Figure
326 6c, third and fourth panels).

327 Cluster 3, the southernmost one, has an elongated shape and VVD azimuth distribution with a
328 WNW-ESE (9° clockwise to the VMT trend) peak. Minor peaks trend N-S, 10° anticlockwise to
329 NLT trend, and NNE-SSW, 10° clockwise to NLT trend (Figure 6d, first panel). The vent
330 alignment azimuth distribution shows a clear main NW-SE (SPT trend) and minor NW-SE (TMT
331 trend) peaks (Figure 6d, second panel). The vent elongation shows a clear main NW-SE (SPT trend)
332 peak (Figure 6d, third and fourth panels).

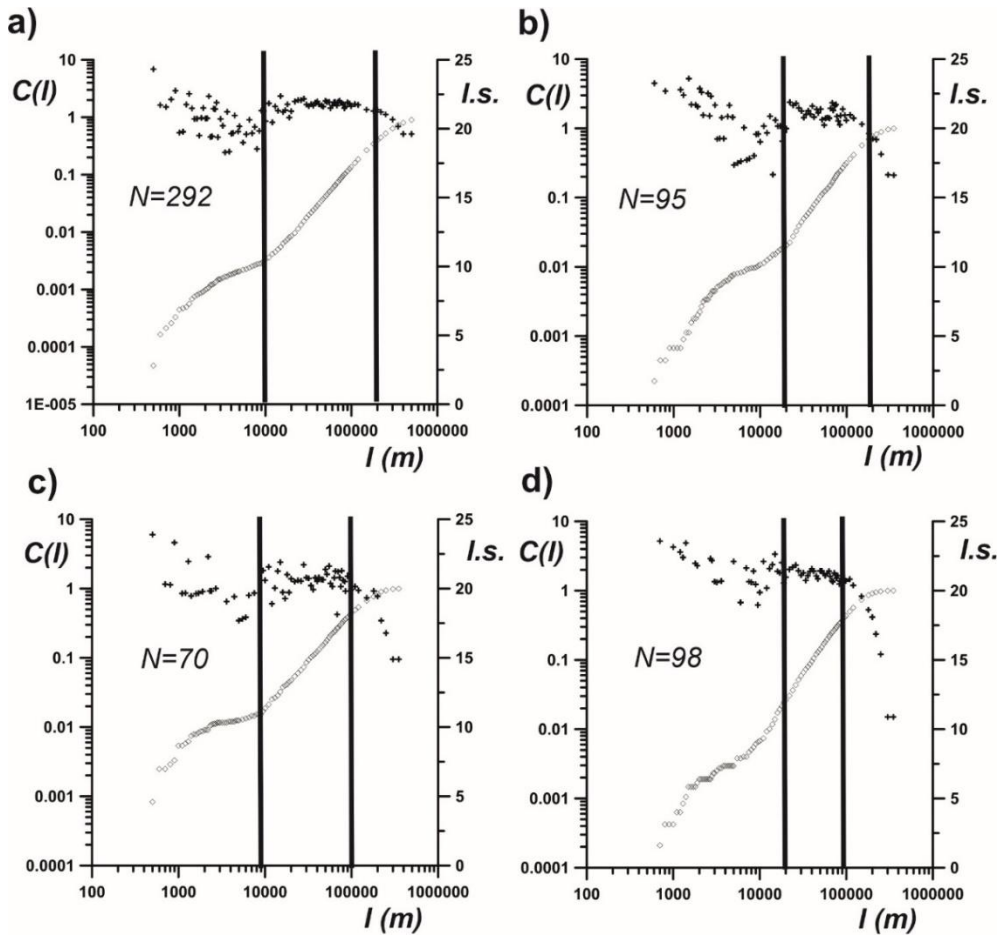
333 Cluster 4 has a dispersed azimuth distribution of the VVD lines with an overall NNE-SSW to NW-
334 SE (19° anticlockwise to TMT trend) elongated shape (Figure 6e, first panel). The vent alignment
335 azimuth distribution is dispersed with a main well-defined N-S (10° anticlockwise to the NLT

336 trend) peak and several minor peaks (Figure 6e, second panel). The vent elongations have azimuth
 337 distributions very similar to that of the vent alignments (Figure 6e, third panel) while the vent
 338 elongations weighted for the vent eccentricity (Figure 6e, fourth panel) have a main NE-SW (TMT
 339 trend) peak, a secondary NNW-SSE (CFT trend) peak and a third N-S (NLT trend).

