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1 **New evidence for sedimentary volcanism on Chryse Planitia, Mars**

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21 **Abstract**

22 Kilometre-sized flows (KSFs) have been observed in many regions on Mars and have been
23 typically interpreted as lava flows. However, sedimentary volcanism has been proposed as an alternative
24 origin for some KSFs. Remarkable examples of such hypothesized sedimentary KSFs are located at the
25 southern margin of Chryse Planitia. There, the flows are associated with conical and dome-shaped
26 edifices, however their formation mechanism remained enigmatic due to the absence of ground truth.
27 Here, we present new morphological results obtained on these KSFs using seven newly available Digital
28 Elevation Models computed from HiRISE stereo pairs. Our investigation confirms that these features
29 are aggradational and formed by the transport of a liquid. This material emerged from identified
30 depressions and the presence of subtle mounds inside them is interpreted to mark the position of feeder
31 vents. We also observe that the margins surrounding the central large channels are not continuous. They
32 are cut by meter-sized troughs linking the central channels to units with distinctive albedo and roughness
33 from their surroundings. These bright units do not have a clear topographical expression, suggesting that
34 the effused material originally flowing away from the central channel was easily removed after its
35 emplacement. Such surface features are unlikely to be related to igneous deposits, since once lava is
36 released from a main channel, it would rapidly solidify due to the heat loss and hence result in
37 topographically distinct features. In contrast, such morphological expressions are more likely related to
38 sedimentary volcanism and the emplacement of low viscosity water-rich mud. Sublimation, evaporation,
39 infiltration or a combination of these processes should lead to water loss without leaving a detectable
40 topographic expression but changing the roughness and hence albedo of the surface. The southern part
41 of Chryse Planitia is a region on Mars where subsurface sediment mobilization operated in the past and
42 hence represents a promising site for future exploration where deeper-sourced sedimentary deposits are
43 exposed at the surface.

44 1 Introduction

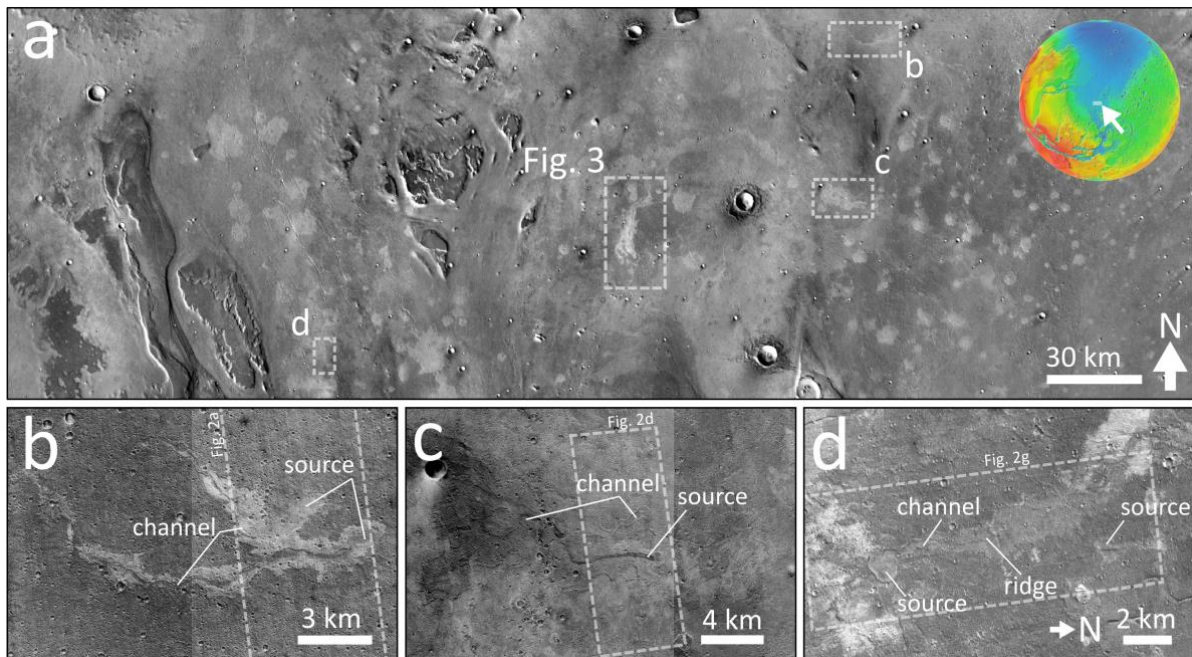
45 High-resolution images have revealed the presence of kilometre-sized flows (KSFs) on Mars.
46 Most of these features are associated with well-known volcanic centres, such as Tharsis, Elysium or
47 Syrtis Major, and therefore have been interpreted as lava flows (e.g., Hodges & Moore, 1994; Bleacher
48 et al., 2007; Keszthelyi et al., 2008; Hauber et al., 2009). Some KSFs, however, occur in regions where
49 a direct link to magmatic activity is not obvious, and an alternative formation scenario related to
50 sedimentary volcanism has been proposed (Wilson and Mouginis-Mark, 2014; Okubo, 2016; Komatsu
51 et al., 2016; Brož et al., 2019). This mechanism has been challenged because the current martian
52 atmospheric pressure is considered too low to allow water to be stable for prolonged periods of time at
53 the surface. If liquid water were exposed on the martian surface today, it would boil and eventually
54 evaporate into the atmosphere, and therefore mud flows, similar to the terrestrial ones, are not supposed
55 to occur (e.g., Hecht, 2002; Bargery et al., 2010). Therefore, it remains unclear if mud would be able to
56 propagate on Mars` surface via mud flows under the current atmospheric pressure.

57 Several studies (e.g., Wilson and Mouginis-Mark, 2014; Brož et al., 2020a,b) have recently
58 shown that the instability of water within the mud is a critical factor which could affect the way that
59 mud propagates over the martian surface. These results show that evaporative cooling would cause the
60 mixture to freeze (Bargery et al., 2010). However, this process would occur only at the flow`s surface
61 (Brož et al., 2020a). Consequently, the mud flow`s interior could remain liquid for prolonged periods of
62 time allowing lateral propagation while “protected” by an icy-muddy crust (Brož et al., 2020a).
63 Therefore, sedimentary volcanism on Mars should exhibit observational evidence that can be identified
64 on the surface, although its precise morphology should differ from mudflows on Earth.