340 5.5 Volcanic field self-similar clustering

341 In Syria Planum, the self-similar clustering of vents (eqs. A3.1 and A3.2 in Appendix A3) was
 342 investigated for the whole data set and for the identified clusters having at least 50 vents (Table 4).
 343 For all the data sets, the self-similarity of the vents is well defined (see the p value in Table 4). The
 344 log-log plot of the whole field has a clear plateau with an upper cut off (Uco) of 110 km and a
 345 fractal exponent D of ~ 1.70 (Figure 5c and 7a).

346 The 110 km upper cut off (Uco) is a common feature shared by the whole data set and by the three
 347 clusters (Table 4 and Figure 7). Cluster 2 has a fractal exponent (D) ~ 1.69 , cluster 3 has $D \sim 1.39$
 348 and cluster 4 has $D \sim 1.77$ (Table 4 and Figure 7).



350
 351 **Figure 7:** Log-log plot of the vent self-similar clustering (see appendix A3), N is the number of vents in each data set.
 352 The size range is defined by the thick black vertical lines (see Figure 4c). **a)** Syria Planum (Table 3); **b)** Cluster 2 (Table
 353 4); **c)** Cluster 3 (Table 4); **d)** Cluster 4 (Table 4).
 354

6. Discussion

Considering the fractal exponent of the three relevant clusters of Syria Planum (see table 4), cluster 3 (~1.4) shows the lower values. Cluster 2 in the NW sector shows a D value (~1.7), very similar to the D value of cluster 4 (~1.8). The vent self-similar clustering of the vents in Syria Planum suggests that the deep magma reservoir is about 100 km deep (Figure 7; Table 4) indicating that a crust 100 km thick existed during the late stage dispersed volcanism. The inferred depth of the main magmatic reservoir is in accordance with the actual crustal thickness derived by MGS of ~90-110 km in correspondence with the Syria Planum bulge (Zuber et al., 2000; Neumann et al., 2004; Zuber, 2001).

In the Syria Planum volcanic field, the elongation of the volcanic field shape and the azimuth distribution of the vent elongations show a well expressed SPT (NW-SE) trend (Figures 5a and 5b). The vent elongations (Figures 5b) show secondary peaks parallel to the main structural trends of the area (Figure 2 and Table 3). Notably, SPT trend is not clearly expressed in the azimuth distribution of faults/fractures in the Syria Planum (Figure 5c). Faults in the studied area show NNW-SSE (5° anticlockwise to CFT trend) and NE-SW (TMT trend) peaks. Secondary peaks trends nearly parallel (within 10°) to the NLT and VMT trends (Figure 5c).

Three out of the four vent clusters identified in Syria Planum show elongated shapes at high angle to the elongation direction of the volcanic field (Figures 4 and 6; Table 2). The cluster, in the northwest sector of the volcanic field, has the azimuth distribution of its structures (Figure 6b) that does not match the nearly E-W trends of the faults (Figure 3). Moving southeastward, in cluster 2 there is a partial match between the trend of faults in the area (Figure 3) and the vent elongations (Figure 6c). The cluster 4 shows an apparent coherence between the vent elongations (Figure 6e) and the trend of faults (Figure 3). The shape of the southeasternmost cluster 3 is 30° anticlockwise rotated to the NW-SE (SPT) trend; while the vent elongations show azimuth distribution with a clear NW-SE trending peak (Figure 6 d) that matches the trend of the faults (Figure 3).

The angular differences between the elongation of the whole volcanic field and its clusters and, in each cluster, between the vent elongation and the main fault trends may be interpreted as resulting from the evolutionary formation of the dispersed volcanism phase in Syria Planum (Richardson et al., 2013).

According to Baptista et al., (2008) and Schultz (1998) the evolutionary sequence of the large-scale structural framework of Valles Marineris, Noctis Labyrinthus and Syria Planum volcanism consisted of a sequence of four macro-events: i) Late Noachian-Early Hesperian: formation of a graben system; ii) Late Hesperian (3.2 Ga) formation of Syria Planum main shield and effusion of

389 fissure-fed flood basalts in NE-SW direction; iii) Early Amazonian (~1.8 Ga) crustal subsidence in
390 the region of Syria Planum; iv) Late Amazonian formation of the main structures of Noctis
391 Labyrinthus EW trending graben system and Noctis Labyrinthus structural framework. According
392 to this reconstruction the Syria Planum volcanic field is therefore part of a late-stage Amazonian
393 volcanism, as it is set on and exploits an already well-developed structural framework, reflecting its
394 main orientation according to each vent cluster location. In this case the correlation between the
395 inherited fabric and the volcanic lineament data suggests that magma exploited pre-existing
396 lineaments and hence it is Late Amazonian.