65 A remarkable example of KSFs accompanied by conical and dome-shaped edifices was reported
66 by Komatsu et al. (2016) from the southern margin of Chryse Planitia on Mars (19.16°N; 322.71°E), at
67 the terminations of the large outflow channels of Simud, Tiu and Ares Valles formed during the
68 Hesperian epoch (Tanaka et al., 2005). Komatsu et al. (2016) proposed that these KSFs were resulted

69 from subsurface sediment mobilization. This conclusion holds on the observation that the studied
70 edifices have morphological and morphometrical similarities with terrestrial mud flows. However,
71 similar morphologies and morphometries could also develop during the emplacement of low viscosity
72 lava flows. Brož et al. (2019) later identified thirty-five similar KSFs as part of large, >1,300 population
73 of dome-shaped, conical, pie-like and flow-like edifices mapped exclusively on sedimentary plains. The
74 authors argued for a genetic link between these features and the associated sedimentary units. Such
75 distinct coupling favours sedimentary volcanism over igneous volcanism as a potential genetic
76 mechanism, although the latter could not be ruled out.

77 Komatsu et al. (2016) and Brož et al. (2019) showed that KSFs at the southern margin of Chryse
78 Planitia typically consist of three morphological elements: a) a central depression from which one or
79 more channels originate, b) leveed channels, c) a distal portion of the fading channel(s) where the
80 material is deposited forming terminal lobes. Based on these morphologies, Brož et al. (2019) later
81 proposed that these KSFs resulted from low viscosity mud extrusions that propagate through channels,
82 gradually losing their transport energy. Without data on the composition and internal structure of the
83 KSF, this hypothesis could not be fully substantiated. The initial studies used images from the Context
84 Camera (CTX) (~5-6 m/px, Malin et al., 2007) and High Resolution Imaging Science Experiment
85 (HiRISE) (~30 cm/px; McEwen et al., 2007), and lacked topographic data to support their inferences.
86 Six KSFs are now covered by HiRISE stereo pairs (Fig. 1) enabling us to generate seven Digital
87 Elevation Models (DEMs) with a ground sampling distance of 1-2 m/px. These new data provide
88 additional details about the shapes of KSFs and new information to validate or disprove whether the
89 observed morphologies are consistent with a sedimentary volcanism scenario.



90

91 Figure 1: Location of investigated KSFs in Chryse Planitia. (a) THEMIS-IR nighttime image of study
 92 area that hosts a large assemblage of surficial features interpreted as sedimentary volcanoes by
 93 Komatsu et al. (2016) and Brož et al. (2019), visible as light-toned units on the lowlands. Image
 94 centred at 19.25°N and 322.34°E. Inset globe, indicating the location of the study area, is based on
 95 colourised MOLA topographic data (blue=low elevation, red=high). The location of the kilometre-
 96 sized flows described in this study are marked on panels (b-d) and on Figure 3. The dashed lines in
 97 panels (b), (c), and (d) mark the position of HiRISE stereo-pairs that are shown in Figure 2. Panels (b),
 98 (c) and (d) are based on the Murray Lab CTX mosaic (Dickson et al., 2018).

99 2 Data and methods

100 This study uses data obtained by two cameras; CTX (Malin et al., 2007) and HiRISE (McEwen
 101 et al., 2007), both on board NASA's Mars Reconnaissance Orbiter spacecraft. The resolution of the CTX
 102 images is around ~6 m/pixel, and for HiRISE images ~30 cm/pixel. While the CTX data were used to
 103 provide context and study the wider surroundings of KSFs, the newly available HiRISE stereo-pairs
 104 were used to compute the high-resolution DEMs. Seven HiRISE DEMs were produced by using the
 105 standard workflow using the software packages ISIS3 and @BAE Systems SOCET SET. The images of
 106 the stereo pairs were first manually co-registered to perform a bundle adjustment, then automatic
 107 extraction of the relief was performed using SOCET SET. The DEMs were vertically controlled to Mars
 108 Orbiter Laser Altimeter (MOLA) elevation data. The vertical precision of the DTMs is estimated as:
 109 maximum resolution/5/tan (convergence angle) (Kirk et al., 2008). CTX and HiRISE images together

110 with the DEMs were then analysed in the ESRI ArcGIS 10 software including extraction of topographic
 111 profiles. Topographic information was obtained by using the 3D Analyst and Spatial Analyst tools
 112 within this software. An estimation of general slope of areas where KSFs were identified was made by
 113 calculating a slope map. To generate the slope map a plane is fitted to the 3x3 neighbourhood
 114 surrounding each pixel in the DEM and its slope calculated (Burrough and McDonell, 1998). Two
 115 separate locations within the study area were defined for this slope analysis. The data were projected in
 116 an Equirectangular Map projection with the central meridian set at 180°E.

DEM	HiRISE Image 1	Pixel Scale image 1 (m)	HiRISE Image 2	Pixel Scale image 2 (m)	Conver- gence angle (°)	Ground- sampling dimension (m)	Vertical precision (m)
Chryse (1)	ESP_064644_ 1990	0.29	ESP_065488_199 0	0.28	13.4	1	0.24
Chryse (2)	ESP_065356_ 1995	0.57	ESP_065422_199 5	0.58	17.8	2	0.36
Chryse (3)	ESP_024082_ 1995	0.57	ESP_023581_199 5	0.6	26.2	2	0.23
Chryse (4)	ESP_025071_ 1995	0.57	ESP_025137_199 5	0.62	30.2	2	0.20
Chryse (5)	ESP_067150_ 2005	0.57	ESP_068034_200 5	0.65	38.1	2	0.15
Chryse (6)	ESP_020469_ 1995	0.29	ESP_037598_199 5	0.29	14.5	1	0.22
Chryse (7)	ESP_064156_ 2005	0.29	ESP_064868_200 5	0.29	26.7	1	0.12

117 Table 1: Details about used HiRISE stereo-pairs, their vertical precision and the software used for their
 118 preparation.

119 3 Observations

120 The studied KSFs can be clearly distinguished in topographic data. They show a topographically
 121 well-defined “source” area with circular, semi-circular or elongated map-view outline (Figs. 1, 2a).
 122 Three source areas are situated on relatively flat plains and are surrounded by elevated, several hundred-
 123 meter-wide rims (Fig. 2d). The other source areas are superposed on higher elevation and inclined pre-
 124 existing surfaces with less laterally extensive rims (Fig. 1). The elevation difference between source

125 area floors and the rims ranges from 10 to 20 m. The elevation of the source area floors is the same as
126 that of the plains beyond the elevated margins on which the KSFs are superposed. The margins of all
127 studied source areas are breached (Figs. 2b, e, h, 3b), presumably enabling the extruded fluid to flow
128 out and propagate resulting in the formation of the observed KSF. Half of the studied source areas are
129 breached in such a way that would allow full drainage (Fig. 2b, h). The other half are drained by channels
130 with a spill point that has a higher elevation than the source area floor (Fig. 3b, c), or are blocked by a
131 topographic obstacle (Fig. 2c, e) preventing complete drainage. Elevated mounds (<10 m high; e.g.
132 Fig. 2b, h) or linear ridges are located inside those source areas that are superposed on inclined surfaces.
133 These raised features, which are not visible in images from either CTX or HiRISE, are not connected
134 with the surrounding rims by elevated areas.