397 Another possible explanation is that vent elongations and structures formed synchronously under
398 the same stress regime. This scenario requires that the evolution of the dispersed volcanism in Syria
399 Planum consisted of different volcanic phases each associated with the formation and the evolution
400 of Tharsis Montes, Valles Marineris, Noctis Labyrinthus and Syria Planum structures. In this case,
401 the dispersed volcanism in Syria Planum lasted for a long time span, from the late Hesperian to the
402 early Amazonian.

403 Whatever the evolutionary history of the dispersed volcanism in Syria Planum, it shows a clear
404 difference between the direction of the elongation of the volcanic field and its clusters with respect
405 to the azimuth distribution of the structures (vent elongation, vent alignment, eruptive fissure)
406 observed in the volcanic field (Figure 3) suggesting that at a shallow crustal level, the magma
407 exploited the actual fracture network that is not necessarily linked to the geometry of the whole
408 volcanic field. The influence of the fracture network at shallow crustal levels on the propagation of
409 dikes and on the site of eruption in volcanic fields has been shown by analogue models (Le Corvec
410 et al., 2013b).

411 On Earth, several examples document how the structural grain of the shallow crust ultimately
412 controls the eruption site of vent and their spatial distribution. The Pleistocene Auckland volcanic
413 field is a clear example of volcanic field whose overall shape is controlled by deep lithospheric
414 structures (e.g., Spörli and Eastwood, 1997). Nonetheless, in the Auckland volcanic field, the actual
415 spatial distribution of vents as well as their morphology are controlled by the shallow crust
416 fault/fracture network (Cassidy and Locke 2010; Kereszturi et al., 2014).

417 In the off-shore of the New Zealand, southern island, the analysis of borehole-constrained 2D
418 seismic reflection data shows that upper crustal structures controlled the location of vents also for
419 the fossil (Cretaceous-Eocene) Tuatara volcanic fields (Phillips and Magee, 2020).

420 In the East African Rift, the shape and elongation of volcanic fields are clearly linked to
421 lithospheric-scale structures whereas the internal spatial distribution of vents is controlled by the
422 shallow fracture network (Mazzarini and Isola, 2022).

The vent spatial distribution in volcanic field also gather information of the geometries of the plumbing system at different depth as for the Jeju Island, South Korea volcanic field (Cañón-Tapia, 2021b). Parallelism between the shape of volcanic fields, the cone elongation and alignment to the maximum crustal horizontal stress has been observed in areas of active tectonic such as the Yucca Mountain (Connor et al., 2000) and the northern Main Ethiopian Rift (e.g., Rooney et al., 2011; Mazzarini et al., 2016).

In summary, the plumbing system of the Syria Planum consists of a deep portion at about 100 km. There is a clear dichotomy between the overall shape of the volcanic field and the direction of the feeders associated with the vents indicating that the deep portion of the plumbing system likely controlled the site and the overall shape of the volcanic field, whereas the shallow plumbing system is ruled by inherited structures that controlled the cone elongation, alignment and distribution. Volcanic field plumbing systems consisting of a deep and a shallow portion have been reported also on Earth in the East African Rift System, for several volcanic fields where the location of the deep magma reservoir is controlled by lithospheric scale structures/geometries and the vent surface distribution and structures are controlled by inherited, shallow crustal, structures (Mazzarini and Isola 2021; 2022; Le Gall et al., 2008).

7. Conclusions

In this work, we have carried out a thorough analysis of the volcanic field in Syria Planum region of Mars, and studied its relation with the major tectonic framework and the time evolution of the region. Four main clusters can be identified among the volcanic vents population and their spatial distribution has been analyzed in terms of fractal clustering. The fractal nature of the plumbing system enabled us to infer the depth of the source magmatic reservoir being located at ~100 km of depth. The eruptive structures, their distribution and the elongation of their vents indeed reflect a well-known process on Earth where large and diffused volcanic fields develop in correspondence of a deep magmatic reservoir and depend on its size, whereas their surface distribution is highly controlled by shallow crustal inherited structures. This makes the Syria Colles in Syria Planum a late-stage magmatic event which could have developed after the formation of the main regional structural framework of Claritas Fossae, Tharsis Montes, Noctis Labyrinthus and Valles Marineris or, alternatively, that formed through different volcanic phases cieval with the formation of the main structure in the region.

458 **Appendix A: Methods used in the spatial distribution analysis of vents and fractures**

459 *A1. Hierarchical Clustering and nearest neighbour distance analysis*

460 Two statistical methods have been used for analyzing the nearest neighbor distance (s) of vents. The
461 ratio between the standard deviation and the mean of the sampled population is the coefficient of
462 variation (CV; Gillespie et al., 1999); $CV > 1$ indicates the clustering of points, $CV = 1$ is for a
463 random or Poisson distribution, and $CV < 1$ is for anticlustering (a homogeneous distribution). The
464 CV statistic investigates how close points are to each other giving information on short-range
465 clustering not probing the pattern of point distribution.

466 The R-c statistics (Clark and Evans, 1954) compare the actual nearest neighbour distance
467 distribution with that expected for a Poisson distribution of N points. The reference density is the
468 ratio between the actual point number (N) and the area of the convex hull containing them. $R < 1$ is
469 for clustering and for a statistically significant departure from randomness at 0.95 and 0.99
470 confidence levels, $|c|$ should be greater than 1.96 and 2.58, respectively.. In particular, in the case of
471 not very large point number, the scavenged statistic has been used (e.g., Baloga et al., 2007; Beggan
472 and Hamilton, 2010).

473 The definition of the number of statistically significant clusters has been performed by applying a
474 clustering analysis based on an agglomerative hierarchical method (e.g., Mazzarini, 2007;
475 Mazzarini and Isola, 2010). The optimal number of clusters is derived from the analysis of the
476 dendrogram that depicts the amalgamation of observations into one cluster. The similarity at any
477 step is the per cent of the maximum distance at that step relative to the initial maximum inter-
478 observation distance (i.e., the maximum distance between the points). An abrupt change in the
479 similarity marks the point for cutting the dendrogram defining the number of clusters statistically
480 significant in the data sets.

481 *A2. PCA and VVD analysis*

482 The PCA analysis provides the shape (ellipse) of the volcanic field and the direction of the first
483 eigenvector represents the trend of the long axis of the ellipse and can be used as a proxy for the
484 field elongation (Mazzarini et al., 2016). The VVD method analyses the azimuth distribution of
485 each of the $N(N - 1)/2$ segments connecting vent pairs. Well-aligned vents will produce a narrow
486 well-defined peak in the azimuth distribution of segments connecting vents and small angular
487 dispersion (i.e. well defined unimodal azimuth distribution). The dispersed distribution of vents or
488 patterned distribution - en echelon vent alignments and vent clusters - will produce several peaks in
489 the azimuth distribution of segments connecting vents (Mazzarini et al., 2016). These analyses have
490 been performed also for selected clusters of volcanic fields derived from the hierarchical clustering.

491 A3. Self-similar clustering

492 The self-similar clustering of vents has been investigated by applying the two-point correlation
493 function method. For a population of N points (i.e. vents), the correlation integral is defined as the
494 correlation sum ($C(l)$) that accounts for all the points at a distance of less than a given length l
495 (Bonnet et al., 2001 and references therein). The term is computed as

$$496 C(l) = 2N(l)/N(N-1) \quad (A3.1)$$

497 where $N(l)$ is the number of pairs of points whose distance is less than l .

498 The fractal distribution is defined by

$$499 C(l) = bl^D \quad (A3.2)$$

500 with b being the normalization constant and D the fractal exponent.