135 In five cases, a single kilometre-sized flow has emerged from the source area and spread over
136 the surrounding terrain. In one example multiple overlapping flows originate from the same source area
137 (Fig. 3a,c) forming a complex KSF. This complex KSF then develops a wide range of morphologies at
138 the distal parts of these flows: some flows have relatively steep margins, others show a smooth transition
139 into the surrounding terrain, or a sinusoidal depression surrounded by well-developed, but laterally
140 limited margins that stand from 10 to 15 meters above the bottom of this depression (Fig. 3a). The width
141 of the margins associated with this complex KSF shows that they are generally wider closer to the source
142 area than in the distal parts. However, there is an exception from this general trend. In one case, we
143 observed that the width as well as the height of the margins increased towards the end of KSF (see
144 position of dashed topographic profile on Fig. 3b and f).

145 Our observations support and refine previous findings by Komatsu et al. (2016) that suggested
146 the presence of two distinct types of margins at the flow edges. One type is characterized by scarps
147 (Fig. 2f) that are several metres high, whereas the other type has a smooth topographical transition into
148 the surrounding terrain and displays a distinct albedo contrast on visible data (i.e., on Fig. 3c marked as
149 bright units). The smooth transitions can be found either associated with discontinuities in meter-high
150 margins (Fig. 3d) or on the edges of small channels propagating on the meter-high margins (Fig. 3e).

151 The terrain over which the studied flows were emplaced is only slightly inclined ($<6^\circ$), but steeper parts
152 are also present. The orientation of the flows reveals that the extruded material was moving downhill.

153 In one instance, we also observed ridge-like feature within the flow (Fig. 2c) as well as the
154 presence of a central channel within the flow surrounded by rims (Fig. 2j). On the other hand, we did
155 not observe the presence of large pits, rootless cones (i.e., constructional features caused by
156 accumulation of volcanic fragments resulting from water-lava interactions), subsidence or other signs
157 of violent explosions in association with source areas or at the margins of flows, which might be
158 expected for volcanic edifices.

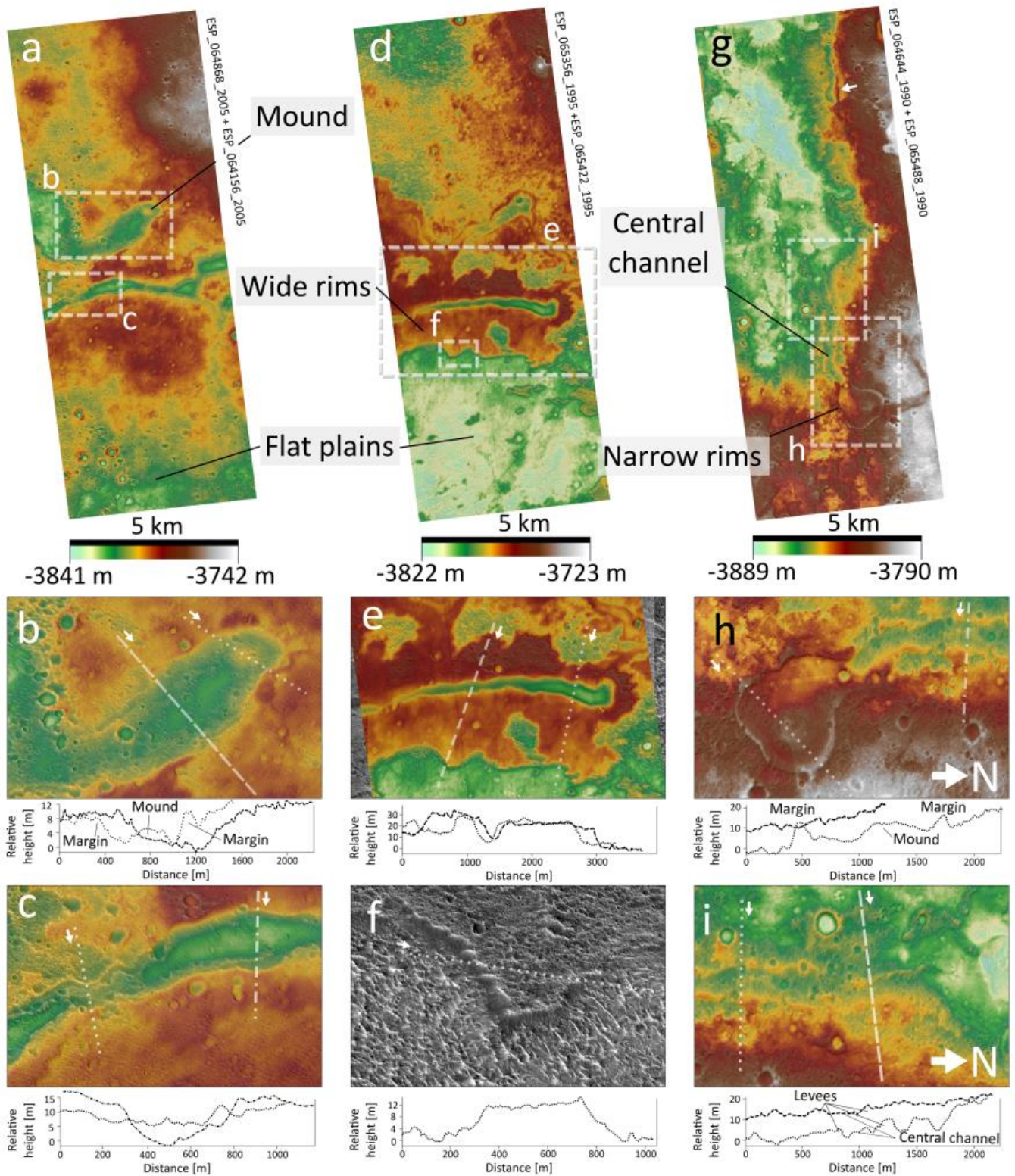
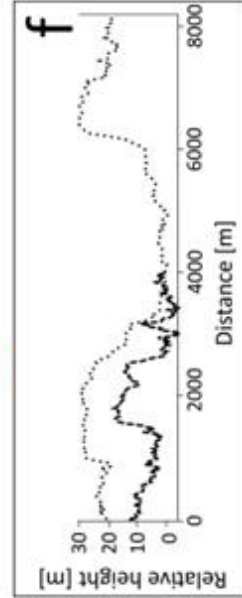
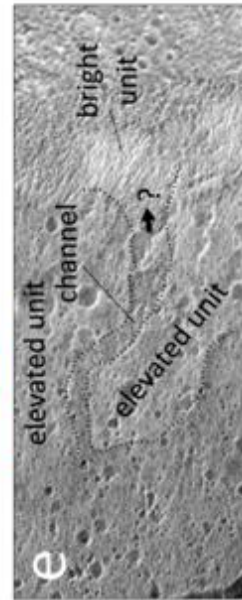
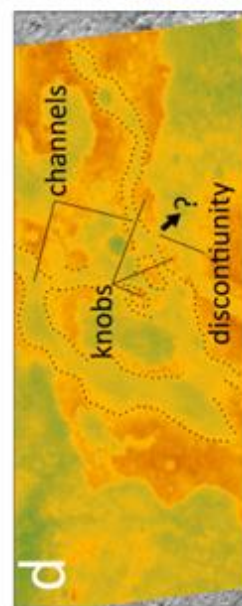
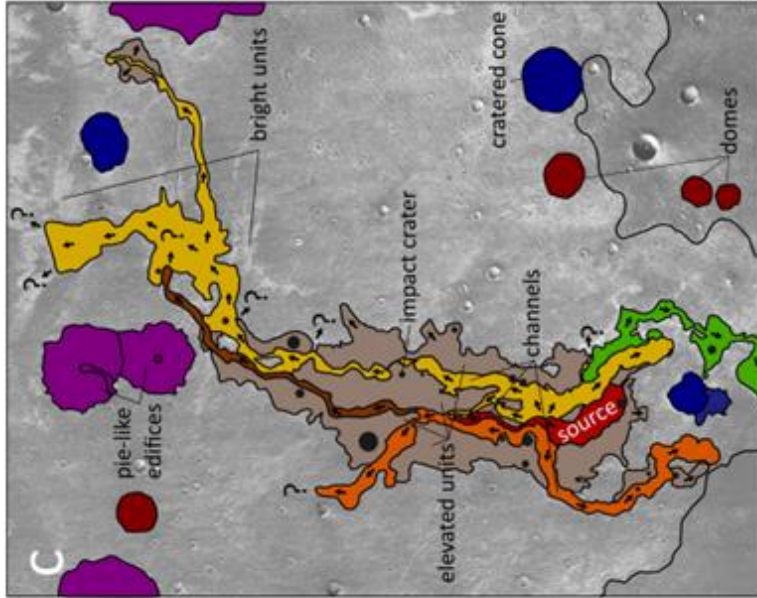
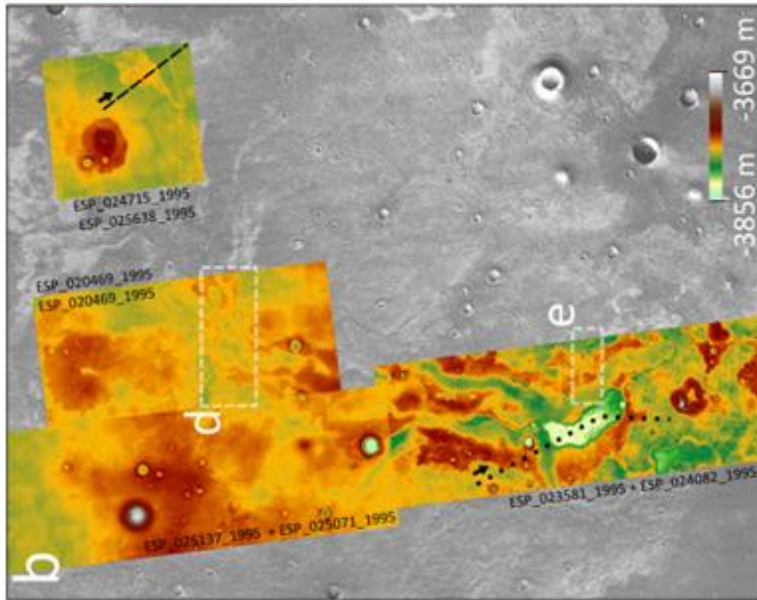
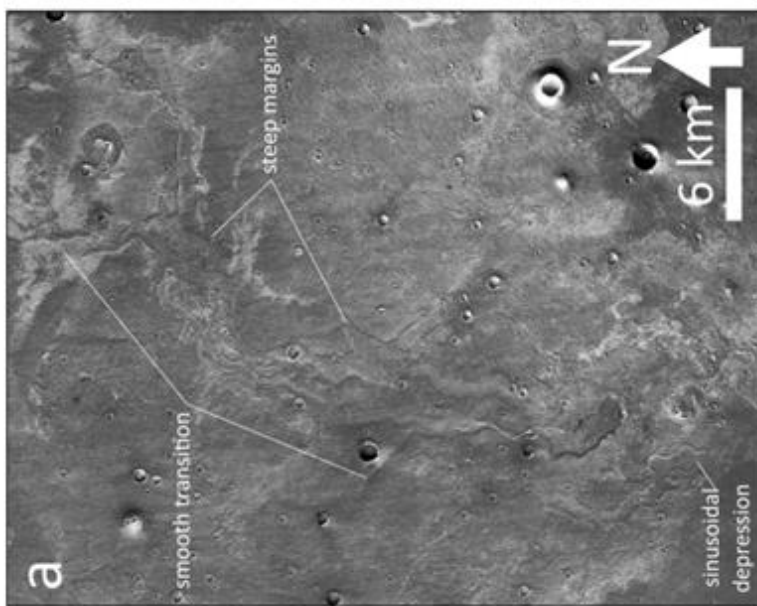


Figure 2: An example of three DEMs computed from HiRISE stereo pairs (a, d, g). For details about the used stereo-pairs see the description within the figure or Table 1. (b) Source area with well-developed central mound, breached towards SW; (c) A central channel; (e) Elongated source area

164 surrounded by kilometre-wide margins; (f) Margin of the flow, highlighting the different appearance
165 of the flow-unit and the underlying terrain (HiRISE ESP_065356_1995); (h) Source area with well-
166 developed mound, surrounded by distinct margins that are only few-hundred meters wide; (i) Middle
167 part of the KSF with central channel (dashed and dashed-dotted lines mark the position of topographic
168 profiles). Except for panels (h,i), north is towards the top of the images.



170 Figure 3: An example of multiple KSFs. (a) Several individual flows originating from a single
171 source area (image: MurrayLab CTX mosaic, centred at 19.246°N, 322.78°E; Dickson et al., 2018);
172 (b) Locations of 4 HiRISE DEMs together with the position of panels (d, e) and two topographic
173 profiles shown on panel (f); (c) Simplified geomorphological sketch map marking the position of
174 individual kilometre-sized flows together with the direction of the flow. Note the presence of
175 associated dome-shaped, conical and pie-like edifices close to the KSF. Different colours denote
176 individual observed flows and the small black arrows the proposed flow direction; (d) Discontinuity in
177 the flow margins surrounding the branching central channel; (e) Detail of elevated unit forming flow
178 margin that is intersected by small channels terminating at bright unit; (f) topographic profiles
179 associated with dashed and dotted line in panel (b).