501 The slope of the curve in a $\log(C(l))$ versus $\log(l)$ diagram yields the D value.

502 The computed D value (fractal exponent of clustering) holds for a defined range of distances (size
503 range) where the equation is valid. For each analysis, the size range of samples is in turn defined by
504 a plateau in $\Delta\log(C(l))/\Delta\log(l)$ (i.e., the local slope) versus $\log(l)$ diagram. The wider the range the
505 better the computation of the power-law distribution (Walsh and Watterson, 1993). The choice of
506 the zones where the plateau is well-defined and the determination of the lower and upper cutoffs
507 (L_{co} and U_{co} , respectively) are done by selecting the wider length range for which the correlation
508 between $\log(l)$ and the local slope is greatest (Mazzarini, 2004). A size range of at least one order of
509 magnitude and at least 50 samples is required to extract robust parameter estimates (Bonnet et al.,
510 2001; Andre-Mayer and Sausse, 2007; Clauset et al., 2009). The random removal of 20% of the
511 analyzed samples from large datasets (i.e., > 200 vents) does not affect the estimation of fractal
512 dimension (less than 0.01% of variation) and the error introduced into the estimation of the cut-offs
513 is less than 1%–2% (Mazzarini and Isola, 2010). Mazzarini et al. (2013) tested the effect of
514 uncertainties in point-like feature locations by adding random errors to the sampled points (in the 0–
515 100 m, 0–300m and 0–500m ranges, i.e., errors as high as 5 to 25 times that of the coarsest image
516 resolution used to locate the points). The 0–100m errors randomly added to the point (vent)
517 locations generated fractal exponent and cut-off values identical to those computed for the original
518 dataset. In the case of 0–500m random errors, the resulting fractal exponent was 3% higher than
519 that computed for the original dataset, and the cut-offs' were very similar to those computed for the
520 original dataset (Mazzarini et al., 2013). The image spatial resolution mostly affects the recognition
521 and definition of the small-wavelength objects (i.e., objects with size less than the image's spatial
522 resolution) and their dimensions are resolved for size greater than three times the image resolution
523 (i.e., image pixels). The image spatial resolution thus lead to an underestimation of the short
524 wavelength features and, in turn, it affects the shape of the left size of the log-log plot.

525 The upper cut off value (Uco) obtained by analyzing several volcanic fields on Earth linearly scales
 526 with the depth of the fluid source (e.g., Mazzarini and Isola 2010). This relationship has been
 527 observed for volcanic vents located in different geotectonic settings such as in the East African Rift
 528 (Mazzarini, 2007; Mazzarini and Isola, 2010), southern Patagonia (Mazzarini and D' Orazio, 2003;
 529 Mazzarini et al., 2008), TransMexican Volcanic Belt in Mexico (Mazzarini et al., 2010) and for
 530 mud volcanoes in the Greater Caucasus in Azerbaijan (Bonini and Mazzarini, 2010).

531 *A4. Two-dimensional symmetric Gaussian kernel*

532 The two-dimensional, symmetric Gaussian kernel density estimate (e.g., Connor and Connor, 2009;
 533 Kiyosugi et al., 2012; Connor et al., 2019) is computed as follows:

$$534 \quad \lambda(x) = \frac{1}{2N\pi h_i^2} \sum_i^N e^{-\frac{d_i^2}{2h_i^2}} \quad (\text{A4.1})$$

535 d_i is the distance between location x and the N vents, and h_i is the smoothing bandwidth for vent i .
 536 Distance values between neighbour samples larger than h_i have a small weight in the computation
 537 of the density estimate. A variable bandwidth value has been applied by computing the half value of
 538 the distance between each sample and its nearest sixth neighbour (Favalli et al., 2012). The vent
 539 density maps of the volcanic field have been created by applying Equation (A4.1); the resulting
 540 matrix possesses cells with the appropriate vent density value (vent/km²).

541

542 **Appendix B: Circular statistics**

543 The definition of the azimuth of the axial data (i.e., cone elongation, fissure trend, vent alignment)
 544 has been assessed by use of the circular statistics (i.e. Mardia, 1972; Davis, 2002) and the PAST
 545 4.12 statistical software (<https://www.nhm.uio.no/english/research/resources/past/>).

546 As first step, all data are plotted together for a visual inspection of possible trends and polymodal
 547 distributions. A buffer of about 10° is used for the azimuth of each main peak for sampling the data.
 548 On the sampled data the, circular mean is computed (equation B1); the 95% confidence interval on
 549 the mean is estimated according to Fisher (1983).

$$550 \quad \bar{\theta} = \tan^{-1} \frac{\sum \sin \theta_i}{\sum \cos \theta_i} \quad (\text{B1})$$

551 The von Mises distribution is estimated by the computation of the Rayleigh's parameter (R ;
 552 equation B2)

$$553 \quad R = \tan^{-1} \sqrt{\frac{(\sum_1^n \cos \theta_i)^2 + (\sum_1^n \sin \theta_1)^2}{n^2}} \quad (\text{B2})$$

554 and by the estimation of the probability of rejection of the null hypothesis (H_0) at the 0.005 level of
 555 confidence (p).

556

557

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