180 4 Discussion

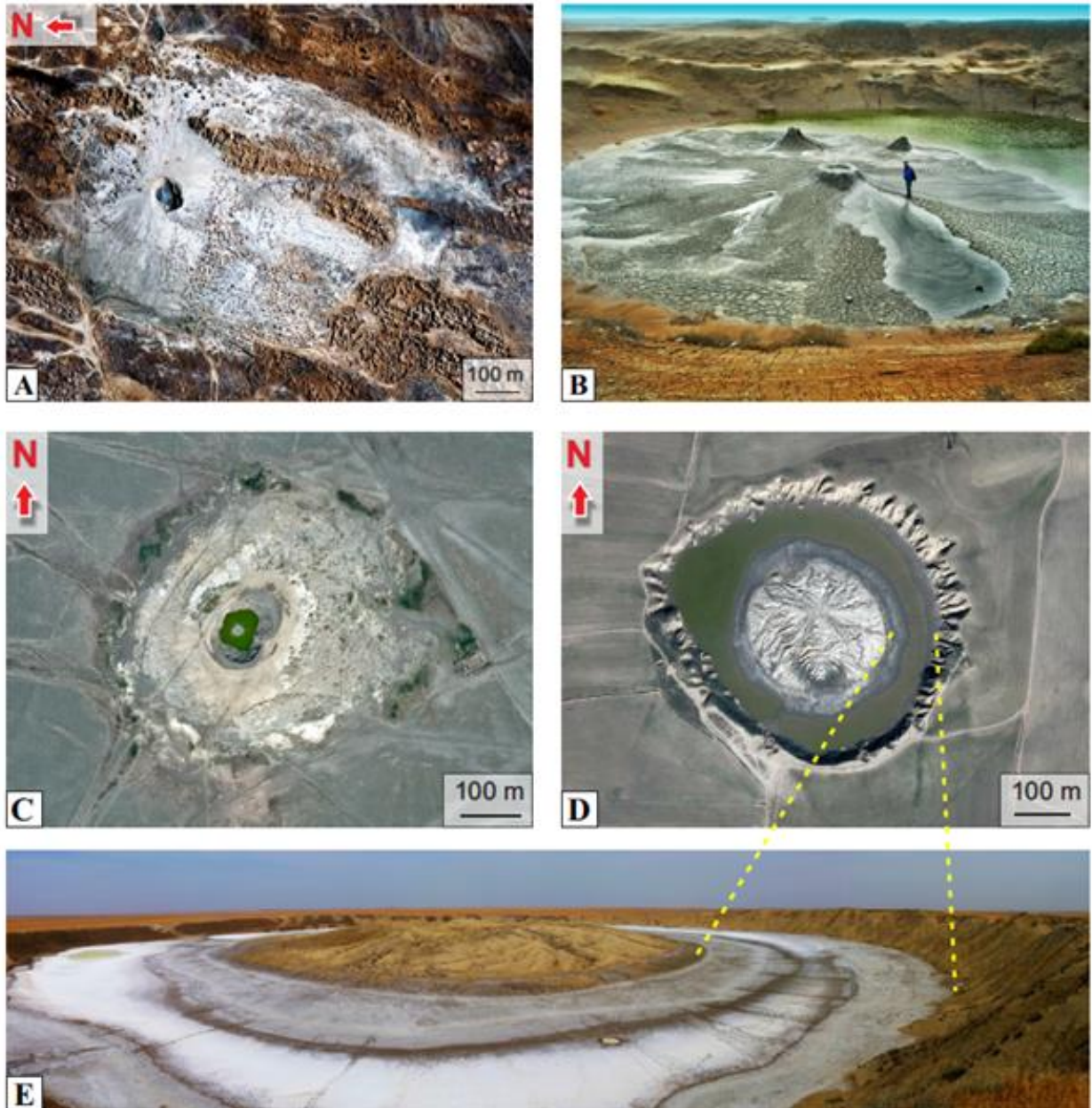
181 4.1. Source areas

182 The inclination of the surfaces as well as the shape of source areas are consistent with the
183 suggestion of Brož et al. (2019) that liquid material has been released from the source areas. Since the
184 elevation of the source area floors is similar to that of the surrounding plains, this suggests that the liquid
185 medium forming KSFs was emplaced directly onto the pre-existing surface from below. The topographic
186 data additionally reveal that some source areas are not breached and instead a central channel-like feature
187 with a floor that stands higher than the source area (Fig. 3b,c) emerges from them. These source areas
188 are not as deep as those we interpret as being fully drained, their floors are relatively flat (see topographic
189 profile on Fig. 3f) and no central mounds or large blocks or fractures are observed. This suggests that
190 part of the material remained within these source areas, partly infilling them, and likely buried any
191 positive relief present in the central part of the feeding vents. All source areas that seem to be fully
192 drained do show the presence of mounds. These mounds are not morphologically consistent with results
193 of mass wasting processes associated with rim collapses or with the remnants of subsidence of the source
194 area's floor. Instead, based on their position within the source areas they appear to be the site where
195 extruded material emerged at the surface.

196 These mounds cannot be identified on CTX or HiRISE visible images and are only revealed by
197 using topography data obtained from HiRISE DEMs. As only seven HiRISE stereo-image pairs are

198 available over six KSFs, hence for a very small subset of the KSF population, we do not know how
199 common such mounds really are within the entire KSF population in the southern part of Chryse Planitia.
200 However, we consider it likely that the central mounds could be a common, yet inconspicuous feature
201 of source areas of KSFs within the Chryse Planitia.

202 This conclusion is supported by the observation of terrestrial mud volcanoes where central
203 mounds are relatively common (Fig. 4) and by the work of Komatsu et al. (2016) who noticed the
204 presence of knobs with heights of several metres within the summit areas of dome-like edifices
205 associated with KSFs within this area. The authors interpreted them as vent structures composed of
206 accumulated sediment, like terrestrial gryphons or mud cones (for details about gryphons and their
207 formation see Mazzini and Etiope, 2017). Later, Brož et al. (2019) studied a larger population of these
208 domes and showed that these central knobs are common. They proposed an alternative formation
209 scenario; expansion of the mud within the feeding conduit towards the end of the eruption induced by
210 bubble growth due to the presence of boiling water (Hecht, 2002; Bargery et al., 2010). An analogous
211 mechanism operating in magma has been previously proposed to explain the strange appearance of
212 smooth mounds within Irregular Mare Patches on the Moon (Wilson and Head, 2017). The idea behind
213 this process is that the low pressure causes expansion of gas bubbles trapped within the liquid (mud or
214 lava), which extrudes a small amount of the remaining fluid from the feeding conduit (Wilson and Head,
215 2017, Brož et al., 2019). We propose that the central mounds reported here and the knobs within the
216 summit areas of dome-like edifices could be produced by such a volumetric expansion.



217

218 Fig. 4: Examples of low nearly flat sedimentary volcanoes on Earth where the floor of the crater
 219 has an elevation below that of the surroundings. A bulged morphology is often common in the central
 220 part of the crater floor (A, C, D are Google Earth satellite images). (A) Bahar Satellite MV, Azerbaijan,
 221 with very smooth surface texture and low elevation and central subsided crater. (B) Field view inside
 222 the Bahar Satellite MV crater where active gryphons and pools located in the central bulge release gas
 223 and mud. (C) Naftliche MV, Iran hosting a lake and a bulge in the central crater where gas and water
 224 seepages occur. (D) Gharniarigh MV, Iran, showing a distinct isolated island inside the crater. (E) Field

225 view of Gharniarigh MV, showing the central bulge. When the water filling the crater evaporates, the
226 area around the bulge features thick salt deposits originating from the seeping brines.

227 Alternatively, the central mounds could also have formed by the ascent of more viscous material
228 during the very late stage of the eruption caused by the partial depletion of the volatile source of the
229 liquid. Under such a scenario, we envisage that the viscosity of the mud, and hence its ability to
230 propagate, may vary during the course of eruption. At the beginning, low viscosity water-rich mud could
231 be released. Such mud would be mobile and capable of propagating to significant distances. As the mud
232 continues to be released, the eruption wane and the viscosity of the mud may change. Under such a
233 scenario, different viscosities of mud would form the domes and the KSFs. Further, viscosity contrasts
234 could explain why knobs occur in some constructs and mounds in others. Higher viscosity mud would
235 be associated with steeper and better recognizable knobs, while lower viscosity mud would
236 instead produce wider and less visible mounds.

237 It remains unclear whether mounds associated with KSFs are the result of the ascent of more
238 viscous material, due to the bubble growth, or combination of these processes, but in both cases these
239 mounds would represent the surface expressions of the feeding conduits. However, as these mechanisms
240 can occur both during lava as well as mud effusions, the presence of the mounds themselves cannot be
241 used as diagnostic evidence to favour sedimentary volcanism over igneous volcanism. Nevertheless, it
242 can be used as clear evidence supporting the extrusion of material from the subsurface. Our observations
243 hence complement previous works (Komatsu et al., 2016, Brož et al., 2019), suggesting that KSFs are
244 aggradational features formed by the transport of a fluid. This conclusion is additionally supported by
245 our observations of the rims around the source areas – while some are only dozens of meters wide, others
246 reach a width up to several kilometres. Our observations suggest that the slope of surrounding terrain is
247 responsible for these variations. Rims situated on relatively flat surroundings are wider than those
248 situated on an inclined surface. This again highlights that the material was extruded from the source
249 areas and spread into the surroundings by following the topographic gradient. However, in one case, we
250 observed that one of the studied north-south oriented flows has the western edge at lower elevation than

251 the eastern one (Fig. 2i and associated topographic profiles). Such imbalance in the flow edge elevation
252 suggests that the terrain over which the flow moved may have partly subsided after the flow's
253 emplacement and points to subsequent deformation of the surface.

254 4.2. Flow margins

255 We were able to confirm the observations of Komatsu et al. (2016), who identified two distinct
256 types of margins at the flow edges. We also observed that those surrounding the central large channels
257 are not continuous. They are often breached by meter-sized channels linking the central one to the bright
258 units (Fig. 3e), or alternatively, by troughs in the margins enabling the propagation of material from the
259 central channels to the surroundings (Fig. 3d). While meter-sized channels are relatively shallow and
260 hence they do not cut through the entire thickness of accumulated deposits. The troughs have the same
261 elevation as surrounding units suggesting that part of the margin was removed completely. In both cases,
262 no significant material accumulation was measurable in these areas of distinct brightness. This shows
263 that the fluid medium was capable of a dual behaviour: a) form elevated margins and b) also propagate
264 into the surroundings without displaying defined topographical boundaries at the surface. The main
265 evidence of these deposits is the resulting surficial expression indicated by brightness variations at the
266 surface. Such expression is unlikely to be related to igneous deposits, even in the case of very low
267 viscosity lavas. This is because once lava is released from the main channel, it would rapidly solidify
268 due to the heat loss. Hence, it would form a relatively resistant unit that should leave a topographic
269 relief, which is not observed. Therefore, the absence of such resistant unit suggests that the media that
270 ran out from these small channels and troughs behaved differently from lava. The deposited material
271 had to be easily erodible and could later be transported from these bright units by some other
272 mechanism(s).

273 Additionally, the presence of a sinusoidal depression associated with the complex KSF marked
274 on Fig. 3a supports a high erodibility and/or an additional transport of the effused fluid after the
275 emplacement. This sinusoidal depression is surrounded by margins standing 10 to 15 meters above the
276 bottom of this depression. This suggests that the incoming material was able to reach such heights, but
277 later was removed or withdraw elsewhere. As no outgoing channel(s) is observed, it is unlikely that the

278 material flowed out of the depression. If lava had flowed through the channel, it would accumulate
279 within such depression and leave some relict evidence that could be observed today, even if the lava
280 flow would partly subside after cooling and solidification and hence decrease its volume. However, at
281 the same time, released fluid has to be also capable of forming topographically positive landforms on
282 the flow edges as indicated by the topographic profile on Fig. 3h with a dashed line.

283 To explain these observations, we therefore propose a scenario that involves the release of large
284 volumes subsurface water-rich sediments that could modify the surface morphology and spread over a
285 broad area. It remains unclear whether the transport of such media was accompanied by evaporative
286 cooling leading to the formation of a protective icy-muddy crust (Brož et al., 2020) as the environmental
287 properties at the time of eruption are currently unknown. However, it should be considered that when
288 such mixture spreads over a wide area, the water may infiltrate into the subsurface if the thermal
289 conditions of the subsurface are favourable (Stähli et al., 1999). Alternatively, liquid water could
290 evaporate into the atmosphere, or the water-mud mixture could completely freeze and later the ice could
291 be removed by sublimation (Bargery et al., 2010; Brož et al., 2020a) leaving behind a rougher and hence
292 brighter surface. Independent of whether sublimation, evaporation, infiltration or a combination of these
293 processes was the dominant factor responsible for the water loss, the water would be lost without leaving
294 a detectable topographic expression, leaving instead a change in the roughness of the surface and hence
295 in the surface albedo.

296 However, it should be noted that when the water-rich mixture moved through narrow
297 topographic depressions, the transported sediment was able to leave deposits on the edges of the flows
298 and flow margins were formed. As a result, further movement was channelized and levees gradually
299 formed around them. As the amount of effused water-rich mud would not be stable over the course of
300 the entire eruption, this might cause overflows and hence a formation of laterally extensive margins.
301 Such mechanism is known from terrestrial floodplains where the water is capable to deposit the carried
302 sediments outside of the main channel during floods and hence form levees and distant layers of
303 sediments (Junk et al., 1989; Bedient et al., 2008; Syvitski et al., 2012).

304 Our observations do not reveal any evidence that favours igneous volcanism over sedimentary
305 volcanism. We do not observe signs of subsidence or explosive excavation, which are often present if
306 features were formed by magmatic eruptions (e.g., Sheridan and Wohletz, 1983; Wohletz and Sheridan,
307 1983; Lorenz, 1986; Brož and Hauber, 2013). We also did not find any signs of explosive activity on
308 the edges of observed KSFs or the presence of rootless cones that often accompany lava flows in other
309 areas of Mars where subsurface volatiles are present (e.g., Fagents and Thordarson, 2007). It remains
310 unclear whether volatiles were present in the subsurface during the period when the studied KSFs
311 formed and if yes, at what depth(s), but the presence of rampart craters within the study area (e.g.,
312 Barlow and Perez, 2003; Reiss et al., 2006) argues for their past presence. The combined observations
313 provide support of sedimentary volcanism over igneous volcanism. However, it should be stressed that
314 individual isolated evidence cannot be used alone as an argument to reject igneous volcanism. This is
315 because explosive features or signs of subsidence do not necessarily form at all effusive igneous
316 eruptions, and/or they could be hidden or modified by subsequent resurfacing processes beyond
317 recognition. Without ground truth data, therefore, the igneous scenario cannot be ruled out.
318 Nevertheless, our observations provide new evidence to support the hypothesis previously proposed by
319 Komatsu et al. (2016) and later supported by Brož et al. (2019) that these studied KSFs were formed by
320 subsurface sediment mobilization. While the central mounds can be explained by igneous as well as
321 sedimentary volcanism, the presence of bright units associated with the release of the fluid from the
322 main channels and the presence of sinusoidal depression would be challenging to explain by the
323 movement of lava.

324 4.3. Implications

325 As previously stated, the KSFs are not the only features within the southern part of Chryse
326 Planitia that have been proposed to be formed by subsurface sediment mobilization (Komatsu et al.,
327 2016; Brož et al., 2019). They are accompanied by conical, dome-shaped, and pie-like edifices of various
328 shapes and sizes, and a genetic connection between these types can be explored. Our study shows that
329 the southern part of Chryse Planitia is a region on Mars hosting a large variety of morphological shapes
330 (domes, cones or KSFs) potentially connected to sedimentary eruptions, whereas other fields of putative

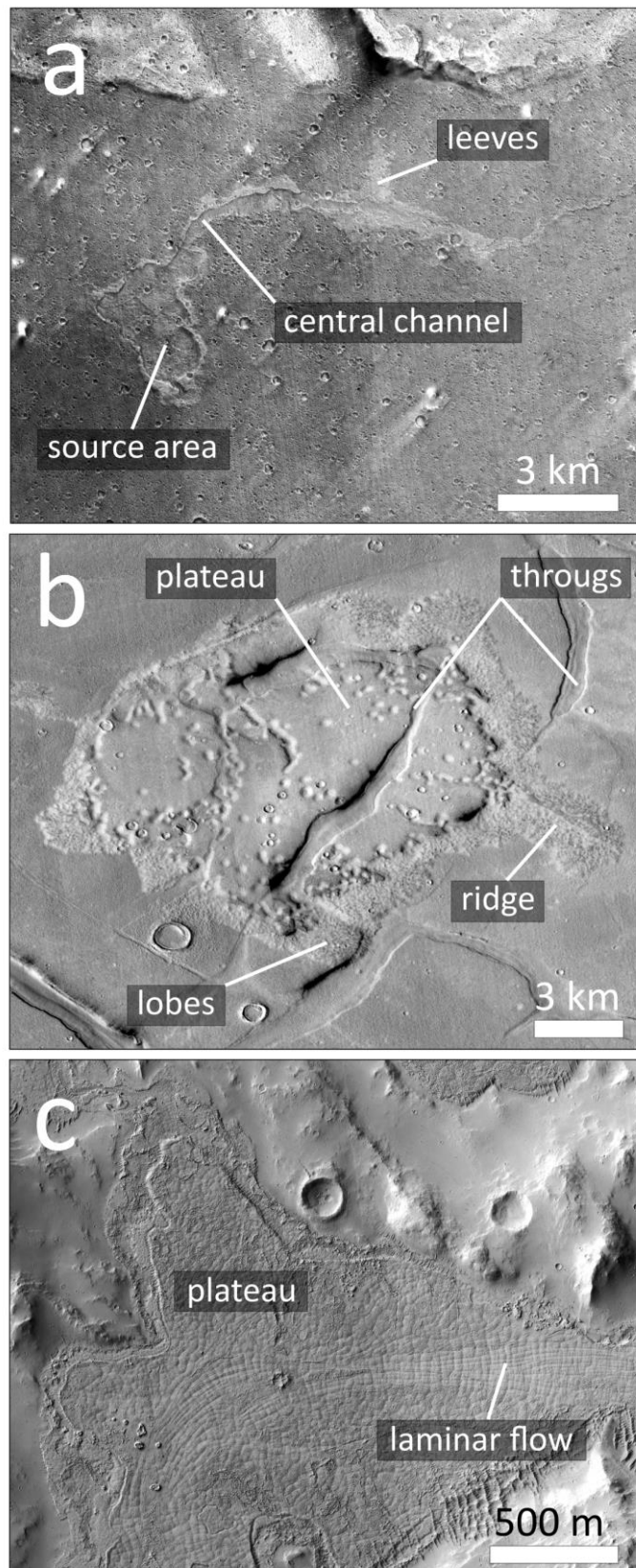
331 sedimentary edifices show larger uniformity in their populations (e.g., Skinner and Tanaka, 2007;
332 Okubo, 2016, Cuřín et al., 2021). For example, the extensive field of edifices within Coprates Chasma
333 shows the presence of pitted cones and associated sub kilometre flows that could be sedimentary
334 (Okubo, 2016) or igneous in origin (Broř et al., 2017), but large KSFs are missing. In contrast, the field
335 of edifices in Adamas Labyrinthus investigated by Ivanov et al. (2017) and Cuřín et al. (2021) shows
336 more than 200 KSFs, but a frequent occurrence of pitted kilometre-sized cones and domes was not
337 observed. These KSFs were interpreted in both studies as being large mud flows formed due to the
338 ascent of a low viscosity mixture of water and sediment. Another large field of kilometre-sized pitted
339 cones in the Nepenthes/Amenthes region, whose origin has been interpreted as either sedimentary
340 (Skinner and Tanaka, 2007) or igneous (Broř and Hauber, 2013), does not show the presence of well-
341 developed KSFs, domes or pie-like edifices. The large variability in the shapes of different edifices in
342 Chryse Planitia suggests that the extruded material had a relatively wide range of viscosities spanning
343 from very low viscosity and hence water-dominated mixtures that formed the studied KSFs, up to
344 relatively viscous mixtures that were unable to move over large distances and hence formed the domes
345 (Broř et al., 2019).

346 We also note that the studied KSFs (Fig. 5a) are very different in appearance from other putative
347 martian kilometre-sized mud flows proposed to be formed by low viscosity muds, such as those situated
348 in Adamas Labyrinthus (Fig. 5b, Cuřín et al., 2021) or the unique 40 km-long flow of Zephyria Fluctus
349 (Fig. 5c, Wilson and Mouginis-Mark, 2014). Flows in both areas are characterized by smooth central
350 uplifted plateaus usually surrounded by a topographically lower boundary formed by an assemblage of
351 lobes or hummocks. However, while uplifted units in Adamas Labyrinthus do not show any flow-like
352 expressions on their surfaces, the flow of Zephyria Floctues shows very clear signs of fluid flow in a
353 laminar fashion (Wilson and Mouginis-Mark, 2014). It remains unclear why such significant variations
354 in shapes and appearances among putative mud KSFs from different regions exist. Different
355 environmental properties, namely atmospheric pressure and temperature of the atmosphere or the
356 surface, might have played a role. Experimental studies (Broř et al. 2020a,b) showed that variations in
357 these parameters may have a profound effect on the way the mud propagates as well as its ability to

358 remain in a liquid phase under reduced martian atmospheric pressure. As these KSFs have been formed
359 in different martian regions and possibly also in different epochs (Ivanov et al., 2016; Brož et al., 2019),
360 these parameters may have varied significantly and hence have an impact on the resulting shapes of
361 these features. Unfortunately, this quandary remains unanswered for the conditions of the studied KSFs
362 in Chryse Planitia, since the investigation of their morphologies and morphometries did not provide any
363 evidence regarding the manner in which the water-rich mud propagated over the surface. Similarly, these
364 factors also remain unknown for other regions. These variations among putative martian mud flows
365 stress the need to develop numerical models capable of simulating how different environmental
366 properties may influence the morphology of resulting sedimentary edifices and flows.

367 Our observations add to the recognition that subsurface sediment mobilization is a potentially
368 significant process shaping several regions of the martian surface (e.g., Skinner and Tanaka, 2007;
369 Skinner and Mazzini, 2009; Okubo, 2016; Komatsu et al., 2016; Ivanov et al., 2017; Hemmi and
370 Miyamoto, 2017, 2018; Di Pietro et al., 2021). These regions are not all identical in their geologic
371 settings, hence it should not be expected that all surface manifestations of sedimentary volcanism are
372 morphologically similar. The depocenters that would host the source reservoirs have different sizes, the
373 sediments would have been sourced from different lithologies and by different processes, and even the
374 conditions (e.g., density stratification, overpressurization) that triggered the liquefaction and
375 mobilization would likely have been different.

376



377

378 Figure 5: A compilation capturing three typical examples of low viscosity KSFs from different
 379 regions of Mars proposed to be sedimentary in origin. a) KSFs at Chryse Planitia typically show a

380 source area, a central channel as well as well-developed levees (based on Murray Beta CTX mosaic,
381 Dickson et al., 2018; centred 19.87°N, 325.93°E); b) KSF in Adamas Labyrinthus are characterized by
382 smooth central uplifted plateaus surrounded by an assemblage of lobes. (based on Murray Beta CTX
383 mosaic, Dickson et al., 2018;; centred 39.14°N, 100.93°E); c) 40-km long flow of Zephyria Fluctus
384 has a very distinct surficial expression as flow patterns can be clearly recognized (based on HiRISE
385 image ESP_027464_1805; centred 0.65°N, 155.39°E).

386 For example, if the edifices studied by Okubo (2016) are indeed sedimentary volcanoes, their
387 source reservoir inside the extensional tectonic structure of Valles Marineris would likely be smaller,
388 and the accumulation process would have been different from those in Chryse Planitia, which are located
389 in a huge ancient impact crater and were accumulated by the transport processes that shaped the outflow
390 channels. It is equally unlikely that the water content in the source reservoirs of all possible sedimentary
391 volcanoes on Mars would have been similar, let alone identical. Specifically, the accumulation of
392 sediments through the circum-Chryse outflow channels would lead to the heterogeneous accumulation
393 of subsurface deposits at different depths that are expected to be variable in composition and water
394 content. The extrusion of mud from one or several of these reservoirs would be expected to generate a
395 greater variety of surface features with morphological differences higher than those n encountered in
396 regions with a more uniform source reservoir.

397 We therefore ascribe the observed morphological diversity of sedimentary volcanism-related
398 landforms in southern Chryse Planitia to a correspondingly large variability of the source reservoir
399 properties, and the studies KSFs would represent features that form by relatively small-volume eruptions
400 of water-rich sediments. As these surface deposits bear a record of exchange processes between the
401 deep, volatile-rich subsurface and the surface, they are very attractive targets for the exploration of past
402 sedimentary processes and possibly associated subsurface habitats.

403 **5 Conclusions**

404 Our study reveals that the morphology of KSFs in Chryse Planitia is consistent with the flow of
405 low-viscosity and hence water-rich mud across the martian surface. Based on the observed morphologies

406 of the studied KSFs it is possible to identify the source area from which the mud was extruded from the
407 subsurface. Once erupted, the transported sediment was deposited on the edges of the flows when its
408 yield strength was sufficiently high, and flows margins were formed. This formed a central channel with
409 leveed margins of various widths. Once the flow event terminated, the infiltration of water into the
410 subsurface and/or sublimation of ice removed substantial volumes from the terminal parts of the flows
411 thus explaining some of the observed morphologies associated with the terminal edges and shapes of
412 source areas. Our findings strengthen the hypothesis proposed by Komatsu et al. (2016) and Brož et al.
413 (2019) that these features are martian mud flows, formed by subsurface sediment mobilization as
414 opposed to igneous volcanism. Hence, these features represent an open window to the subsurface and
415 are interesting targets for in-situ analyses to access and investigate buried deposits (Komatsu and Brož,
416 2021) that are beyond our reach with the current technology.

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